A Global Perspective on Boron Removal: Treatment Technologies and Practical Applications

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Abstract Proposed mining of a borate orebody has led to increased investigation into water treatment options for pumped mine water with high concentrations of boron and arsenic. Concentrations of boron vary by region, but can be found as high as 1,000 mg/L or higher at some locations. Although there are a number of technologies that are suitable for removing low boron concentrations (<10 mg/L), these technologies are not always suitable for removing high boron concentrations (>100 mg/L). A literature review was performed to evaluate the most common commercial methods for removing boron from source water. Evaluated technologies include pre- or post-treatment, thermal-based, pressure-driven membrane, electric potential driven membrane and alternative technologies.

Keywords Boron, treatment technologies, mine water, global

Introduction

The purpose of this task was to develop conceptual treatment plans for treatment of water from mining sites. A literature review of various treatment technologies was performed, and a summary proposed for the removal of boron and arsenic from a proposed borate mine, as these compounds are expected to exceed discharge limits significantly. The processes were then used to prepare process flow diagrams and the development of cost estimates.

Boron Deposits

Boron is a relatively rare element, with over 60 % of the world reserves located in Turkey. Boron is also mined in other Eastern European countries (*e.g.* Serbia), along with the United States and South America (Chile, Argentina, Peru and Bolivia), with the largest boron mine located in Boron, California. This mine accounts for nearly half of the world’s boron production. After extraction, boron ore is refined and used for the production of glass and ceramics, detergents, semiconductors, magnets and other pharmaceutical and biological applications.

Common borate minerals include borax, ulexite, kernite, ezcurrite, searlesite, and colemanite. These borate minerals are often found in lacustrine and evaporate deposits.

Common Water Quality Issues

The concentration of boron in groundwater in and adjacent to borate deposits is related to the lithology and mineralogy of the area. Often associated with high boron concentrations in these types of deposits, are high concentrations of arsenic, which can be difficult to remove from water. Silica and phosphates are also commonly associated with these deposits, which can cause scaling in treatment processes such as reverse osmosis. Although the act of mining excavation itself does not result in pollution of the groundwater, it is the discharge of this water without additional treatment that can cause detrimental effects to the surrounding environment (Okay *et al.* 1985). Additionally, large volumes of boron and arsenic contaminated water can be generated as a result of dewatering for mining applications.

Treated Water Quality Requirements

Discharge limits vary by region and the end-source location for discharge. A review of the literature yielded varying degrees of required treatment; a limited number of global standards are summarized in Table 1.

Literature Review

A literature review was performed to evaluate the most common commercial methods for removing boron from source water. Evaluated technologies include pre- or post-treatment technologies, thermal-based technologies, pressure-drive membrane technologies, electric potential driven membrane technologies and alternative technologies.

Treatment technologies used for low concentrations of boron (<10 mg/L), include flocculation, sedimentation, oxidation, filtration and advanced treatment processes including ion exchange, reverse osmosis and electrolytic recovery.

Although many of these technologies have been evaluated for the treatment of boron, many of these technologies have only been tested on waters with concentrations as high as 10 mg/L (*e.g.* activated alumina). Additionally, some of these technologies have only been evaluated at the bench scale stage, and require additional testing, either in pilot scale or full scale, prior to being considered a viable technology for the removal of boron (*e.g.* electrocoagulation). Based on a comprehensive literature review, the maximum removal for boron using a variety of process technologies is summarized in Table 2.

Options Evaluation

Three options have were been identified as potential process trains for the treatment of water with high boron concentrations:

1. Softening followed by pH adjustment and reverse osmosis
2. Softening followed by metals precipitation and ion exchange
3. Thermal treatment followed by ion exchange.

Option 1 – Softening/Clarification/Reverse Osmosis

Option 1 includes softening to remove hardness upstream of the RO system to prevent scaling. Softening will be accomplished through lime softening, which will also assist in the removal of boron and other metals like iron and manganese as well as phosphates and silica. The slurry produced by the reaction is contacted to a flocculent and fed to a clarifier for solid/liquid separation. The sludge is collected from the bottom of the clarifier and can be either pumped to a storage area or pressure-filtered to increase its density prior to transport. The combination of lime softening and clarification for pretreatment is extensively used in industrial water treatment applications.

pH will be adjusted upstream of the RO system in order to ensure that all of the boron present in the flow stream is in the borate ion form, which is a highly soluble charged ion, and more easily removed through the membranes (Xu and Jiang 2008). The RO system is a 2-pass system in which permeate from the first pass is sent through an additional set of RO membranes due to the very high boron and arsenic concentrations. RO concentration from both passes of RO will be combined and will require additional treatment prior to disposal.

In addition to boron removal, other constituents of concern, including arsenic,

Parameter (mg/L)	Michigan, United States[1]	WHO (2011 provisional)	South America (Agricultural)	South America (Mining Specific)
Arsenic (As)	0.05	0.01	0.05	0.1 / 0.8[2]
Boron (B)	0.5	2.4	0.56	--
Iron (Fe)	2.0	--	1.0	2.0 / 1.6
Nitrate (NO_3)	10.0	50.0	10.0	--
Nitrite (NO_2)	--	3.0	0.06	--
Ammonia (NH_3)	10.0	--	--	TBD

1. Kennecott Eagle Minerals 2006
2. Maximum / Yearly Average

Table 1 *Global Treatment Requirements for Selected Parameters in Mining*

Technology	Boron Removal (%)[1]	Arsenic Removal (%)[2]
Lime Softening	60	90
Metals Precipitation	87	95
Adsorption	65	95
Ion Exchange (Basic)	96	95
Ion Exchange (Boron Selective)	99	--
Electrodialysis	75	60
Reverse Osmosis	99	60 (as As(III)) >95 (as As(IV))
Liquid-liquid Extraction	--	--
Electrocoagulation	50[3] / 99[4]	--
Evaporation / Crystallization	--[5]	--

1. Removal percentages collected from various literature reviews
2. USEPA 2000
3. At bench scale level testing only
4. At concentrations of 100 mg/L and below
5. A set percentage removal was not provided by GE, however it was indicated, via personal correspondence (GE 2012) that an effluent limit of 0.3 could be achieved through thermal treatment

Table 2 *Maximum Constituent Removal through Various Technologies*

nitrate/nitrite, ammonia/ammonium and iron will also be removed through this proposed treatment train. While iron may be co-precipitated through the lime softening process (the high pH allows iron to oxidize and precipitate out of solution), nitrate/nitrite will be removed through the RO system along with ammonia/ammonium.

Option 2 – Softening/Clarification/Metals Precipitation/Ion Exchange

Option 2 includes softening to remove hardness followed by metals precipitation and ion exchange for polishing.

In addition to boron removal, other constituents of concern, including arsenic, nitrate/nitrite, ammonia/ammonium and

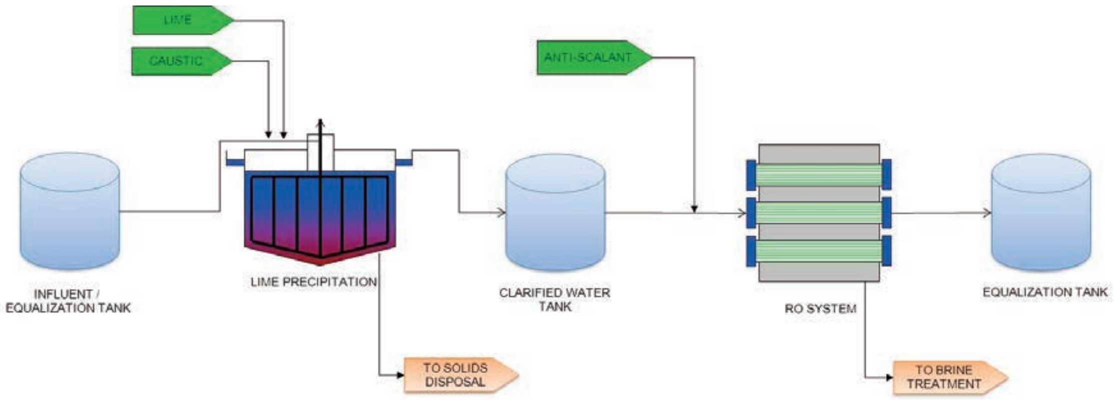

Fig. 1 *Option 1 – Proposed Flow Schematic.*

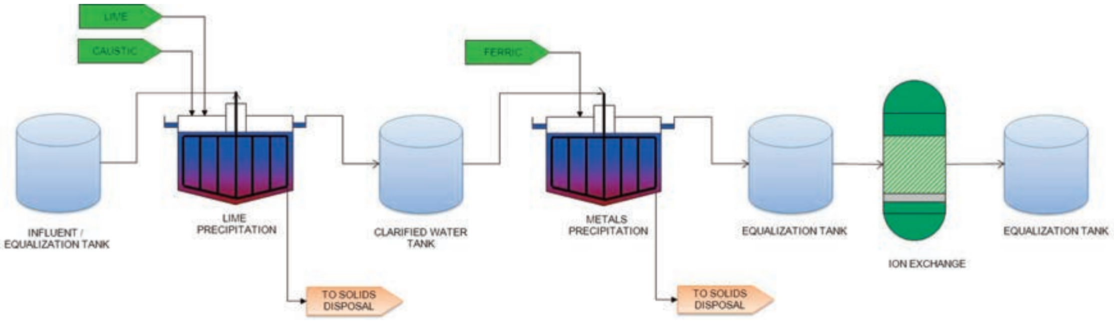

Fig. 2 *Option 2– Proposed Flow Schematic.*

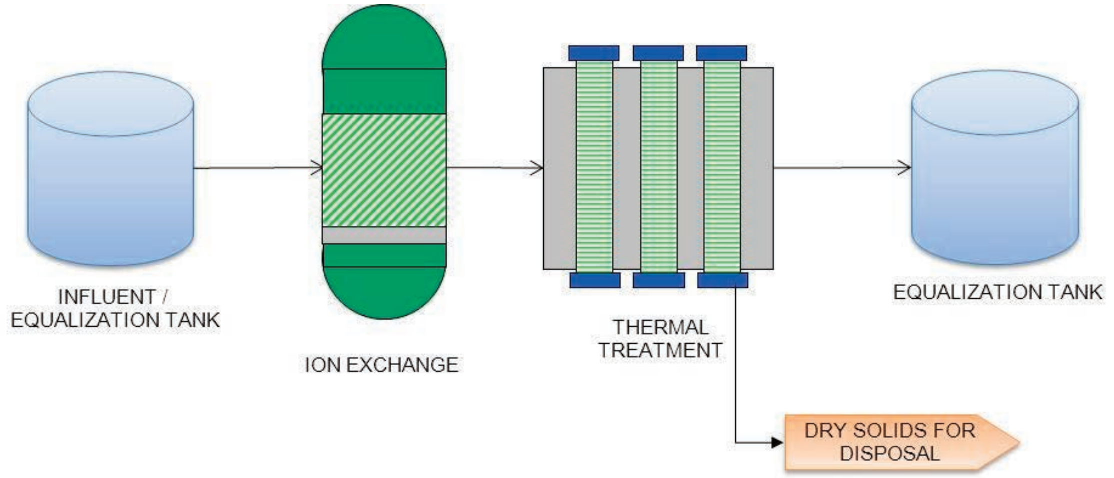

Fig. 3 *Option 3 – Proposed Flow Schematic.*

iron will also be removed through this proposed treatment train. While iron may be co-precipitated through the lime softening process (the high pH allows iron to oxidize and precipitate out of solution), nitrate/nitrite will be removed through the RO system along with ammonia/ammonium.

Option	CAPEX	OPEX	$/1,000 L
Option 1 – Softening / Clarification / Reverse Osmosis	$14,000,000	$1,950,000	50
Option 2 – Softening / Clarification / Metals Precipitation / Ion Exchange	$6,100,000	$1,370,000	23
Option 3 – Ion Exchange / Thermal Treatment	$18,000,000	--	--

1. "--" = Not calculated

Table 3 *Option 1 – Preliminary Cost Estimate*

Option 3 – Ion Exchange/Thermal Treatment
Option 3 includes ion exchange for softening followed by thermal treatment.

Cost Comparison

The cost estimates for these conceptual designs were based on a Class 5 Opinion of Probable Construction Cost (OPCC) estimate and are summarized in Table 3. These cost estimates assume an influent boron concentration of >100 mg/L at a flow rate of approximately 10 L/s. Although cost estimates for treatment processes for lower influent concentrations are not presented in this report, they are expected to be significantly lower, due to the less complex systems required to achieve discharge limits.

Conclusions

The general conclusion is that a three-step unit process treatment scheme is needed to achieve the set effluent goals. Essentially, on one end of the spectrum is a treatment train based on RO and on the other a train based on precipitation. Thermal processes and IX are both viable options which might offer less labor, less chemical and less generation of waste streams. However, there are a host of unknowns which must be characterized in the water quality, bench-scale testing, and detailed process design to determine if these processes can be applied. None of the treatment train options have previously proved to treat such high levels of boron or arsenic.

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