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Treatment Technologies for Mining-Influenced Water

Review of Non-Peer-Reviewed Performance Data

Office of the Administrator
Office of Applied Science & Environmental Solutions
Environmental Solutions Division

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Treatment Technologies for Mining-Influenced Water

Review of Non-Peer-Reviewed Performance Data

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Acknowledgments

During technical and peer reviews of a 2020 USEPA report (EPA 542-R-20-002: Review of Peer-Reviewed Documents on Treatment Technologies Used at Mining Waste Sites), reviewers indicated awareness of other studies that were not included in the report. The reason was that development of EPA 542-R-20-002 relied on peer-reviewed studies found in publicly available literature (journal articles, published reports, and conference papers). This report compiles performance data and information from unpublished or non-peer-reviewed studies of technologies used at Superfund sites to treat mining-influenced water that were not captured in the 2020 report. Studies for 12 sites were obtained from either site contacts or the Superfund site web pages. One additional public study that was not included in the 2020 report was obtained through a Google search. Reviewers of the 2020 USEPA report are acknowledged for having prompted development of this report. The following individuals are acknowledged for their helpful comments and suggestions for improvements to this report during their technical and peer reviews: Drs. Anna Wade and Todd Luxton of the USEPA, Randy Parker, retired USEPA, and Dr. Jeffrey Gillow, Arcadis.

Cover Page Photo Credit: Anoxic limestone drain. Elizabeth Mine, Courtesy: USEPA Region 1.

Abbreviations

ALD	Anoxic Limestone Drain
AML	Abandoned Mine Lands
AOA	Area of Attainment
BCR	Biochemical Reactor
BOD	Biochemical Oxygen Demand
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfs	cubic feet per second
COC	Constituent of Concern
DL	Detection Limit
DOC	Dissolved Organic Carbon
FBR	Fluidized Bed Reactor
ft	feet
gpm	gallons per minute
GRO	Groundwater Remedy Optimization
HDS	High Density Sludge
ITRC	Interstate Technology and Regulatory Council
L	liter
lbs	pounds
µg/L	micrograms per liter
mg/L	milligrams per liter
$Mg(OH)_2$	magnesium hydroxide
min	minute
MIW	Mining Influenced Water
MNA	Monitored Natural Attenuation
N/A	not available
ND	non-detect
NPL	National Priorities List
OLEM	Office of Land and Emergency Management
PRB	Permeable Reactive Barrier
RO	Reverse Osmosis
RPM	Remedial Project Managers
SAPS	Successive Alkalinity Producing Systems
STC	Seep Treatment Cell
SRB	Sulfate Reducing Bacteria

SRBR	Sulfate Reducing Bioreactor
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
VFR	Vertical Flow Reactor

Executive Summary

During technical and peer reviews of a 2020 U.S. Environmental Protection Agency (USEPA) report (EPA 542-R-20-002: Review of Peer-Reviewed Documents on Treatment Technologies Used at Mining Waste Sites), reviewers indicated awareness of other studies that were not included in the report. The reason was that development of EPA 542-R-20-002 relied on peer-reviewed studies found in publicly available literature (journal articles, published reports, and conference papers). The purpose of this project was to compile unpublished or non-peer-reviewed data and information on technologies that have been tested or used to treat mining-influenced water (MIW) report, to discuss how they performed, and to provide information on limitations that influenced performance. This project documents the performance of these MIW treatment studies as reported in the unpublished and non-peer-reviewed studies. This project is not a critical review of the MIW studies, and no analysis or opinion was included outside of efficiency calculations. The intention is that the collected information may contribute to knowledge on these technologies to support decisions about whether a particular treatment technology could be applied at other sites with similar results. Data studies discussed in this report were performed under Superfund by contractors under Regional USEPA or other Federal or State Agency control and assumed to have had approved QA/QC plans, and no additional quality assessment of data was performed by USEPA Office of Research and Development (ORD). However, calculated percent recovery values using the secondary data have been verified to have been accurately calculated.

For this project, a total of 13 non-peer-reviewed studies that documented performance from active (require constant care, energy supply or chemical reagents), passive (do not require constant care, focused on biological or natural reactions), or semi-passive (requires occasional care and amendment or chemical reagent additions) treatment systems were compiled. These were treatment systems implemented at hard rock mining sites for remediating contaminants from MIW. This report contains summaries of data from treatability studies, pilot studies, monitoring and maintenance reports, reports of activities, demonstration reports, and five-year review reports (all referred to as treatability studies for the purposes of this project). The search yielded a total of 13 treatability studies from 1997 to 2024, encompassing 12 sites and 13 treatment technologies. Studies for treatment systems at 12 sites were obtained from either site contacts or the Superfund site web pages. One additional public study that was not included in the 2020 report was obtained through a Google search. Minimum and maximum influent concentrations and their associated effluent concentrations for each of the analytes provided in each study found were documented and removal efficiencies provided in the studies were documented or calculated for this report if not provided in the treatability studies found. Removal efficiencies for four conditions were calculated where available. The four conditions are the maximum influent concentration treated/corresponding effluent concentration attained, minimum influent concentration treated/corresponding effluent concentration attained, maximum effluent concentration attained/corresponding influent concentration treated, and minimum effluent concentration attained/corresponding influent concentration treated. While removal efficiencies for all four conditions are presented in this report, the influent and effluent are only presented for the maximum and minimum influent concentrations treated and their corresponding effluent concentrations attained. The other conditions (maximum and minimum effluent and corresponding influent) are presented in Appendix A.

Active technologies reviewed in this report are the fluidized bed reactor (FBR) located at the Smoky Canyon Mine in Idaho and pond neutralization at White King Mine in Oregon. The FBR treatment focused on selenium removal and reported a 97% removal efficiency (Formation Environmental 2023). The pond neutralization treatment involved the application of hydrated lime to a pond containing MIW.

Constituent of concern (COC) concentrations were measured before and after lime application at pond depths of 9.1 and 15.2 meters (~30 and 50 feet) (Roy F. Weston 1999). Pond neutralization had the greatest removal efficiency for dissolved aluminum compared to other COCs included in the study, at 94% – 96%.

Passive technologies included Aquafix® (water-powered quicklime application system), biochemical reactor (BCR), permeable reactive barrier (PRB), constructed wetlands, evaporation, and monitored natural attenuation (MNA). Only one treatability study was found for the Aquafix®, constructed wetlands, evaporation, and MNA technologies; therefore, they could be compared generally with other passive technologies but not with treatments of these specific technology types. Aquafix® implemented at Silver Dyke Adit at Carpenter-Snow Creek Mine had average removal efficiencies for COCs ranging from 89.1% (for dissolved aluminum) to 98.3% (for dissolved lead) (Tetra Tech 2017). The constructed wetlands treatment design at Champion Mine in Oregon focused on arsenic and iron removal, and the study reported a 91.8% maximum removal efficiency for total arsenic and a 94.2% maximum removal efficiency for total iron (CES 2013). Evaporation and MNA were each implemented at the Monticello Mills Tailings site in Utah for the purposes of uranium reduction. Evaporation resulted in a maximum uranium plume reduction of 39.3% over 6 years (USDOE 2022), while MNA resulted in a maximum uranium plume reduction of 48.1% over 11 years (USDOE 2021).

Four of the passive studies were BCR treatments: Danny-T Adit in the Barker-Hughesville Mining District in Montana, Blue Ledge Mine in California, Ely Copper Mine in Vermont, and Formosa Mine in Oregon. The BCRs had varying substrates; some were stand-alone BCRs, and others were part of treatment trains. The stand-alone BCRs were located at Danny-T Adit, Blue Ledge Mine, and Formosa Mine. Some BCRs at these locations were also part of treatment trains as described below. The Danny-T Adit BCRs had maximum removal efficiencies that ranged from > 72% (thallium) to > 99% (cadmium and copper) (CDM Smith 2014), while the Blue Ledge Mine BCRs had maximum removal efficiencies ranging from 10.2% (nickel) to 99.9% (cadmium, copper, and zinc) (CDM Smith 2015). The stand-alone BCRs at Formosa Mine had a maximum removal efficiency of 99.2% for dissolved zinc (Parametrix and CDM Smith 2014).

The BCRs that were part of treatment trains were at the Danny-T Adit in the Barker-Hughesville Mining District, Formosa Mine, and Ely Copper Mine. The Ely Copper Mine study reported a range of removal efficiencies for COCs from -26.6% for manganese to 99.9% for iron, with a removal efficiency greater than 90% for aluminum and iron (McSurdy et al. 1997). The Danny-T Adit and Formosa Mine studies provided influent and effluent data for multiple COCs. Maximum removal efficiencies for dissolved metals at the Danny-T Adit ranged from > 92% for aluminum and arsenic to > 99% for cadmium and copper (CDM Smith 2014), while the maximum removal efficiency for nickel at Formosa Mine was negative, all other COCs had a positive maximum removal efficiency with a maximum of 99.7% for dissolved copper and dissolved zinc (Parametrix and CDM Smith 2014). Several technologies reviewed in this report resulted in negative removal efficiencies. There are multiple reasons for the negative efficiencies including insufficient, inaccurate, or ineffective substrate mixtures in particular technologies; harsh weather conditions that affected substrates and/or microbial communities; clogging due to metals precipitation; and automated system failure (needing more hands-on maintenance).

The Danny-T Adit and the Blue Ledge Mine studies also included analysis of the pre-treatments that were included as part of the treatment trains. Magnesium hydroxide ($Mg(OH)_2$), Chitorem® (proprietary material made up of processed crab shells), and successive alkalinity producing system (SAPS) pre-treatment barrels were included in the Danny-T Adit study, and two SAPS barrels were included in the

Blue Ledge Mine study. The $Mg(OH)_2$ barrel had a removal efficiency for metals ranging from 4.7% for dissolved manganese to 99.8% for dissolved lead (CDM Smith 2014). Although the Chitorem® pre-treatment resulted in negative removal efficiencies for arsenic, cobalt, and nickel, positive removal efficiencies were observed for other metals and ranged from 82.6% for total cadmium to 99.2% for total lead. There were also negative removal efficiencies for arsenic and manganese in the SAPS pre-treatment barrels, but positive removal efficiencies ranged from 30.9% for total arsenic in BCR5 at Blue Ledge Mine (CDM Smith 2015) to 100% removal of dissolved copper at Danny-T Adit (CDM Smith 2014). Removal efficiencies of 99.9% were also observed in BCR treatment: dissolved cadmium and copper at BCRs 4 and 5 at Blue Ledge Mine; total cadmium at BCR 5 at Blue Ledge Mine; and dissolved zinc at the Danny-T Adit and BCRs 4 and 5 at Blue Ledge Mine.

Passive permeable reactive barriers (PRBs) were installed at three of the mine study sites: Ballard Mine in Idaho, Monticello Mill Tailings in Utah, and Conda/Woodall Mine in Idaho. The Ballard Mine study was different than the others in that it did not provide a direct correlation between influent and effluent values for COCs; therefore, removal efficiencies could not be determined. Maximum removal efficiencies for metals at Monticello Mill Tailings were 84.8% and greater for arsenic, molybdenum, nitrate + nitrite selenium, uranium, and vanadium, but negative for manganese which had a removal efficiency of -890.5%. Conda/Woodall Mine COC removal efficiencies were mostly positive with metal removal efficiencies of up to 99.9% including for cadmium, selenium, and zinc. Dissolved and total arsenic, total iron, and total and dissolved manganese, all had negative removal efficiencies (Formation Environmental and NewFields 2022).

The semi-passive treatments include a selenium-reducing bioreactor at Smoky Canyon Mine in Idaho and a vertical flow reactor (VFR) at Reed Mercury Mine in California. The selenium-reducing bioreactor had a removal efficiency ranging from 5% to 99% (Formation Environmental 2017). The VFR treatment was successful in reducing arsenic, iron, and cobalt from MIW influent, but was not successful in reducing other metals, including nickel and manganese (Terracon 2022 and 2023). While each site had different concerns, constraints, treatment technologies and primary COCs, some common themes arose in the lessons learned. Issues impacting the performance of the treatments generally fell into three categories:

- The need for more maintenance to ensure the system is functioning correctly both at system start-up and regularly through operations;
- Better site understanding prior to design and implementation of the treatment technology, including better characterization of the soils and subsurface hydrology;
- Recommended design improvements related to undersized containers, flow rate adjustments to balance treatment reaction times, improved reaction substrate materials and quantities, and consideration for temperature impacts on reactions.

Cost was rarely provided in the treatability studies. If studies included costs of the technology itself (i.e., capital costs, plus materials), they were included in each technology chapter. Any cost information in this report is presented as reported in the treatability studies and has not been adjusted for inflation.

Current treatment of MIW at Superfund mining sites generally includes costly water treatment plants (e.g., reverse osmosis, high density sludge (HDS) lime), which are viewed by the public as having the most potential to alleviate impacts to human health and the environment, as well as being common industrial treatment technologies with documented performance capabilities. This project focused on alternative active technologies, as well as all passive and semi-passive treatments, which tend to be less costly. Passive systems typically require less maintenance than active systems and are more cost-effective (USEPA 2014). A publicly available report of alternative technologies tested at sites and showing performance, including those that are passive or less costly, might provide remedial project managers (RPMs) with more confidence in technologies with which they have less knowledge or familiarity. The study data compiled in this report can be used as a reference for RPMs and others to review various MIW treatment options to support decisions on which treatment technologies may be viable alternative options to costly active treatment systems.

1 Introduction

During technical and peer reviews of a 2020 USEPA report (EPA 542-R-20-002: Review of Peer-Reviewed Documents on Treatment Technologies Used at Mining Waste Sites), reviewers indicated awareness of other studies that were not included in the report. The reason was that development of EPA 542-R-20-002 relied on peer-reviewed studies found in publicly available literature (journal articles, published reports, and conference papers). The purpose of this project was to compile non-peer-reviewed data and information on technologies that have been tested or used to treat mining-influenced water (MIW), report on how they performed, and provide information on limitations that influenced performance. Per the EPA Reference Guide to Treatment Technologies for Mining-Influenced Waters (2014), mining influenced-water (MIW) is characterized as "*as any water whose chemical composition has been affected by mining or mineral processing and includes acid rock drainage (ARD), neutral and alkaline waters, mineral processing waters and residual waters. MIW can contain metals, metalloids and other constituents in concentrations above regulatory standards*". The intention is that the collected information may contribute to knowledge on these technologies to support decisions about whether a particular treatment technology could be applied at other sites with similar results.

This project acquired non-peer-reviewed, site-specific performance data on MIW treatment technologies for metals/metalloids/sulfate field tested (pilot or full-scale) at metal mining Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites. The overall goal was to compile previously non-peer-reviewed data to assist the Office of Land and Emergency Management (OLEM) and remedial project managers (RPMs) in determining what technologies have been tested, details on how they performed, longevity of their performance, and the details that influenced performance to enable decisions for a technology's use or exclusion at other sites. To work toward meeting this goal, the USEPA conducted a literature search to accumulate and consolidate treatment technology performance data provided in non-peer-reviewed CERCLA documents. Treatability studies examining treatment technologies used for remediating MIW have been conducted at many hard rock mining sites and range in type from bench studies to full-scale field studies. The literature review for this report was conducted to capture the capabilities, efficiencies, technological and site-specific requirements, and lessons learned for technologies and methods used. This report is not intended to provide a comprehensive overview of all mining-influenced waters treatment options, rather it is intended to supplement existing literature. USEPA's 2014 *Reference Guide to Treatment Technologies for Mining-Influenced Water* provides a detailed overview of treatment technologies and the treatable contaminants, pre-treatment requirements, maintenance, performance, and costs. The report addressed both passive and active technologies.

1.1 Methodology

1.1.1 Project Scoping

Treatments of interest included monitored natural attenuation (only if there was concentration data provided prior to the start of monitoring and at time points post initial assessment that were (or are) used to evaluate its performance); active treatments including biogenic sulfide, chemical sulfide, fluidized bed reactors, electrocoagulation; and both passive and semi-passive treatments including wetlands, vertical flow ponds, biochemical reactors, anoxic limestone drains, oxic limestone drains, in-pit amendments, and innovative lime delivery systems (e.g., Aquafix®). Types of treatment and studies that were not of interest included the following:

- Management of solid waste material (e.g., removal, caps/covers) to mitigate or remove the source of the MIW, diversions of water, or plugging of adits, unless water behind the plug or water exiting the adit through a controlled flow is also treated.
- Standard industrial technologies, such as high-density sludge (HDS) lime treatment (or standard lime treatment) within a water treatment plant, nanofiltration, or reverse osmosis (RO).
- Standard pump and treat for groundwater, where ion exchange, RO, filtration, or lime is used as primary treatment in a treatment plant.
- Bench studies in the absence of a subsequent field pilot or full-scale treatment system.

To develop this project, USEPA first identified CERCLA mining sites for inclusion through a search of the USEPA Superfund Site Searchable Database (https://cumulis.epa.gov/supercpad/CurSites/srchsites.cfm) using the following search options:

- Site Status – Active
- State – All States
- Region – All Regions
- Federal Agency – All Agencies
- Native American Interest (NAI) – All (which means those with yes and those with no would be included)
- Indian Entity – All Entities
- NPL or Superfund Alternative Approach (SAA) – All Sites (which means sites with any status or stage of the NPL process would be included)
- Non-NPL Status Category – All Sites
- Site Type – Mining, sub-type box – All
- Construction Complete – All
- HRS Score Range
- Federal Facility Indicator – All
- Site-wide Ready for Anticipated Use – All
- Human Exposure Under Control – All Sites
- Groundwater Migration Under Control – All Sites
- Include contaminant details in Excel search results

The query identified 542 sites, which were assessed for project inclusion through the steps in Figure 1-1:

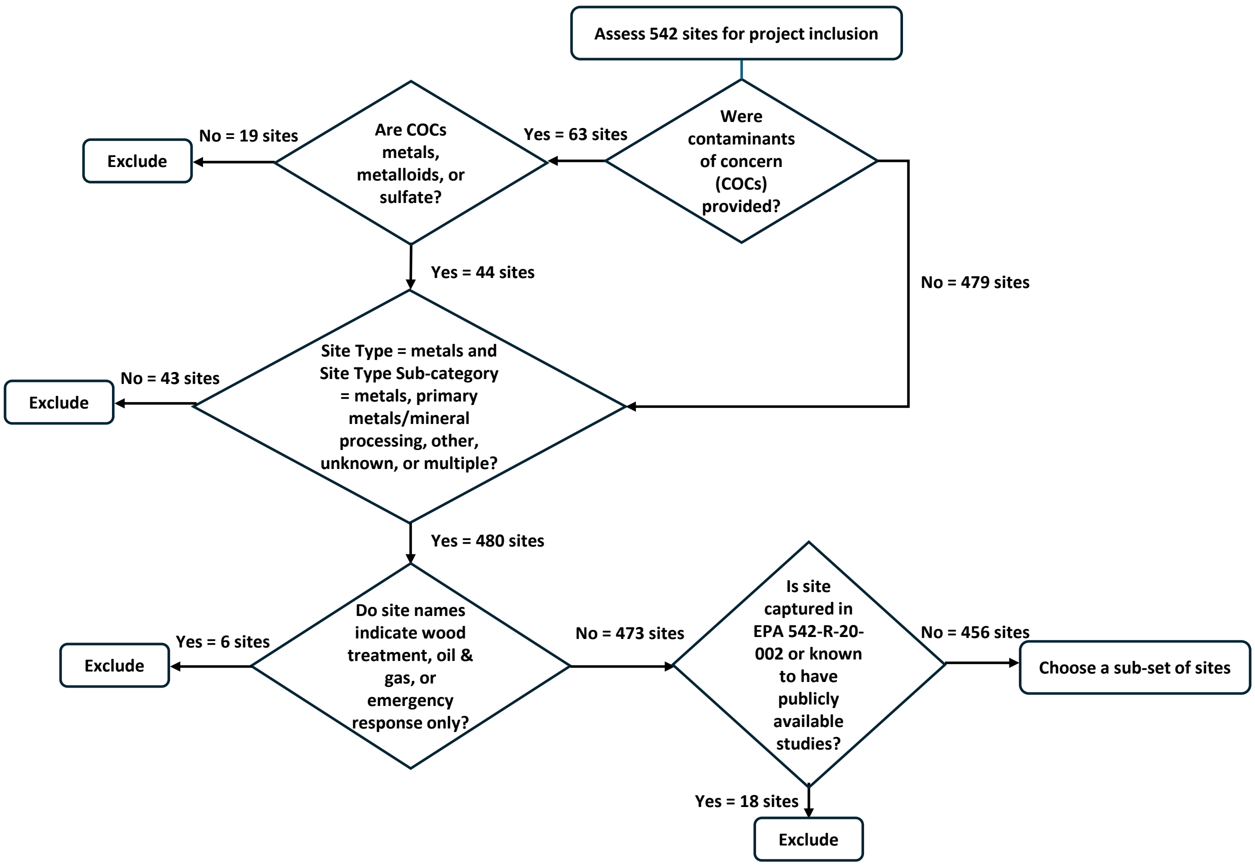

Figure 1-1. Flow diagram of the decision points to determine whether to include a study in the project.

The query identified 542 sites, 63 of which had available information on constituents of concern (COCs). The sites not having a metal/metalloid or sulfate COCs were removed (19 sites), leaving 44 sites with known COCs. The remaining group of 523 sites (44 with known COCs plus 479 sites without COCs listed in the database) was further sorted by "Site Type" and "Site-type Sub-Category." Those not having both "mining" listed in the "Site Type" and "metals" or "primary metals/mineral processing" listed, and those having "non-metal minerals" listed in the "Site-type Sub- Category" were removed (43 sites). Site types retained included those where the "Site-type Sub-Category" was listed as "other," "unknown," or "multiple" because of a lack of information to exclude them, resulting in a list of 480 sites retained. From these sites, 3 sites were excluded based on site names indicating they were oil and gas, or wood treatment sites, 3 sites that were emergency response only listings (i.e., sites that require a quick removal action or other activity and not a water treatment) were excluded, and 18 sites previously captured in the OLEM/Office Research and Development publication EPA 542-R-20-002 (USEPA 2020) (or not captured in the publication but known to have publicly available studies) were excluded, leaving 456 sites.

Of these 456 sites, a subset was chosen to focus on for this project. The subset chosen included only NPL sites (any stage of the process) and non-NPL sites that were noted as being managed by states, other federal agencies, managed under enforcement, or associated with sites managed by any of these entities (i.e., noted as "part of another NPL" site or "part of another Non-NPL site"). Because there may have been decisions that have not yet been updated in the USEPA database, all sites having a federal agency identified, regardless of whether the "Non-NPL Status" included the statement "Other Cleanup Activity – Federal Facility-Lead Cleanup" were retained. The resulting file contained 191 sites.

The 191 sites were screened to determine where case study data could be obtained through searching online for documentation indicating whether sites had pilot testing or current water treatment meeting the criteria for this project. The screening was conducted by searching for the site's ID and/or name and/or aliases on one or more of the following sites:

- On-scene coordinator (https://response.epa.gov/)
- Superfund sites
    - https://www.epa.gov/superfund/search-superfund-documents
    - https://www.epa.gov/superfund/search-superfund-sites-where-you-live
    - https://cumulis.epa.gov/supercpad/cursites/srchsites.cfm
    - https://semspub.epa.gov/src/home/search.jsf
- Other federal agency-specific websites
- Bureau of Land Management (Department of the Interior) (https://www.blm.gov/)
- Forest Service (U.S. Department of Agriculture) (https://www.fs.usda.gov/)
- National Park Service (Department of the Interior) (https://www.nps.gov/index.htm)
- State agency websites, if a site was noted as managed by a state
- Google - Using the site name or USEPA ID with keywords "water treatment", "treatment", "remediation" and/or "Superfund" along with the state of federal agency (where appropriate). In most cases, this led to finding government reports that were not found by searching USEPA, state, or other federal agency sites.

As documents were found for each of the 191 sites, they were searched for the words "treatment," "water treatment," or "pilot" and a scan of the context was conducted to find indication of whether MIW had been treated or is currently being treated at each site. Of the 191 sites, 32 sites were identified as having documentation indicating a pilot test had been done, or there is current treatment meeting the criteria for this project. Non-peer-reviewed studies documenting performance (i.e., comparison between influent and effluent or pre and post treatment concentrations of elements/ions or parameters) and site-specific data on MIW treatment technologies for metals/metalloids/sulfate field tested (pilot or full-scale) at metal mining CERCLA sites were sought for this project.

RPMs or other agency contacts were contacted to obtain study data if documents were not readily found through online searches. Data tabulated from studies obtained were restricted to the actual treatment of water, where influent and effluent concentrations of elements/ions or parameters were monitored to assess the performance of a technology. Thirteen of the 32 sites were found to have relevant documents, including treatability studies, pilot studies, monitoring and maintenance reports, reports of activities, demonstration reports, and five-year review reports (all referred to as treatability studies for the purposes of this project). The treatability studies were reviewed, and performance data and other key information were tabulated in an Excel spreadsheet (see Appendix A). The performance data and other data collected from the treatability studies and entered into the Excel spreadsheet included the following:

- site name
- CERCLA ID
- operable unit
- treatment technology tested
- source of MIW

- whether treatment is part of a treatment train
- geographic conditions
- scale and duration of the study
- COCs
- maximum and minimum influent and the associated effluent
- maximum and minimum effluent and associated influent
- average influent and effluent if provided
- average removal efficiency if provided
- water chemistry associated with documented concentrations
- load information if available
- whether treatment goals were met
- limitations/constraints
- longevity
- lessons learned
- cost data
- any other performance details

1.1.2 Data Evaluation Procedures

The alternative treatment technologies presented in this report from 13 sites were categorized as active, passive, or semi-passive technologies. All three of these technology types combine physical, biological, and chemical approaches to lower acidity in groundwater and reduce metal concentrations. Active technologies typically rely on the addition of alkaline chemicals to neutralize acidity. Active technologies also require constant care and chemical reagents for continued operation (Zipper et al. 2018 and Taylor et al. 2005). Passive technologies do not require constant oversight and maintenance and do not require chemical additions after construction (Zipper et al. 2018 and Kleinmann et al. 2022). Passive technologies rely on natural biological, geochemical, and gravitational processes and provide an appropriate environment for those processes. Semi-passive technologies combine the qualities of active and passive technologies and do not require consistent oversight and maintenance (Kleinmann et al. 2022). Semi-passive treatment technologies include periodic addition of amendments and chemicals using approaches that do not require complex machinery. These systems rely on gravity flow and the infrequent management of accumulating metal residue.

The synthesis of data tabulated in the spreadsheet in Appendix A is presented in this report by grouping technology types (i.e., active, passive and semi-passive) and treatment types within those technology types (e.g., wetlands, fluidized bed reactors), with details provided, such as ranges of maximum (and minimum) concentrations treatable and their corresponding effluent concentrations obtained, percent removal efficiencies, and ranges of average influent and effluent concentrations and efficiency data when provided in the studies. When removal efficiencies were not provided in the studies, they were calculated for this report for four conditions, where available, using the influent and the corresponding effluent. The four conditions are the maximum influent concentration treated/corresponding effluent concentration attained, minimum influent concentration treated /corresponding effluent concentration attained, maximum effluent concentration attained /corresponding influent concentration treated, and minimum effluent concentration attained /corresponding influent concentration treated. If the corresponding effluent concentration was a non-detected value, one-half the detection limit was used for calculating the removal efficiency. The *Removal Efficiency* sections of this report indicate whether the efficiencies were reported by the relevant studies or calculated for this report. While removal efficiencies for all four conditions are presented in this report, the influent and effluent are only presented for the maximum and minimum influent concentrations and the corresponding effluent concentrations. The other conditions (maximum and minimum effluent concentrations and corresponding influent concentrations) are presented in Appendix A.

MIW concentrations included in Appendix A and discussed in this report are influent and effluent concentrations from technologies treating MIW directly, upgradient and downgradient for technologies treating mining-influenced groundwater, or pre- and post-treatment for MIW treated as a whole (e.g., a pond or groundwater plume). Concentration and removal efficiency data, as well as flows treated, costs, and lessons learned, are presented within each technology chapter. The focus of this report is treatment for reductions in metals, metalloids, sulfate, and associated parameters. In some studies, other analytes (e.g., calcium, sodium, chloride, phosphorus) were also measured at several sites and those data, while not reported here, are included in Appendix A.

Minimum and maximum pre-treatment and corresponding post-treatment data were obtained from evaluation of tables or text in the treatability studies. Minimum pre-treatment concentrations chosen were the lowest concentrations reported that exceeded a study's reported detection limit (DL) for each constituent. The DL or range of limits are included in the spreadsheet for informational purposes. This same approach was followed for maximum values — maximums are the highest value not indicated as below the DL. For any influent values that are not above the DL, they are noted as "non-detect" (ND) for both maximum and minimum values. If influent maximum or minimum are ND, but there are values above detection in the effluent, the range of effluent values above the DL are provided.

Average pre-treatment and post-treatment concentrations were reported by the authors of the treatability studies. Unless otherwise noted, minimum, maximum, and average removal efficiencies were reported by the authors of the case studies. Concentrations reported in treatability study references were converted to a consistent unit of measure where applicable (either milligrams per liter [mg/L] or micrograms per liter [µg/L]) for comparison across technologies.

For each technology, data in the appendix were collected across all treatability studies for each of the constituents treated to present the technology-based minimum and maximum pre-treatment concentrations (influent) and their corresponding post-treatment concentrations (effluent), the average pre-treatment and post-treatment concentrations where available, and the removal efficiencies. These data are presented in tables and discussed in each technology chapter.

1.2 Limitations

As noted above, relevant treatability studies were identified for 13 sites. Relevant studies could not be identified for the remaining 19 sites due to a variety of reasons including no treatment was constructed, the treatment was out of the scope of this project, a lack of water quality data, restrictions on making those data public, and a lack of response from any federal or state entity or responsible party to the request for documentation.

Although data from the treatability studies were examined in aggregate within each technology type (i.e., active, passive, and semi-passive), it is important to note that not all treatability studies were conducted in the same way. Some studies have different detection limits for the same constituents or different overall water chemistries, which may have influenced treatability study results in unknown ways. For some technologies, data reported in a treatability study may not be the most effective data for assessing treatment.

EPA's Reference Guide to Treatment Technologies for Mining-Influenced Waters (2014) identifies 30 potential treatment technologies and describes in detail seven passive technologies and nine active technologies. This report covers two active, seven passive and two semi-passive treatment technologies. The treatment technologies discussed herein are limited by the availability of relevant data and reports. No inferences about technology prevalence or industry-preferred treatment options should be made based on the types of treatments discussed in this report.

For most treatment technologies, this report includes only one or two treatability studies that met the required criteria; therefore, the ability to determine the general capability of those technologies is limited. In instances where a given constituent may have been monitored in only one treatability study, generalized capability of the technology with respect to that constituent is limited. The constraints and limitations presented for each of the technologies in each chapter were identified by the authors of the cited studies. The noted constraints are not intended to reflect all potential constraints/limitations of the given technology. In addition, the treatability studies do not represent long-term performance, but instead are primarily focused on contaminant removal effectiveness at the beginning of operations and during pilot studies. Given the limited number of treatability studies and lack of long-term performance data for each treatment technology, extrapolation of the efficiencies provided in this report to performance at other sites is necessarily limited. While these data can provide potential performance values, not enough data are presented to provide conclusive expected treatment efficiencies. This document is intended to be an additional source of information that can be used when determining whether a particular treatment technology would be appropriate at other sites.

Another challenge with comparing technologies across multiple treatability studies was that not all studies reported the same type of data. For example, some studies only provided total or dissolved metals, while others provided both. Some studies reported total analyte concentrations but may not have indicated the method used to determine the total concentration. Some studies reported dissolved concentrations, but did not indicate the filter size; therefore, dissolved concentrations may not be directly comparable across studies.

Each treatment technology also includes a lessons learned section that paraphrases the lessons enumerated by the authors of the available treatability studies. These lessons are not discussed at length in this report but are intended to provide insights into the limitations of certain technologies. Some studies did not include lessons learned, therefore, lessons learned are not available for all treatment technologies in this report. Each site is unique, and the lessons learned are not exhaustive inventories of design and operation factors impacting performance for each of the technologies but provides some issues to consider when determining the applicability of the treatment technology to other sites.

1.3 Data Quality Assurance

Tetra Tech conducted the literature search, data compilation, calculation of removal efficiencies (when not provided in the treatability studies), and treatment technology comparison, under an approved Office of Research and Development (ORD) Quality Assurance Project Plan (K-LRTD-0034214-QP-1-1). This report provides information about numerous technologies used in remediation of MIW from Superfund treatability studies, pilot test studies, treatment demonstration studies, five-year review studies, and monitoring and maintenance reports. The studies at 12 sites were obtained from either site contacts or the Superfund site web pages. A 13th public study was obtained through a Google search. The studies were not peer reviewed except for the studies completed by USDOE at the Monticello Mill

Tailings site. Data studies discussed in this report were performed under Superfund by contractors under Regional USEPA or other Federal or State Agency control and assumed to have had approved QA/QC plans, and no additional quality assessment of data was performed by USEPA ORD. However, calculated percent recovery values using the secondary data have been verified to have been accurately calculated.

MIW data from each study were manually entered into the Excel file included as Appendix A of this report. Twenty percent of the manual data entries from each study were checked, and any errors were corrected. If greater than 5% of the checked entries were found to be incorrect, then 100% of the entries from that study were checked and corrected if necessary. An R script (computer code written in the R programming language) was created to pull the maximum and minimum influent and effluent and the corresponding influent and effluent for each treatment type and COC from the Excel file in Appendix A into summary tables. The summary tables were reviewed to make sure all COCs were included and that the values were pulled in correctly. The summary tables were used to populate the influent and effluent tables in this report. All tables in the report were checked for accuracy and updated as necessary. Twenty percent of the rows in each report table were checked for numerical accuracy. Any observed errors were corrected, including typographical errors in titles, headings, and citations. If more than 5% of the rows in a report table contained inaccuracies, then 100% of the rows in the table were checked and corrected if necessary.

2 Active Technologies

Active technologies for acidic mine drainage typically rely on the addition of alkaline chemicals to neutralize acidity. Active technologies also generally require constant care and chemical reagents for continued operation (Zipper et al. 2018 and Taylor et al. 2005).

2.1 Treatability Studies Reviewed

This chapter provides information on treatability studies in which non-excluded active technologies (see section 1.1.1) were the primary component of MIW treatment. The two treatability studies examined were an anaerobic fluidized bed reactor (FBR) and an aerobic pond neutralization at pilot-scale implementation at mines in Idaho and Oregon, respectively. Table 2-1 summarizes site names and locations, treatment type, and references for each of the treatability studies. The chapter presents capability, constraints and limitations, costs, and lessons learned for the active treatments evaluated in the treatability studies.

Table 2-1. Active Treatability Study Sites

Site name and location	Treatment type	Data collection period	Study type	Reference	Reference type
Caribou-Targhee National Forest: Smoky Canyon Mine Site, Idaho	Fluidized bed reactor (FBR)	1 week in February 2018	Pilot study	Formation Environ-mental 2023	Treatability Study Report
Fremont National Forest/ White King and Lucky Lass Uranium Mines Lakeview, OR	Application of hydrated lime for pond neutralization	August 1998 – November 1998	Pilot study	Roy F. Weston, Inc. 1999	Neutralization Report

2.2 Treatment System Description and Treatable Contaminants

2.2.1 Fluidized Bed Reactor (FBR)

The FBR pilot study at Smoky Canyon Mine focused on selenium because selenium exceeds the surface water preliminary remediation goal at the site; however, FBRs are also commonly used to treat chromium, nitrate, and perchlorate (USEPA 2014). The FBR is part of a treatment train with ultrafiltration (UF) and reverse osmosis (RO) pre-treatment. There is a UF/RO system and two FBR units. The UF system removes particulate material in advance of the RO system to protect the RO membranes from fouling. The RO system concentrates solutes (including selenium) in the water at a 3 to 1 ratio. The RO concentrate is pumped to the two FBR units in parallel where selenium is converted to a particulate form and removed using a biofilter. Backwashed selenium-laden solids from the FBRs are removed from the system for disposal. The FBR effluent is treated using an activated sludge post-treatment system prior to discharge (Formation Environmental 2023).

2.2.2 Pond Neutralization

Lime treatment at White King and Lucky Lass Uranium Mines focused on remediation goals for arsenic, aluminum and pH but included other mining-related metals as well. Lime treatment can increase pH and treat aluminum, arsenic, cadmium, chromium, copper, iron, lead, manganese, nickel, selenium, and zinc (USEPA 2006; Madsen et al. 2012; Butler and Hathaway 2020). A hydrated lime slurry was delivered to White King Pond (an open pit uranium mine now filled with water) by means of a revolving spray nozzle mounted on a float. The slurry was pumped from a tanker truck to the spray nozzle and conveyed through 500 feet of floating 3-inch-diameter hose (Roy F. Weston, Inc. 1999).

2.3 Capability

2.3.1 Fluidized Bed Reactor (FBR)

FBRs can be designed as aerobic or anaerobic systems, with the FBR in this study being anaerobic. Microorganisms grow on a hydraulically fluidized bed of fine media, such as sand or granular activated carbon, eventually developing a biofilm on the media surface. Contaminated water is pumped into the FBR and passes through the suspended media, where nitrate and selenium reduction occur. Treated water from the FBR system is then discharged to a downstream liquid/solids separation system (USEPA 2014). Because only one study was reviewed for FBR, limited data restrict the ability to determine the general capability for FBR treatment.

2.3.1.1 Flow Rates

The FBR design capacity was based on a maximum 7,949 L/min (2,100 gallons per minute [gpm]) influent flow to the ultrafiltration (UF) system (Formation Environmental 2023). Seven thousand five hundred and seventy-one L/min (2,000 gpm) flowed from the UF system to the RO, and 379 L/min (100 gpm) of backwash was sent into the discharge pipe downstream of the effluent blend tank. Five thousand six hundred and seventy-eight L/min (1,500 gpm) of permeate from the RO is discharged to the effluent blend tank and then to the effluent stream. The other 1,893 L/min (500 gpm) of concentrate was routed from the RO to the FBR units. Between 2018 and 2020, the treatment system treated an average of 6,814 L/min (1,800 gpm) of influent flow under normal operating conditions.

2.3.1.2 Range of Applicability

Table 2-2 lists influent concentrations of metals and other constituents and their corresponding effluent concentrations from the FBR treatment at the Smoky Canyon Mine. Only a single sampling event was reported. There were two identical FBRs implemented at Smoky Canyon Mine: FBR1 and FBR2. Performance sampling data for the FBR systems at Smoky Canyon Mine were provided as individual observations for only one date. Data are presented as the influent concentration and corresponding effluent concentration. The influent concentrations to each FBR were from a single source; therefore, the influent was the same for each FBR and is not specified as maximum or minimum. The effluent concentrations were often the same at both FBRs, but if the effluent varied at each FBR, it is indicated in Table 2-2. Influent and effluent concentrations for the COCs at the FBR study are included in Table 2-2; however, additional analytes were sampled and are included in Appendix A.

Table 2-2. FBR Influent and Corresponding Effluent Concentrations at Smoky Canyon Mine

Constituent	Influent Concentration (mg/L)	Corresponding Effluent Concentration (mg/L)
Alkalinity (as CaCO3)	780	790
Aluminum, dissolved	ND (< 0.0076)[a]	0.0069[b], ND (< 0.0076)[c]
Aluminum, total	0.0098	ND (< 0.0076)[b], 0.0114[c]
Ammonia	ND (< 0.026)	3.9[b], 3.52[c]
Arsenic, dissolved	0.0014	ND (< 0.000398)
Arsenic, total	0.0016	0.0006
Boron, dissolved	0.04	0.0409[b], 0.0387[c]
Boron, total	0.0422	0.0417[b], 0.0424[c]
Cadmium, dissolved	ND (< 0.0000362)	ND (< 0.0000362)
Cadmium, total	0.0000654	ND (< 0.0000362)
Chromium, dissolved	0.0024	0.0016
Chromium, total	0.0029	0.0017[b], 0.002[c]
Cobalt, dissolved	0.0003	0.0081[b], 0.0084[c]
Cobalt, total	0.0003	0.0074[b], 0.0077[c]
Copper, dissolved	0.0002	0.0003[b], 0.0005[c]
Copper, total	0.0009	0.0017[b], 0.0013[c]
Iron, dissolved	ND (< 0.01)	ND (< 0.01 mg/L)
Iron, total	0.0875	0.0356[b], 0.0309[c]
Lead, dissolved	ND (< 0.0000554)	ND (< 0.0000554)
Lead, total	ND (< 0.0000554)	ND (< 0.0000554)
Manganese, dissolved	0.0017	0.0055[b], 0.0064[c]
Manganese, total	0.0019	0.0057[b], 0.0062[c]
Nickel, dissolved	0.0011	0.0077[b], 0.0085[c]
Nickel, total	ND (< 0.0000533)	0.0078[b], 0.0073[c]
Nitrate	1.23	0.28[b], 0.24[c]
Nitrate + Nitrite	1.23	0.281[b], 0.238[c]
Selenium(IV) (selenite)	ND (< 0.00005)	ND (< 0.00005)[b], 0.001[c]
Selenium (VI) (selenate)	0.599	0.0002[b], 0.0001[c]
Selenium, dissolved	0.62	0.0039[b], 0.0072[c]
Selenium, total	0.574	0.0144[b], 0.0109[c]
Sulfate	219	229[b], 226[c]
Sulfide, total	ND (< 1)	ND (< 1)
Total Organic Carbon	0.638	7.2[b], 7.65[c]
Uranium, dissolved	0.0067	0.0063[b], 0.0064[c]
Uranium, total	0.0068	0.0063[b], 0.0067[c]
Zinc, dissolved	0.0069	0.0058[b], 0.0073[c]
Zinc, total	0.0065	0.0065[b], 0.0081[c]

Source: Formation Environmental 2023

[a] ND = non-detect

[b] FBR1

[c] FBR2

2.3.1.3 Removal Efficiency

Selenium removal was the focus of the FBR study at Smoky Canyon Mine. Between 2018 and 2020, the average selenium removal efficiency from FBR1 was 97%, while the average selenium removal efficiency for FBR2 was 98% (Formation Environmental 2023). Removal efficiencies for other constituents were not provided in the treatability study but were calculated for this report. Table 2-3 presents the calculated removal efficiencies. Constituents with removal efficiencies above 50% were total aluminum (61% at FBR1), arsenic (86% dissolved and 62 - 64% total), total cadmium (72%), total iron (59% and 65%), nitrate (77% and 81%), nitrate + nitrite (77% and 81%), selenium 6 (>99%), dissolved selenium (99%), and total selenium (987%).

Table 2-3. Calculated Removal Efficiencies for the FBR Systems at Smoky Canyon Mine

Constituent	System	Removal efficiency (%)
Aluminum, total	FBR1	61.2[a]
Aluminum, total	FBR2	-16.3
Arsenic, dissolved	FBR1	86.0a
Arsenic, dissolved	FBR2	86.0a
Arsenic, total	FBR1	63.6
Arsenic, total	FBR2	61.9
Boron, dissolved	FBR1	-2.3
Boron, dissolved	FBR2	3.3
Boron, total	FBR1	1.2
Boron, total	FBR2	-0.5
Cadmium, total	FBR1	72.3a
Cadmium, total	FBR2	72.3a
Chromium, dissolved	FBR1	32.2
Chromium, dissolved	FBR2	30.1
Chromium, total	FBR1	40.7
Chromium, total	FBR2	32.4
Cobalt, dissolved	FBR1	-2,451.7
Cobalt, dissolved	FBR2	-2,533.2
Cobalt, total	FBR1	-2,255.6
Cobalt, total	FBR2	-2,347.6
Copper, dissolved	FBR1	-72.3
Copper, dissolved	FBR2	-162.8
Copper, total	FBR1	--86.0
Copper, total	FBR2	-42.7
Iron, total	FBR1	59.3
Iron, total	FBR2	64.7
Manganese, dissolved	FBR1	-232.5
Manganese, dissolved	FBR2	-286.1
Manganese, total	FBR1	-204.3
Manganese, total	FBR2	-232.1
Mercury, dissolved	FBR1	6.4

Constituent	System	Removal efficiency (%)
Mercury, dissolved	FBR2	11.1
Mercury, total	FBR1	-9.6
Mercury, total	FBR2	-7.7
Nickel, dissolved	FBR1	-613.0
Nickel, dissolved	FBR2	-686.1
Nitrate	FBR1	77.2
Nitrate	FBR2	80.5
Nitrate + Nitrite	FBR1	77.2
Nitrate + Nitrite	FBR2	80.7
Selenium (VI)	FBR1	100
Selenium (VI)	FBR2	100
Selenium, dissolved	FBR1	99.4
Selenium, dissolved	FBR2	98.9
Selenium, total	FBR1	97.5
Selenium, total	FBR2	98.1
Uranium, dissolved	FBR1	4.8
Uranium, dissolved	FBR2	4.1
Uranium, total	FBR1	7.8
Uranium, total	FBR2	1.3
Zinc, dissolved	FBR1	16.2
Zinc, dissolved	FBR2	-6.9
Zinc, total	FBR1	-0.5
Zinc, total	FBR2	-25.0

[a] Effluent was below detection limit. Assumed to be ½ the detection limit. Refer to Table 2-2 for detection limit.

2.3.2 Pond Neutralization

Neutralization involves the use of reagents to facilitate the formation of insoluble metal precipitates from the MIW that can be separated from treated water. Alkaline reagents used for treating MIW include limestone ($CaCO_3$), lime (CaO), hydrated lime ($Ca(OH)_2$), sodium hydroxide (NaOH), soda ash (Na_2CO_3), and magnesium hydroxide ($Mg(OH)_2$) (USEPA 2021). Neutralization can occur in active, passive, or semi-passive treatment systems. In active systems, coagulants and flocculants are “added to facilitate faster separation of the solids from the water column, whereas in passive or semi-passive systems, settling typically occurs over time in a pond or wetland without using additional chemicals” (USEPA 2021). Although the neutralization at White King Pond involved settling in a pond, the treatment is considered active in this report because lime was manually applied to the pond two times.

Hydrated lime application to White King Pond occurred over two days with the application of approximately 4.5 tons (9,000 Ibs) (dry weight) in a slurry form in August 1998 and a second application of 0.1 ton (200 lbs) in paper sacks dropped into the pond one month later in September of 1998 (Roy F. Weston, Inc. 1999). Surface water quality observations were collected before and after the August application. The slurry was pumped from a tanker truck through 152.4 meters (500 feet) of floating hose (7.6 centimeters, or 3 inches, in diameter) and applied to the pond through a revolving spray nozzle mounted on a float. The float and spray nozzle were moved to the desired locations throughout the pond, and the spray nozzle would rotate one circular revolution with a diameter of 30.5 meters (100 feet) before being moved to the next location. Because only one study was reviewed for neutralization in a pond application, determining the method's general capability is limited.

2.3.2.1 Range of Applicability

Table 2-4 lists pre-lime application concentrations of metals and other constituents and their corresponding post-lime application concentrations. Performance data for the pond neutralization study were provided as individual observations on September 18, 1998 (pre-lime application) and September 19, 1998 (post-lime application). Observations were provided at a depth of 9.1 meters (30 feet (ft)) and a depth of 15.2 meters (50 ft.) The pH of the pond was 4.5 prior to lime application and 8.34 after lime application at a depth of 9.1 meters (30 ft) and 4.35 and 7.09, respectively, at a depth of 15.2 meters (50 ft.).

Table 2-4. Pre- and Post-lime Application Concentrations at 30 and 50 ft at White King Pond

Constituent	Pre-lime application concentration at 30 ft (mg/L)	Post-lime application concentration at 30 ft (mg/L)	Pre-lime application concentration at 50 ft (mg/L)	Post-lime application concentration at 50 ft (mg/L)
Alkalinity	ND (0.46)	2.1	ND (0.46)	1.4
Aluminum, dissolved	1.5	0.09	1.52	0.066
Aluminum, total	1.55	0.73	1.6	0.78
Arsenic, dissolved	0.032	0.012	0.072	0.015
Arsenic, total	0.047	0.027	0.097	0.046
Cadmium, dissolved	ND (0.0017)	ND	ND (0.0017)	ND
Cadmium, total	ND (0.0017)	ND	ND (0.0017)	ND
Chromium, dissolved	ND (0.0054)	ND	ND (0.0054)	ND
Chromium, total	ND (0.0054)	ND	ND (0.0054)	ND
Copper, dissolved	ND (0.0058)	ND	ND (0.0058)	ND
Copper, total	ND (0.0058)	ND	ND (0.0058)	ND
Iron, dissolved	0.3	ND (0.16)	0.38	ND (0.16)
Iron, total	0.32	0.2	0.46	0.25
Lead, dissolved	ND (0.0065)	ND	ND (0.0065)	ND
Lead, total	ND (0.0065)	ND	ND (0.0065)	ND
Manganese, dissolved	0.677	0.571	0.681	0.596
Manganese, total	0.685	0.607	0.695	0.628
Nickel, dissolved	0.062	0.0444	0.061	0.0455
Nickel, total	0.063	0.051	0.064	0.053
pH	4.5	8.34	4.35	7.11
Selenium, dissolved	ND (0.0059)	ND	ND (0.0059)	ND
Selenium, total	ND (0.0059)	ND	ND (0.0059)	ND
Sulfate	143	148	147	142
Zinc, dissolved	0.101	0.035	0.106	0.062
Zinc, total	0.098	0.069	0.132	0.088

Source: Roy F. Weston, Inc. 1999

ND = non-detect

2.3.2.2 Removal Efficiency

Removal efficiencies for pond neutralization were not provided in the White King Pond neutralization study; however, removal efficiencies were calculated for this report using the pre- and post-lime application observations (see Table 2-5). If the post-lime concentration was a non-detected value, one-half the detection limit was used for calculating the removal efficiency. Constituents with removal efficiencies above 50% were dissolved aluminum (94% – 96%), total aluminum (51% – 53%), dissolved arsenic (63% – 79%), total arsenic (53%), dissolved iron (73% – 79%), and dissolved zinc (65%). The pH of White King Pond increased by 85% at the 30 ft depth and 63% at the 50 ft depth.

Table 2-5. Calculated Removal Efficiencies for Pond Neutralization at White King Mine

Constituent	Removal efficiency at 30 ft (%)	Removal efficiency at 50 ft (%)
Aluminum, dissolved	94.0	95.7
Aluminum, total	52.9	51.3
Arsenic, dissolved	62.5	79.2
Arsenic, total	41.3	52.6
Iron, dissolved	73.3[a]	79.0[a]
Iron, total	37.5	45.7
Manganese, dissolved	15.7	12.5
Manganese, total	11.4	9.7
Nickel, dissolved	28.4	25.4
Nickel, total	19.1	17.2
Sulfate	-3.5	3.4
Zinc, dissolved	65.4	41.5
Zinc, total	29.6	33.3

[a] Effluent was below detection limit. Assumed to be ½ the detection limit. Refer to Table 2-4 for detection limits.

2.4 Constraints and Limitations

No limitations or constraints were provided in the study for the FBR at Smoky Canyon Mine. The study for pond neutralization at White King Mine found that the conveyance hose for the slurry was not long enough to cover the surface of the entire pond, therefore, the lime slurry was not applied to the portions of the pond the hose could not reach (Roy F. Weston, Inc. 1999).

2.5 Costs

FBR systems have a relatively small footprint; however, FBRs are energy-intensive and have high operating power costs (USEPA 2014). The total cost for the UF/RO FBR treatment system in the pilot study was $29,753,900, including capital costs for remedial design, mobilization/demobilization, construction of the treatment plant, water and sediment control, and project/construction management (Formation Environmental 2023). The cost of construction of the 7,570 L/min (2,000 gpm) UF/RO FBR Treatment System alone was $22,000,000. The costs for O&M for the entire system were an additional $1,560,000, including nutrients and chemicals for dosing; disposal of used filter media, chemical waste from cleaning, and dewatered sludge; and effectiveness monitoring and reporting. Cost information in this report is presented as reported in the treatability studies and has not been adjusted for inflation.

No cost data were provided in the pond neutralization study.

2.6 Lessons Learned

The FBR study did not provide any lessons learned. The White King Pond neutralization study provided limited information on lessons learned. While the pond neutralization study found that the conveyance hose for the slurry was not long enough to cover the surface of the entire pond, the authors noted consistent color across the entire pond's surface within one day of the hydrated lime application. The consistent color on the pond’s surface indicated that natural mixing processes occurred, which was supported by subsequent water quality sampling (Roy F. Weston, Inc. 1999).

3 Passive Technologies

Passive technologies do not require constant oversight and maintenance and do not require chemical additions after construction (Zipper et al. 2018 and Kleinmann et al. 2022). Passive technologies rely on natural biological, geochemical, and gravitational processes and provide an appropriate environment for those processes.

3.1 Treatability Studies Reviewed

This chapter provides information on treatability studies in which passive technologies were used to treat MIW. The treatability studies examined included an Aquafix® water-powered quicklime application system; biochemical reactors (BCRs); permeable reactive barriers (PRBs); a constructed wetland; evaporation; and natural attenuation. Magnesium hydroxide ($Mg(OH_2)$), Chitorem®, and successive alkalinity producing system (SAPS) were passive pre-treatments in treatment trains, but data were provided for them as individual units along with data provided for the overall treatment trains. These pilot-scale studies were conducted at mines in Montana, California, Vermont, Oregon, Idaho, and Utah. Table 3-1 summarizes site names and locations, treatment design information, and references for each of the treatability studies. This chapter presents capability, constraints and limitations, costs, and lessons learned for the passive treatment technologies evaluated in the treatability studies.

Table 3-1. Passive Treatability Study Sites

Site name and location	Treatment type	Data collection period	Study type	Reference	Reference type
Silver Dyke Adit in the Carpenter-Snow Creek Mining District Cascade County, MT	Aquafix®	October 2016 – March 2017	Pilot study	Tetra Tech, Inc. 2017	Pilot Test Technical Memorandum
Danny-T Adit in the Barker-Hughesville Mining District, MT	Biochemical Reactor (BCR)	July 2013 – September 2013	Pilot study	CDM Smith 2014	Treatability Study Technical Memorandum
Blue Ledge Mine Siskiyou County, CA	BCR	October 2012 – December 2012	Pilot study	CDM Smith 2015	Treatability Study Technical Memorandum
Ely Copper Mine Vershire, VT	BCR	June 1995 – October 1995	Pilot study	McSurdy (Borek) et al. 1997	Report of Activities
Formosa Mine Douglas County, OR	BCR	July 2013 – September 2013	Pilot study	CDM Smith and Parametrix 2014	Treatability Study Technical Memorandum
Ballard Mine, ID	Permeable Reactive Barrier (PRB)	December 2021 – October 2022	Data not available	Stantec 2023	Treatability Study
Monticello Mill Tailings San Juan County, UT	PRB	1999-2002 (data are presented for averaged 2002 sampling event)	Pilot Study	USDOE 2002	Treatability Study, Demonstration Report, and Five-Year Review Report

Site name and location	Treatment type	Data collection period	Study type	Reference	Reference type
Conda/ Woodall Mountain Mine, ID	PRB	June 2020 – October 2021	Pilot Study	Formation Environmental and NewFields 2022	Treatability Study
Champion Mine Lane County, OR	Constructed Wetland	2003-2012	Full Scale	Cascade Earth Sciences (CES) 2013	Technical Memorandum
Monticello Mill Tailings San Juan County, UT	Evaporation	2015-2021	Full Scale	USDOE 2022	Five-Year Review Report
Monticello Mill Tailings San Juan County, UT	Natural Attenuation	2008-2019	Full Scale	USDOE 2021	Demonstration Report
Danny-T Adit in the Barker-Hughesville Mining District, MT	Magnesium Hydroxide ($Mg(OH)_2$)	July 2013 – September 2013	Pilot study	CDM Smith 2014	Treatability Study Technical Memorandum
Danny-T Adit in the Barker-Hughesville Mining District, MT	Chitorem®	July 2013 – September 2013	Pilot study	CDM Smith 2014	Treatability Study Technical Memorandum
Danny-T Adit in the Barker-Hughesville Mining District, MT	Successive Alkalinity Producing System (SAPS)	July 2013 – September 2013	Pilot study	CDM Smith 2014	Treatability Study Technical Memorandum

3.2 Treatment System Description and Treatable Contaminants

3.2.1 Aquafix®

The COCs for the Aquafix® study at Silver Dyke Adit were aluminum, cadmium, cobalt, copper, iron, lead, manganese, nickel, and zinc (Tetra Tech, Inc. 2017). Aquafix® is a quicklime application system powered by the MIW at the Silver Dyke Adit. It uses natural water gradients to power a quick lime dispensing system. The quicklime raises the pH of the water, causing precipitation of metals. Once the MIW passes through the Aquafix® system, the treated water is routed to a retention pond where the metal precipitates settle out (Tetra Tech, Inc. 2017). Lime treatment can increase pH and decrease concentrations of multiple elements, including aluminum, arsenic, cadmium, chromium, copper, iron, lead, nickel, and zinc (USEPA 2014; USEPA 2021).

3.2.2 Biochemical Reactor (BCR)

BCRs increase pH and remove sulfate and metals such as zinc, lead, copper, cadmium, cobalt, and nickel from MIW (USEPA 2014). Other metals and metalloids that may also be removed include arsenic, chromium, selenium, thallium, and uranium. There were four BCR studies included in this project and each of them is described in this section.

The Danny T Adit study at the Barker Hughesville Mining District focused on mining-related metals including aluminum, arsenic, beryllium, cadmium, cobalt, copper, iron, lead, manganese, nickel, thallium, and zinc (CDM Smith 2014). MIW was collected from the Danny T Adit and directed to a feed tank that supplied the treatment system with the MIW. The influent MIW was fed by gravity into four 5-gallon head tanks and then into each 55-gallon pre-treatment or BCR barrel. Pre-treatment was provided for three of the four treatment trains. Alkaline addition pre-treatment (magnesium hydroxide [$Mg(OH)_2$]) was installed downstream of head tank 4, Chitorem® pre-treatment was installed downstream of head tank 3, and SAPS pre-treatment was installed downstream of head tank 2. Flow from head tank 1 was fed directly into BCR1 without pre-treatment. Following pre-treatment, the MIW flowed into the BCR barrels 2-3 where it was treated by a biologically mediated process in which a carbon source (substrate) was provided as an electron donor for sulfate-reducing bacteria (SRB) to reduce sulfate present in the MIW. The metals present in MIW react with the sulfide species to form metal sulfide precipitates.

The Blue Ledge Mine BCR study focused on mining-related metals and was meant to simulate in-situ treatment of MIW within the mine workings or within a groundwater system (CDM Smith 2015). These BCRs utilized liquid or solid slurries as carbon sources to stimulate sulfate reduction and formation of metal sulfides. MIW was collected at a central location and routed by pipe via gravity flow down to a treatment building. Within the treatment building, the MIW was gravity-fed through the treatment system. A total of five BCR barrels were tested, each with a different reactor substrate material. This study also tested pre-treatment using a SAPS system. The pre-treatment was not followed by a subsequent BCR treatment but was operated in parallel with the four other BCR barrels.

The Ely Copper Mine study focused on pH, iron, calcium, aluminum, manganese, copper, and zinc (McSurdy (Borek) et al. 1997). Additional analytes that were collected but not considered COCs are included in Appendix A. The treatment process at Ely Copper Mine included a combination of biological and chemical treatment. Limestone was used to add alkalinity and raise the pH of the drainage before it entered the sulfate reduction BCR. Organic carbon for bacterial activity was supplied from a combination of manure and composted materials.

The Formosa Mine study focused on cadmium, chromium, copper, lead, nickel, silver, and zinc, but also considered arsenic, mercury, aluminum, and iron to be important metals for evaluation (CDM Smith and Parametrix 2014). Additional analytes collected during the Formosa Mine BCR study are presented in Appendix A. The MIW for this study was collected by pipe at an adit portal and routed via flow to a water storage feed tank. From the feed tank, adit MIW gravity-flowed through pre-treatment processes, followed by treatment in the BCR barrels, and discharge to the lower portion of the adit water diversion system. A total of two pre-treatment barrels and six BCR barrels were tested to compare the performance of two BCR substrates with two selected pre-treatment systems and with a non-pre-treatment system.

3.2.3 Permeable Reactive Barrier (PRB)

PRBs have successfully treated many different constituents, including radionuclides, trace metals, and anions; some examples are hexavalent chromium, nickel, lead, uranium, technetium, iron, manganese, selenium, copper, cobalt, cadmium and zinc, sulfate, nitrate, phosphate, and arsenic (USEPA 2014). Two of the PRB studies included in this review also included data for treatment of molybdenum (Monticello Mine) and vanadium (Monticello Mine and Conda Mine) (USDOE 2002; Formation Environmental and NewFields 2022).

Biomulch PRBs were installed at the Ballard Mine site to treat selenium and other trace metal contamination (e.g., arsenic, nickel, cadmium, zinc) in alluvial groundwater (Stantec 2023). The PRBs were constructed using a mixture of inert support media (i.e., quartzite sand) and solid organic substrate (chopped alfalfa hay and wood chips/shavings). The biomulch PRBs promote selenium removal through microbial reduction of soluble oxidized selenium species, selenate (SeO_4^{-2}) and selenite (SeO_3^{-2}), to low-solubility elemental selenium (Se).

The COCs at the Monticello Mill Tailings site are arsenic, manganese, molybdenum, nitrate, selenium, uranium, and vanadium (USDOE 2002). The PRB consists of a permeable reactive gate and impermeable slurry walls to funnel groundwater from the mine site to the gate. The downgradient gravel zone is composed of washed pea gravel and includes an air-sparging system as an option to precipitate iron and manganese by increasing the concentration of dissolved oxygen if necessary. The PRB is a rectangular area 103 ft long by 8 ft wide. The soils inside the PRB area were excavated and the area was filled with reactive material (zero valent ion [ZVI]) and two gravel zones. The groundwater flows through the PRB, and more than 70 monitoring wells were installed in or near the PRB to collect samples for chemical analysis above and below the PRB.

Conda/Woodall Mine study focused on mining-related metals aluminum, arsenic, cadmium, cobalt, iron, nickel, selenium, thallium, uranium, vanadium, and zinc (Formation Environmental and NewFields 2022). The PRB technology was implemented as two treatment units: 1. Seep Treatment Cell (STC) and 2. Groundwater PRB. The Northeast Sedimentation Basin and the Northeast Seep 5 Pond were filled with treatment media to create a pre-treatment cell for the high concentration seep water discharging into the basins via a subsurface rock drain. The groundwater PRB was constructed in a trench situated downstream of the STC. The trench was excavated through water-bearing zones of the alluvial deposits and into the underlying weathered bedrock. The treatment media in both the STC and PRB was primarily sand, amended with alfalfa hay and woodchips.

3.2.4 Constructed Wetland

Constructed wetlands are designed to treat contaminants over a long period and can be used as the sole technology or as part of treatment train, such as an aerobic wetland operating as a polishing step for effluents from BCRs or other anaerobic or alkalinity-producing processes. Contaminants may be removed from MIW through plant uptake, volatilization, oxidation/reduction (chemical and/or microbial), precipitation, and adsorption. Some treatment systems use both aerobic and anaerobic wetlands for complete treatment of a variety of metals and acidity in MIW. The primary advantages of wetland treatment are low capital and operation and maintenance costs (USEPA 2014). Constructed wetlands can treat MIW containing sulfate and various metals, including iron, manganese, arsenic, aluminum, copper, zinc, cadmium, selenium, nickel, and lead (USEPA 2014). The water from the constructed wetland at Champion Mine was analyzed for reductions of arsenic and iron, but other analytes were sampled including aluminum, antimony, cadmium, chromium, copper, lead, magnesium, manganese, mercury, and zinc (CES 2013). The wetland treatment system for adit discharge includes a settling pond and five-tiered vegetated system that flows directly into Champion Creek. Flocculent logs were installed in three catch basins immediately upstream of the settling pond (CES 2013).

3.2.5 Evaporation

At the Monticello Mill Tailings site, evaporation was used as part of groundwater remedy optimization (GRO) to treat several COCs including uranium, manganese, vanadium, selenium, arsenic, molybdenum, and nitrate, with a focus on uranium (USDOE 2022). The system remediates groundwater in a focused Area of Attainment (AOA) within the contaminant plume that contains the highest uranium concentrations. The AOA encompasses approximately 6 acres of land immediately downgradient of the former mill site. Eight vertical wells are used to extract groundwater in the AOA and send it to a pond for evaporation (USDOE 2022).

3.2.6 Natural Attenuation

The study at the Monticello Mill Tailings site monitored natural attenuation (USDOE 2021) and evaluated the decrease in uranium concentrations at individual groundwater monitoring wells throughout a plume. Potential closure strategies were evaluated for the site to provide for termination of active groundwater remediation within the existing regulatory framework while protecting human health and the environment. The preferred strategy recommended for the site was transitioning to a remedy consisting of monitored natural attenuation (MNA), institutional controls (ICs), and contingencies, with no active remediation (USDOE 2021).

3.2.7 Magnesium Hydroxide ($Mg(OH)_2$), Chitorem®, and Successive Alkalinity Producing System (SAPS)

$Mg(OH)_2$, Chitorem®, and SAPs were each used as pre-treatments to BCR treatment in the Danny-T Adit study (CDM Smith 2014). SAPS treatment was also included at the Blue Ledge Mine (CDM Smith 2015). These treatment technologies can remove acidity and can also remove metals such as aluminum, iron, manganese, zinc, lead, copper, cadmium, cobalt, and nickel from MIW.

An alkaline addition was conducted using a magnesium hydroxide ($Mg(OH)_2$) solution (CDM Smith 2014). The treatment system required the use of a solar charger and battery-powered dosing pump, timer switch, slurry mixer, a $Mg(OH)_2$ stock tank, and associated piping and tubing. The process operated sequentially with a batch of $Mg(OH)_2$ solution fed into the 55-gallon pre-treatment barrel, followed by a batch flow of influent MIW at timed intervals, a set reaction time inside the reactor (static flow condition), and an effluent timer valve that drained the treated water into a subsequent BCR barrel.

The Chitorem® treatment system was installed in a 30-gallon barrel that was filled with approximately 17.5 gallons of substrate material (CDM Smith 2014). Chitorem® is a proprietary material from JRW Bioremediation, LLC that contains 30% by weight calcium carbonate, 40% protein, and 20% chitin (processed crab shell). Chitorem® also contains its own bacteria and over time the material disintegrates into tiny particles that produce carbonates, which adds alkalinity.

The SAPS treatment system was set up the same as the Chitorem® treatment system (see above), except the Chitorem® substrate was replaced with the SAPS substrate mixture (CDM Smith 2014). The SAPS substrate consisted of 0.75-inch to 1.5-inch size limestone gravel, overlain by a manure and compost layer. By volume percent, the manure/compost layer consisted of approximately 25% of the volume, and the limestone consisted of approximately 75% of the volume. The SAPS treatment at Blue Ledge Mine was applied in two barrels and contained an equal part compost/manure mixture over a limestone layer above a drainage layer of inert gravel (CDM Smith 2015). One of the SAPS barrels also included an ethanol dose.

3.3 Capability

3.3.1 Aquafix®

The Aquafix® system uses MIW flow to power a quicklime dispensing system that raises the pH of the water and causes precipitation of metals (Tetra Tech 2017). The treated water is routed to a retention pond where the metal precipitates settle out.

3.3.1.1 Flow Rates

Flow rates through the Aquafix® system were not provided for the study period.

3.3.1.2 Range of Applicability

Table 3-2 lists maximum and minimum influent concentrations of COCs and their corresponding effluent concentrations from Aquafix® treatment of drainage from the Silver Dyke Adit in the Carpenter-Snow Creek Mining District, Montana. Influent pH ranged from 3.27 to 5.03, while effluent pH ranged from 5.04 to 12.04 (Tetra Tech 2017). Influent and effluent data for additional analytes treated by the Aquafix® system at the Silver Dyke Adit are presented in Appendix A.

Table 3-2. Maximum and Minimum Influent and Corresponding Effluent Concentrations at Silver Dyke Adit

Constituent	Maximum Influent Concentration (µg/L)	Corresponding Effluent Concentration (µg/L)	Minimum Influent Concentration (µg/L)	Corresponding Effluent Concentration (µg/L)
Aluminum, dissolved	2,960	62	1,270	1,090
Aluminum, total	2,780	3,060	1,270	1,280
Cadmium, dissolved	886	112	661	397
Cadmium, total	879	728	661	477
Cobalt, dissolved	338	36.2	243	140
Cobalt, total	335	322	243	173
Copper, dissolved	14,900	1,960	5,820	4,030
Copper, total	15,000	12,700	5,820	4,600
Iron, dissolved	36,500	30,100	26,400	16,200
Iron, total	55,600	4,510	30,800	23,200
Lead, dissolved	950	51.6	765	5.73
Lead, total	977	434	806	558
Manganese, dissolved	159,000	3,350	127,000	71,600
Manganese, total	162,000	157,000	127,000	92,000
Nickel, dissolved	374	26	262	149
Nickel, total	371	344	262	182
Zinc, dissolved	175,000	166,000	128,000	118,000
Zinc, total	178,000	175,000	132,000	87,900

Source: Tetra Tech (2017)

3.3.2 Average Influent and Effluent Concentrations

Table 3-3 presents the average influent and average effluent concentrations for the Aquafix® system at Silver Dyke Adit, respectively. The average concentrations were presented in the treatability study and decreased for all constituents except total suspended solids once the MIW passed through the Aquafix® system (Tetra Tech 2017).

Table 3-3. Average Influent and Average Effluent Concentrations at Silver Dyke Adit from October 2016 – March 2017

Constituent	Average Influent Concentration (µg/L)	Average Effluent Concentration (µg/L)
Aluminum, total	2,138	1,999
Aluminum, dissolved	2,213	202
Cadmium, total	788	552
Cadmium, dissolved	785	35
Cobalt, total	297	206
Cobalt, dissolved	295	10
Copper, total	10,368	6,823
Copper, dissolved	10,494	297
Iron, total	38,995	26,954
Iron, dissolved	32,152	1,629
Lead, total	908	386
Lead, dissolved	849	15
Manganese, total	143,227	83,951
Manganese, dissolved	140,905	8,446
Nickel, total	327	266
Nickel, dissolved	323	N/A
Zinc, total	149,545	102,624
Zinc, dissolved	145,476	4,942

Source: Tetra Tech (2017)

N/A = not available

The error (or standard deviation) associated with average values was not provided in the study.

3.3.2.1 Removal Efficiency

Removal percentages for dissolved metals were presented in the study using concentrations at the adit discharge and concentrations at the discharge from the retention pond when the Aquafix® system was operational (Tetra Tech 2017) (see Table 3-4). Removal efficiencies for four conditions at Silver Dyke Adit were calculated for this project for total and dissolved metals and are presented in Table 3-5. The four conditions are the maximum influent concentration treated/corresponding effluent concentration attained, minimum influent concentration treated/corresponding effluent concentration attained, maximum effluent concentration attained/corresponding influent concentration treated, and minimum effluent concentration attained/corresponding influent concentration treated. While removal efficiencies for all four conditions are presented in this report, the influent and effluent are only presented for the maximum and minimum influent concentrations and the corresponding effluent concentrations (Table 3-2). The other conditions (maximum and minimum effluent concentrations and corresponding influent concentrations) are presented in Appendix A.

Table 3-4. Removal Efficiencies for the Aquafix® System at Silver Dyke Adit*

Constituent	Removal efficiency (%)
Aluminum, dissolved	89.1
Cadmium, dissolved	96.1
Cobalt, dissolved	96.8
Copper, dissolved	97.2
Iron, dissolved	95.5
Lead, dissolved	98.3
Manganese, dissolved	93.9
Nickel, dissolved	97.3
Zinc, dissolved	96.7

*Removal efficiencies were provided in the Silver Dyke Adit study (Tetra Tech 2017).

Table 3-5. Calculated Removal Efficiencies for the Aquafix® System at Silver Dyke Adit*

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]
Aluminum, total	-10.1	-0.8	-51.4	96.5
Aluminum, dissolved	97.9	14.2	73.9	99.2
Cadmium, total	17.2	27.8	0.58	99.4
Cadmium, dissolved	87.4	39.9	87.4	99.9[e]
Cobalt, total	3.9	28.8	3.9	99.1
Cobalt, dissolved	89.3	42.4	89.4	99.5
Copper, total	15.3	21.0	6.6	99.6
Copper, dissolved	86.9	30.8	87.1	99.9
Iron, total	91.9	24.7	7.3	99.7
Iron, dissolved	17.5	38.6	86.5	99.3
Lead, total	55.6	30.8	-57.2	98.6
Lead, dissolved	94.6	99.3	94.6	99.9
Manganese, total	3.1	27.6	10.3	99.2
Manganese, dissolved	97.9	43.6	62.4	100.0
Nickel, total	7.3	30.5	7.3	99.3[e]
Nickel, dissolved	93.1	43.1	93.1	99.1-99.2[e]
Zinc, total	1.7	33.4	-0.7	99.2
Zinc, dissolved	5.1	7.8	83.5	99.8

[a] Removal efficiency is based on the maximum influent concentration treated and the corresponding effluent concentration attained.
[b] Removal efficiency is based on the minimum influent concentration treated and the corresponding effluent concentration attained.
[c] Removal efficiency is based on the maximum effluent concentration attained and the corresponding influent concentration treated.
[d] Removal efficiency is based on the minimum effluent concentration attained and the corresponding influent concentration treated.
[e] Removal efficiency based on ½ the detection limit for the effluent. Detection limits are provided in Appendix A.

3.3.3 Biochemical Reactors (BCR)

BCRs treat MIW using microorganisms to increase pH in the treated water and remove contaminants. BCRs can be constructed as open or buried ponds, tanks, or trenches between mine waste and a surface waterbody (USEPA 2014).

BCRs can address a wide range of flows, acidity and metals loading and can operate as either passive or active systems. Most BCRs at mine sites, like all reviewed in this report, operate anaerobically and use sulfate-reducing bacteria that facilitate precipitation of metal sulfides. Anaerobic BCRs are sometimes called sulfate-reducing bioreactors (SRBRs).

Active BCR systems include an external source of liquid organic substrate, such as liquid ethanol and biosolids waste fluid, and separate tanks or zones for the biological, chemical, and physical (solids separation) processes (USEPA 2014). Active systems require frequent human interaction to replace the carbon source and may have greater power needs that require frequent maintenance visits. Passive BCRs, such as the BCRs presented in this review, use a simple gravity-fed flow design that requires minimal maintenance. Passive BCR systems also use a solid organic carbon source for the bacteria. Substrate materials used in these systems, such as wood chips, straw, or biosolids, are often obtained locally. Organic waste materials, such as biosolids or manure, are put to new use when employed as part of the treatment system within a BCR (Gusek 2002). The BCR substrate often contains limestone to provide additional neutralizing capacity and gravel to increase permeability (USEPA 2014). Other sources of organic carbon include fish bones, chitin, and biosolids.

Polishing steps follow BCR treatment to oxygenate the effluent, remove constituents introduced by microbial activity (e.g., H_2S, biochemical oxygen demand), and settle out any solids released during the process.

3.3.3.1 Flow Rates

The MIW flow rate in the Danny-T Adit BCR study (CDM Smith 2014) was set to 37.5 milliliters per minute (mL/min).

The MIW flow rate to each BCR barrel at the Blue Ledge Mine was an average of 0.008 L/min (CDM Smith 2015). The target flow rate for each BCR tank at the Formosa Mine was 0.08 L/min (CDM Smith and Parametrix 2014).

3.3.3.2 Range of Applicability

Three of the studies included stand-alone (not part of a treatment train) BCR treatments: Danny-T Adit in the Barker-Hughesville Mining District, Blue Ledge Mine, and Formosa Mine. The Danny-T Adit and the Formosa Mine studies also had BCR treatments as part of treatment trains, which are discussed in section 3.3.10.

BCR 1 at the Danny-T Adit contained a substrate comprising sawdust, wood chips, compost, dairy manure, and limestone chips (CDM Smith 2014). Blue Ledge BCR 1 had a sawdust and wood chips-based substrate, BCR 2 had a sawdust and wood chips-based substrate with compost, and BCR 3 had a Chitorem® substrate (CDM Smith 2015). Formosa BCR 1 had a woody material mixture as the substrate and BCR 2 had a substrate of Chitorem® and sand (CDM Smith 2014 and Parametrix).

Table 3-6 and Table 3-7 present maximum and minimum influent concentrations, respectively, with their associated effluents for the stand-alone BCR treatments.

Table 3-6. Maximum Influent and Corresponding Effluent Concentrations

Constituent	Maximum influent concentration	Corresponding effluent concentration	Mine
Alkalinity, bicarbonate (as $CaCO_3$) (mg/L)	ND (< 10)[a]	100 – 570	BCR1 Blue Ledge Mine[e]
Alkalinity, bicarbonate (as $CaCO_3$) (mg/L)	ND (< 10)[a]	75 – 920	BCR2 Blue Ledge Mine[e]
Alkalinity, bicarbonate (as $CaCO_3$) (mg/L)	ND (< 10)[a]	1,100 – 9,600	BCR 3 Blue Ledge Mine[e]
Alkalinity, carbonate (as $CaCO_3$) (mg/L)	ND (< 10)	ND	BCRs 1, 2, and 3 Blue[e] Ledge Mine
Alkalinity, total (as $CaCO_3$) (mg/L)	5	125 – 2,000[b]	BCR 1 Formosa Mine[f]
Alkalinity, total (as $CaCO_3$) (mg/L)	5	3,440 – 30,000[b]	BCR 2 Formosa Mine[f]
Aluminum, dissolved (µg/L)	28,800	ND (< 200)	BCR 1 Blue Ledge Mine[e]
Aluminum, total (µg/L)	26,300	76.1	BCR 1 Blue Ledge Mine[e]
Aluminum, total (µg/L)	26,300	ND (< 200)	BCR 2 Blue Ledge Mine[e]
Aluminum, total (µg/L)	26,300	ND (< 200)	BCR 3 Blue Ledge Mine[e]
Arsenic, dissolved (mg/L)	0.039	ND (0.04)	BCRs 1 and 2 Formosa Mine[f]
Arsenic, total (mg/L)	0.055	ND (0.04)	BCR 1 Formosa Mine[f]
Arsenic, total (mg/L)	0.055	0.264	BCR 2 Formosa Mine[f]
Arsenic, dissolved (µg/L)	311	15	BCR 1 Danny-T Adit[d]
Arsenic, total (µg/L)	324	94	BCR 1 Danny-T Adit[d]
Beryllium, dissolved (µg/L)	8	ND (1)	BCR 1 Danny T Adit[d]
Beryllium, total (µg/L)	8	ND (1)	BCR 1 Danny T Adit[d]
Cadmium, dissolved (µg/L)	316	ND (1)	BCR 1 Danny-T Adit[d]
Chromium, dissolved (µg/L)	263	ND (22)	BCR 2 Formosa Mine[f]
Chromium, dissolved (µg/L)	263	130	BCR 1 Formosa Mine[f]
Chromium, total (µg/L)	272	24	BCR 2 Formosa Mine[f]
Chromium, total (µg/L)	272	134	BCR 1 Formosa Mine[f]
Cobalt, dissolved (µg/L)	124	163	BCR 1 Blue Ledge Mine[e]
Cobalt, dissolved (µg/L)	124	49.2	BCR 2 Blue Ledge Mine[e]
Cobalt, dissolved (µg/L)	124	5.9	BCR 3 Blue Ledge Mine[e]
Cobalt, total (µg/L)	125	38.3	BCR 1 Blue Ledge Mine[e]
Cobalt, total (µg/L)	125	5	BCR 2 Blue Ledge Mine[e]
Cobalt, total (µg/L)	125	10.4	BCR 3 Blue Ledge Mine[e]
Copper, dissolved (µg/L)	21,500	1,910	BCR 1 Blue Ledge Mine[e]
Copper, dissolved (µg/L)	21,500	741	BCR 2 Blue Ledge Mine[e]
Copper, dissolved (µg/L)	21,500	25.9	BCR 3 Blue Ledge Mine[e]
Copper, total (µg/L)	21,600	2,260	BCR 1 Blue Ledge Mine[e]
Copper, total (µg/L)	21,600	1,020	BCR 2 Blue Ledge Mine[e]

Constituent	Maximum influent concentration	Corresponding effluent concentration	Mine
Copper, total (µg/L)	21,600	33.5	BCR 3 Blue Ledge Mine[e]
Dissolved Organic Carbon (DOC) (mg/L)	1.3	1,900	BCR 1 Blue Ledge Mine[e]
DOC (mg/L)	1.3	2,000	BCR 2 Blue Ledge Mine[e]
DOC (mg/L)	1.3	13,000	BCR 3 Blue Ledge Mine[e]
Iron, dissolved (µg/L)	180,000	5,100	BCR 1 Danny-T Adit[d]
Iron, total (µg/L)	179,000	8,490	BCR 1 Danny-T Adit[d]
Lead, dissolved (µg/L)	252	ND (1)	BCR 1 Danny-T Adit[d]
Lead, total (µg/L)	258	9	BCR 1 Danny-T Adit[d]
Manganese, dissolved (µg/L)	128,900	122,000	BCR 1 Danny-T Adit[d]
Manganese, total (µg/L)	129,000	21,900	BCR 1 Danny-T Adit[d]
Mercury, dissolved (µg/L)	0.042	0.034	BCR 1 Blue Ledge Mine[e]
Mercury, dissolved (µg/L)	0.042	0.029	BCR 2 Blue Ledge Mine[e]
Mercury, dissolved (µg/L)	0.042	ND (< 0.2)	BCR 3 Blue Ledge Mine[e]
Mercury, total (µg/L)	0.029	ND (< 0.2)	BCR 1 Blue Ledge Mine[e]
Mercury, total (µg/L)	0.029	0.044	BCR 2 Blue Ledge Mine[e]
Mercury, total (µg/L)	0.029	ND (< 0.2)	BCR 3 Blue Ledge Mine[e]
Nickel, dissolved (µg/L)	414	12.9	BCR 1 Blue Ledge Mine[e]
Nickel, dissolved (µg/L)	414	4.7	BCR 2 Blue Ledge Mine[e]
Nickel, dissolved (µg/L)	414	21.3	BCR 3 Blue Ledge Mine[e]
Nickel, total (µg/L)	424	16.3	BCR 1 Blue Ledge Mine[e]
Nickel, total (µg/L)	424	5.2	BCR 2 Blue Ledge Mine[e]
Nickel, total (µg/L)	424	22.6	BCR 3 Blue Ledge Mine[e]
Selenium, dissolved (µg/L)	ND (ranged from <5 to < 50)	ND[b]	BCR 1 Blue Ledge Mine[e]
Selenium, dissolved (µg/L)	ND (ranged from <5 to < 50)	ND[b]	BCR 2 Blue Ledge Mine[e]
Selenium, dissolved (µg/L)	ND (ranged from <5 to < 50)	ND[b] – 69.1	BCR 3 Blue Ledge Mine[e]
Selenium, total (µg/L)	3	ND (< 25)	BCR 1 Blue Ledge Mine[e]
Selenium, total (µg/L)	3	0.58	BCR 2 Blue Ledge Mine[e]
Selenium, total (µg/L)	3	6.3	BCR 3 Blue Ledge Mine[e]
Sulfate, total (mg/L)	2,500	1,100	BCR 1 Danny-T Adit[d]
Sulfide (mg/L)	ND (< 1)	3.1	BCR 1 Blue Ledge Mine[e]
Sulfide (mg/L)	ND (< 1)	1.9	BCR 2 Blue Ledge Mine[e]
Sulfide (mg/L)	ND (< 1)	5.9	BCR 3 Blue Ledge Mine[e]
Thallium, dissolved (µg/L)	2.3	ND (0.5)	BCR 1 Danny T Adit[d]
Thallium, total (µg/L)	2.5	ND (0.5)	BCR 1 Danny T Adit[d]
Zinc, dissolved (µg/L)	72,500	121	BCR 1 Formosa Mine[f]
Zinc, dissolved (µg/L)	72,500	560	BCR 2 Formosa Mine[f]

Constituent	Maximum influent concentration	Corresponding effluent concentration	Mine
Zinc, total (µg/L)	71,000	3,690	BCR 1 Danny-T Adit[d]

[a] ND = non-detect (detection limit of < 10 mg/L). A range of values is shown for the effluent to reflect multiple days with influent below the detection limit.

[b] A range of values is shown for the effluent to reflect multiple days with the same influent.

[c] ND = non-detect (detection limits of < 2 mg/L and < 20 mg/L at Blue Ledge Mine and 0.095 mg/L and 0.106 mg/L at Formosa Mine).

[d] CDM Smith 2014

[e] CDM Smith 2015

[f] CDM Smith and Parametrix 2014

Table 3-7. Minimum Influent and Corresponding Effluent Concentrations

Constituent	Minimum influent concentration	Corresponding effluent concentration	Mine
Alkalinity, bicarbonate (as $CaCO_3$) (mg/L)	ND (< 10)	100 – 570[a]	BCR 1 Blue Ledge Mine[b]
Alkalinity, bicarbonate (as $CaCO_3$) (mg/L)	ND (< 10)	75 – 920[a]	BCR 2 Blue Ledge Mine[b]
Alkalinity, bicarbonate (as $CaCO_3$) (mg/L)	ND (< 10)	1,100 – 9,600[a]	BCR 3 Blue Ledge Mine[b]
Alkalinity, carbonate (as $CaCO_3$) (mg/L)	ND (< 10)	ND[a] – 8.2[a]	BCR 1 Blue Ledge Mine[b]
Alkalinity, carbonate (as $CaCO_3$) (mg/L)	ND (< 10)	ND[a]	BCRs 2 and 3 Blue Ledge Mine[b]
Alkalinity, total (as $CaCO_3$) (mg/L)	ND*	70 – 1,400	BCR 1 Danny-T Adit[c]
Aluminum, dissolved (µg/L)	6,470	ND (< 200)	BCRs 1, 2, and 3 Blue Ledge Mine[b]
Aluminum, total (µg/L)	6,610	58.9	BCR 2 Blue Ledge Mine[b]
Aluminum, total (µg/L)	6,610	ND (< 200)	BCRs 1 and 3 Blue Ledge Mine[b]
Arsenic, dissolved (mg/L)	0.039	ND (0.036)	BCRs 1 and 2 Formosa Mine[d]
Arsenic, total (mg/L)	0.051	ND (0.036)	BCRs 1 and 2 Formosa Mine[d]
Arsenic, dissolved (µg/L)	0.38	0.96	BCR 1 Blue Ledge Mine[b]
Arsenic, dissolved (µg/L)	0.38	0.26	BCR 2 Blue Ledge Mine[b]
Arsenic, dissolved (µg/L)	0.38	17.9	BCR 3 Blue Ledge Mine[b]
Arsenic, total (µg/L)	1.2	0.78	BCR 1 Blue Ledge Mine[b]
Arsenic, total (µg/L)	1.2	ND (< 10)	BCR 2 Blue Ledge Mine[b]
Arsenic, total (µg/L)	1.2	38.5	BCR 3 Blue Ledge Mine[b]
Beryllium, dissolved (µg/L)	6	ND (< 1)	BCR 1 Danny T Adit[c]
Beryllium, total (µg/L)	5	1	BCR 1 Danny T Adit[c]
Cadmium, dissolved (µg/L)	65.3	ND (< 1)	BCRs 1, 2, and 3 Blue Ledge Mine[b]

Constituent	Minimum influent concentration	Corresponding effluent concentration	Mine
Cadmium, total (µg/L)	66	ND (< 1)	BCRs 1, 2, and 3 Blue Ledge Mine[b]
Chromium, dissolved (µg/L)	2.6	ND (< 2)	BCRs 1, 2, and 3 Blue Ledge Mine[b]
Chromium, total (µg/L)	2.7	ND (< 2)	BCRs 1, 2, and 3 Blue Ledge Mine[b]
Cobalt, dissolved (µg/L)	12	ND (11)	BCRs 1 and 2 Formosa Mine[d]
Cobalt, total (µg/L)	12	ND (11)	BCRs 1 and 2 Formosa Mine[d]
Copper, dissolved (µg/L)	924	ND (5)	BCR 1 Danny-T Adit[c]
Copper, total (µg/L)	1,180	ND (5)	BCR 1 Danny-T Adit[c]
DOC (mg/L)	1.3	1,900	BCR 1 Blue LedgeMine[b]
DOC (mg/L)	1.3	2,000	BCR 2 Blue LedgeMine[b]
DOC (mg/L)	1.3	13,000	BCR 3 Blue Ledge Mine[b]
Iron, dissolved (µg/L)	1,580	4,230	BCR 1 Blue Ledge Mine[b]
Iron, dissolved (µg/L)	1,580	5,960	BCR 2 Blue Ledge Mine[b]
Iron, dissolved (µg/L)	1,580	3,920	BCR 3 Blue Ledge Mine[b]
Iron, total (µg/L)	1,560	4,640	BCR 1 Blue Ledge Mine[b]
Iron, total (µg/L)	1,560	6,650	BCR 2 Blue Ledge Mine[b]
Iron, total (µg/L)	1,560	4,160	BCR 3 Blue Ledge Mine[b]
Lead, dissolved (µg/L)	3.4	ND (< 1)	BCRs 1, 2, and 3 Blue Ledge Mine[b]
Lead, total (µg/L)	3.4	ND (< 1)	BCRs 1, 2, and 3 Blue Ledge Mine[b]
Manganese, dissolved (µg/L)	629	3,250	BCR 1 Blue Ledge Mine[b]
Manganese, dissolved (µg/L)	629	4,170	BCR 2 Blue Ledge Mine[b]
Manganese, dissolved (µg/L)	629	411	BCR 3 Blue Ledge Mine[b]
Manganese, total (µg/L)	621	3,300	BCR 1 Blue Ledge Mine[b]
Manganese, total (µg/L)	621	4,110	BCR 2 Blue Ledge Mine[b]
Manganese, total (µg/L)	621	457	BCR 3 Blue Ledge Mine[b]
Mercury, dissolved (µg/L)	0.042	0.034	BCR 1 Blue Ledge Mine[b]
Mercury, dissolved (µg/L)	0.042	0.029	BCR 2 Blue Ledge Mine[b]
Mercury, dissolved (µg/L)	0.042	ND (< 0.2)	BCR 3 Blue Ledge Mine[b]
Mercury, total (µg/L)	0.029	ND (< 0.2)	BCRs 1 and 3 Blue Ledge Mine[b]
Mercury, total (µg/L)	0.029	0.044	BCR 2 Blue Ledge Mine[b]
Nickel, dissolved (µg/L)	27	ND (4)	BCR 1 Formosa Mine[d]
Nickel, dissolved (µg/L)	27	8	BCR 2 Formosa Mine[d]
Nickel, total (µg/L)	23	ND (4)	BCR 1 Formosa Mine[d]
Nickel, total (µg/L)	23	11	BCR 2 Formosa Mine[d]

Constituent	Minimum influent concentration	Corresponding effluent concentration	Mine
Selenium, dissolved (µg/L)	ND (< 50)	ND	BCRs 1 and 2 Blue Ledge Mine[b]
Selenium, dissolved (µg/L)	ND (< 50)	ND– 69.1[a]	BCR 3 Blue Ledge Mine[b]
Selenium, total (µg/L)	1.8	ND	BCRs 1, 2, and 3 Blue Ledge Mine[b]
Sulfate, total (mg/L)	210	380	BCR 1 Blue Ledge Mine[b]
Sulfate, total (mg/L)	210	350	BCR 2 Blue Ledge Mine[b]
Sulfate, total (mg/L)	210	420	BCR 3 Blue Ledge Mine[b]
Sulfide (mg/L)	ND (< 1)	3.1	BCR 1 Blue Ledge Mine[b]
Sulfide (mg/L)	ND (< 1)	1.9	BCR 2 Blue Ledge Mine[b]
Sulfide (mg/L)	ND (< 1)	5.9	BCR 3 Blue Ledge Mine[b]
Thallium, dissolved (µg/L)	1.8	ND (< 0.5)	BCR 1 Danny T Adit[c]
Thallium, total (µg/L)	2.5	ND (< 0.5)	BCR 1 Danny T Adit[c]
Zinc, dissolved (µg/L)	12,000	19,500	BCR 1 Blue Ledge Mine[b]
Zinc, dissolved (µg/L)	12,000	5.9	BCR 2 Blue Ledge Mine[b]
Zinc, dissolved (µg/L)	12,000	14.4	BCR 3 Blue Ledge Mine[b]
Zinc, total (µg/L)	12,700	20,900	BCR 1 Blue Ledge Mine[b]
Zinc, total (µg/L)	12,700	1,100	BCR 2 Blue Ledge Mine[b]
Zinc, total (µg/L)	12,700	ND (< 22.2)	BCR 3 Blue Ledge Mine[b]

ND = non-detect

[a] A range of effluent values is shown to reflect multiple days with the same influent.

[b] CDM Smith 2015

[c] CDM Smith 2014

[d] CDM Smith and Parametrix 2014

3.3.3.3 Removal Efficiency

The removal efficiencies that were presented in the Danny-T Adit (CDM Smith 2014) and Blue Ledge Mine (CDM Smith 2015) studies are presented in Table 3-8. The removal efficiency for each BCR treatment and constituent is presented as either the minimum removal efficiency or a range of removal efficiencies, depending on how the information was presented in each study. Removal efficiencies for the BCR treatments at Formosa Mine were not provided; however, they were calculated for this report. Removal efficiencies for four conditions at all sites were calculated and are presented in Table 3-9. While removal efficiencies for all four conditions are presented in this report, the influent and effluent are only presented for the maximum and minimum influent and the corresponding effluent (Table 3-6 and Table 3-7). The other conditions (maximum and minimum effluent and corresponding influent) are presented in Appendix A.

Positive removal efficiencies reported for BCR treatments range from 10.2% to 99.9%. The 10.2% removal was for dissolved nickel at Blue Ledge Mine BCR 3. A maximum efficiency of 99.9% was achieved for dissolved cadmium and dissolved copper at Blue Ledge Mine BCRs 1, 2, and 3 and dissolved zinc at Blue Ledge Mine BCR 3.

Table 3-8. Reported Removal Efficiencies – Stand-alone BCRs

Constituent	Removal efficiency (%)	Mine
Aluminum, dissolved	> 92.0	Danny-T Adit BCR 1[b]
Aluminum, total	> 92.0	Danny-T Adit BCR 1[b]
Aluminum, dissolved	> 90.0[a]	Blue Ledge Mine BCR 1[c]
Aluminum, dissolved	> 90.0	Blue Ledge Mine BCR 2[c]
Aluminum, dissolved	95.4 – 99.0	Blue Ledge Mine BCR 3[c]
Arsenic, dissolved	> 92.0	Danny-T Adit BCR 1[b]
Beryllium, dissolved	> 83.0[a]	Danny-T Adit BCR 1[b]
Cadmium, dissolved	> 99.0	Danny-T Adit BCR 1[b]
Cadmium, dissolved	78.9 – 99.9	Blue Ledge Mine BCR 1[c]
Cadmium, dissolved	90.2 – 99.9	Blue Ledge Mine BCR 2[c]
Cadmium, dissolved	88.0 – 99.9	Blue Ledge Mine BCR 3[c]
Copper, dissolved	> 99.0	Danny-T Adit BCR 1[b]
Copper, dissolved	87.2 – 99.9	Blue Ledge Mine BCR 1[c]
Copper, dissolved	93.8 – 99.9	Blue Ledge Mine BCR 2[c]
Copper, dissolved	99.4 – 99.9	Blue Ledge Mine BCR 3[c]
Lead, dissolved	> 96.0[a]	Danny-T Adit BCR 1[b]
Manganese, dissolved	34.7 – 90.8	Blue Ledge Mine BCR 3[c]
Nickel, dissolved	10.2 – 96.6	Blue Ledge Mine BCR 3[c]
Thallium, dissolved	> 72.0[a]	Danny-T Adit BCR 1[b]
Zinc, dissolved	98.7 – 99.9	Blue Ledge Mine BCR 3[c]

[a] Effluent was below detection limit. Assumed to be ½ the detection limit. Refer to Table 3-6 for detection limit.
[b] CDM Smith 2014
[c] CDM Smith 2015

Table 3-9. Calculated Removal Efficiencies – Stand-alone BCRs

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine
Aluminum, dissolved	99.2	96.7	92.3	99.4	Danny-T Adit BCR 1
Aluminum, total	94.3	92.0	94.3	93.1	Danny-T Adit BCR 1
Aluminum, dissolved	99.7[e]	98.5[e]	79.0	92.9	Blue Ledge Mine BCR 1
Aluminum, dissolved	99.7[e]	98.5[e]	92.5	97.8	Blue Ledge Mine BCR 2
Aluminum, dissolved	99.7[e]	98.5[e]	N/A	N/A	Blue Ledge Mine BCR 3
Aluminum, total	99.7	98.5[e]	77.8	99.7	Blue Ledge Mine BCR 1

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine
Aluminum, total	99.6[e]	99.1	90.9	99.1	Blue Ledge Mine BCR 2
Aluminum, total	99.6[e]	98.5[e]	N/A	N/A	Blue Ledge Mine BCR 3
Arsenic, dissolved	95.2	93.6	95.2	93.6	Danny-T Adit BCR 1
Arsenic, total	71.0	93.3	71.0	93.3	Danny-T Adit BCR 1
Arsenic, dissolved	23.6	-152.6	N/A	N/A	Blue Ledge Mine BCR 1
Arsenic, dissolved	(-)354.6 – 54.6[e]	31.6	N/A	31.6	Blue Ledge Mine BCR 2
Arsenic, dissolved	-1,381.8	-4,610.5	N/A	N/A	Blue Ledge Mine BCR 3
Arsenic, total	59.4	35.0	N/A	35.0	Blue Ledge Mine BCR 1
Arsenic, total	(-)56.3 – 84.4[e]	(-)316.7 – 58.3[e]	N/A	N/A	Blue Ledge Mine BCR 2
Arsenic, total	-368.8	-3,108.3	N/A	N/A	Blue Ledge Mine BCR 3
Arsenic, dissolved	53.9[e]	53.9[e]	N/A	N/A	Formosa Mine BCRs 1 & 2
Arsenic, total	63.6[e]	60.8[e]	N/A	N/A	Formosa Mine BCR 1
Arsenic, total	63.6	60.8[e]	-2,746.2	N/A	Formosa Mine BCR 2
Beryllium, dissolved	93.8[e]	83.3 – 91.7[e]	83.3	91.7 – 93.8	Danny-T Adit BCR 1
Beryllium, total	93.8[e]	80.0	80.0	93.8	Danny-T Adit BCR 1
Cadmium, dissolved	99.8[e]	99.7[e]	99.4	99.7 – 99.8	Danny-T Adit BCR 1
Cadmium, total	92.8	99.3	92.8	99.3	Danny-T Adit BCR 1
Cadmium, dissolved	99.9[e]	99.2[e]	78.6	84.1	Blue Ledge Mine BCR 1
Cadmium, dissolved	99.9[e]	99.2[e]	90.2 – 92.6	90.2 – 92.6	Blue Ledge Mine BCR 2
Cadmium, dissolved	99.9[e]	99.2[e]	88.0	99.8	Blue Ledge Mine BCR 3
Cadmium, total	81.2	99.2[e]	81.2	99.8	Blue Ledge Mine BCR 1
Cadmium, total	89.2	99.2[e]	89.2	99.8	Blue Ledge Mine BCR 2
Cadmium, total	97.1	99.2[e]	87.9	99.8	Blue Ledge Mine BCR 3
Cobalt, dissolved	73.7[e]	58.3[e]	-729.4	16.7	Formosa Mine BCR 1
Cobalt, dissolved	73.7[e]	58.3[e]	-957.1	-186.7	Formosa Mine BCR 2

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine
Cobalt, total	16.7	54.2	16.7	13.3	Formosa Mine BCR 1
Cobalt, total	69.4[e]	54.2[e]	-993.3	-166.7	Formosa Mine BCR 2
Copper, dissolved	99.7	99.7[e]	99.7	99.7 – 99.9	Danny-T Adit BCR 1
Copper, total	90.6	99.8[e]	90.6	99.8	Danny-T Adit BCR 1
Copper, dissolved	91.1	100.0[e]	87.3	100.0	Blue Ledge Mine BCR 1
Copper, dissolved	96.6	100.0[e]	93.8	100.0	Blue Ledge Mine BCR 2
Copper, dissolved	99.9	100.0[e]	99.4	100.0	Blue Ledge Mine BCR 3
Copper, total	89.5	99.8	84.3	100.0	Blue Ledge Mine BCR 1
Copper, total	95.3	99.8	92.8	99.9	Blue Ledge Mine BCR 2
Copper, total	99.8	N/A	99.4	100.0	Blue Ledge Mine BCR 3
Chromium, dissolved	58.3[e]	N/A	N/A	N/A	Danny-T Adit BCR 1
Chromium, total	58.3[e]	N/A	N/A	N/A	Danny-T Adit BCR 1
Chromium, dissolved	81.8[e]	61.5[e]	63.0 – 85.7	63.0 – 85.7	Blue Ledge Mine BCR 1
Chromium, dissolved	81.8[e]	61.5[e]	63.0 – 85.7	63.0 – 85.7	Blue Ledge Mine BCR 2
Chromium, dissolved	81.8[e]	61.5[e]	63.0 – 85.7	63.0 – 85.7	Blue Ledge Mine BCR 3
Chromium, total	85.7[e]	63.0[e]	63.0 – 85.7	63.0 – 85.7	Blue Ledge Mine BCR 1
Chromium, total	85.7[a]	63.0[e]	63.0 – 85.7	63.0 – 85.7	Blue Ledge Mine BCR 2
Chromium, total	85.7[e]	63.0[e]	63.0 – 85.7	63.0 – 85.7	Blue Ledge Mine BCR 3
Chromium, dissolved	50.6	31.9	19.5	95.3	Formosa Mine BCR 1
Chromium, dissolved	95.8[e]	90.3[e]	86.2	94.6	Formosa Mine BCR 2
Chromium, total	50.7	45.2	19.7	83.3	Formosa Mine BCR 1
Chromium, total	91.2	92.3[e]	85.0	85.0	Formosa Mine BCR 2
Iron, dissolved	97.2	33.3	14.8	97.2	Danny-T Adit BCR 1
Iron, total	95.3	35.4	34.6	95.3	Danny-T Adit BCR 1
Iron, dissolved	79.4	-167.7	-95.5	42.2	Blue Ledge Mine BCR 1

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine
Iron, dissolved	66.0	-277.2	-50.4	22.8	Blue Ledge Mine BCR 2
Iron, dissolved	90.8	-148.1	14.1	69.6	Blue Ledge Mine BCR 3
Iron, total	79.3	-197.4	-87.7	18.7	Blue Ledge Mine BCR 1
Iron, total	66.4	-326.3	-14.5	7.8	Blue Ledge Mine BCR 2
Iron, total	78.8	-166.7	-8.9	40.2	Blue Ledge Mine BCR 3
Lead, dissolved	99.8[e]	99.6[e]	99.6 – 99.8	99.6 – 99.8	Danny-T Adit BCR 1
Lead, total	96.5	76.5	76.5	97.7	Danny-T Adit BCR 1
Lead, dissolved	78.8[e]	85.3[e]	N/A	N/A	Blue Ledge Mine BCR 1
Lead, dissolved	78.8[e]	85.3[e]	N/A	N/A	Blue Ledge Mine BCR 2
Lead, dissolved	78.8[e]	85.3[e]	N/A	N/A	Blue Ledge Mine BCR 3
Lead, total	98.0[e]	85.3[e]	N/A	N/A	Blue Ledge Mine BCR 1
Lead, total	98.0[e]	85.3[e]	N/A	N/A	Blue Ledge Mine BCR 2
Lead, total	98.0[e]	85.3[e]	N/A	N/A	Blue Ledge Mine BCR 3
Manganese, dissolved	4.7	-0.2	(-)5.2 – 4.7	82.5	Danny-T Adit BCR 1
Manganese, total	83.0	-1.0	-1.0	83.0	Danny-T Adit BCR 1
Manganese, dissolved	-16.8	-416.7	-62.7	-112.0	Blue Ledge Mine BCR 1
Manganese, dissolved	-53.1	-563.0	-53.1	35.4	Blue Ledge Mine BCR 2
Manganese, dissolved	90.8	34.7	36.4	74.4	Blue Ledge Mine BCR 3
Manganese, total	20.3	-431.4	-69.3	-101.8	Blue Ledge Mine BCR 1
Manganese, total	47.5	-561.8	-66.0	47.5	Blue Ledge Mine BCR 2
Manganese, total	66.7	26.4	31.3	74.8	Blue Ledge Mine BCR 3
Nickel, dissolved	96.9	-493.3	-74.3	96.9	Blue Ledge Mine BCR 1
Nickel, dissolved	98.9	12.7	52.9	98.9	Blue Ledge Mine BCR 2

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine
Nickel, dissolved	94.9	69.9	10.2	94.5	Blue Ledge Mine BCR 3
Nickel, total	96.2	-519.3	-96.3	96.2	Blue Ledge Mine BCR 1
Nickel, total	98.8	17.6	53.5	98.8	Blue Ledge Mine BCR 2
Nickel, total	94.7	62.8	15.0	91.7	Blue Ledge Mine BCR 3
Nickel, dissolved	84.7[e]	92.6[e]	50.0	45.5	Formosa Mine BCR 1
Nickel, dissolved	-538.8	70.4	-538.8	81.8	Formosa Mine BCR 2
Nickel, total	70.8	89.1[e]	48.8	70.8	Formosa Mine BCR 1
Nickel, total	-571.5	52.2	-571.5	81.8	Formosa Mine BCR 2
Thallium, dissolved	89.1[e]	86.1[e]	86.1 – 89.1[e]	86.1 – 89.1[e]	Danny-T Adit BCR 1
Thallium, total	90.0[e]	90.0[e]	90.0	90.0	Danny-T Adit BCR 1
Zinc, dissolved	99.9	11.5	11.5	99.9	Danny-T Adit BCR 1
Zinc, total	94.8	25.0	25.0	94.8	Danny-T Adit BCR 1
Zinc, dissolved	50.0	-62.5	-33.9	99.9	Blue Ledge Mine BCR 1
Zinc, dissolved	100.0	100.0	86.8	N/A	Blue Ledge Mine BCR 2
Zinc, dissolved	100.0	99.9	98.7	99.9	Blue Ledge Mine BCR 3
Zinc, total	90.5	-64.6	-25.4	96.7	Blue Ledge Mine BCR 1
Zinc, total	92.3	91.3	79.7	99.1	Blue Ledge Mine BCR 2
Zinc, total	99.6	99.9[e]	98.4	100.0	Blue Ledge Mine BCR 3
Zinc, dissolved	99.8	57.6	59.4	99.8	Formosa Mine BCR 1
Zinc, dissolved	99.2	99.6	99.23	99.9	Formosa Mine BCR 2
Zinc, total	56.3	93.8	56.3	93.8	Formosa Mine BCR 1
Zinc, total	99.7	98.3	98.3	100.0	Formosa Mine BCR 2

N/A = not available. Data not provided or influent was below detection limit and efficiency could not be calculated.

[a] Removal efficiency is based on the maximum influent concentration treated and the corresponding effluent concentration attained.

[b] Removal efficiency is based on the minimum influent concentration treated and the corresponding effluent concentration attained.

[c] Removal efficiency is based on the maximum effluent concentration attained and the corresponding influent concentration treated.

[d] Removal efficiency is based on the minimum effluent concentration attained and the corresponding influent concentration treated.

[e] Effluent was below detection limit. Assumed to be ½ the detection limit. Refer to Table 3-6 and Table 3-7 for detection limit.

3.3.4 Permeable Reactive Barrier (PRB)

A PRB is a subsurface zone consisting of a reactive material to treat constituents of concern in groundwater (ITRC 2011). The reactive material, which can include zero-valent iron (ZVI), limestone, compost, zeolites, activated carbon or apatite, is in direct contact with the surrounding aquifer material (USEPA 2014). ZVI is the most commonly used reactive material because of its ability to treat common organic and inorganic contaminants in groundwater (ITRC 2005). A PRB is placed so that a plume of contaminated groundwater flows through the reactive media and treated water flows out via gravity (USEPA 2014). Because PRBs work through gravity flow, they do not require access to power and other infrastructure (Formation Environmental and NewFields 2022).

Treatment within a PRB can be physical, chemical, biological, or a combination. Chemical mechanisms include adsorption, ion exchange, oxidation-reduction, or precipitation (Wright and Conca 2006). Microbial communities can be stimulated by addition of organic carbon and nutrients to facilitate conversion of inorganic constituents to immobile precipitates (Conca and Wright 2006 and Wright and Conca 2006), such as through the formation of metal sulfides.

PRBs can be built as a funnel-and-gate type or a continuous type (USEPA 2014). The funnel-and-gate PRB uses impermeable walls such as sheet pilings or slurry walls to funnel the contaminant plume to a gate that contains the reactive media, while the continuous PRB completely transects the plume flow path with reactive media.

A PRB must be installed to the bedrock, and the reactive zone permeability must be kept equal to or greater than the permeability of the aquifer to avoid diversion of the groundwater around the reactive zone (USEPA 2014). The plume must not pass over, under or around the PRB. Minimal maintenance is required for PRBs, but performance can decline over time due to clogging.

3.3.4.1 Flow Rates

Flow rates specific to the anaerobic PRBs at Ballard Mine were not provided (Stantec 2023); however, USDOE (2002) reported 34.1 L/min (9 gpm) as the estimated flow rate through the PRB at the Monticello Mill Tailings site.

3.3.4.2 Range of Applicability

Two stand-alone PRB studies are included in this section and a treatment train having a PRB following a pre-treatment is discussed in section 3.3.10 (Conda/Woodall Mountain Mine). Maximum and minimum pre- and post-PRB COC concentrations were provided for the PRB treatment at Ballard Mine in Idaho and average upgradient and downgradient concentrations were provided for the Monticello Mill Tailings site in Utah. The Ballard Mine study (Stantec 2023) was different than the other PRB studies in that the pre-PRB concentrations were presented as a range of values rather than individual sample values. The Ballard Mine site did not have monitoring stations upstream and downstream of the PRB but did have monitoring wells installed prior to PRB installation to allow for a comparison of groundwater conditions pre- and post-construction. The values of the contaminants of concern were presented as a range of values for the study period and are presented in Table 3-10. Upgradient and downgradient maximum and minimum concentrations were not provided for the stand-alone PRB at Monticello Mill Tailings site, but the average upgradient and downgradient values are presented in section 3.3.4.3.

Table 3-10. Maximum Pre-PRB Installation and Corresponding Post-PRB Installation Concentrations at Ballard Mine. (Maximum and minimum range of values were identical for all constituents except Se. Separate rows of data for Maximum and Minimum are presented.)

Constituent	Pre-PRB installation concentration (µg/L)	Post-PRB installation concentration (µg/L)
Arsenic, total	0.3 – 2.5	ND (< 0.5) – 1.8
Cadmium, total	N/A[a]	ND (< 0.08)
Manganese, total	6 – 537	11.1 – 43.4
Selenium, total (maximum)	33.3 – 44.8	16.3 – 1.6
Selenium, total (minimum)	10 – 15	12.5 – 26.8
Sulfate, dissolved	Dry – 80.4	27.2 – 55.3

Source: Stantec (2023)

N/A = not available

ND = non-detect

[a] Pre-installation values were stated as < MCL in the study.

3.3.4.3 Average Influent and Effluent Concentrations

Maximum and minimum upgradient concentrations and associated downgradient concentrations were not provided for Monticello Mill Tailings site, but the study did provide average upgradient and average downgradient data (see Table 3-11).

Table 3-11. Average upgradient and downgradient concentrations attained at the Monticello Mill Tailings site

Constituent*	Average upgradient concentration	Average downgradient concentration
Arsenic (µg/L)	9.6	1.2
Manganese (µg/L)	137	1,357
Molybdenum (µg/L)	45.4	6.9
Nitrate + Nitrite (µg/L)	2,470	ND (< 4.9)
Selenium (µg/L)	112	ND (< 0.2)
Uranium (µg/L)	513	9
Vanadium (µg/L)	351	8.1

Source: USDOE (2002)

*The study did not specify whether COCs were total or dissolved.

ND = non-detect.

3.3.4.4 Removal Efficiency

Removal efficiencies for the PRB treatment at the Monticello Mill Tailings were not provided; however, they were calculated for this report using the average upgradient concentration treated and the average downgradient concentration reported. If the corresponding downgradient concentration was a non-detected value, one-half the detection limit was used in calculations. Removal efficiencies were not calculated for the Ballard Mine PRB because the pre- and post-installation data were provided as a range over the study period and did not provide a direct correlation between the pre- and post-installation values. The calculated removal efficiencies for Monticello Mill Tailings are presented in Table 3-12. Removal efficiencies for COCs ranged from 84.8% for molybdenum to 99.9% for nitrate + nitrite and selenium (USDOE 2002).

Table 3-12. Calculated Removal Efficiencies for Stand-alone PRBs at Monticello Mill Tailings

Constituent	Removal efficiency (%)
Arsenic	87.5
Manganese	-890.5
Molybdenum	84.8
Nitrate + Nitrite	99.9[a]
Selenium	99.9[a]
Uranium	98.3
Vanadium	97.7

[a] Effluent was below detection limit. Assumed to be ½ the detection limit. Refer to Table 3-10 for detection limit.

3.3.5 Monitored Natural Attenuation (MNA)

The use of MNA at MIW sites relies on natural processes to reduce concentrations of contaminants in groundwater through biodegradation, sorption, dilution, evaporation, or chemical reactions (USEPA 2014). MNA is usually applied as the last step in the cleanup process when contaminant sources have been removed, and low concentrations of contaminants remain in the groundwater. Natural processes are then relied on to remove the remaining contaminants while the site is monitored to make sure contaminants are not spreading and that natural attenuation is working toward meeting the site's cleanup goals. MNA does not involve any physical actions to treat the groundwater.

3.3.5.1 Flow Rates

Groundwater in the alluvial aquifer at the Monticello Mill Tailings site flows at a velocity of 0.1 to 11 meters per day (0.3 to 36 feet per day), and the estimated median groundwater flow rate across the site is approximately 530 L/min (140 gpm) (USDOE 2021).

3.3.5.2 Range of Applicability

Maximum and minimum effluent concentrations were not provided for MNA at the Monticello Mill Tailing site, but the average concentrations over time were provided. The average uranium concentration in the plume was 275 µg/L in 2008 and 160 µg/L in 2019 (USDOE 2021). The USDOE (2021) study also presented uranium in the plume as a mass, which was 23.6 kilograms (kg) (52 pounds [lbs]) in 2008 and 13.6 kg (30 lbs) in 2019.

3.3.5.3 Removal Efficiency

A removal efficiency was not provided by USDOE (2021) but using the average plume observations from 2008 and 2019, a reduction of 41.8% was calculated for that period.

3.3.6 Evaporation

A contingency evaporation process was initiated at the Monticello Mill Tailings site after it was determined that the original MNA remedy was unlikely to achieve the water quality restoration goals (USDOE 2022). The evaporation process actively remediates groundwater in an area within the contaminant plume that contains the highest uranium concentrations. The evaporation system uses eight vertical wells to extract groundwater upgradient of the PRB and the Monticello Mill Tailings site. The extracted water is pumped to a groundwater transfer building where it is batched and then pumped to a pond. The pumping system operates by balancing the extraction rate and the pond evaporation rate while maintaining the pond's storage volume between 18,927,059 liters (5,000,000 gallons) and 30,283,294 liters (8,000,000 gallons) (the maximum storage volume of the pond is approximately 59,052,423 liters [15,600,000 gallons]).

3.3.6.1 Range of Applicability

Uranium removal at the Monticello Mill Tailings site is mass-based and compared over time rather than by comparing the influent and effluent (USDOE 2022). The total uranium mass treated since evaporation start-up in 2015 was 55.8 Kg (123 lbs) with a removal of 90.1 million liters (23.8 million gallons) of groundwater. The maximum uranium observation in the plume at start-up in 2015 was 1,400 µg/L and 850 µg/L six years later in 2021.

3.3.6.2 Removal Efficiency

Evaporation removal efficiencies were not provided in the Monticello Mill Tailings study but using the maximum plume observations from 2015 and 2021, a reduction of 39.3% was calculated for that period.

3.3.7 Magnesium Hydroxide ($Mg(OH)_2$) Treatment

Magnesium hydroxide $Mg(OH)_2$ was used as an alkaline pre-treatment at the Danny-T Adit BCR treatment (CDM Smith 2014). $Mg(OH)_2$ as a pre-treatment helped to maintain the target pH of 4.5 to 5.5 for subsequent BCR treatment in a treatment train (see Section 3.3.10). The process at the Danny-T Adit in the Barker-Hughesville Mining District, Montana involved the addition of a $Mg(OH)_2$ solution to the pre-treatment barrel, followed by the addition of MIW. The $Mg(OH)_2$ solution and MIW stayed in the barrel for a set reaction time, which was not provided in the study (CDM Smith 2014), and then was added to the BCR barrel. While $Mg(OH)_2$ was used as a pre-treatment, the influent and effluent were sampled prior to input into the BCR barrels to be observed as a stand-alone treatment.

3.3.7.1 Flow Rates

The flow rate was initially set to 60 mL/min, which delivered a 120 mL dose of $Mg(OH)_2$ solution for each 9 L batch of MIW. The flow rate for the $Mg(OH)_2$ metering pump was later reduced to 25 mL/min, resulting in a 125 mL dose every 4 hours.

3.3.7.2 Range of Applicability

Table 3-13 presents the maximum and minimum influent concentrations and their corresponding effluent concentrations for the $Mg(OH)_2$ treatment (CDM Smith 2014).

Table 3-13. Maximum and Minimum Influent and Corresponding Effluent Concentrations – $Mg(OH)_2$ treatment at the Danny-T Adit

Constituent	Maximum influent concentration	Corresponding effluent concentration	Minimum influent concentration	Corresponding effluent concentration
Alkalinity (mg/L)	ND (< 1)	ND (< 1 – < 13)	ND (< 1)	ND (< 1 – < 13)
Aluminum, dissolved (µg/L)	15,600	870	8,710	180
Aluminum, total (µg/L)	18,900	1,560	12,600	3,410
Arsenic, dissolved (µg/L)	311	7	93	12
Arsenic, total (µg/L)	324	34	150	34
Cadmium, dissolved (µg/L)	316	249	154	140
Cadmium, total (µg/L)	293	248	150	161
Chromium, dissolved (µg/L)	6	ND (< 5)	ND	ND
Chromium, total (µg/L)	6	ND (< 5)	ND	ND
Cobalt, dissolved (µg/L)	58	44	36	35
Cobalt, total (µg/L)	56	44	39	38
Copper, dissolved (µg/L)	2,160	361	924	480
Copper, total (µg/L)	2,040	463	1,180	362
Iron, dissolved (µg/L)	180,000	41,000	112,000	37,600
Iron, total (µg/L)	179,000	54,800	129,000	36,300
Lead, dissolved (µg/L)	252	ND (< 1)	122	52
Lead, total (µg/L)	258	58	255	20
Manganese, dissolved (µg/L)	128,000	122,000	98,400	92,100
Manganese, total (µg/L)	129,000	101,000	101,000	98,800
Nickel, dissolved (µg/L)	39	30	28	28
Nickel, total (µg/L)	39	31	29	27
Sulfate (mg/L)	2,500	1,000	1,600	1,200
Zinc, dissolved (µg/L)	69,100	47,500	44,500	36,200
Zinc, total (µg/L)	71,000	47,600	45,700	44,400

Source: CDM Smith (2014)

[a] A range of effluent values reflects more than one day with the same influent.

ND = non-detect

3.3.7.3 Removal Efficiency

Removal efficiencies were not provided for the $Mg(OH)_2$ treatment (CDM Smith 2014); however, they were calculated for this report. Removal efficiencies are presented in Table 3-14 for the four influent/effluent combinations previously described. The positive removal efficiencies for metals with the $Mg(OH)_2$ treatment ranged from a low of 2.27% for total manganese to a high of 99.8% for dissolved lead.

Table 3-14. Calculated Removal Efficiencies for $Mg(OH)_2$ Treatment at the Danny-T Adit

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]
Aluminum, dissolved	94.4	97.9	0.0	97.9
Aluminum, total	91.8	72.9	72.9	91.8
Arsenic, dissolved	97.8	87.1	27.6	99.6[e]
Arsenic, total	89.5	77.3	89.5	77.3
Cadmium, dissolved	21.2	9.1	6.0	9.1
Cadmium, total	15.4	-7.3	15.4	-7.3
Chromium, dissolved	58.3[e]	N/A	N/A	N/A
Chromium, total	58.3[e]	N/A	N/A	N/A
Cobalt, dissolved	24.1	2.8	7.3	2.8
Cobalt, total	21.4	2.6	21.4	2.6
Copper, dissolved	83.3	48.0	-12.1	93.0
Copper, total	77.3	69.3	77.3	69.3
Iron, dissolved	77.2	66.4	99.0	99.7
Iron, total	69.4	71.9	69.4	71.9
Lead, dissolved	99.8[e]	57.4	4.6	99.6-99.8[e]
Lead, total	77.5	92.2	77.5	92.2
Manganese, dissolved	4.7	6.4	4.7	6.4
Manganese, total	21.7	2.2	21.7	2.2
Nickel, dissolved	23.1	0	2.7	13.3
Nickel, total	20.5	6.9	20.5	6.9
Sulfate	60	25.0	-4.6	41.8
Zinc, dissolved	31.3	18.7	0.4	18.7
Zinc, total	33.0	2.8	33.0	2.8

N/A = not available. Data not provided or influent was below detection limit and efficiency could not be calculated.

[a] Removal efficiency is based on the maximum influent concentration treated and the corresponding effluent concentration attained.

[b] Removal efficiency is based on the minimum influent concentration treated and the corresponding effluent concentration attained.

[c] Removal efficiency is based on the maximum effluent concentration attained and the corresponding influent concentration treated.

[d] Removal efficiency is based on the minimum effluent concentration attained and the corresponding influent concentration treated.

[a] Removal efficiency based on ½ the detection limit for the effluent. Detection limits are provided in Appendix A.

3.3.8 Chitorem®

An anaerobic Chitorem® treatment barrel was installed as the pre-treatment component with BCR in a treatment train at the Danny-T Adit site. Chitorem® is a proprietary material that is made up of 30% calcium carbonate, 40% protein, and 20% chitin, which is processed crab shell that can be used as a source of organic carbon (CDM Smith 2014). Chitorem® contains bacteria that causes the material to disintegrate over time producing carbonates that add alkalinity.

The Chitorem® barrel was filled with approximately 66.2 liters (17.5 gallons) of substrate material made up of 40% Chitorem®, 30% standard construction sand, and 30% pea gravel. Inert gravel was also placed in the bottom of the barrel as the drainage layer. Approximately 40.9 liters (10.8 gallons) of open space was left at the top of the barrel to provide headspace to allow room for the MIW influent piping distribution system. The MIW influent flowed into the Chitorem® barrel through a pipe gallery that distributed the MIW as evenly as possible across the barrel surface area.

The MIW flowed from the Chitorem® barrel into the BCR barrel through an effluent pipe that was embedded in the inert gravel drainage area. The design of the barrel provided a constant water surface elevation above the substrate layer to ensure that anaerobic and saturated conditions remained throughout the treatability study. While Chitorem® was used as a pre-treatment, the influent and effluent were sampled prior to input into the BCR barrels to be observed as a stand-alone treatment.

3.3.8.1 Flow Rates

The flow rate in the Chitorem® treatment barrel was approximately 25 mL/min (CDM Smith 2014).

3.3.8.2 Range of Applicability

Table 3-15 presents the maximum and minimum influent concentrations and their corresponding effluent concentrations for the Chitorem® treatment barrel at the Danny-T Adit (CDM Smith 2014).

Table 3-15. Maximum and Minimum Influent and Corresponding Effluent Concentrations – Chitorem® treatment at the Danny-T Adit

Constituent	Maximum influent concentration	Corresponding effluent concentration	Minimum influent concentration	Corresponding effluent concentration
Alkalinity (as $CaCO_3$) (mg/L)	ND (< 1)	620 – 23,000[a]	ND	620 – 23,000[a]
Aluminum, dissolved (µg/L)	15,600	300	8,710	90
Aluminum, total (µg/L)	18,900	710	12,600	110
Arsenic, dissolved (µg/L)	311	4,180	93	34
Arsenic, total (µg/L)	324	4,280	150	42
Cadmium, dissolved (µg/L)	316	44	154	ND (< 1)
Cadmium, total (µg/L)	293	51	150	2
Carbonate (as $CaCO_3$) (mg/L)	ND (< 1)	ND	ND	ND
Chromium, dissolved (µg/L)	6	ND (< 5 – < 23)	ND (< 5)	ND (< 5)
Chromium, total (µg/L)	6	25	ND (< 5)	ND
Cobalt, dissolved (µg/L)	58	183	36	11
Cobalt, total (µg/L)	56	190	39	8
Copper, dissolved (µg/L)	2,160	430	924	ND (< 5 µg/L)
Copper, total (µg/L)	2,040	550	1,180	21
Iron, dissolved (µg/L)	180,000	26,500	112,000	39,400
Iron, total (µg/L)	179,000	26,200	129,000	45,300
Lead, dissolved (µg/L)	252	7	122	ND (< 1)

Constituent	Maximum influent concentration	Corresponding effluent concentration	Minimum influent concentration	Corresponding effluent concentration
Lead, total (µg/L)	258	2	255	11
Manganese, dissolved (µg/L)	128,000	8,880	98,400	94,100
Manganese, total (µg/L)	129,000	3,290	101,000	109,000
Nickel, dissolved (µg/L)	39	1,060	28	5
Nickel, total (µg/L)	39	1,110	29	8
Phosphorus (mg/L)	0.478	40.2	ND (< 0.1)	47.7
Sulfate (mg/L)	2,500	520	1,600	2,300
Zinc, dissolved (µg/L)	69,100	1,040	44,500	20
Zinc, total (µg/L)	71,000	1,460	45,700	660

Source: CDM Smith (2014)

ND = non-detect

[a] A range of effluent values reflects more than one day with the same influent.

3.3.8.3 Removal Efficiency

The Chitorem® treatment had a > 98% removal efficiency for both dissolved aluminum and dissolved zinc (CDM Smith 2014). Removal efficiencies for the other constituents monitored at the site were not provided in the study; however, they were calculated for this report. Removal efficiencies are presented in Table 3-16. The positive removal efficiencies for metals using the Chitorem® treatment ranged from a low of 4.4% for total dissolved manganese and a high of 100% for dissolved zinc.

Table 3-16. Calculated Removal Efficiencies for Chitorem® Treatment at Danny-T Adit

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]
Aluminum, dissolved	98.1	99.0	98.1	99.9[e]
Aluminum, total	96.2	99.1	96.2	99.1
Arsenic, dissolved	-1,244.1	63.4	-1,244.1	86.3
Arsenic, total	-1,221.0	72.0	-1,221.0	72.0
Cadmium, dissolved	86.1	99.7 [e]	86.1	99.7-99.8 [e]
Cadmium, total	82.6	98.7	82.6	98.7
Chromium, dissolved	(-)283.3 – 58.33 [e]	N/A	-283.3	N/A
Chromium, total	-316.7	N/A	-316.7	N/A
Cobalt, dissolved	-215.5	69.4	-215.5	86.8
Cobalt, total	-239.3	79.5	-239.3	79.5
Copper, dissolved	80.1	99.7 [e]	80.1	99.7-99.9 [e]
Copper, total	73.0	98.2	73.0	98.2
Iron, dissolved	85.3	64.8	64.8-69.7	99.5
Iron, total	85.4	64.9	64.9	85.4
Lead, dissolved	97.2	99.6 [e]	97.2	99.6-99.8 [e]
Lead, total	99.2	95.7	95.7	99.2

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]
Manganese, dissolved	93.1	4.4	-9.7	97.5
Manganese, total	97.5	-7.9	-7.9	97.5
Nickel, dissolved	-2,618.0	82.1	-2,618.0	82.1
Nickel, total	-2,746.2	72.4	-2,746.2	72.4
Sulfate	79.2	-43.8	-43.8	79.2
Zinc, dissolved	98.5	100.0	98.5	100.0
Zinc, total	97.9	98.6	97.9	98.6

Source: calculated

N/A = not available. Data not provided or influent was below detection limit and efficiency could not be calculated.

[a] Removal efficiency is based on the maximum influent concentration treated and the corresponding effluent concentration attained.

[b] Removal efficiency is based on the minimum influent concentration treated and the corresponding effluent concentration attained.

[c] Removal efficiency is based on the maximum effluent concentration attained and the corresponding influent concentration treated.

[d] Removal efficiency is based on the minimum effluent concentration attained and the corresponding influent concentration treated.

[a] Removal efficiency based on ½ the detection limit for the effluent. Detection limits are provided in Appendix A.

3.3.9 Successive Alkalinity Systems (SAPS)

SAPS are anaerobic systems that contain limestone overlain by compost, which is overlain by several feet of water. MIW enters the top of the ponded water and flows downward through the compost, where oxygen is used up and it becomes more reducing. The water then flows through the limestone where it gains alkalinity, which raises the pH of the water and causes precipitation of elements.

The SAPS treatment unit at the Danny-T Adit was filled with approximately 66.2 liters (17.5 gallons) of substrate material made up of 40% SAPS substrate mixture, 30% standard construction sand, and 30% pea gravel (CDM Smith 2014). The SAPS substrate consisted of limestone gravel overlain by a manure and compost layer. The manure/compost layer made up approximately 25% of the volume, and the limestone made up approximately 75% of the volume. The compost and manure mixture was split evenly based on volume. Inert gravel was placed on the bottom of the SAPS barrel to act as a drainage layer. While SAPS was used as a pre-treatment at Danny T Adit, the influent and effluent were sampled prior to input into the BCR barrels to be observed as a stand-alone treatment.

The Blue Ledge Mine site also included SAPS in their study (CDM Smith 2015). The SAPS treatments (barrels 4 and 5) contained an equal part compost/manure mixture over a limestone layer above a drainage layer of inert gravel. The compost/manure layer made up about 10% of the treatment area, while the limestone made up the remaining 90%. One of the SAPS barrels (barrel 5) also included an ethanol dose that was set to approximately 2% of the MIW influent flow rate.

3.3.9.1 Flow Rates

No flow rate was provided for the Danny-T Adit SAPS treatment (CDM Smith 20214). The flow rate into the SAPS barrels at Blue Ledge Mine was approximately 15 L of MIW per day or 2.5 L per batch (6 batches per day) (CDM Smith 2015).

3.3.9.2 Range of Applicability

Table 3-17 and Table 3-18 present the maximum and minimum influent concentrations and their corresponding effluent concentrations, respectively, for the SAPS treatments at the Danny-T Adit (CDM Smith 2014) and the Blue Ledge Mine (CDM Smith 2015).

Table 3-17. Maximum Influent and Corresponding Effluent Concentrations – SAPS treatment at the Danny-T Adit and the Blue Ledge Mine

Constituent	Maximum influent concentration	Corresponding effluent concentration	Mine
Alkalinity (as $CaCO_3$) (mg/L)	ND (< 1)	ND (< 1) – ND (< 750)[a]	Danny-T Adit SAPS[b]
Alkalinity (as $CaCO_3$) (mg/L)	ND (< 10)	89 – 870[a]	Barrel 4 Blue Ledge Mine[c]
Alkalinity (as $CaCO_3$) (mg/L)	ND (< 10)	100 – 900[a]	Barrel 5 Blue Ledge Mine[c]
Aluminum, dissolved (µg/L)	15,600	40	Danny-T Adit SAPS[b]
Aluminum, dissolved (µg/L)	28,800	ND (< 200)	Barrel 4 Blue Ledge Mine[c]
Aluminum, dissolved (µg/L)	28,800	92.7	Barrel 5 Blue Ledge Mine[c]
Aluminum, total (µg/L)	18,900	220	Danny-T Adit SAPS[b]
Aluminum, total (µg/L)	26,300	118	Barrel 4 Blue Ledge Mine[c]
Aluminum, total (µg/L)	26,300	1,880	Barrel 5 Blue Ledge Mine[c]
Arsenic, dissolved (µg/L)	311	6	Danny-T Adit SAPS[b]
Arsenic, dissolved (µg/L)	1.1	0.62	Barrel 4 Blue Ledge Mine[c]
Arsenic, dissolved (µg/L)	3.2	ND (< 1 – < 10)	Barrel 5 Blue Ledge Mine[c]
Arsenic, total (µg/L)	324	56	Danny-T Adit SAPS[b]
Arsenic, total (µg/L)	3.2	2.1	Barrel 4 Blue Ledge Mine[c]
Arsenic, total (µg/L)	1.1	0.76	Barrel 5 Blue Ledge Mine[c]
Cadmium, dissolved (µg/L)	316	ND (< 1)	Danny-T Adit SAPS[b]
Cadmium, dissolved (µg/L)	161	ND (< 0.2)	Barrel 4 Blue Ledge Mine[c]
Cadmium, dissolved (µg/L)	161	0.37	Barrel 5 Blue Ledge Mine[c]
Cadmium, total (µg/L)	293	19	Danny-T Adit SAPS[b]
Cadmium, total (µg/L)	161	6.5	Barrel 4 Blue Ledge Mine[c]
Cadmium, total (µg/L)	161	ND (< 0.2)	Barrel 5 Blue Ledge Mine[c]
Chromium, dissolved (µg/L)	6	ND (< 0.2)	Danny-T Adit SAPS[b]
Chromium, dissolved (µg/L)	5.5	ND (< 0.2)	Barrel 4 Blue Ledge Mine[c]
Chromium, dissolved (µg/L)	5.5	ND (< 0.2)	Barrel 5 Blue Ledge Mine[c]
Chromium, total (µg/L)	6	ND (< 0.2)	Danny-T Adit SAPS[b]
Chromium, total (µg/L)	7	ND (< 0.2)	Barrel 4 Blue Ledge Mine[c]
Chromium, total (µg/L)	7	ND (< 0.2)	Barrel 5 Blue Ledge Mine[c]
Cobalt, dissolved (µg/L)	58	ND (< 5)	Danny-T Adit SAPS[b]
Cobalt, dissolved (µg/L)	124	10.1	Barrel 4 Blue Ledge Mine[c]
Cobalt, dissolved (µg/L)	124	10.1	Barrel 5 Blue Ledge Mine[c]
Cobalt, total (µg/L)	56	8	Danny-T Adit SAPS[b]
Cobalt, total (µg/L)	125	1.1	Barrel 4 Blue Ledge Mine[c]
Cobalt, total (µg/L)	125	18.2	Barrel 5 Blue Ledge Mine[c]
Copper, dissolved (µg/L)	2,160	ND (< 0.2)	Danny-T Adit SAPS[b]

Constituent	Maximum influent concentration	Corresponding effluent concentration	Mine
Copper, dissolved (µg/L)	21,500	531	Barrel 4 Blue Ledge Mine[c]
Copper, dissolved (µg/L)	21,500	50.3	Barrel 5 Blue Ledge Mine[c]
Copper, total (µg/L)	2,040	88	Danny-T Adit SAPS[b]
Copper, total (µg/L)	21,600	640	Barrel 4 Blue Ledge Mine[c]
Copper, total (µg/L)	21,600	262	Barrel 5 Blue Ledge Mine[c]
DOC (mg/L)	1.3	710	Barrel 4 Blue Ledge Mine[c]
DOC (mg/L)	1.3	3,800	Barrel 5 Blue Ledge Mine[c]
Iron, dissolved (µg/L)	180,000	2,630	Danny-T Adit SAPS[b]
Iron, dissolved (µg/L)	14,400	678	Barrel 4 Blue Ledge Mine[c]
Iron, dissolved (µg/L)	14,400	277	Barrel 5 Blue Ledge Mine[c]
Iron, total (µg/L)	179,000	4,860	Danny-T Adit SAPS[b]
Iron, total (µg/L)	14,800	2,130	Barrel 4 Blue Ledge Mine[c]
Iron, total (µg/L)	14,800	583	Barrel 5 Blue Ledge Mine[c]
Lead, dissolved (µg/L)	252	ND (< 1)	Danny-T Adit SAPS[b]
Lead, dissolved (µg/L)	11.8	ND (< 5)	Barrel 4 Blue Ledge Mine[c]
Lead, dissolved (µg/L)	11.8	ND (< 5)	Barrel 5 Blue Ledge Mine[c]
Lead, total (µg/L)	258	1,950	Danny-T Adit SAPS
Lead, total (µg/L)	25.5	ND (< 1)	Barrel 4 Blue Ledge Mine[c]
Lead, total (µg/L)	25.5	ND (< 1)	Barrel 5 Blue Ledge Mine[c]
Manganese, dissolved (µg/L)	128,000	135,000	Danny-T Adit SAPS[b]
Manganese, dissolved (µg/L)	4,180	5,840	Barrel 4 Blue Ledge Mine[c]
Manganese, dissolved (µg/L)	4,180	4,990	Barrel 5 Blue Ledge Mine[c]
Manganese, total (µg/L)	129,000	42,600	Danny-T Adit SAPS[b]
Manganese, total (µg/L)	4,590	1,360	Barrel 4 Blue Ledge Mine[c]
Manganese, total (µg/L)	4,590	1,040	Barrel 5 Blue Ledge Mine[c]
Mercury, dissolved (µg/L)	0.042	ND (< 0.2)	Barrel 4 Blue Ledge Mine[c]
Mercury, dissolved (µg/L)	0.042	0.087	Barrel 5 Blue Ledge Mine[c]
Mercury, total (µg/L)	0.029	0.045	Barrel 4 Blue Ledge Mine[c]
Mercury, total (µg/L)	0.029	0.19	Barrel 5 Blue Ledge Mine[c]
Nickel, dissolved (µg/L)	39	5	Danny-T Adit SAPS[b]
Nickel, dissolved (µg/L)	414	3.7	Barrel 4 Blue Ledge Mine[c]
Nickel, dissolved (µg/L)	414	32.7	Barrel 5 Blue Ledge Mine[c]
Nickel, total (µg/L)	39	10	Danny-T Adit SAPS[b]
Nickel, total (µg/L)	424	4.8	Barrel 4 Blue Ledge Mine[c]
Nickel, total (µg/L)	424	32	Barrel 5 Blue Ledge Mine[c]
Selenium, dissolved (µg/L)	ND (< 5) – ND (< 50)	ND	Barrel 4 Blue Ledge Mine[c]
Selenium, dissolved (µg/L)	ND (< 5 L) – ND (< 50)	ND	Barrel 5 Blue Ledge Mine[c]
Selenium, total (µg/L)	3	ND (< 25)	Barrel 4 Blue Ledge Mine[c]
Selenium, total (µg/L)	3	ND (< 5– ND (< 50)	Barrel 5 Blue Ledge Mine[c]
Sulfide (mg/L)	ND (< 1)	4.3	Barrel 4 Blue Ledge Mine[c]

Constituent	Maximum influent concentration	Corresponding effluent concentration	Mine
Sulfide (mg/L)	ND (< 1)	5.5	Barrel 5 Blue Ledge Mine[c]
Sulfate (mg/L)	2,500	1,300	Danny-T Adit SAPS[b]
Sulfate (mg/L)	610	470	Barrel 4 Blue Ledge Mine[c]
Sulfate (mg/L)	610	490	Barrel 5 Blue Ledge Mine[c]
Zinc, dissolved (µg/L)	69,100	70	Danny-T Adit SAPS[b]
Zinc, dissolved (µg/L)	29,000	ND (< 2.7)	Barrel 4 Blue Ledge Mine[c]
Zinc, dissolved (µg/L)	29,000	1,470	Barrel 5 Blue Ledge Mine[c]
Zinc, total (µg/L)	71,000	6,050	Danny-T Adit SAPS[b]
Zinc, total (µg/L)	28,200	539	Barrel 4 Blue Ledge Mine[c]
Zinc, total (µg/L)	28,200	162	Barrel 5 Blue Ledge Mine[c]

ND = non-detect

[a] A range of effluent values reflects more than one day with the same influent concentration.

[b] CDM Smith (2014)

[c] CDM Smith (2015)

Table 3-18. Minimum Influent and Corresponding Effluent Concentrations – SAPS treatment at the Danny-T Adit and Blue Ledge Mine

Constituent	Minimum influent concentration	Corresponding effluent concentration	Mine
Alkalinity (mg/L)	ND (< 1)	ND (< 1 – < 750)	Danny-T Adit SAPS[b]
Alkalinity (mg/L)	ND (< 10)	89 – 870[a]	Barrel 4 Blue Ledge Mine[c]
Alkalinity (mg/L)	ND (< 10)	100 – 900[a]	Barrel 5 Blue Ledge Mine[c]
Alkalinity, Bicarbonate (as CaCO3) (mg/L)	ND (< 10)	89 – 870[a]	Barrel 4 Blue Ledge Mine[c]
Alkalinity, Bicarbonate (as CaCO3) (mg/L)	ND (< 10)	100 – 900[a]	Barrel 5 Blue Ledge Mine[c]
Alkalinity, Carbonate (as CaCO3) (mg/L)	ND (< 10)	ND	Barrel 4 Blue Ledge Mine[c]
Alkalinity, Carbonate (as CaCO3) (mg/L)	ND (< 10)	ND	Barrel 5 Blue Ledge Mine[c]
Alkalinity, Hydroxide (as CaCO3) (mg/L)	ND (< 10)	ND	Barrel 4 Blue Ledge Mine[c]
Alkalinity, Hydroxide (as CaCO3) (mg/L)	ND (< 10)	ND	Barrel 5 Blue Ledge Mine[c]
Aluminum, dissolved (µg/L)	8,710	2,020	Danny-T Adit SAPS[b]
Aluminum, dissolved (µg/L)	6,470	ND (< 200)	Barrel 4 Blue Ledge Mine[c]
Aluminum, dissolved (µg/L)	6,470	216	Barrel 5 Blue Ledge Mine[c]
Aluminum, total (µg/L)	12,600	154,000	Danny-T Adit SAPS[b]
Aluminum, total (µg/L)	6,610	13	Barrel 4 Blue Ledge Mine[c]
Aluminum, total (µg/L)	6,620	568	Barrel 5 Blue Ledge Mine[c]
Arsenic, dissolved (µg/L)	93	52	Danny-T Adit SAPS[b]
Arsenic, dissolved (µg/L)	0.38	1.3	Barrel 4 Blue Ledge Mine[c]

Constituent	Minimum influent concentration	Corresponding effluent concentration	Mine
Arsenic, dissolved (µg/L)	0.38	0.38	Barrel 5 Blue Ledge Mine[c]
Arsenic, total (µg/L)	150	746	Danny-T Adit SAPS[b]
Arsenic, total (µg/L)	1.2	1.7	Barrel 4 Blue Ledge Mine[c]
Arsenic, total (µg/L)	1.2	1.8	Barrel 5 Blue Ledge Mine[c]
Cadmium, dissolved (µg/L)	154	100	Danny-T Adit SAPS[b]
Cadmium, dissolved (µg/L)	65.3	ND (< 2)	Barrel 4 Blue Ledge Mine[c]
Cadmium, dissolved (µg/L)	65.3	2.3	Barrel 5 Blue Ledge Mine[c]
Cadmium, total (µg/L)	150	584	Danny-T Adit SAPS[b]
Cadmium, total (µg/L)	66	ND (< 1)	Barrel 4 Blue Ledge Mine[c]
Cadmium, total (µg/L)	66	6.6	Barrel 5 Blue Ledge Mine[c]
Chromium, dissolved (µg/L)	ND (< 5)	ND (< 5 – < 6)[a]	Danny-T Adit SAPS[b]
Chromium, dissolved (µg/L)	2.6	ND (< 2)	Barrel 4 Blue Ledge Mine[c]
Chromium, dissolved (µg/L)	2.6	ND (< 2)	Barrel 5 Blue Ledge Mine[c]
Chromium, total (µg/L)	ND (< 5)	82	Danny-T Adit SAPS[b]
Chromium, total (µg/L)	2.7	ND (< 2)	Barrel 4 Blue Ledge Mine[c]
Chromium, total (µg/L)	2.7	ND (< 2)	Barrel 5 Blue Ledge Mine[c]
Cobalt, dissolved (µg/L)	36	39	Danny-T Adit SAPS[b]
Cobalt, dissolved (µg/L)	19.5	ND (< 5)	Barrel 4 Blue Ledge Mine[c]
Cobalt, dissolved (µg/L)	19.5	ND (< 5)	Barrel 5 Blue Ledge Mine[c]
Cobalt, total (µg/L)	39	38	Danny-T Adit SAPS[b]
Cobalt, total (µg/L)	20.4	5.5	Barrel 4 Blue Ledge Mine[c]
Cobalt, total (µg/L)	20.4	5.4	Barrel 5 Blue Ledge Mine[c]
Copper, dissolved (µg/L)	924	780	Danny-T Adit SAPS[b]
Copper, dissolved (µg/L)	9,830	ND (< 10)	Barrel 4 Blue Ledge Mine[c]
Copper, dissolved (µg/L)	9,830	ND (< 10)	Barrel 5 Blue Ledge Mine[c]
Copper, total (µg/L)	1,180	10,100	Danny-T Adit SAPS[b]
Copper, total (µg/L)	10,100	27.6	Barrel 4 Blue Ledge Mine[c]
Copper, total (µg/L)	10,100	527	Barrel 5 Blue Ledge Mine[c]
DOC (mg/L)	1.3	710	Barrel 4 Blue Ledge Mine[c]
DOC (mg/L)	1.3	3,800	Barrel 5 Blue Ledge Mine[c]
Iron, dissolved (µg/L)	112,000	107,000	Danny-T Adit SAPS[b]
Iron, dissolved (µg/L)	1,580	1,560	Barrel 4 Blue Ledge Mine[c]
Iron, dissolved (µg/L)	1,580	4,320	Barrel 5 Blue Ledge Mine[c]
Iron, total (µg/L)	129,000	669,000	Danny-T Adit SAPS[b]
Iron, total (µg/L)	1,560	2,350	Barrel 4 Blue Ledge Mine[c]
Iron, total (µg/L)	1,560	4,260	Barrel 5 Blue Ledge Mine[c]
Lead, dissolved (µg/L)	122	184	Danny-T Adit SAPS[b]
Lead, dissolved (µg/L)	3.4	ND (< 1)	Barrel 4 Blue Ledge Mine[c]
Lead, dissolved (µg/L)	3.4	ND (< 1)	Barrel 5 Blue Ledge Mine[c]
Lead, total (µg/L)	255	14	Danny-T Adit SAPS[b]

Constituent	Minimum influent concentration	Corresponding effluent concentration	Mine
Lead, total (µg/L)	3.4	ND (< 1)	Barrel 4 Blue Ledge Mine[c]
Lead, total (µg/L)	3.4	ND (< 1)	Barrel 5 Blue Ledge Mine[c]
Manganese, dissolved (µg/L)	98,400	99,000	Danny-T Adit SAPS[b]
Manganese, dissolved (µg/L)	629	3,470	Barrel 4 Blue Ledge Mine[c]
Manganese, dissolved (µg/L)	629	3,080	Barrel 5 Blue Ledge Mine[c]
Manganese, total (µg/L)	101,000	96,300	Danny-T Adit SAPS[b]
Manganese, total (µg/L)	621	3,470	Barrel 4 Blue Ledge Mine[c]
Manganese, total (µg/L)	621	3,180	Barrel 5 Blue Ledge Mine[c]
Mercury, dissolved (µg/L)	0.042	ND (< 0.2)	Barrel 4 Blue Ledge Mine[c]
Mercury, dissolved (µg/L)	0.042	0.087	Barrel 5 Blue Ledge Mine[c]
Mercury, total (µg/L)	0.029	0.045	Barrel 4 Blue Ledge Mine[c]
Mercury, total (µg/L)	0.029	0.19	Barrel 5 Blue Ledge Mine[c]
Nickel, dissolved (µg/L)	28	29	Danny-T Adit SAPS[b]
Nickel, dissolved (µg/L)	58.5	7.5	Barrel 4 Blue Ledge Mine[c]
Nickel, dissolved (µg/L)	58.5	8	Barrel 5 Blue Ledge Mine[c]
Nickel, total (µg/L)	29	30	Danny-T Adit SAPS[b]
Nickel, total (µg/L)	59.1	ND (< 6.5)	Barrel 4 Blue Ledge Mine[c]
Nickel, total (µg/L)	59.1	ND (< 11.2)	Barrel 5 Blue Ledge Mine[c]
Nitrate-Nitrite (mg/L)	0.15	0.027	Barrel 4 Blue Ledge Mine[c]
Nitrate-Nitrite (mg/L)	0.15	0.096	Barrel 5 Blue Ledge Mine[c]
Phosphorus, total (mg/L)	ND (< 0.1)	10.4	Danny-T Adit SAPS[b]
Selenium, dissolved (µg/L)	ND (< 5 – < 50)	ND [a]	Barrel 4 Blue Ledge Mine[c]
Selenium, dissolved (µg/L)	ND (< 5 – < 50)	ND [a]	Barrel 5 Blue Ledge Mine[c]
Selenium, total (µg/L)	1.8	ND (< 50)	Barrel 4 Blue Ledge Mine[c]
Selenium, total (µg/L)	1.8	ND (< 50)	Barrel 5 Blue Ledge Mine[c]
Sulfide (mg/L)	ND (< 1)	4.3	Barrel 4 Blue Ledge Mine[c]
Sulfide (mg/L)	ND (< 1)	5.5	Barrel 5 Blue Ledge Mine[c]
Sulfate (mg/L)	1,600	600	Danny-T Adit SAPS[b]
Sulfate (mg/L)	210	310	Barrel 4 Blue Ledge Mine[c]
Sulfate (mg/L)	210	230	Barrel 5 Blue Ledge Mine[c]
Zinc, dissolved (µg/L)	44,500	53,200	Danny-T Adit SAPS[b]
Zinc, dissolved (µg/L)	12,000	4.1	Barrel 4 Blue Ledge Mine[c]
Zinc, dissolved (µg/L)	12,000	635	Barrel 5 Blue Ledge Mine[c]
Zinc, total (µg/L)	45,700	69,800	Danny-T Adit SAPS[b]
Zinc, total (µg/L)	12,700	941	Barrel 4 Blue Ledge Mine[c]
Zinc, total (µg/L)	12,700	1,510	Barrel 5 Blue Ledge Mine[c]

ND = non-detect

[a] A range of effluent values reflects more than one day with the same influent concentration.

[b] CDM Smith (2014)

[c] CDM Smith (2015)

3.3.9.3 Removal Efficiency

Removal efficiencies for dissolved aluminum, cadmium, cobalt, copper, nickel, and zinc at the Blue Ledge Mine SAPS treatment were provided by CDM Smith (2015), but removal efficiencies for the remaining constituents at Blue Ledge Mine and all constituents at the Danny-T Adit (CDM Smith 2014) were not provided. Removal efficiencies for all conditions were calculated for the remaining Blue Ledge Mine constituents and for the Danny-T Adit SAPS treatment. Reported removal efficiencies are presented in Table 3-19 and calculated removal efficiencies are presented in Table 3-20. Note that Blue Ledge Mine barrel 4 in Table 3-19 is the SAPS barrel, while barrel 5 is the SAPS barrel with the addition of ethanol (CDM Smith 2015).

Positive removal efficiencies for metals of interest reported at Blue Ledge Mine and Danny-T Adit ranged from -655.8% for total lead at Danny-T Adit to 100% for dissolved copper at the Danny-T Adit SAPS. Several SAPS treatments also had a 99.9% removal efficiency including total cadmium, dissolved cadmium, dissolved copper, and dissolved zinc in barrels 4 and 5 (SAPS plus ethanol) at Blue Ledge Mine, as well as dissolved zinc at the Danny-T Adit.

Table 3-19. Reported Removal Efficiencies for SAPS treatments at Blue Ledge Mine and Danny-T Adit

Constituent	Removal efficiency (%)	Mine
Aluminum, dissolved	99.7	Danny-T Adit SAPS
Aluminum, dissolved	96.0 – 99.3	Barrel 4 Blue Ledge Mine
Aluminum, dissolved	96.7 – 99.2	Barrel 5 Blue Ledge Mine
Aluminum, total	98.8	Danny-T Adit SAPS
Aluminum, total	99.6	Barrel 4 Blue Ledge Mine
Aluminum, total	92.9	Barrel 5 Blue Ledge Mine
Arsenic, dissolved	98.1	Danny-T Adit SAPS
Arsenic, dissolved	43.6	Barrel 4 Blue Ledge Mine
Arsenic, dissolved [a]	-56.3 – 96.9	Barrel 5 Blue Ledge Mine
Arsenic, total	82.7	Danny-T Adit SAPS
Arsenic, total	34.4	Barrel 4 Blue Ledge Mine
Arsenic, total	30.9	Barrel 5 Blue Ledge Mine
Cadmium, dissolved	99.8	Danny-T Adit SAPS
Cadmium, dissolved	96.5 – 99.9	Barrel 4 Blue Ledge Mine
Cadmium, dissolved	91.3 – 99.8	Barrel 5 Blue Ledge Mine
Cadmium, total	93.5	Danny-T Adit SAPS
Cadmium, total	96.0	Barrel 4 Blue Ledge Mine
Cadmium, total	99.9	Barrel Blue Ledge Mine
Chromium, dissolved [a]	98.3	Danny-T Adit SAPS
Chromium, dissolved [a]	98.2	Barrel 4 Blue Ledge Mine
Chromium, dissolved [a]	98.2	Barrel 5 Blue Ledge Mine
Chromium, total [a]	98.3	Danny-T Adit SAPS
Chromium, total [a]	98.6	Barrel 4 Blue Ledge Mine
Chromium, total [a]	98.6	Barrel 5 Blue Ledge Mine
Cobalt, dissolved [a]	95.7	Danny-T Adit SAPS
Cobalt, dissolved	74.4 – 99.1	Barrel 4 Blue Ledge Mine

Constituent	Removal efficiency (%)	Mine
Cobalt, dissolved	91.9	Barrel 5 Blue Ledge Mine
Cobalt, total	85.7	Danny-T Adit SAPS
Cobalt, total	99.1	Barrel 4 Blue Ledge Mine
Cobalt, total	85.4	Barrel 5 Blue Ledge Mine
Copper, dissolved [a]	100.0	Danny-T Adit SAPS
Copper, dissolved	97.4 – 99.9	Barrel 4 Blue Ledge Mine
Copper, dissolved	98.3 – 99.9	Barrel 5 Blue Ledge Mine
Copper, total	95.7	Danny-T Adit SAPS
Copper, total	97.0	Barrel 4 Blue Ledge Mine
Copper, total	98.8	Barrel 5 Blue Ledge Mine
DOC	-54,515.4	Barrel 4 Blue Ledge Mine
DOC	-29,2207.7	Barrel 5 Blue Ledge Mine
Iron, dissolved	98.5	Danny-T Adit SAPS
Iron, dissolved	95.3	Barrel 4 Blue Ledge Mine
Iron, dissolved	98.1	Barrel 5 Blue Ledge Mine
Iron, total	97.3	Danny-T Adit SAPS
Iron, total	85.6	Barrel 4 Blue Ledge Mine
Iron, total	96.1	Barrel 5 Blue Ledge Mine
Lead, dissolved [a]	99.8	Danny-T Adit SAPS
Lead, dissolved [a]	78.8	Barrel 4 Blue Ledge Mine
Lead, dissolved [a]	78.8	Barrel 5 Blue Ledge Mine
Lead, total	-655.8	Danny-T Adit SAPS
Lead, total [a]	98.0	Barrel 4 Blue Ledge Mine
Lead, total [a]	98.0	Barrel 5 Blue Ledge Mine
Manganese, dissolved	-5.5	Danny-T Adit SAPS
Manganese, dissolved	-39.7	Barrel 4 Blue Ledge Mine
Manganese, dissolved	-19.4	Barrel 5 Blue Ledge Mine
Manganese, total	67.0	Danny-T Adit SAPS
Manganese, total	70.4	Barrel 4 Blue Ledge Mine
Manganese, total	77.3	Barrel 5 Blue Ledge Mine
Mercury, dissolved [a]	-138.1	Barrel 4 Blue Ledge Mine
Mercury, dissolved	-107.1	Barrel 5 Blue Ledge Mine
Mercury, total	-55.2	Barrel 4 Blue Ledge Mine
Mercury, total	-555.2	Barrel 5 Blue Ledge Mine
Nickel, dissolved	87.2	Danny-T Adit SAPS
Nickel, dissolved	81.4 – 99.1	Barrel 4 Blue Ledge Mine
Nickel, dissolved	92.1	Barrel 5 Blue Ledge Mine
Nickel, total	74.4	Danny-T Adit SAPS
Nickel, total	98.9	Barrel 4 Blue Ledge Mine
Nickel, total	92.5	Barrel 5 Blue Ledge Mine
Nitrate-Nitrite	82.0	Barrel 4 Blue Ledge Mine

Constituent	Removal efficiency (%)	Mine
Nitrate-Nitrite	36.0	Barrel 5 Blue Ledge Mine
Phosphorus, total	77.0	Danny-T Adit SAPS
Selenium, total [a]	-316.7	Barrel 4 Blue Ledge Mine
Selenium, total [a]	-733.3 – 16.7	Barrel 5 Blue Ledge Mine
Sulfate	48.0	Danny-T Adit SAPS
Sulfate	23.0	Barrel 4 Blue Ledge Mine
Sulfate	19.7	Barrel 5 Blue Ledge Mine
Zinc, dissolved	99.9	Danny-T Adit SAPS
Zinc, dissolved	96.9 – 99.9	Barrel 4 Blue Ledge Mine
Zinc, dissolved	94.7 – 99.9	Barrel 5 Blue Ledge Mine
Zinc, total	91.5	Danny-T Adit SAPS
Zinc, total	98.1	Barrel 4 Blue Ledge Mine
Zinc, total	99.4	Barrel 5 Blue Ledge Mine

Source: CDM Smith (2015 and 2014)

[a] Removal efficiency based on ½ the detection limit for the effluent. Detection limits are provided in Table 3-17 and Table 3-18.

Table 3-20. Calculated Removal Efficiencies for SAPS Treatments at Blue Ledge Mine and Danny-T Adit

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine
Aluminum, dissolved	99.7	76.8	80.1	99.7	Danny-T Adit SAPS
Aluminum, dissolved	99.7 [e]	98.5 [e]	96.0	97.8	Barrel 4 Blue Ledge Mine
Aluminum, dissolved	99.7	96.7	96.7	99.5	Barrel 5 Blue Ledge Mine
Aluminum, total	98.8	-1,122.2	-1,122.2	98.8	Danny-T Adit SAPS
Aluminum, total	99.6	98.0	92.8	99.6	Barrel 4 Blue Ledge Mine
Aluminum, total	92.9	91.4	92.9	99.7	Barrel 5 Blue Ledge Mine
Arsenic, dissolved	98.1	44.1	44.1	97.4	Danny-T Adit SAPS
Arsenic, dissolved	43.6	-242.1	N/A	N/A	Barrel 4 Blue Ledge Mine
Arsenic, dissolved	30.9	0.0	N/A	0.0	Barrel 5 Blue Ledge Mine
Arsenic, total	82.7	-397.3	-397.3	82.7	Danny-T Adit SAPS
Arsenic, total	34.4	-41.7	N/A	N/A	Barrel 4 Blue Ledge Mine
Arsenic, total	-56.3 – 84.4 [e]	-50.0	N/A	N/A	Barrel 5 Blue Ledge Mine
Cadmium, dissolved	99.8 [e]	35.0	35.0	99.8 [e]	Danny-T Adit SAPS

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine
Cadmium, dissolved	99.9 [e]	98.5 [e]	96.5	99.4	Barrel 4 Blue Ledge Mine
Cadmium, dissolved	99.8	96.5	91.5	99.8	Barrel 5 Blue Ledge Mine
Cadmium, total	93.5	-289.3	-289.3	93.5	Danny-T Adit SAPS
Cadmium, total	96.0	99.2 [e]	94.0	99.6	Barrel 4 Blue Ledge Mine
Cadmium, total	99.4 [e]	90.0	88.6	98.5	Barrel Blue Ledge Mine
Chromium, dissolved	58.3 [e]	N/A	N/A	N/A	Danny-T Adit SAPS
Chromium, dissolved	81.8 [e]	61.5 [e]	63.0 – 85.7 [e]	63.0 – 85.7 [e]	Barrel 4 Blue Ledge Mine
Chromium, dissolved	81.8 [e]	61.5 [e]	63.0 – 85.7 [e]	63.0 – 85.7 [e]	Barrel 5 Blue Ledge Mine
Chromium, total	58.3 [e]	N/A	N/A	58.3 [e]	Danny-T Adit SAPS
Chromium, total	85.7 [e]	63.0 [e]	63.0 – 85.7 [e]	63.0 – 85.7 [e]	Barrel 4 Blue Ledge Mine
Chromium, total	85.7 [e]	63.0 [e]	63.0 – 85.7 [e]	63.0 – 85.7 [e]	Barrel 5 Blue Ledge Mine
Cobalt, dissolved	95.7 [e]	-8.3	-29.2	95.7 [e]	Danny-T Adit SAPS
Cobalt, dissolved	91.9	87.2 [e]	63.5	99.1	Barrel 4 Blue Ledge Mine
Cobalt, dissolved	91.9	87.2 [e]	39.7	86.8	Barrel 5 Blue Ledge Mine
Cobalt, total	85.7	2.6	2.6	85.7	Danny-T Adit SAPS
Cobalt, total	99.1	73.0	52.0	96.0	Barrel 4 Blue Ledge Mine
Cobalt, total	85.4	73.5	41.2	73.5	Barrel 5 Blue Ledge Mine
Copper, dissolved	99.9 [e]	15.6	15.6	99.8 – 99.9 [e]	Danny-T Adit SAPS
Copper, dissolved	97.5	100.0 [e]	97.5	N/A	Barrel 4 Blue Ledge Mine
Copper, dissolved	99.8	100.0 [e]	98.3	100.0	Barrel 5 Blue Ledge Mine
Copper, total	95.7	-755.9	-755.9	95.7	Danny-T Adit SAPS
Copper, total	97.0	99.7	93.3	99.9	Barrel 4 Blue Ledge Mine
Copper, total	98.8	94.8	N/A	99.7	Barrel 5 Blue Ledge Mine
DOC	-5,4515.4	-5,4515.4	-5,4515.4	N/A	Barrel 4 Blue Ledge Mine

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine
DOC	-292,207.7	-292,207.7	N/A	N/A	Barrel 5 Blue Ledge Mine
Iron, dissolved	98.5	4.5	31.5	98.5	Danny-T Adit SAPS
Iron, dissolved	95.3	1.3	-4.4	84.1	Barrel 4 Blue Ledge Mine
Iron, dissolved	98.1	-173.4	-92.2	97.79	Barrel 5 Blue Ledge Mine
Iron, total	97.3	-418.6	-273.7	97.3	Danny-T Adit SAPS
Iron, total	85.6	-50.6	-126.9	62.0	Barrel 4 Blue Ledge Mine
Iron, total	96.1	-173.1	-128.6	93.8	Barrel 5 Blue Ledge Mine
Lead, dissolved	99.8 [e]	-50.8	-50.8	99.8 [e]	Danny-T Adit SAPS
Lead, dissolved	78.8 [e]	85.3 [e]	N/A	N/A	Barrel 4 Blue Ledge Mine
Lead, dissolved	78.8 [e]	85.3 [e]	N/A	N/A	Barrel 5 Blue Ledge Mine
Lead, total	-655.8	94.5	-655.8	94.5	Danny-T Adit SAPS
Lead, total	98.0 [e]	85.3 [e]	N/A	N/A	Barrel 4 Blue Ledge Mine
Lead, total	98.0 [e]	85.3 [e]	N/A	N/A	Barrel 5 Blue Ledge Mine
Manganese, dissolved	-5.5	-0.6	-5.5	65.8	Danny-T Adit SAPS
Manganese, dissolved	-39.7	-451.7	-148.9	68.4	Barrel 4 Blue Ledge Mine
Manganese, dissolved	-19.4	-389.7	-129.8	-103.7	Barrel 5 Blue Ledge Mine
Manganese, total	67	4.7	4.65	67.0	Danny-T Adit SAPS
Manganese, total	70.4	-458.8	-49.5	70.4	Barrel 4 Blue Ledge Mine
Manganese, total	77.3	-412.1	-130.9	77.3	Barrel 5 Blue Ledge Mine
Mercury, dissolved	-138.1 [e]	-138.1 [e]	N/A	N/A	Barrel 4 Blue Ledge Mine
Mercury, dissolved	-107.1	-107.1	N/A	N/A	Barrel 5 Blue Ledge Mine
Mercury, total	-55.2	-55.2	N/A	-55.2	Barrel 4 Blue Ledge Mine
Mercury, total	-555.2	-555.2	-555.2	N/A	Barrel 5 Blue Ledge Mine
Nickel, dissolved	87.2	-3.6	-23.5	87.2	Danny-T Adit SAPS

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine
Nickel, dissolved	99.1	87.2	81.4	99.1	Barrel 4 Blue Ledge Mine
Nickel, dissolved	92.1	86.3	61.8	97.2	Barrel 5 Blue Ledge Mine
Nickel, total	74.4	-3.5	-3.5	74.4	Danny-T Adit SAPS
Nickel, total	98.9	94.5 [e]	76.7	98.9	Barrel 4 Blue Ledge Mine
Nickel, total	92.5	90.5 [e]	61.9	96.6	Barrel 5 Blue Ledge Mine
Nitrate-Nitrite	82.0	82.0	82.0	82.0	Barrel 4 Blue Ledge Mine
Nitrate-Nitrite	36.0	36.0	36.0	36.0	Barrel 5 Blue Ledge Mine
Phosphorus, total	77.0	N/A	N/A	61.5	Danny-T Adit SAPS
Selenium, total	-316.7 [e]	-1,288.9 [e]	N/A	N/A	Barrel 4 Blue Ledge Mine
Selenium, total	-316.7 [e]	-1,288.9 [e]	N/A	N/A	Barrel 5 Blue Ledge Mine
Sulfate	48.0	62.5	22.7	62.5	Danny-T Adit SAPS
Sulfate	23.0	-47.6	-24.4	18.5	Barrel 4 Blue Ledge Mine
Sulfate	19.7	-9.5	-26.8	44.4	Barrel 5 Blue Ledge Mine
Zinc, dissolved	99.9	-19.6	-18.6	99.9	Danny-T Adit SAPS
Zinc, dissolved	100.0[e]	100.0	96.9	100.0 [e]	Barrel 4 Blue Ledge Mine
Zinc, dissolved	94.9	94.7	N/A	100.0	Barrel 5 Blue Ledge Mine
Zinc, total	91.5	-52.7	-52.7	91.5	Danny-T Adit SAPS
Zinc, total	98.1	92.6	90.5 – 93.0	98.1	Barrel 4 Blue Ledge Mine
Zinc, total	99.4	88.1	67.0	99.4	Barrel 5 Blue Ledge Mine

N/A = not available. Data not provided or influent was below detection limit and efficiency could not be calculated.

[a] Removal efficiency is based on the maximum influent concentration treated and the corresponding effluent concentration attained.

[b] Removal efficiency is based on the minimum influent concentration treated and the corresponding effluent concentration attained.

[c] Removal efficiency is based on the maximum effluent concentration attained and the corresponding influent concentration treated.

[d] Removal efficiency is based on the minimum effluent concentration attained and the corresponding influent concentration treated.

[a] Removal efficiency based on ½ the detection limit for the effluent. Detection limits are provided in Appendix A.

3.3.10 Treatment Trains

A treatment train is a group of technologies set up in a series to work together to treat MIW. Treatment trains can include technologies that are active, passive, and/or semi-passive. Treatment trains were used in several of the studies reviewed for this report, including three of the BCR studies (Danny-T Adit, Ely Copper Mine, and Formosa Mine), the Conda/Woodall Mountain Mine PRB study, and the Champion Mine constructed wetland study. This section discusses the treatment trains in terms of influent to the first component in the trains and effluent from the last component in the treatment train. These are detailed below and summarized in Table 3-21.

BCRs 2, 3, and 4 in the Danny T Adit study had the same substrate as BCR 1 (sawdust, wood chips, compost, dairy manure and limestone chips [CDM Smith 2014]) but also had pre-treatment (i.e., in a treatment train): SAPS for BCR 2, Chitorem® for BCR 3, and $Mg(OH)_2$ for BCR 4. Four BCR barrels at Formosa Mine were also part of treatment trains, where BCR 3 and BCR 4 received outflow from a SAPS pre-treatment barrel and BCR 5 and BCR 6 received outflow from a Chitorem® pre-treatment barrel (CDM Smith 2014 and Parametrix). BCRs 3 and 5 had a woody mixture substrate and BCRs 4 and 6 had a Chitorem® and sand mixture as their substrate. The STC pre-treatment and PRB at Conda/Woodall Mountain Mine both used the same treatment media (sand, alfalfa hay, and woodchips). Finally, the BCR at Ely Copper Mine had a limestone pre-treatment (McSurdy et al. 1997). Technology components in these treatment trains have been described in prior sections of this report, except for constructed wetlands. Wetlands consist of saturated soils, water cover at or near the surface for at least part of the year, and vegetation that can survive in saturated soils. Constructed wetlands are created to treat metals or other contaminants present in groundwater or surface water through oxidation (aerobic) or reduction (anaerobic) reactions (USEPA 1994). As previously noted, the wetland at Champion Mine was a system consisting of a settling pond and a five-tiered wetland.

Table 3-21. Treatment train configurations

System	Pre-treatment	Treatment
Danny T Adit BCR2	SAPS	BCR
Danny T Adit BCR3	Chitorem®	BCR
Danny T Adit BCR4	$Mg(OH)_2$	BCR
Formosa BCR3	SAPS	BCR
Formosa BCR4	SAPS	BCR
Formosa BCR5	Chitorem®	BCR
Formosa BCR6	Chitorem®	BCR
Ely Copper	Limestone	BCR
Conda/Woodall Mine	Seep Treatment Cell	PRB
Champion Mine	Settling Pond	Constructed Wetlands

3.3.10.1 Flow Rates

The MIW flow rate in the Danny-T Adit BCR study (CDM Smith 2014) was originally set to 37.5 milliliters per minute (mL/min); however, modifications made during the study resulted in a 25 mL/min (0.025 L/min) flow rate for the Chitorem® treatment (BCR 3) and the $Mg(OH)_2$ treatment (BCR 4) to prevent barrel overflow and battery drain, respectively.

The MIW flow through the Ely Copper Mine BCR system was set at 0.1 L/min (McSurdy et al. 1997). The target flow rate for each BCR tank at the Formosa Mine was 0.08 L/min (CDM Smith and Parametrix 2014).

Flow rates specific to the Conda/Woodall Mine treatment train were not provided (Formation Environmental and NewFields 2022).

Flow rates at the constructed wetland at Champion Mine were measured along with the concentrations of COCs. Flow into the constructed wetland system (flocculent logs to a settling pond that flowed to the constructed wetland) ranged from 221 – 423 L/min (0.13 – 0.249 cfs), and the flow at the wetland outfall ranged from 187 – 629 L/min (0.11 – 0.37 cfs) (CES 2013).

3.3.10.2 Range of Applicability

Table 3-22 and Table 3-23 present maximum and minimum concentrations, respectively, with corresponding effluents for treatment trains at Danny-T Adit, Formosa Mine, and Ely Copper Mine.

Table 3-22. Maximum Influent and Corresponding Effluent Concentrations for Danny-T Adit, Formosa Mine, and Ely Copper Mine

Constituent	Maximum influent concentration	Corresponding effluent concentration	Mine
Alkalinity, total (as $CaCO_3$) (mg/L)	ND (< 1)	100 – 1,700[a]	BCR 2 Danny-T Adit[c]
Alkalinity, total (as $CaCO_3$) (mg/L)	ND (< 1)	1,300 – 2,600[a]	BCR 3 Danny-T Adit[c]
Alkalinity, total (as $CaCO_3$) (mg/L)	ND (< 1)	93 – 1,500[a]	BCR 4 Danny-T Adit[c]
Alkalinity (as $CaCO_3$) (mg/L)[b]	51.9	53.5	Ely Copper Mine[d]
Aluminum, dissolved (µg/L)	15,600	140	BCR 2 Danny-T Adit[c]
Aluminum, dissolved (µg/L)	15,600	170	BCR 3 Danny-T Adit[c]
Aluminum, dissolved (µg/L)	15,600	130	BCR 4 Danny-T Adit[c]
Aluminum, total (µg/L)	18,900	1,050	BCR 2 Danny-T Adit[c]
Aluminum, total (µg/L)	18,900	790	BCR 3 Danny-T Adit[c]
Aluminum, total (µg/L)	18,900	1,070	BCR 4 Danny-T Adit[c]
Aluminum (mg/L)	36.44	1.87	Ely Copper Mine[d]
Arsenic, dissolved (mg/L)	0.039	ND (0.036)	BCRs 3, 4, and 5 Formosa Mine[e]
Arsenic, dissolved (mg/L)	0.039	0.045	BCR 6 Formosa Mine[e]
Arsenic, total (mg/L)	0.055	ND (0.036)	BCRs 3 and 5 Formosa Mine[e]
Arsenic, total (mg/L)	0.055	0.098	BCR 4 Formosa Mine[e]
Arsenic, total (mg/L)	0.055	0.053	BCR 6 Formosa Mine[e]
Arsenic, dissolved (µg/L)	311	20	BCRs 2 and 4 Danny-T Adit[c]
Arsenic, dissolved (µg/L)	311	75	BCR 3 Danny-T Adit[c]
Arsenic, total (µg/L)	324	64	BCR 2 Danny-T Adit[c]
Arsenic, total (µg/L)	324	107	BCR 3 Danny-T Adit[c]
Arsenic, total (µg/L)	324	118	BCR 4 Danny-T Adit[c]

Constituent	Maximum influent concentration	Corresponding effluent concentration	Mine
Arsenic (mg/L)[b]	ND (0.1)	ND	Ely Copper Mine[d]
Cadmium, dissolved (µg/L)	316	ND (< 1)	BCRs 2, 3, and 4 Danny-T Adit[c]
Cadmium, total (µg/L)	293	9	BCR 2 Danny-T Adit[c]
Cadmium, total (µg/L)	293	7	BCR 3 Danny-T Adit[c]
Cadmium, total (µg/L)	293	27	BCR 4 Danny-T Adit[c]
Cadmium (mg/L)[b]	0.02	ND (0.01)	Ely Copper Mine[d]
Chromium, dissolved (µg/L)	263	46	BCR 3 Formosa Mine[e]
Chromium, dissolved (µg/L)	263	ND (< 22)	BCRs 4, 5, and 6 Formosa Mine[e]
Chromium, total (µg/L)	272	48	BCR 3 Formosa Mine[e]
Chromium, total (µg/L)	272	ND (< 22)	BCRs 4, 5, and 6 Formosa Mine[e]
Chromium (mg/L)[b]	0.05	0.02	Ely Copper Mine[d]
Cobalt, dissolved (µg/L)	58	11	BCR 2 Danny-T Adit[c]
Cobalt, dissolved (µg/L)	58	24	BCR 3 Danny-T Adit[c]
Cobalt, dissolved (µg/L)	58	6	BCR 4 Danny-T Adit[c]
Cobalt, total (µg/L)	56	16	BCR 2 Danny-T Adit[c]
Cobalt, total (µg/L)	56	23	BCR 3 Danny-T Adit[c]
Cobalt, total (µg/L)	56	13	BCR 4 Danny-T Adit[c]
Cobalt (mg/L)[b]	0.56	0.20	Ely Copper Mine[d]
Copper, dissolved (µg/L)	7,500	25	BCR 3 Formosa Mine[e]
Copper, dissolved (µg/L)	7,500	70	BCR 4 Formosa Mine[e]
Copper, dissolved (µg/L)	7,500	27	BCR 5 Formosa Mine[e]
Copper, dissolved (µg/L)	7,500	230	BCR 6 Formosa Mine[e]
Copper, total (µg/L)	5,470	1,010	BCR 3 Formosa Mine[e]
Copper, total (µg/L)	5,470	400	BCR 4 Formosa Mine[e]
Copper, total (µg/L)	5,470	686	BCR 5 Formosa Mine[e]
Copper, total (µg/L)	5,470	279	BCR 6 Formosa Mine[e]
Copper (mg/L)[b]	13.24	0.17	Ely Copper Mine[d]
Iron, dissolved (µg/L)	180,000	5,080	BCR 2 Danny-T Adit[c]
Iron, dissolved (µg/L)	180,000	8,710	BCR 3 Danny-T Adit[c]
Iron, dissolved (µg/L)	180,000	3,420	BCR 4 Danny-T Adit[c]
Iron, total (µg/L)	179,000	6,540	BCR 2 Danny-T Adit[c]
Iron, total (µg/L)	179,000	9,660	BCR 3 Danny-T Adit[c]
Iron, total (µg/L)	179,000	6,090	BCR 4 Danny-T Adit[c]
Iron (mg/L)[b]	98.2	0.12	Ely Copper Mine[d]
Lead, dissolved (µg/L)	252	ND (< 1)	BCRs 2, 3, and 4 Danny-T Adit[c]
Lead, total (µg/L)	258	1	BCRs 2 and 4 Danny-T Adit[c]
Lead, total (µg/L)	258	3	BCR 3 Danny-T Adit[c]
Lead (mg/L)[b]	ND (0.1)	ND	Ely Copper Mine[d]
Manganese, dissolved (µg/L)	128,000	102,000	BCR 2 Danny-T Adit[c]

Constituent	Maximum influent concentration	Corresponding effluent concentration	Mine
Manganese, dissolved (µg/L)	128,000	1,720	BCR 3 Danny-T Adit[c]
Manganese, dissolved (µg/L)	128,000	61,100	BCR 5 Danny-T Adit[c]
Manganese, total (µg/L)	129,000	7,590	BCR 2 Danny-T Adit[c]
Manganese, total (µg/L)	129,000	6,510	BCR 3 Danny-T Adit[c]
Manganese, total (µg/L)	129,000	11,600	BCR 5 Danny-T Adit[c]
Manganese (mg/L)[b]	2,750	3,480	Ely Copper Mine[d]
Mercury (µg/L)	ND (< 0.139)	ND	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Mercury, total (µg/L)	ND (< 0.139)	ND	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Nickel, dissolved (µg/L)	49	35	BCR 3 Formosa Mine[e]
Nickel, dissolved (µg/L)	49	202	BCR 4 Formosa Mine[e]
Nickel, dissolved (µg/L)	49	52	BCR 5 Formosa Mine[e]
Nickel, dissolved (µg/L)	49	398	BCR 6 Formosa Mine[e]
Nickel, total (µg/L)	48	44	BCR 3 Formosa Mine[e]
Nickel, total (µg/L)	48	210	BCR 4 Formosa Mine[e]
Nickel, total (µg/L)	48	601	BCR 5 Formosa Mine[e]
Nickel, total (µg/L)	48	402	BCR 6 Formosa Mine[e]
Nickel (mg/L)[b]	0.13	0.04	Ely Copper Mine[d]
Selenium (mg/L)[b]	ND (400)	ND	Ely Copper Mine[d]
Sulfate, total (mg/L)	2,500	1,000	BCRs 2 and 4 Danny-T Adit[c]
Sulfate, total (mg/L)	2,500	350	BCR 3 Danny-T Adit[c]
Zinc, dissolved (µg/L)	72,500	193	BCR 3 Formosa Mine[e]
Zinc, dissolved (µg/L)	72,500	320	BCR 4 Formosa Mine[e]
Zinc, dissolved (µg/L)	72,500	195	BCR 5 Formosa Mine[e]
Zinc, dissolved (µg/L)	72,500	606	BCR 6 Formosa Mine[e]
Zinc, total (µg/L)	71,000	1,580	BCR 2 Danny-T Adit[c]
Zinc, total (µg/L)	71,000	620	BCR 3 Danny-T Adit[c]
Zinc, total (µg/L)	71,000	3,270	BCR 4 Danny-T Adit[c]
Zinc (mg/L)[b]	2.02	0.82	Ely Copper Mine[d]

ND = non-detect

[a] A range of effluent values is shown to reflect multiple days with the same influent.

[b] The Ely Copper Mine study (McSurdy et al. 1997) did not identify whether constituents were total or dissolved.

[c] CDM Smith (2014)

[d] McSurdy et al. (1997)

[e] CDM Smith and Parametrix (2014)

Table 3-23. Minimum Influent and Corresponding Effluent Concentrations for Danny-T Adit, Formosa, and Ely Copper Mine

Constituent	Minimum influent concentration	Corresponding effluent concentration	Mine
Alkalinity, total (as $CaCO_3$) (mg/L)	ND (< 1)	100 – 1,700[a]	BCR 2 Danny-T Adit[c]
Alkalinity, total (as $CaCO_3$) (mg/L)	ND (< 1)	1,300 – 2,600[a]	BCR 3 Danny-T Adit[c]
Alkalinity, total (as $CaCO_3$) (mg/L)	ND (< 1)	93 – 1,500[a]	BCR 4 Danny-T Adit[c]
Alkalinity (as $CaCO_3$) (mg/L)[b]	0	0 – 139.1[a]	Ely Copper Mine[d]
Aluminum, dissolved (µg/L)	8,710	60	BCRs 2 and 4 Danny-T Adit[c]
Aluminum, dissolved (µg/L)	8,710	ND (< 30)	BCR 3 Danny-T Adit[c]
Aluminum, total (µg/L)	12,600	120	BCR 2 Danny-T Adit[c]
Aluminum, total (µg/L)	12,600	160	BCR 3 Danny-T Adit[c]
Aluminum, total (µg/L)	12,600	130	BCR 4 Danny-T Adit[c]
Aluminum, total (µg/L)	12,600	ND (< 30)	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Aluminum (mg/L)[b]	5.79	0.16	Ely Copper Mine[d]
Arsenic, dissolved (mg/L)	0.039	0.045	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Arsenic, dissolved (mg/L)	0.039	ND (0.036)	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Arsenic, total (mg/L)	0.051	ND (0.036)	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Arsenic, dissolved (mg/L)	0.039	ND (0.036)	BCRs 3, 4, and 5 Formosa Mine[e]
Arsenic (mg/L)	0.039	0.045	BCR 6 Formosa Mine[e]
Arsenic, total (mg/L)	0.051	ND (0.036)	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Arsenic (mg/L)[b]	ND (< 0.1 – < 0.2)[a]	ND [a]	Ely Copper Mine[d]
Cadmium, dissolved (µg/L)	141	ND (< 2)	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Cadmium, total (µg/L)	136	ND (< 2)	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Cadmium (mg/L)[b]	ND (< 0.01)	ND	Ely Copper Mine[d]
Chromium, dissolved (µg/L)	ND (< 5)	ND	BCRs 2, 3, and 4 Danny-T Adit[c]
Chromium, total (µg/L)	ND (< 5)	ND	BCRs 2, 3, and 4 Danny-T Adit[c]
Chromium (mg/L)[b]	ND (< 0.01)	ND	Ely Copper Mine[d]
Cobalt, dissolved (mg/L)	12	ND (0.01)	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Cobalt, total (mg/L)	12	ND (0.01)	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Cobalt (mg/L)[b]	0.08	ND (< 0.01)	Ely Copper Mine[d]
Copper, dissolved (µg/L)	924	ND (< 5)	BCRs 2, 3, and 4 Danny-T Adit[c]
Copper, total (µg/L)	1,180	ND (< 5)	BCRs 2, 3, and 4 Danny-T Adit[c]
Copper (mg/L)[b]	1.45	ND (< 0.01)	Ely Copper Mine[d]
Iron, dissolved (µg/L)	112,000	33,700	BCR 2 Danny-T Adit[c]
Iron, dissolved (µg/L)	112,000	520	BCR 3 Danny-T Adit[c]
Iron, dissolved (µg/L)	112,000	29,800	BCR 4 Danny-T Adit[c]
Iron, total (µg/L)	129,000	45,000	BCR 2 Danny-T Adit[c]
Iron, total (µg/L)	129,000	550	BCR 3 Danny-T Adit[c]
Iron, total (µg/L)	129,000	51,900	BCR 4 Danny-T Adit

Constituent	Minimum influent concentration	Corresponding effluent concentration	Mine
Iron (mg/L)[b]	6	4.67	Ely Copper Mine[d]
Lead (mg/L)	0.041	ND (0.019)	BCRs 3, 4, 5, and 6 Formosa[e]
Lead, total (mg/L)	0.040	ND (0.019)	BCRs 3, 4, 5, and 6 Formosa[e]
Lead (mg/L)[b]	ND (< 0.1 – < 0.2)[a]	ND[a]	Ely Copper Mine[d]
Manganese, dissolved (mg/L)	2.09	3.01	BCR 3 Formosa Mine[e]
Manganese, dissolved (mg/L)	2.09	1.56	BCR 4 Formosa Mine[e]
Manganese, dissolved (mg/L)	2.09	4.04	BCR 5 Formosa Mine[e]
Manganese, dissolved (mg/L)	2.09	2.37	BCR 6 Formosa Mine[e]
Manganese, total (mg/L)	2.06	3.64	BCR 3 Formosa Mine[e]
Manganese, total (mg/L)	2.06	1.71	BCR 4 Formosa Mine[e]
Manganese, total (mg/L)	2.06	5.07	BCR 5 Formosa Mine[e]
Manganese, total (mg/L)	2.06	2.52	BCR 6 Formosa Mine[e]
Manganese (mg/L)[b]	740	1,290	Ely Copper Mine[d]
Mercury, dissolved (µg/L)	ND (0.139)	ND	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Mercury, total (µg/L)	ND (0.139)	ND	BCRs 3, 4, 5, and 6 Formosa Mine[e]
Nickel, dissolved (µg/L)	27	ND (< 5)	BCRs 3, 4, and 5 Formosa Mine[e]
Nickel, dissolved (µg/L)	27	11	BCR 6 Formosa Mine[e]
Nickel, total (µg/L)	23	ND (< 5)	BCRs 3 and 5 Formosa Mine[e]
Nickel, total (µg/L)	23	7	BCR 4 Formosa Mine[e]
Nickel, total (µg/L)	23	12	BCR 6 Formosa Mine[e]
Nickel (mg/L)[b]	0.02	ND (< 0.01)	Ely Copper Mine[d]
Selenium (mg/L)[b]	ND (< 0.2 – 0.5)	ND	Ely Copper Mine[d]
Sulfate (mg/L)[b]	165.29	119.7	Ely Copper Mine[d]
Zinc, dissolved (µg/L)	44,500	13,700	BCR 2 Danny-T Adit[c]
Zinc, dissolved (µg/L)	44,500	40	BCR 3 Danny-T Adit[c]
Zinc, dissolved (µg/L)	44,500	10,400	BCR 4 Danny-T Adit[c]
Zinc, total (µg/L)	45,700	15,500	BCR 2 Danny-T Adit[c]
Zinc, total (µg/L)	45,700	30	BCR 3 Danny-T Adit[c]
Zinc, total (µg/L)	45,700	14,600	BCR 4 Danny-T Adit[c]
Zinc (mg/L)[b]	0.45	0.01	Ely Copper Mine[d]

ND = non-detect

[a] A range of effluent values is shown to reflect multiple days with the same influent.

[b] The Ely Copper Mine study (McSurdy et al. 1997) did not identify whether constituents were total or dissolved.

[c] CDM Smith (2014)

[d] McSurdy et al. (1997)

[e] CDM Smith and Parametrix (2014)

Table 3-24 and Table 3-25 present the upgradient and downgradient results for the PRB plus seep treatment cell (STC) pre-treatment at the Conda/Woodall Mountain Mine.

Table 3-24. Maximum Upgradient and Corresponding Downgradient Concentrations at Conda/Woodall Mountain Mine

Constituent	Maximum upgradient concentration (mg/L)	Corresponding downgradient concentration (mg/L)
Alkalinity, total (as $CaCO_3$)	316	694
Arsenic, dissolved	0.00179	0.0106
Arsenic, total	0.00746	0.0124
Cadmium, dissolved	0.018	ND (0.00006)
Cadmium, total	0.0212	ND (0.00006)
Chromium, dissolved	0.0086	ND (0.002)
Chromium, total	0.0937	ND (0.002)
Dissolved Organic Carbon	4.86	40.7
Iron, dissolved	0.657	0.456
Iron, total	10.7	2.18
Manganese, dissolved	0.024	13.3
Manganese, total	0.19	21.9
Nitrate	3.11	ND(0.05)
Selenium, dissolved	7.57	0.0085
Selenium, total	7.24	0.0107
Sulfate, total	2,220	1,620
Total Organic Carbon	5.7	14.4
Uranium, dissolved	0.0232	0.00373
Uranium, total	0.0249	0.00218
Vanadium, dissolved	0.0277	0.00527
Vanadium, total	0.0956	0.0057
Zinc, dissolved	1.13	ND (0.002)
Zinc, total	1.3	ND (0.002)

Table 3-25. Minimum Upgradient and Corresponding Downgradient Concentrations at Conda/Woodall Mine

Constituent	Minimum upgradient concentration (mg/L)	Corresponding downgradient concentration (mg/L)
Alkalinity, total (as $CaCO_3$)	243	1,650
Arsenic dissolved	0.00083	0.00729
Arsenic, total	0.00074	0.0114
Cadmium, dissolved	0.0106	ND (0.00006)
Cadmium, total	0.0135	0.00115
Chromium, dissolved	0.0026	ND (0.002)
Chromium, total	0.0054	0.0053

Constituent	Minimum upgradient concentration (mg/L)	Corresponding downgradient concentration (mg/L)
Dissolved Organic Carbon	2.62	17.4
Iron, dissolved	ND (0.56)	0.469 – 30.9
Iron, total	0.09	39.2
Manganese, dissolved	ND (0.0034)	13.7 – 32.2
Manganese, total	0.0146	35.9
Nitrate	1.07	0.047
Selenium, dissolved	1.97	0.0183
Selenium, total	1.81	0.0225
Sulfate, total	1,930	27.1
Total Organic Carbon	2.84	39.00
Uranium, dissolved	0.0186	0.0164
Uranium, total	0.0204	0.00575
Vanadium, dissolved	0.0143	0.0043
Vanadium, total	0.0132	0.0126
Zinc, dissolved	0.835	0.0025
Zinc, total	0.657	0.0053

The Champion Mine study was the only one that included a constructed wetland (CES 2013). Water quality samples were collected to represent the entire constructed wetland system, which included a settling pond that flows into a five-tiered vegetated system and then directly into Champion Creek. Flocculent logs were also placed above the settling pond. Table 3-26 presents the maximum and minimum influent to the wetland system and the corresponding effluents.

Table 3-26. Maximum and Minimum Influent and Corresponding Effluent Concentrations at Champion Mine

Constituent	Maximum influent concentration	Corresponding effluent concentration	Minimum influent concentration	Corresponding effluent concentration
Aluminum, total (µg/L)	460	100	390	90
Arsenic, total (µg/L)	32.9	2.5	28.9	2.1
Cadmium, total (µg/L)	8	4.3	7.2	3.9
Chromium, total (µg/L)	ND (< 0.5)	ND	ND	ND
Copper, total (µg/L)	180	20	160	20
Iron, total (µg/L)	7,160	380	6,290	270
Lead, total (µg/L)	5.8	0.3	4.8	0.6
Mercury, total (µg/L)	0.011	0.014	0.0018	0.0007
Manganese, total (µg/L)	1,120	1,020	1,030	643
Sulfate (mg/L)	104	101	93	97
Zinc, total (µg/L)	1,370	760	1,300	830

Source: CES (2013)

ND = non-detect

3.3.10.3 Removal Efficiency

The removal efficiencies presented in Table 3-27 and Table 3-28 are for BCR treatments that were part of a treatment train (e.g., included pre-treatment). The removal efficiency for each BCR treatment and constituent at Danny-T Adit was reported in the study (CDM Smith 2014) and is presented in Table 3-27 as either the minimum removal efficiency or a range of removal efficiencies, depending on how the information was presented in the study. Removal efficiencies for the BCR treatments at the Ely Copper Mine and Formosa Mine were not provided; however, removal efficiencies for four conditions at all sites were calculated and are presented in Table 3-28. The four conditions are the maximum influent concentration treated/corresponding effluent concentration attained, minimum influent concentration treated/corresponding effluent concentration attained, maximum effluent concentration attained/corresponding influent concentration treated, and minimum effluent concentration attained/corresponding influent concentration treated. While removal efficiencies for all four conditions are presented in this report, the influent and effluent concentrations are only presented for the maximum and minimum influent concentrations and the corresponding effluent concentrations (Table 3-22 and Table 3-23). The other conditions (maximum and minimum effluent concentrations and corresponding influent concentrations) are presented in Appendix A.

Reported removal efficiencies for metals at Danny-T Adit were all greater than 90%. Positive calculated removal efficiencies for BCR treatments that are part of treatment trains range from 2.3% for dissolved cobalt at Danny-T Adit BCR 2 to 100% for multiple contaminants of concern (copper at Ely Copper Mine; dissolved iron at Danny-T Adit BCR 3 and Formosa Mine BCRs 5 and 6; dissolved zinc at Danny-T Adit BCRs 2, 3, and 4 and Formosa Mine BCRs 4, 5, and 6; and total zinc at Formosa Mine BCRs 4 and 6).

Several Danny-T Adit BCRs were successful with efficiencies greater than 99% for dissolved COCs aluminum, cadmium, copper, lead, and zinc at BCRs 2, 3, and 4, which are BCR with SAPs pre-treatment, BCR with Chitorem® pre-treatment, and BCR with $Mg(OH)_2$ pre-treatment, respectively. Additional COCs with removal efficiencies greater than 99% at Danny-T Adit include total cadmium and total copper at BCRs 2, 3, and 4; total aluminum at BCR 2; dissolved cobalt and total zinc at BCR 3; dissolved and total iron at BCRs 3 and 4; and total lead at BCRs 2 and 4.

The maximum removal efficiency at Formosa Mine was greater than 99% for dissolved and total aluminum, dissolved arsenic, dissolved cadmium, total and dissolved copper, and dissolved zinc at BCRs 3, 4, 5, and 6. Additional metals with calculated removal efficiencies greater than 99% at Formosa Mine include total cadmium (at BCR 5), total and dissolved iron (BCRs 5 and 6), and total zinc (BCRs 4, 5, and 6). BCR 3 at Formosa Mine has a woody mixture substrate with a SAPS pre-treatment, while BCR 5 has a woody mixture substrate with Chitorem® pre-treatment. BCR 4 has a Chitorem® and sand mixture substrate with a Chitorem® pre-treatment and BCR 6 has a Chitorem® and sand mixture substrate with Chitorem® pre-treatment. As with the BCRs that are not part of a treatment train, several of the calculated removal efficiencies at Ely Copper Mine and Formosa Mine were negative, including arsenic, barium, manganese, and nickel. Ely Copper Mine saw the greatest reduction in copper with a removal efficiency of 100%.

Table 3-27. Reported Removal Efficiencies for Treatment Trains having a BCR Component

Constituent	Removal efficiency (%)	Mine[a]
Aluminum, dissolved	> 90.0	Danny-T Adit BCR 2[c]
Aluminum, dissolved	> 98.0	Danny-T Adit BCR 3[c]
Aluminum, dissolved	> 99.0	Danny-T Adit BCR 4[c]
Cadmium, dissolved[b]	> 99.0	Danny-T Adit BCR 2[c]
Cadmium, dissolved[b]	> 99.0	Danny-T Adit BCR 3[c]
Cadmium, dissolved[b]	> 99.0	Danny-T Adit BCR 4[c]
Copper, dissolved	> 99.0	Danny-T Adit BCR 2[c]
Copper, dissolved	> 99.0	Danny-T Adit BCR 3[c]
Copper, dissolved	> 99.0	Danny-T Adit BCR 4[c]
Lead, dissolved[b]	> 99.0	Danny-T Adit BCR 2[c]
Lead, dissolved[b]	> 99.0	Danny-T Adit BCR 3[c]
Lead, dissolved[b]	> 99.0	Danny-T Adit BCR 4[c]
Zinc, dissolved	> 99.0	Danny-T Adit BCR 3[c]

[a] Danny-T Adit BCR2 = BCR with SAPS pre-treatment; BCR 3 = BCR with Chitorem® pre-treatment; BCR 4 = BCR with $Mg(OH)_2$ pre-treatment.

[b] Effluent was below detection limit. Assumed to be ½ the detection limit. Refer to Table 3-24 and Table 3-25 for detection limit.

[c] CDM Smith (2014)

Table 3-28. Calculated Removal Efficiencies for Treatment Trains having a BCR Component

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine[e,f,g]
Aluminum, dissolved	99.1	99.3	99.1	99.9	Danny-T Adit BCR 2[f]
Aluminum, dissolved	98.9	99.8[h]	98.9	99.8 – 99.9[h]	Danny-T Adit BCR 3[f]
Aluminum, dissolved	99.2	99.3	99.2	99.9[h]	Danny-T Adit BCR 4[f]
Aluminum, total	94.4	99.1	94.4	99.1	Danny-T Adit BCR 2[f]
Aluminum, total	95.8	98.7	95.8	98.7	Danny-T Adit BCR 3[f]
Aluminum, total	94.3	99.0	94.3	99.0	Danny-T Adit BCR 4[f]
Arsenic, dissolved	93.6	97.9	93.6	97.9	Danny-T Adit BCR 2[f]
Arsenic, dissolved	75.9	83.9	75.9	83.9	Danny-T Adit BCR 3[f]
Arsenic, dissolved	93.6	97.9	93.6	97.9	Danny-T Adit BCR 4[f]
Arsenic, total	80.3	98.0	80.3	98.0	Danny-T Adit BCR 2[f]
Arsenic, total	67.0	80.7	67.0	80.7	Danny-T Adit BCR 3[f]
Arsenic, total	63.6	96.0	63.6	96.0	Danny-T Adit BCR 4[f]
Beryllium, dissolved	93.8[h]	91.7[h]	91.7 – 93.8[h]	91.7 – 93.8[h]	Danny-T Adit BCR 2[f]
Beryllium, dissolved	93.8[h]	91.7[h]	91.7 – 93.8[h]	91.7 – 93.8[h]	Danny-T Adit BCR 3[f]
Beryllium, dissolved	93.8[h]	91.7[h]	91.7 – 93.8[h]	91.7 – 93.8[h]	Danny-T Adit BCR 4[f]
Beryllium, total	93.8[h]	90.0[h]	90.0 – 93.8[h]	90.0 – 93.8[h]	Danny-T Adit BCR 2[f]
Beryllium, total	93.8[h]	90.0[h]	90.0 – 93.8[h]	90.0 – 93.8[h]	Danny-T Adit BCR 3[f]
Beryllium, total	93.8[h]	90.0[h]	90.0 – 93.8[h]	90.0 – 93.8[h]	Danny-T Adit BCR 4[f]

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine[e,f,g]
Cadmium, dissolved	99.8[h]	99.7[h]	99.7 – 99.8[h]	99.7 – 99.8[h]	Danny-T Adit BCR 2[f]
Cadmium, dissolved	99.8[h]	99.7[h]	99.7 – 99.8[h]	99.7 – 99.8[h]	Danny-T Adit BCR 3[f]
Cadmium, dissolved	99.8[h]	99.7[h]	99.7 – 99.8[h]	99.7 – 99.8[h]	Danny-T Adit BCR 4[f]
Cadmium, total	96.9	99.7[h]	96.9	99.7[h]	Danny-T Adit BCR 2[f]
Cadmium, total	97.6	99.7[h]	97.6	99.7[h]	Danny-T Adit BCR 3[f]
Cadmium, total	90.8	99.7[h]	90.8	99.7[h]	Danny-T Adit BCR 4[f]
Chromium, dissolved	58.3[h]	N/A	N/A	N/A	Danny-T Adit BCR 2[f]
Chromium, dissolved	58.3[h]	N/A	N/A	N/A	Danny-T Adit BCR 3[f]
Chromium, dissolved	58.3[h]	N/A	N/A	N/A	Danny-T Adit BCR 4[f]
Chromium, total	16.7	N/A	16.7	N/A	Danny-T Adit BCR 2[f]
Chromium, total	58.3[h]	N/A	N/A	N/A	Danny-T Adit BCR 3[f]
Chromium, total	58.3[h]	N/A	N/A	N/A	Danny-T Adit BCR 4[f]
Cobalt, dissolved	81.0	2.8	2.8 – 7.9	85.4	Danny-T Adit BCR 2[f]
Cobalt, dissolved	58.6	93.1	58.6	93.1 – 99.5	Danny-T Adit BCR 3[f]
Cobalt, dissolved	89.7	47.2	-13.2	94.8[h]	Danny-T Adit BCR 4[f]
Cobalt, total	71.4	5.1	5.1	71.4	Danny-T Adit BCR 2[f]
Cobalt, total	58.9	93.6[h]	58.9	93.6[h]	Danny-T Adit BCR 3[f]
Cobalt, total	76.8	-12.8	-12.8	76.8	Danny-T Adit BCR 4
Copper, dissolved	99.8	99.7[h]	99.8	99.7 – 99.9[h]	Danny-T Adit BCR 2
Copper, dissolved	99.6	99.7[h]	99.6	99.7 – 99.9[h]	Danny-T Adit BCR 3
Copper, dissolved	99.9[h]	99.7[h]	99.7 – 99.9[h]	99.7 – 99.9[h]	Danny-T Adit BCR 4
Copper, total	90.9	99.8[h]	90.9	99.8[h]	Danny-T Adit BCR 2
Copper, total	91.7	99.8[h]	91.7	99.8[h]	Danny-T Adit BCR 3
Copper, total	91.6	99.8[h]	91.6	99.8[h]	Danny-T Adit BCR 4
Iron, dissolved	97.2	69.9	52.5	97.2	Danny-T Adit BCR 2
Iron, dissolved	95.2	99.5	95.2	100.0[h]	Danny-T Adit BCR 3
Iron, dissolved	98.1	73.4	59.6	99.2	Danny-T Adit BCR 4
Iron, total	96.4	65.1	65.1	96.4	Danny-T Adit BCR 2
Iron, total	94.6	99.6	94.6	99.6	Danny-T Adit BCR 3
Iron, total	96.6	59.8	59.8	96.6	Danny-T Adit BCR 4
Lead, dissolved	99.8[h]	99.6[h]	99.6 – 99.8[h]	99.6 – 99.8[h]	Danny-T Adit BCR 2
Lead, dissolved	99.6	99.6[h]	99.6	99.6 – 99.8[h]	Danny-T Adit BCR 3
Lead, dissolved	99.8[h]	99.6[h]	99.6 – 99.8[h]	99.6 – 99.8[h]	Danny-T Adit BCR 4
Lead, total	99.6	71.8	71.8	99.6	Danny-T Adit BCR 2
Lead, total	98.8	71.0	71.0	98.8	Danny-T Adit BCR 3
Lead, total	99.8[h]	67.1	67.1	99.8[h]	Danny-T Adit BCR 4
Manganese, dissolved	20.3	-1.5	-9.5	-0.6	Danny-T Adit BCR 2
Manganese, dissolved	98.7	37.7	37.7	98.7	Danny-T Adit BCR 3

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine[e,f,g]
Manganese, dissolved	52.3	12.2	-25.9	91.1	Danny-T Adit BCR 4
Manganese, total	94.1	-1.0	-1.0	94.1	Danny-T Adit BCR 2
Manganese, total	95.0	39.4	39.4	95.0	Danny-T Adit BCR 3
Manganese, total	91.0	-11.9	-11.9	91.0	Danny-T Adit BCR 4
Nickel, dissolved	10.3	14.3	10.3	93.2[h]	Danny-T Adit BCR 2
Nickel, dissolved	-69.2	91.1[h]	-69.2	91.1 – 91.7[h]	Danny-T Adit BCR 3
Nickel, dissolved	25.6	-3.6	(-)3.6 – 25.6	91.4 – 93.2[h]	Danny-T Adit BCR 4
Nickel, total	0.0	6.9	0.0	6.9	Danny-T Adit BCR 2
Nickel, total	-76.9	91.4[h]	-74.4	91.4[h]	Danny-T Adit BCR 3
Nickel, total	18.0	-6.9	18.0	-6.9	Danny-T Adit BCR 4
Thallium, dissolved	89.1[h]	86.1[h]	86.1 – 89. 1[h]	86.1 – 89. 1[h]	Danny-T Adit BCR 2
Thallium, dissolved	89.1[h]	86.1[h]	86.1 – 89. 1[h]	86.1 – 89. 1[h]	Danny-T Adit BCR 3
Thallium, dissolved	89.1[h]	86.1[h]	86.1 – 89. 1[h]	86.1 – 89. 1[h]	Danny-T Adit BCR 4
Thallium, total	90.0[h]	90.0[h]	90.0[h]	90.0[h]	Danny-T Adit BCR 2
Thallium, total	90.0[h]	90.0[h]	80.0	90.0[h]	Danny-T Adit BCR 3
Thallium, total	90.0[h]	90.0[h]	90.0[h]	90.0[h]	Danny-T Adit BCR 4
Zinc, dissolved	99.9	69.2	69.2	100.0	Danny-T Adit BCR 2
Zinc, dissolved	99.9	99.9	99.9	100.0[h]	Danny-T Adit BCR 3
Zinc, dissolved	99.9	76.6	78.2	100.0	Danny-T Adit BCR 4
Zinc, total	97.8	66.1	66.1	97.8	Danny-T Adit BCR 2
Zinc, total	99.1	99.9	99.1	99.9	Danny-T Adit BCR 3
Zinc, total	95.4	68.1	68.1	95.4	Danny-T Adit BCR 4
Aluminum[i]	94.9	97.2	2.6	71.8 – 82.5[h]	Ely Copper Mine
Cadmium[i]	75.0[h]	N/A	-400.0	N/A	Ely Copper Mine
Chromium[i]	90.0	N/A	-250.0	N/A	Ely Copper Mine
Cobalt[i]	99.1	93.8	-12.5	95.8 – 98.9[h]	Ely Copper Mine
Copper[i]	100.0	99.7[h]	-0.2	99.8 – 100.0[h]	Ely Copper Mine
Iron[i]	-35.3	88.6	-35.3	99.9	Ely Copper Mine
Manganese[i]	-26.6	-74.3	-9,652.0	-74.3	Ely Copper Mine
Nickel[i]	96.2	75.0[h]	-75.0	75.0 – 94.4[h]	Ely Copper Mine
Zinc[i]	59.4	97.8	-3.5	99.7[h]	Ely Copper Mine
Aluminum, dissolved	97.6	99.6[h]	97.3	98.7	Formosa Mine CRs 3
Aluminum, dissolved	78.5	99.6[h]	78.5	94.0	Formosa Mine BCR 4
Aluminum, dissolved	91.3	99.6[h]	91.3	98.4	Formosa Mine BCR 5
Aluminum, dissolved	66.2	99.6[h]	66.2	92.1	Formosa Mine BCR 6
Aluminum, total	88.6	99.6[h]	88.6	99.6[h]	Formosa Mine BCR 3
Aluminum, total	75.0	99.6[h]	75.0	99.6[h]	Formosa Mine BCR 4
Aluminum, total	85.0	99.6[h]	85.0	99.6[h]	Formosa Mine BCR 5
Aluminum, total	66.0	99.6[h]	66.0	99.6[h]	Formosa Mine BCR 6

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine[e,f,g]
Arsenic, dissolved	53.9[h]	53.9[h]	N/A	N/A	Formosa Mine BCR 3
Arsenic, dissolved	53.9[h]	53.9[h]	N/A	N/A	Formosa Mine BCR 4
Arsenic, dissolved	53.9[h]	53.9[h]	N/A	N/A	Formosa Mine BCR 5
Arsenic, dissolved	53.9	-15.38	N/A	-15.38	Formosa Mine BCR 6
Arsenic, total	63.6[h]	60.8[h]	N/A	N/A	Formosa Mine BCRs 3
Arsenic, total	63.6	60.8[h]	-1,621.2	N/A	Formosa Mine BCR 4
Arsenic, total	63.6[h]	60.8[h]	-73.1	N/A	Formosa Mine BCR 5
Arsenic, total	63.6	60.8[h]	-2,938.5	N/A	Formosa Mine BCR 6
Cadmium, dissolved	99.5[h]	99.3[h]	99.3 – 99.5[h]	99.3 – 99.5[h]	Formosa Mine BCR 3
Cadmium, dissolved	97.4	99.3[h]	97.4	97.4	Formosa Mine BCR 4
Cadmium, dissolved	99.5[h]	99.3[h]	99.3 – 99.5[h]	99.3 – 99.5[h]	Formosa Mine BCR 5
Cadmium, dissolved	87.1	99.3[h]	87.1	87.1	Formosa Mine BCR 6
Cadmium, total	90.1	98.9[h]	90.1	90.1	Formosa Mine BCR 3
Cadmium, total	89.6	98.9[h]	89.6	89.6	Formosa Mine BCR 4
Cadmium, total	93.2	98.9[h]	92.8 – 93.2	99.2	Formosa Mine BCR 5
Cadmium, total	84.4	98.9[h]	84.4	84.4	Formosa Mine BCR 6
Chromium, dissolved	82.5	76.1	57.2	76.1	Formosa Mine BCR 3
Chromium, dissolved	95.8[h]	90.3[h]	90.4	90.4	Formosa Mine BCR 4
Chromium, dissolved	95.8[h]	90.3[h]	90.3 – 95.8[h]	90.3 – 95.8[h]	Formosa Mine BCR 5
Chromium, dissolved	95.8[h]	90.3[h]	83.1	83.1	Formosa Mine BCRs 6
Chromium, total	82.4	83.2	54.3	83.2	Formosa Mine BCR 3
Chromium, total	95.6[h]	92.3[h]	88.0	88.0	Formosa Mine BCRs 4
Chromium, total	95.6[h]	92.3[h]	86.3	86.3	Formosa Mine BCR 5
Chromium, total	95.6[h]	92.3[h]	80.7	80.7	Formosa Mine BCRs 6
Copper, dissolved	99.7	99.9[h]	97.5	99.7	Formosa Mine BCR 3
Copper, dissolved	99.1	99.9[h]	99.1	99.8	Formosa Mine BCR 4
Copper, dissolved	99.6	99.9[h]	99.6	99.6	Formosa Mine BCR 5
Copper, dissolved	96.9	99.9[h]	96.9	96.9	Formosa Mine BCR 6
Copper, total	81.5	99.2	81.5	99.2	Formosa Mine BCR 3
Copper, total	92.7	99.9[h]	92.7	99.7	Formosa Mine BCR 4
Copper, total	87.5	98.1	87.5	99.7	Formosa Mine BCR 5
Copper, total	94.9	99.9[h]	94.9	99.9	Formosa Mine BCR 6
Iron, dissolved	83.1	97.7	56.2	97.7	Formosa Mine BCR 3
Iron, dissolved	97.3	93.7	93.7	98.8	Formosa Mine BCR 4
Iron, dissolved	100.0	97.6	97.6	100.0	Formosa Mine BCR 5
Iron, dissolved	100.0	86.6	86.6	100.0	Formosa Mine BCR 6
Iron, total	82.7	91.5	49.7	91.5	Formosa Mine BCR 3
Iron, total	97.1	88.2	88.2	98.3	Formosa Mine BCR 4
Iron, total	99.3	91.4	91.4	99.6	Formosa Mine BCR 5

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]	Mine[e,f,g]
Iron, total	99.1	81.2	81.2	99.0	Formosa Mine BCR 6
Lead, dissolved	79.3[h]	79.3[h]	N/A	N/A	Formosa Mine BCR 3
Lead, dissolved	79.3[h]	79.3[h]	N/A	N/A	Formosa Mine BCR 4
Lead, dissolved	79.3[h]	79.3[h]	N/A	N/A	Formosa Mine BCR 5
Lead, dissolved	79.3[h]	79.3[h]	N/A	N/A	Formosa Mine BCR 6
Lead, total	76.8[h]	76.3[h]	N/A	N/A	Formosa Mine BCR 3
Lead, total	76.8[h]	76.3[h]	N/A	N/A	Formosa Mine BCR 4
Lead, total	76.8[h]	76.3[h]	N/A	N/A	Formosa Mine BCR 5
Lead, total	76.8[h]	76.3[h]	N/A	N/A	Formosa Mine BCR 6
Manganese, dissolved	-50.2	-44.0	-50.2	-13.0	Formosa Mine BCR 3
Manganese, dissolved	51.1	25.4	6.1	51.1	Formosa Mine BCR 4
Manganese, dissolved	58.1	-93.3	-93.3	58.1	Formosa Mine BCR 5
Manganese, dissolved	57.1	-13.4	-13.4	68.9	Formosa Mine BCR 6
Manganese, total	-12.5	-76.7	-76.7	-12.5	Formosa Mine BCR 3
Manganese, total	8.9	17.0	8.9	44.3	Formosa Mine BCR 4
Manganese, total	33.0	-146.1	-146.1	50.7	Formosa Mine BCR 5
Manganese, total	65.4	-22.3	-22.3	65.4	Formosa Mine BCR 6
Nickel, dissolved	28.6	92.6[h]	28.6	28.6	Formosa Mine BCR 3
Nickel, dissolved	95.9	92.6[h]	-312.2	84.9	Formosa Mine BCR 4
Nickel, dissolved	-6.1	92.6[h]	-6.1	(-)2,930 – (-)2,074	Formosa Mine BCR 5
Nickel, dissolved	-712.2	59.3	-712.2	59.3	Formosa Mine BCR 6
Nickel, total	8.3	89.1[h]	8.3	8.3	Formosa Mine BCR 3
Nickel, total	-337.5	69.6	-337.5	78.8	Formosa Mine BCR 4
Nickel, total	-1,152.1	89.1[h]	-27.1	81.8 – 86.7	Formosa Mine BCR 5
Nickel, total	-737.5	47.8	-737.5	47.8	Formosa Mine BCR 6
Zinc, dissolved	99.7	98.9	98.9	99.8	Formosa Mine BCR 3
Zinc, dissolved	99.6	99.6	99.6	100.0	Formosa Mine BCR 4
Zinc, dissolved	99.7	99.5	99.5	100.0	Formosa Mine BCR 5
Zinc, dissolved	99.2	99.6	99.2	100.0	Formosa Mine BCR 6
Zinc, total	97.4	89.3	89.3	97.4	Formosa Mine BCR 3
Zinc, total	100.0	95.8	95.8	100.0	Formosa Mine BCR 4
Zinc, total	99.9	90.5	90.5	99.9	Formosa Mine BCR 5
Zinc, total	99.9	98.5	98.5	100.0	Formosa Mine BCR 6

N/A = not available. Data not provided or influent was below detection limit and efficiency could not be calculated.

[a] Removal efficiency is based on the maximum influent concentrations treated and the corresponding effluent concentrations attained.

[b] Removal efficiency is based on the minimum influent concentrations treated and the corresponding effluent concentrations attained.

[c] Removal efficiency is based on the maximum effluent concentrations attained and the corresponding influent concentrations treated.

[d] Removal efficiency is based on the minimum effluent concentrations attained and the corresponding influent concentrations treated.

[e] Danny-T Adit BCR2 = BCR with SAPS pre-treatment; BCR 3 = BCR with Chitorem® pre-treatment; BCR 4 = BCR with $Mg(OH)_2$ pre-treatment.

[f] Ely Copper Mine = BCR with limestone pre-treatment

[g] Formosa BCR 3 = woody mixture BCR substrate with SAPS pre-treatment; BCR 4 = Chitorem® and sand mixture BCR substrate with SAPS pre-treatment; BCR 5 = woody mixture BCR substrate with Chitorem® pre-treatment; BCR 6 = Chitorem® and sand mixture BCR substrate with Chitorem® pre-treatment.

[h] Effluent was below detection limit. Assumed to be ½ the detection limit. Refer to Table 3-22 and Table 3-23 for detection limit.

[I] The Ely Copper Mine study (McSurdy et al. 1997) did not identify whether constituents were total or dissolved.

Removal efficiencies for the STC plus PRB treatment at the Conda/Woodall Mountain Mine were not provided; however, they were calculated for this report for all four conditions. The calculated removal efficiencies for Conda/Woodall Mountain Mine are presented in Table 3-29.

Positive calculated removal efficiencies for metals at Conda/Woodall Mountain Mine ranged from 4.9% for total uranium to 99.9% for total cadmium, total and dissolved selenium, and total and dissolved zinc. There were several removal efficiencies below zero including arsenic, chromium, iron, and manganese.

Table 3-29. Calculated Removal Efficiencies for Conda/Woodall Mountain Mine

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]
Arsenic, dissolved	-492.2	-778.3	-1,825.6	-363.4
Arsenic, total	-66.2	-1,440.5	-2,029.5	-76.9
Cadmium, dissolved	99.8[e]	99.7[e]	98.4	99.7-99.8[e]
Cadmium, total	99.9[e]	91.5	91.5	99.8-99.9[e]
Chromium, dissolved	88.4[e]	61.5[e]	-45.8	<83.6[e]
Chromium, total	98.9[e]	1.85	70.5	90.3-98.9[e]
Iron, dissolved	30.6	N/A	N/A	-135.7
Iron, total	79.6	-43,455.6	-43,455.6	81.2
Manganese, dissolved	-55,316.7	N/A	-336,174.5	-219,900.0
Manganese, total	-11,426.3	-245,790.4	-245,790.4	-17,955.6
Nitrate	99.2[e]	95.6	78.8	99.2[e]
Selenium, dissolved	99.9	99.6	99.5	100.0
Selenium, total	99.9	99.4	99.3	100.0
Uranium, dissolved	83.9	11.8	11.8	90.9
Uranium, total	91.2	71.8	4.9	91.2
Vanadium, dissolved	81.0	69.9	9.2	69.9
Vanadium, total	94.0	4.6	21.6	93.9
Zinc, dissolved	99.9[e]	99.7	99.5	99.9[e]
Zinc, total	99.9[e]	99.2	99.3	99.9[e]

N/A = not available. Data not provided or influent was below detection limit and efficiency could not be calculated.
[a] Removal efficiency is based on the maximum influent concentration treated and the corresponding effluent concentration attained.
[b] Removal efficiency is based on the minimum influent concentration treated and the corresponding effluent concentration attained.
[c] Removal efficiency is based on the maximum effluent concentration attained and the corresponding influent concentration treated.
[d] Removal efficiency is based on the minimum effluent concentration attained and the corresponding influent concentration treated.
[e] Effluent was below detection limit. Assumed to be ½ the detection limit. Refer to Table 3-24 and Table 3-25 for detection limit.

Removal efficiencies reported in the Champion Mine study (CES 2013) were 91.8% (total arsenic) and 94.2% (total iron). Removal efficiencies for the other sampled analytes were not provided; however, they were calculated for all four conditions for this report (Table 3-30). Removal efficiencies for all four conditions are presented in this report but the influent and effluent are only presented for the maximum and minimum influent and the corresponding effluent (Table 3-26). The other conditions (maximum and minimum effluent and corresponding influent) are presented in Appendix A. Mercury was the only metal constituent with a negative removal efficiency (-27.3%). The range of removal efficiencies for the remaining metal constituents was 8.9% for manganese to 97.4% for lead.

Table 3-30. Calculated removal efficiencies for Champion Mine

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]
Aluminum, total	89.1	88.5	89.1	90.7
Arsenic, total	92.4	92.7	77.7	92.7
Cadmium, total	46.3	45.8	37.3	45.8
Copper, total	94.4	93.8	94.4	97.1
Iron, total	94.7	95.7	78.6	95.7
Lead, total	97.4	87.5	87.5	97.4
Manganese, total	8.9	37.6	8.9	41.6
Mercury, total	-27.3	80.6	-27.3	80.6
Sulfate	2.9	-4.3	2.9	0.0
Zinc, total	44.5	36.2	16.7	47.0

[a] Removal efficiency is based on the maximum influent concentration treated and the corresponding effluent concentration attained.
[b] Removal efficiency is based on the minimum influent concentration treated and the corresponding effluent concentration attained.
[c] Removal efficiency is based on the maximum effluent concentration attained and the corresponding influent concentration treated.
[d] Removal efficiency is based on the minimum effluent concentration attained and the corresponding influent concentration treated.

3.4 Constraints and Limitations

This section discusses constraints and limitations identified in the reviewed studies. This includes constraints and limitations on the technologies and/or data that were reported.

The authors of the Aquafix® study did not provide any general constraints or limitations.

The Formosa Mine BCR study did not provide any general constraints or limitations.

The Danny-T Adit BCR study (CDM Smith 2014) in the Barker-Hughesville Mining District indicated that the reduced number of sampling events caused by funding issues and winter weather had an effect on achieving study objectives. Seasonal weather and water quality influent changes may not be observed with a shortened sampling season. In addition, the shorter operation schedule and smaller data set resulted in less information to develop conclusions regarding long-term treatment effectiveness.

There was also a shortage of manure and limestone for the BCR substrate mixture, which may have had an effect on the effectiveness of the BCR treatments (CDM Smith 2014). A sufficient amount of limestone is needed to buffer the acidity in the MIW influent. Sufficient manure is also needed to provide sulfite-reducing bacteria (SRB) and soluble organics to support the sulfate reduction process. The Blue Ledge Mine's short study period and cold weather that caused cold influent water also had a negative effect on establishing microbial communities and sustaining sulfate reduction (CDM Smith 2015).

Constraints at the Ely Copper Mine BCR study (McSurdy et al. 1997) included that more maintenance was required for the passive system in the first few months of operation, as opposed to the remainder of the study period, to provide debugging and system improvements. In addition, the unit loads removed at Ely Copper Mine could not be determined due to inconsistent flows (McSurdy et al. 1997). The system's flow was only tracked on monitoring days; during non-monitoring periods, the flow was inconsistently achieved.

The Ballard Mine, Monticello Mill Tailings, and Conda/Woodall Mountain Mine PRB studies did not provide any specific constraints or limitations.

The Champion Mine study did not provide any specific constraints or limitations.

The Monticello Mill Tailings evaporation and MNA studies did not provide any information on specific constraints or limitations.

The Barker Hughesville Mining District $Mg(OH)_2$ and SAPS pre-treatment studies did not provide any information on specific constraints or limitations.

CDM Smith (2014) noted that a lack of consistent flow through the Chitorem® pre-treatment and subsequent BCR treatment at the Danny-T Adit in the Barker Hughesville Mining District resulted in a flow that was much less than the other treatment processes. Because of this lack of flow, the study was unable to complete a direct comparison between treatments.

3.5 Costs

Costs were provided for only two of the passive treatability studies reviewed – the Monticello Mill Tailings and Conda/Woodall PRB studies.

The PRB at the Monticello Mill Tailings site cost a total of $1,668,800, including implementation and deployment (USDOE 1999). The implementation (construction and monitoring) alone cost $1,195,600. The Conda/Woodall study provided more recent cost data. The operation and maintenance cost at Conda/Woodall Mine, including remote monitoring and performance monitoring, ranged between $20,000 to $40,000 per month (Formation Environmental and NewFields 2022). The capital cost for the construction of the PRB and a seep treatment cell was approximately $1.2 million, which equates to approximately $180/cubic yard of reactive media. Cost information in this report is presented as reported in the treatability studies and has not been adjusted for inflation.

3.6 Lessons Learned

Studies for constructed wetlands at the Champion Mine (CES 2013), as well as evaporation and natural attenuation at the Monticello Mill Tailings site (USDOE 2021, 2022), did not provide any lessons learned. The authors of the remaining passive studies did provide lessons learned and those are summarized below.

3.6.1 Aquafix®

Although the Aquafix® system was identified as a passive system, it required 1 to 2 weekly visits to keep it working properly (Tetra Tech 2017). Fine-grained lime particles in the quicklime caused it to bridge (i.e., form a solid layer) in the Aquafix® hopper, which had a negative effect on the system's performance. The quicklime in the hopper had to be stirred, removed, and sieved to greater than 0.25 inch to prevent bridging (Tetra Tech 2017). In addition, depending on the MIW flow rate, the hopper often required refilling more than once a week. This issue could be solved by installing a larger hopper. The retention pond was also too small for the resulting precipitate accumulation. During the study (five months), the 1,529 cubic meter (2,000 cubic yard) pond filled to almost two-thirds. It was recommended that a larger pond or a series of ponds be used for future systems (Tetra Tech 2017).

3.6.2 BCRs

Danny-T Adit

The Danny-T Adit BCR study contained a control BCR barrel that did not have pre-treatment (CDM Smith 2014). The results of the control BCR barrel study indicate that pre-treatment is needed to treat high acidity MIW ahead of the BCR. The study also found that some of the BCR barrels were overloaded with acidity and could not maintain sulfate reduction. It is recommended that limestone in the substrate be increased, so there is a greater alkalinity content to provide more buffering to highly acidic MIW at this site (CDM Smith 2014). The study also found that acidity loading to the BCRs should be decreased by decreasing the average influent MIW flow rate. The decrease in flow rate would reduce the amount of substrate volume needed for treatment. The acidity load needs to be balanced by the alkalinity generation from sulfate reduction and from limestone dissolution in the BCR (CDM Smith 2014).

Blue Ledge Mine

The Blue Ledge Mine BCR study found that the sulfate reduction reactions in some BCR barrels were limited due to the use of a dried and aged horse manure (CDM Smith 2015). Based on a literature review by the authors of the Blue Ledge Mine study, they suggest that fresh dairy cow manure should be used rather than horse manure in the barrel substrate. Dairy manure has been shown to contain higher numbers and diversity of SRB than horse or other manure types (CDM Smith 2015).

Ely Copper Mine

The BCR system at Ely Copper Mine needed more frequent maintenance than the 3 days per month it received (McSurdy et al. 1997). More maintenance was required in the first few months of operations to address debugging and make improvements. This was a very small treatment system, and the authors noted that larger systems are less sensitive to infrequent maintenance.

Formosa Mine

The Formosa Mine study authors noted that according to USEPA, toxic effects on sulfate-reducing bacteria have been observed with zinc concentrations greater than 20mg/L, but MIW entered the Formosa Mine BCR system with zinc concentrations between 60 and 70 mg/L, leading to poor conditions for the growth of sulfate-reducing bacteria in the BCR substrate (CDM Smith and Parametrix 2014). The study indicates that BCR performance could be enhanced by including pre-treatment to reduce the elevated zinc load to the sulfate-reducing bacteria.

The Chitorem® substrate also had persistent issues maintaining design flow over the course of the study. The authors suggested that the Chitorem® mix be altered to increase the grain size of the crab shell and increase the percentage of inert material, such as sand and gravel, to add porosity (CDM Smith and Parametrix 2014).

3.6.3 PRBs

Ballard Mine

Monitoring at the Ballard Mine PRB resulted in variable parameter concentrations during the 2022 sampling period (Stantec 2023). Stantec (2023) indicates that longer-term monitoring is needed to determine whether concentrations stabilize over time or continue to fluctuate due to spring runoff or other factors.

Monticello Mill Tailings

In the Monticello PRB study, authors identified several areas of concern to be considered for future PRB projects (USDOE 2002). Project implementers should communicate with local, state, and federal regulators at the project inception. Regularly scheduled communication should continue throughout the duration of the project. Test trenches or holes should be dug to understand the soil conditions that will be encountered while installing the PRB. Finally, the frequency of water level monitoring should be increased to closely track water levels in the PRB. If water levels in the PRB reach the top of the reactive media, the study authors recommend taking measures to prevent flooding of the ground surface.

Conda/Woodall Mine

The Conda/Woodall PRB study authors suggested that a hydrogeological investigation of the site should be conducted in the spring to better characterize flux and water-bearing zones during high water conditions (Formation Environmental and NewFields 2022). The Conda/Woodall Mine PRB design did not have the capacity to contain the flux of snow melt and seep water because the hydrogeological study for the PRB was performed during fall low-flow conditions rather than spring high-flow conditions.

The authors also indicated that soils around the PRB are tight, therefore, future PRBs should incorporate a gravel pressure relief or effluent storage area downgradient of the PRB to increase the soil's ability to receive effluent water or to allow the effluent to flow onto the land surface if capacity is reached.

3.6.4 Magnesium Hydroxide ($Mg(OH)_2$), Chitorem®, and Successive Alkalinity Producing System (SAPS)

Lessons learned from the $Mg(OH)_2$, Chitorem® and SAPS treatments, which were each used as pre-treatments to BCRs in treatment trains at the Danny-T Adit, are discussed in this section. In general, the study recommended that the systems be checked once per week to make sure they are operating properly to ensure that study time is not lost due to equipment related issues (CDM Smith 2014).

A specific lesson regarding $Mg(OH)_2$ treatment included the consideration of using NaOH rather than $Mg(OH)_2$. Since $Mg(OH)_2$ is a suspension, more maintenance and operator presence may be required to dose the system compared to a NaOH system (CDM Smith 2014).

As with the Chitorem® used at the Formosa Mine, the Danny-T Adit study authors found that the substrate mixture should be modified to increase permeability. It was suggested that the percentage of Chitorem® and sand be reduced while the percentage of inert gravel be increased. The study found that when the substrate was replaced with two parts pea gravel to one-part original mixture, the substrate was free draining (CDM Smith 2014).

The authors (CDM Smith 2014) indicated that the SAPS 30-gallon barrel should be replaced with a 55-gallon barrel to increase the substrate volume to provide more surface area for contact with the MIW, more organic matter to reduce oxidation state, and more limestone to provide alkalinity.

There were also flow issues with the Chitorem® pre-treatment barrel at Formosa Mine (CDM Smith and Parametrix 2014). The pre-treatment barrel received 2 times the flow as the subsequent BCR, leading to decreased performance in the Chitorem® pre-treatment.

3.6.5 Treatment Trains

Authors of the Formosa Mine BCR study indicate that matching flow in pre-treatment and subsequent BCRs should be included in future system designs (CDM Smith and Parametrix 2014). There were also flow issues with the Chitorem® BCR reactor with pre-treatment at Formosa Mine (CDM Smith and Parametrix 2014). The pre-treatment barrel received 2 times the flow as the subsequent BCR, leading to decreased performance in the Chitorem® pre-treatment. Flow issues were also observed at the Danny T Adit. Because the size of the treatment train at the Danny-T Adit was "undersized with respect to flow rate" (CDM Smith 2014), the flow rate through the SAPS and BCR in the treatment train should also be decreased so that the reactions decrease the acidity load from the MIW influent.

At the Danny-T Adit, the SAPS/BCR2 treatment train was unable to maintain sulfate reducing conditions, minimizing longer term metals removal, but the Chitorem/BCR3 treatment train was able maintain sulfate reducing conditions allowing for iron and zinc removal through the life of the study (CDM Smith 2014). Of the BCR treatment trains, Chitorem®/BCR3 was best able to sustain negative ORP, high pH and the greatest sulfate concentration reduction. However, Chitorem's® low permeability and biofouling made gravity draining difficult, causing influent to overflow. The study authors note that the slow draining of influent through the Chitorem® slowed the flow rate and increased hydraulic retention time, which may have been beneficial. The poor hydraulic performance could not be resolved through a series of technical changes, and the substrate had to be replaced and supplemented with pea gravel to improve conditions. These changes were only made one week prior to the end of sampling, so the impacts were inconclusive. The authors caution about comparing performance between SAPS and Chitorem® under the study conditions. Sulfate reduction could not be maintained in SAPS/BCR2 and $Mg(OH)_2$/BCR4, which meant that most of the metals removal was attributed to sorption and oxy-hydroxide or carbonate precipitation, rather than sulfate reduction, which would limit removal after the sorption site became saturated. Overall, hydraulic retention time was an issue in all three pre-treatment systems, with flow being too slow in Chitorem®/BCR3 and too fast in the remaining treatments, limiting the author's ability to identify an optimal hydraulic retention time. The study recommended using post-BCR treatment aerobic wetlands to improve BOD removal, reduce high pH, and reduce phosphorus concentrations in effluent.

4 Semi-passive Technologies

Semi-passive technologies combine the qualities of active and passive technologies and do not require consistent oversight and maintenance (Kleinmann et al. 2022). Semi-passive treatment technologies include periodic addition of amendments and chemicals using approaches that do not require complex machinery. These systems rely on gravity flow and the infrequent management of accumulating metal residue.

4.1 Treatability Studies Reviewed

This chapter provides information on treatability studies in which semi-passive technologies were the primary component of MIW treatment. The treatability studies included a selenium-reducing bioreactor and a vertical flow reactor (VFR) at mines in Idaho and California, respectively. Table 4-1 summarizes site names and locations, treatment design information, and references for each of the treatability studies. The chapter presents capability, constraints and limitations, costs, and lessons learned for the semi-passive treatments evaluated in the treatability studies.

Table 4-1. Semi-passive Treatability Study Sites

Site name and location	Treatment type	Data collection period	Study type	Reference	Reference type
Southeast Idaho Selenium Project/AKA Smoky Canyon Mine, Idaho	Selenium-Reducing Bioreactor	July 2013 – November 2015	Pilot study	Formation Environmental 2017	Pilot Study Report
Reed Mercury Mine, CA	Vertical Flow Reactor (VFR)	September 2021 – October 2022 and March 2023 – December 2023	Remediation project	Terracon 2023, 2024	Annual Operations, Monitoring, and Maintenance Report

4.2 Treatment System Description and Treatable Contaminants

4.2.1 Selenium-Reducing Bioreactor

The focus of the Formation Environmental (2017) selenium-reducing bioreactor study at Smoky Canyon Mine was the removal of selenium from MIW, but the authors noted that the bioreactor is also capable of removing other constituents and trace metals such as aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, thallium, uranium, vanadium, and zinc.

The system consisted of an influent collection and conveyance system; influent measurement system; nutrient amendments; two bioreactors (in series); and an effluent measurement system. Seep water was collected and gravity-fed to a nearby holding tank. Water flowed from the holding tank to two bioreactor vessels. The bioreactor vessels were dosed with nutrients as needed. Samples were collected at both the inlet and outlet of the vessels (Formation Environmental 2017).

4.2.2 Vertical Flow Reactor (VFR)

The objective of the VFR system at the Reed Mercury Mine was to reduce aluminum, cobalt, iron, manganese, mercury, and nickel concentrations (Terracon 2023). A semi-passive staged drainage treatment system was installed to treat adit drainage. The staged drainage treatment system comprises a drainage collector, VFR, a wetland, and an infiltration trench. Collection and laboratory analysis was conducted for the VFR influent and effluent water samples, while monitoring of the other treatment system components consisted of visual observations. The objective of the semi-passive treatment system is to reduce aluminum, cobalt, iron, manganese, mercury, and nickel concentrations in the MIW (Terracon 2023).

4.3 Capability

4.3.1 Selenium-Reducing Bioreactor

A selenium-reducing bioreactor is an anaerobic, biologically-based selenium treatment that uses bacteria, algae, or aquatic plants to remove selenium and other contaminants from MIW (Formation Environmental 2017). Semi-passive bioreactors typically contain an inert medium along with nutrients and organic carbon added to the system by hand to support the bacteria. Solids build up in the system over time and the medium is replaced once it reaches saturation. In this study, the bioreactor vessels were filled with floating polyethylene bio-rings, which provided sufficient surface area for the growth of selenium-reducing bacteria (Formation Environmental 2017). The substrate added to the bioreactors was soil containing selenium-reducing bacteria.

4.3.1.1 Flow Rates

The Smoky Canyon Mine MIW was diverted from a small impoundment downstream of a seep to a holding tank that fed two 7,570.8-liter (2,000-gallon) bioreactors (in series) at an initial influent flow rate of 2.7 L/min (0.72 gpm) and an average influent of 5.0 L/min (1.32 gpm) during operation and maintenance (Formation 2017). The study also included flow rates for influent and effluent for specific sample dates. The range of influent flow rates across the study period (July 2013 to November 2013) was 1.9 to 12.3 L/min (0.5 to 3.26 gpm), while the effluent flow rate ranged from 1.1 L/min (0.3 gpm) to 7.0 L/min (1.84 gpm).

4.3.1.2 Range of Applicability

Although the selenium-reducing bioreactor is capable of removing a variety of metals, only selenium data were provided in the study (Formation Environmental 2017). The maximum and minimum influents and their corresponding effluents for selenium for the Smoky Canyon Mine study are presented in Table 4-2.

Table 4-2. Maximum and Minimum Influent and Corresponding Effluent Concentrations at Smoky Canyon Mine

Constituent	Maximum influent concentration	Corresponding effluent concentration	Minimum influent concentration	Corresponding effluent concentration
Selenium, dissolved (µg/L)	5.28	0.32	0.788	0.0373
Selenium, total (µg/L)	5.31	0.941	0.833	0.301

Source: Formation Environmental (2017)

4.3.1.3 Removal Efficiency

The removal efficiency of total selenium from the selenium-reducing bioreactor at Smoky Canyon Mine had a reported ranged of 5% to 99% for the entire study period (July 2013 to November 2015), while the dissolved selenium removal efficiency ranged from 17% to 99% (Formation Environmental 2017). The selenium-reducing bioreactor was most effective at removing selenium during the summer and fall months, with the maximum efficiency of 99% occurring on the day with the highest temperatures (14.9 °C). In addition to the removal efficiencies reported in the selenium-reducing bioreactor study, selenium removal efficiencies for all four conditions were also calculated for this report (Table 4-3). calculated selenium removal efficiencies ranged from 5.2% for total selenium to 99.4% for dissolved selenium.

Table 4-3. Calculated Removal Efficiencies for Selenium-Reducing Bioreactor Treatments at Smoky Canyon

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]
Selenium, dissolved	93.9	95.3	17.1	99.4
Selenium, total	82.3	63.9	5.2	98.5

[a] Removal efficiency is based on the maximum influent concentration treated and the corresponding effluent concentration attained.

[b] Removal efficiency is based on the minimum influent concentration treated and the corresponding effluent concentration attained.

[c] Removal efficiency is based on the maximum effluent concentration attained and the corresponding influent concentration treated.

[d] Removal efficiency is based on the minimum effluent concentration attained and the corresponding influent concentration treated.

4.3.2 Vertical Flow Reactor (VFR)

The elements of VFR systems are similar to anaerobic wetlands, but a drainage system is added to force MIW downward through the system into direct contact with an alkalinity-producing substrate (Zipper et al. 2018). VFRs neutralize acidity and promote metal precipitation. Acid neutralization is more rapid in VFRs than in anaerobic wetlands because of forced contact of the MIW and limestone, requiring shorter residence times and smaller surface areas.

A VFR consists of three main elements: a permeable layer of organic compost, a layer of limestone, and a drainage system (Zipper et al. 2018). Bacteria in the compost layer remove oxygen from the MIW to reduce the amount of floc that clogs the limestone layer and support sulfate reduction. The compost reduces clogging within the limestone, but some metal precipitation does occur. A VFR needs to be cleaned regularly by flushing water through the system at high pressure to force accumulated metals and sediment out of the system. As MIW flows through the limestone, the limestone dissolves, adding alkalinity and increasing pH. Below the compost and limestone layers is the drainage system that passes the treated water into a settling pond or another part of the treatment train where metals can precipitate. The drainage system controls water depths and ensures that the organic and limestone layers remain submerged.

The VFR implemented at the Reed Mine is a component of a system made up of a drainage collector, VFR, wetland, and an infiltration trench in sequence (Terracon 2023, 2024). However, the VFR was the only component specifically sampled for performance data.

4.3.2.1 Flow Rates

Influent to the VFR ranged from 2.3 L/min (0.6 gpm) in January 2022 to 1.5 L/min (0.4 gpm) in October 2022 (Terracon 2023), and the effluent flow matched the influent flow on those dates. The 2022 VFR data indicated that flow into the VFR "declined from over 1.9 L/min (0.5 gpm) to 1.5 L/m (0.4 gpm) since the VFR was installed" (Terracon 2023). However, influent to the VFR was sampled on four dates in 2023 and ranged from 10.0 L/min (2.65 gpm) in June 2023 to 4.4 L/min (1.16 gpm) in December 2023 (Terracon 2024). The study indicated that flow through the influent pipe decreased after about three months of operation due to hydrous iron oxide precipitate forming in the pipe. The influent flow was restored periodically by agitating the pipe to loosen the accumulated precipitate.

4.3.2.2 Range of Applicability

The maximum and minimum influent and their corresponding effluents at the VFR treatment at the Reed Mine are presented in Table 4-4 and Table 4-5.

Table 4-4. Maximum and Minimum Influent and Corresponding Effluent Concentrations at the Reed Mine

Constituent	Maximum influent concentration	Corresponding effluent concentration	Minimum influent concentration	Corresponding effluent concentration
Aluminum, dissolved (µg/L)	ND (< 56.1)	ND (< 56.1)	ND (< 18.5)	ND (< 18.5) – 37
Arsenic, dissolved (µg/L)	3.39	0.258	1.19	0.243
Cadmium, dissolved (µg/L)	ND (< 1.5)	ND (< 1.5)	ND (< 0.15)	ND (< 0.15)
Chromium, dissolved (µg/L)	2.53	2.37	ND (< 1.24)	1.24 – 1.29
Cobalt, dissolved (µg/L)	57.2	47.5	33	15.2 – 16
Copper, dissolved (µg/L)	2.94	3.42	ND (< 1.51 µg/L)	1.75
Iron, dissolved (µg/L)	41,000	ND (< 18)	20,600	28.3
Lead, dissolved (µg/L)	ND (< 0.849)	ND	ND	ND
Manganese, dissolved (µg/L)	1,690	1,880	939	855
Mercury, dissolved (µg/L)	0.133	ND (< 0.1)	ND (< 0.1)	ND
Molybdenum, dissolved (µg/L)	ND (< 1.16)	ND(< 1.16 – < 1.53)[a]	0.6	2.47 – 2.48[a]
Nickel, dissolved (µg/L)	1,000	699	723	314 – 335[g]
Selenium, dissolved (µg/L)	ND (< 0.3)	ND (< 0.3 – < 0.604)[a]	ND (< 0.3)	ND (< 0.3 – < 0.604)[a]
Zinc, dissolved (µg/L)	24.1	28.3	ND (< 3.02)	ND

Source: Terracon (2023 and 2024)

ND = non-detect

[a] A range of effluent values reflects more than one day with the same influent concentration.

4.3.2.3 Removal Efficiency

The VFR removal efficiency results were presented in two annual operations, monitoring, and maintenance documents for 2021/2022 and 2023 (Terracon 2023, 2024). Reported removal ranges are presented in Table 4-5 and calculated removal efficiencies for all conditions are presented in Table 4-6. The VFR was able to consistently remove arsenic and iron from MIW influent. The VFR did not significantly reduce copper concentrations in 2022 or 2023 and did not significantly reduce nickel or manganese concentrations in 2023. Aluminum and mercury were not consistently detected in influent or effluent, so they are not included in Table 4-5 and Table 4-6. Mercury concentrations were always reported below the detection limit, and aluminum was detected in the effluent in September 2021 but was reported below the detection limit in all other influent and effluent samples.

Table 4-5 Reported Removal Efficiencies for VFR treatments at Reed Mine

Constituent	Removal Efficiency Range (%)	Source
Arsenic, dissolved	69.0 – 92.0	Terracon 2023
Arsenic, dissolved	85.7 – 89.7	Terracon 2024
Cobalt, dissolved	41.0 – 96.0	Terracon 2023
Cobalt, dissolved	12.8 – 48.2	Terracon 2024
Copper	0	Terracon 2023
Copper	-77.0 – 1.1	Terracon 2024
Iron, dissolved	96.0 – 99.9	Terracon 2023
Iron, dissolved	94.9 – 99.9	Terracon 2024
Manganese, dissolved	16.0 – 93.0	Terracon 2023
Manganese, dissolved	-11.2 – 14.4	Terracon 2024
Nickel, dissolved	24.0 – 66.0	Terracon 2023
Nickel, dissolved	-5.6 – 30.1	Terracon 2024

Table 4-6. Calculated Removal Efficiencies for VFR Treatments at Reed Mine

Constituent	Removal efficiency (%) (max. influent)[a]	Removal efficiency (%) (min. influent)[b]	Removal efficiency (%) (max. effluent)[c]	Removal efficiency (%) (min. effluent)[d]
Arsenic, dissolved	92.4	79.6	63.6	94.2 – 94.3 [e]
Cobalt, dissolved	17.0	51.5 - 53.9	17.0	95.5
Copper	-16.3	N/A	-77.1	N/A
Iron, dissolved	100.0 [e]	99.9	94.9	100.0 [e]
Manganese, dissolved	-11.2	9.0	-11.2	92.7
Nickel, dissolved	30.1	53.7 - 56.6	-17.8	66.3

N/A = not available. Data not provided or influent was below detection limit and efficiency could not be calculated.

[a] Removal efficiency is based on the maximum influent concentration treated and the corresponding effluent concentration attained.

[b] Removal efficiency is based on the minimum influent concentration treated and the corresponding effluent concentration attained.

[c] Removal efficiency is based on the maximum effluent concentration attained and the corresponding influent concentration treated.

[d] Removal efficiency is based on the minimum effluent concentration attained and the corresponding influent concentration treated.

[e] Removal efficiency based on ½ the detection limit for the effluent. Detection limits are provided in Appendix A.

4.4 Constraints and Limitations

This section discusses constraints and limitations identified in the reviewed studies. This includes constraints and limitations on the technologies and/or data that were reported.

The authors of the selenium-reducing bioreactor study at the Smoky Canyon Mine found that treatment efficiency was dependent on temperature (Formation Environmental 2017). Another constraint was that weekly manual addition of sugar beet or molasses feed was necessary because the automatic feeders would clog. The system had to be cleaned out to remove selenium precipitate, which had to be disposed of in a landfill.

Quarterly maintenance was needed for the VFR system to function as designed because metal precipitates would clog the collection pipe (Terracon 2023, 2024). Some wildlife mortality also occurred when amphibians became trapped in the VFR.

4.5 Costs

Cost data were not provided for the VFR (Terracon 2023, 2024). Formation Environmental (2017) provided an estimated cost for the selenium-reducing bioreactor based on the pilot study. The pilot study selenium-reducing bioreactor was operated at approximately 1 gpm, but the cost was estimated for a full-sized treatment system with a flow of 6 gpm. The capital cost for constructing a larger system, including materials, equipment, and labor for installation, is approximately $220,000. Operation and maintenance costs are estimated to be approximately $20,000 per year, including nutrients and amendments, materials, equipment, labor, and monitoring. Cost information in this report is presented as reported in the treatability studies and has not been adjusted for inflation.

4.6 Lessons Learned

In the selenium-reducing bioreactor pilot study, the authors found that the system was not able to treat water to the aquatic life standard of 0.005 mg/L, but it was capable of reducing selenium by 56% on an average annual basis (Formation Environmental 2017). It was also found that the selenium-reducing bioreactor was more difficult to operate during the winter and spring periods due to cold temperatures and additional maintenance needs. Cold winter temperatures caused issues with freezing within the bioreactor and winter weather made access to the system difficult. Additional maintenance was needed in the spring to clean and flush out the system after extended periods of minimal maintenance over the winter.

Regular visual monitoring at the VFR site found deceased amphibians within the VFR; therefore, it was recommended that fencing be installed to prevent wildlife from becoming trapped in the VFR (Terracon 2023, 2024). Visual monitoring also found decreasing flow through the influent pipe shortly after the system was implemented, which was caused by hydrous iron oxide precipitate forming in the pipe. The discharge pipe was also clogging due to accumulation of precipitates. Flow through the influent pipe was restored by agitating the pipe to loosen the accumulated precipitate, while flow through the effluent pipe was restored by using wooden tool handles to remove the precipitate.

5 Conclusions

Conventional active MIW treatment systems were not the focus of this project, therefore, most of the studies included in this report are for passive treatment systems. This project focused on alternative active technologies as well as all passive and semi-passive treatments, which tend to be less expensive. Passive systems typically require less maintenance than active systems and are more cost-effective (USEPA 2014). Cost was rarely provided in the treatability studies but if studies included costs, they were included in each technology chapter. Any cost information in this report is presented as reported in the treatability studies and has not been adjusted for inflation.

Each site had different concerns, constraints, treatment technologies and primary COCs, but some of the lessons learned in the studies were common across several of the studies. Common issues impacting the performance of the treatments generally fell into three categories:

- **Maintenance –** The need for more maintenance to ensure the system is functioning correctly both at system start-up and more regularly through operations. Many of the treatment systems required maintenance to reduce clogging, reduce bridging, and to increase porosity.
- **Site Characteristics –** Better site understanding prior to design and implementation of the treatment technology, including better characterization of the soils and subsurface hydrology.
- **Design Improvements –** Recommended design improvements related to undersized containers, flow rate adjustments to balance treatment reaction times, improved reaction substrate materials and quantities, and consideration for temperature impacts on reactions. The BCR treatment train studies specifically found that the flow rate to the pre-treatment and subsequent BCR barrels should match (CDM Smith and Parametrix 2014). In addition, the flow should be kept at a low enough rate to allow reaction time for acidity reduction (CDM Smith 2014).

Although performance varied widely across the COCs and different treatment systems, the studies summarized in this project demonstrate an ability to effectively reduce COCs using a variety of alternative active, passive, and semi-passive systems. The study data compiled in this report can be used as a reference for site managers to review various MIW treatment options to determine which treatment technologies will work best for their specific scenarios.

6 References

NOTE: References that are publicly available have a link associated with them. See Appendix A for contact information for references without a link.

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Appendix A

Appendix A is an inventory of site-specific performance data and other site characteristics used as the basis of this report. It is provided as an attached Excel file.

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