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Environmental Protection
Agency

Best Available Technologies and Small System Compliance Technologies for Perchlorate in Drinking Water

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Abbreviations and Acronyms

AWWARF	American Water Works Association Research Foundation
BAT	best available technology
EBCT	empty bed contact time
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
GAC	granular activated carbon
MCL	maximum contaminant limit
MHI	median household income
MGD	million gallons per day
mg/L	milligrams per liter
NF	nanofiltration
O&M	operating and maintenance
POU	point-of-use
RO	reverse osmosis
SDWA	Safe Drinking Water Act
SSCT	small system compliance technology
UF	ultrafiltration
µg/L	micrograms per liter
WBS	Work Breakdown Structure

1 Introduction

The U.S. Environmental Protection Agency (EPA) is considering setting a federal maximum contaminant limit (MCL) for perchlorate in drinking water under the Safe Drinking Water Act (SDWA). This document addresses treatment technologies that drinking water systems could use to meet this potential new MCL. Specifically, it provides an evaluation of several technologies against predefined criteria to determine whether they might be considered best available technologies (BATs) to meet the potential MCL. In addition, it provides an evaluation of technologies for small systems against criteria to determine whether they can be designated small system compliance technologies (SSCT).

The three technologies included in the BAT evaluation are: ion exchange, biological treatment, and reverse osmosis (RO).[1] Exhibit 1 provides a list of the six major criteria considered for the BAT evaluation, along with specific evaluation questions. Sections 2 through 4 provide a discussion of the extent to which each technology meets the BAT criteria. Section 5 provides a summary of the BAT evaluation results. The detailed discussion is based primarily on literature search information and technical analysis conducted during development of the document, *Technologies and Costs for Treating Perchlorate-Contaminated Water* (USEPA, 2018). That document contains more complete description of each technology and the state of science regarding their use for perchlorate treatment.

The SDWA, as amended in 1996, requires that EPA list technologies for small systems [Section 1412(b)(4)(E)(ii)]:

> The Administrator shall include in the list any technology, treatment technique, or other means that is affordable, as determined by the Administrator in consultation with the States, for small public water systems serving -
> (I) a population of 10,000 or fewer but more than 3,300;
> (II) a population of 3,300 or fewer but more than 500; and
> (III) a population of 500 or fewer but more than 25;
> and that achieves compliance with the MCL or treatment technique, including packaged or modular systems and point-of-entry or point-of-use treatment units (POU).

Section 6 of this document provides EPA's analysis to identify SSCTs for the proposed rule. Specifically, it evaluates four technologies against the affordability and compliance effectiveness criteria for SSCTs. The technologies are the three included in the BAT analysis and POU reverse osmosis. EPA's affordability criterion uses an affordability threshold of 2.5 percent of the median household income (MHI) of the median water system (as ranked by MHI) in each small system size category (i.e., systems serving populations of (1) 25 – 500; (2) 501 – 3,300; and (3) 3,301 – 10,000 people). As long as the sum of baseline expenditures on water (i.e., current costs excluding perchlorate treatment costs) and the incremental expenditures associated with a

[1] Granular activated carbon (GAC) is not included in this evaluation. Although there have been a few studies on the use of specially-modified GAC media for perchlorate removal, there have been no full-scale demonstrations of the technology and no apparent effort to certify the modified GAC media as safe for drinking water use.

particular perchlorate treatment technology do not exceed 2.5 percent of MHI, then that technology meets the affordability criterion.

Exhibit 1. BAT Criteria for Perchlorate Technologies Evaluation

CRITERION
1. High Removal Efficiency
1.1. Have high removal efficiencies that achieve potential MCLs been documented?
1.2. Are the effects of water quality parameters on treatment effectiveness and reliability well-known?
1.3. Is the technology reliable enough to continuously meet a drinking water MCL?
1.4. Is additional research needed?
2. History of Full-Scale Operation
2.1. Do existing studies include full-scale operations at drinking water treatment facilities?
2.2. Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options?
2.3. Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling?
2.4. Is additional research needed?
3. General Geographic Applicability
3.1. What regions do the existing research studies represent?
3.2. Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas?
3.3. Are there any regional issues with respect to residuals handling or water resource use?
3.4. Is additional research needed?
4. Compatibility with Other Treatment Processes
4.1. Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated?
4.2. Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train?
4.3. Is additional research needed?
5. Ability to Bring All of the Water System into Compliance
5.1. Will the treatment process adversely affect the distribution system or water resource decisions?
5.2. Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns?
5.3. Is additional research needed?
6. Reasonable Cost Basis for Large and Medium Systems
6.1. Is the technology currently used by medium and large systems (including uses for other treatment purposes)?
6.2. Do the treatment studies provide sufficient information on design assumptions to allow cost modeling?
6.3. Is additional research needed?

2 Best Available Technology Evaluation for Ion Exchange

The State of California has identified ion exchange (along with fluidized bed biological treatment) as one of two BATs for achieving compliance with its standard for perchlorate in drinking water (CCR, Title 22, Chapter 15, Section 64447.2). Ion exchange is a physical/chemical separation process in which an ion (such as perchlorate) in the feed water is exchanged for an ion (typically chloride) on a resin generally made of synthetic beads or gel. A variety of resin types have been tested for perchlorate removal. These resin types include strong-base polyacrylic, strong-base polystyrenic (including nitrate-selective), weak-base polyacrylic, weak-base polystyrenic, and perchlorate-selective.[2]

In application, feed water passes through a bed of resin in a vessel or column. The operation typically continues until the resin is exhausted, meaning that the chloride on enough of the resin's available exchange sites has been replaced with ions from the feed water that the resin is no longer effective for removing the ion. At this point, the resin may be disposed and replaced or regenerated. Based on data from full-scale operations (see below), it is likely that most systems using ion exchange to comply with a perchlorate MCL would use a perchlorate-selective resin that would be disposed, rather than regenerated, when exhausted. This resin choice has implications for technology feasibility, particularly with regard to residuals management, as discussed below.

2.1 High Removal Efficiency for Ion Exchange

2.1.1 Have high removal efficiencies that achieve potential MCLs been documented?

Yes. The literature documents perchlorate removal efficiencies for ion exchange that are typically in the high 90 percent range and to levels well below the potential MCLs, especially when using perchlorate-selective resin. This includes results from studies conducted in the laboratory, in the field at pilot scale, and in full-scale application. Exhibit 2 summarizes the removal efficiencies and resulting concentrations reported in the literature. Ion exchange with various types of resin is capable of removing perchlorate to levels below 4 micrograms per liter (μg/L), even given very high influent perchlorate concentrations. For perchlorate-selective resins, the research has shown that levels below 1 to 2 μg/L are achievable.

[2] While Tripp et al. (2003) also examined strong base polyvinylpyridine resins, comparable quantitative data on their removal efficiency are not available.

Exhibit 2. Perchlorate Effectiveness Results for Ion Exchange

Resin Type (a)	Removal Efficiency	Resulting Concentration (µg/L)	Study Scale (b)	Data Source(s)
SB	>77% to >94%	<4	P	GWRTAC, 2001; Venkatesh et al., 2000
	>95.7% to >97%	<4	F	Berlien, 2003; GWRTAC, 2001; Praskins, 2003)
	>97.5% to >98.1%	<2,000	F	GWRTAC, 2001; Praskins, 2003; Wagner and Drewry, 2000
	>98%	<4	P	ITRC Team, 2008
	>98% and >99.6%	<4	P	GWRTAC, 2001; Venkatesh et al., 2000
SB-S, SB-A, WB-S, WB-A	>99.9%	<20	L	Batista et al., 2003; 2000
NS	>44%	<4	F	CalEPA, 2004
	>60%	<4	F	CalEPA, 2004
	>60%	<4	F	CalEPA, 2004
	>76%	<4	F	ITRC Team, 2008
	>85% and >96%	<4	P	Burge and Halden, 1999
	>99.3%	<3	P	Gu et al., 1999; Gu et al., 2002
PS	Not specified	<4	F	ITRC Team, 2008
	>60%	<4	F	ITRC Team, 2008
	>60% to >73%	<4	F	Hayward and Gillen, 2005; Siemens Water Technologies, 2009b
	>75% to >80%	<2	L, P	Blute et al., 2006
	>82%	<2	P	Lutes et al., 2010
	>83% to >95%	<2	P	Russell et al., 2008
	>84%	<4	P	ITRC Team, 2008
	>92%	<4	F	ITRC Team, 2008
	>93.3% to >97.8%	<1	F	Membrane Technology, 2006; Siemens Water Technologies, 2009c
	>94%	<2	P	Wu and Blute, 2010
	>97.5%	<0.35	F	ITRC Team, 2008
	>98%	<1	P	ITRC Team, 2008
	>98.6%	<4	F	ITRC Team, 2008
	>97.6% to >99.2%	<0.5	F	Drago and Leserman, 2011
	>99.3%	<3	P	Gu et al., 1999; Gu et al., 2002
	>99.7%	<3	L	Gu et al., 1999
WB-S	>98.5%	<0.1	P	U.S. DoD, 2008b
	>99.7%	<4	P	U.S. DoD, 2007
Not specified	>60%	<4	F	CalEPA, 2004
	>60% to >98%	<4	F	ITRC Team, 2008
	>71%	<4	F	ITRC Team, 2008
	>73%	<4	F	Fontana Water Company, 2010; ITRC Team, 2008
	>75%	<5	F	Santschi, 2010
	>90%	<2	F	ITRC Team, 2008
	>96% to >99.7%	<4	L	GWRTAC, 2001
	>99%	<4	F	Siemens Water Technologies, 2009a

Notes:
a. SB = strong-base; SB-S = strong-base polystyrenic; SB-A = strong-base polyacrylic; WB-S = weak-base polystyrenic; WB-A = weak-base polyacrylic; NS = nitrate-selective strong-base polystyrenic; PS = perchlorate selective
b. L = laboratory study; P = field pilot study; F = full-scale

2.1.2 Are the effects of water quality parameters on treatment effectiveness and reliability well-known?

Yes. Effectiveness varies depending on water quality, but for perchlorate-selective resins the effect is limited. The most significant raw water quality consideration in ion exchange perchlorate treatment is the concentration of competing anions (particularly sulfate, nitrate, bicarbonate, and chloride). The effect of these anions is to decrease a resin's longer-term capacity to adsorb perchlorate, as they compete with perchlorate for exchange sites. There are significant differences among resin types in terms of the relative impact of competing anions. This impact is related to the relative affinity of the resin for each anion present. The order of affinity for perchlorate-selective resins is as follows (Boodoo, 2003):

perchlorate > nitrate > sulfate > chloride > bicarbonate.

In particular, the perchlorate affinity relative to nitrate affinity is nearly an order of magnitude greater (Boodoo, 2003). Although Boodoo (2003) suggests that perchlorate-selective resins would be negatively affected by high nitrate concentrations, a multitude of studies show that these resins are not, in fact, very sensitive to competing anions. Perchlorate capacity remains high for a wide range of nitrate and sulfate concentrations (Blute et al., 2006; Drago and Leserman, 2011; Gu et al., 1999; 2007; 2002; Min et al., 2003; Lutes et al., 2010; Russell et al., 2008; Tripp et al., 2003; Wu and Blute, 2010).

Although most investigators identify bicarbonate and chloride as other major competing anions, the affinity of ion exchange resins, particularly perchlorate-selective resins, for these anions is less than that for perchlorate, sulfate, and nitrate. Therefore, their impact on resin perchlorate capacity would be expected to be less than that of sulfate and nitrate. There are, however, no quantitative data in the literature on the effects of these major anions. Other co-contaminants that may affect perchlorate capacity include arsenic (Berlien, 2003; Tripp et al., 2003), uranium (Min et al., 2003; Tripp et al., 2003), and chromium (Min et al., 2003). Based on the high affinity of most resins for perchlorate, direct competition from these co-contaminants would be expected to be low.

2.1.3 Is the technology reliable enough to continuously meet a drinking water MCL?

Yes. Numerous full-scale drinking water facilities are using ion exchange to meet the State of California's MCL for perchlorate (see Question 2.2.1, below). In general, ion exchange is an established, reliable technology that has been used successfully to meet other MCLs.

2.1.4 Is additional research needed?

No. Additional research is not required.

2.2 History of Full-Scale Operation for Ion Exchange

2.2.1 Do existing studies include full-scale operations at drinking water treatment facilities?

Yes. The literature identifies 44 full-scale facilities applying ion exchange for perchlorate removal (USEPA, 2018). Many of these facilities are drinking water treatment facilities. With the majority of these facilities located in California, the full-scale use of the technology appears to be focused on compliance with that State's MCL for perchlorate.

The data on full-scale facilities demonstrate the increasing use of perchlorate-selective resins. Currently, more than half of the identified full-scale facilities (18 of 23 facilities where information on resin type is available) use perchlorate-selective resins. An additional two facilities are reportedly planning to switch to perchlorate-selective resin (Blute, 2012; Wu and Blute, 2010). Thus, perchlorate-selective resin appears to have become the technology of choice for perchlorate ion exchange facilities.

2.2.2 Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options?

Yes. Almost 79 percent (30 of 38) of the full-scale perchlorate ion exchange facilities for which waste management data are available operate on a throwaway basis. This statistic includes all but one of the full-scale facilities using perchlorate-selective resin. An additional two facilities are reportedly planning to switch away from regeneration to disposal of spent resin (Blute, 2012; Wu and Blute, 2010). These systems generate solid waste in the form of spent resin loaded with perchlorate and other anions. The facilities that operate with resin regeneration are older facilities. New facilities installed to comply with a perchlorate MCL would be unlikely to adopt this mode of operation.

The primary concern with spent resin is that hazardous co-contaminants (such as arsenic, uranium, and chromium) might accumulate on the resin. For example, Tripp et al. (2003) suggest that a perchlorate-selective resin would require frequent disposal to prevent arsenic and uranium build-up. Recent studies of various perchlorate-selective resins, however, have shown that build-up of metals results in concentrations that are below regulatory limits that would require disposal as a hazardous waste, both under federal requirements and California's more stringent limits (Blute et al., 2006; Russell et al., 2008; Wu and Blute, 2010). The same studies found that uranium build-up might require special handling as a radioactive waste in only one of the 12 samples tested (total across all three studies).

Because of the shorter life of conventional (not perchlorate-selective) resins, metals accumulation in these resins likely would be even lower and, thus, the same result should hold true (although few full-scale systems would be expected to use these resins). A number of studies are also available characterizing spent regenerant (Batista et al., 2003; Berlien, 2003; Case et al., 2004; Gu et al., 2002; Lutes et al., 2010; Montgomery Watson Harza and University of Houston, 2003). Again though, few full-scale systems would be expected to operate with resin regeneration.

2.2.3 Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling?

Yes. As a mature and established technology, the scale-up of ion exchange, in general, from bench- to pilot- to full-scale is well understood.

2.2.4 Is additional research needed?

No. Additional research is not required.

2.3 General Geographic Applicability for Ion Exchange

2.3.1 What regions do the existing research areas represent?

Studies of ion exchange treatment of perchlorate have primarily been conducted in California and Nevada. For perchlorate-selective resin in particular, most recent studies have used water that is representative of those areas.

2.3.2 Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas?

No. Although most of the existing research is for a limited region, there are no data indicating that regional water quality variations will limit effectiveness or reliability. Given that the effect of source water quality parameters on perchlorate-selective resin is limited (see Question 2.1.2), source water conditions in other regions are not likely to have a substantial impact.

2.3.3 Are there any regional issues with respect to residuals handling or water resource use?

There are regions where disposal of spent regenerant would be an issue. Few full-scale systems, however, would be expected to operate with resin regeneration. Regional barriers are not anticipated with respect to spent resin disposal unless co-occurring contaminants that accumulate on the resin are classified as hazardous or radioactive (see Question 2.2.2).

2.3.4 Is additional research needed?

No. Additional research is not required.

2.4 Compatibility of Ion Exchange with Other Treatment Processes

2.4.1 Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated?

Yes. Ion exchange can have an adverse effect on treated water chemistry by increasing corrosivity (see Question 2.5.1). The technology can also have a beneficial effect by removing other undesirable anions from the treated water (e.g., arsenic, uranium), even when using perchlorate-selective resin (see Questions 2.1.2 and 2.2.2).

2.4.2 Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train?

Possibly. The treated water chemistry changes resulting from ion exchange might require post-treatment corrosion control or alter existing corrosion control or disinfection requirements.

2.4.3 Is additional research needed?

No. Additional research is not required.

2.5 Ability of Ion Exchange to Bring all of the Water System into Compliance

2.5.1 Will the treatment process adversely affect the distribution system or water resource decisions?

Ion exchange treatment can increase the corrosivity of treated water (Berlien, 2003; Betts, 1998; USEPA, 2005) because of the addition of chloride ions and/or removal of carbonates and bicarbonates. Berlien (2003) reports this problem with a full-scale application of ion exchange for perchlorate treatment. Treated water had a pH of approximately 7 and created red water problems in older homes with galvanized steel pipe. The operators corrected this problem by adding sodium hydroxide to raise the pH to approximately 8.2 and adding polyphosphates as an additional protection measure. Thus, distribution system effects can be managed by adjusting corrosion control programs.

The potentially large volume of spent regenerant could be a barrier in regions with water resource issues. Few full-scale systems, however, would be expected to operate with resin regeneration.

2.5.2 Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns?

The disposal of large volumes of spent regenerant could create an environmental quality concern. Few full-scale systems, however, would be expected to operate with resin regeneration.

2.5.3 Is additional research needed?

No. Additional research is not required.

2.6 Reasonable Cost Basis for Ion Exchange for Large and Medium Systems

2.6.1 Is the technology currently used by medium and large systems (including uses for other treatment purposes)?

Yes. The 44 full-scale perchlorate ion exchange systems identified in the literature include a number of medium and large systems: 31 are larger than 1 million gallons per day (MGD) and six are larger than 10 MGD, with the largest being 14.4 MGD.

2.6.2 Do the treatment studies provide sufficient information for design assumptions to allow cost modeling?

Detailed data are available from the treatment studies for all of the relevant design parameters, including:

- Resin type
- Vessel configuration (i.e., number of vessels in series)
- Empty bed contact time (EBCT)
- Resin bed life
- Surface loading rate

- Regeneration parameters.

2.6.3 Is additional research needed?

No. Additional research is not required.

3 Best Available Technology Evaluation for Biological Treatment

The State of California has identified biological treatment (along with ion exchange) as one of two BATs for achieving compliance with its standard for perchlorate in drinking water (CCR, Title 22, Chapter 15, Section 64447.2). Biological treatment of perchlorate is the process by which bacteria are used to reduce perchlorate to chlorate, chlorite, chloride, and oxygen. The process typically involves the addition of an oxidizable substrate (also referred to as the electron donor or "food"), such as acetate or ethanol. Biological treatment offers complete destruction of the perchlorate ion, eliminating the need for management of perchlorate-bearing waste streams.

The most promising designs for biological treatment of perchlorate at drinking water facilities are those that operate either in a fixed bed or a fluidized bed configuration. Both fixed bed and fluidized bed designs involve a media bed that provides a surface on which perchlorate-reducing bacteria grows. For fixed bed reactors, influent water is typically passed under pressure through a static media bed located in a vessel. An alternative fixed bed design uses a gravity-fed concrete basin to hold the biologically active media. Fluidized bed bioreactor designs use vessels where high influent rates in an up-flow design fluidize the media bed allowing for more surface area for biomass growth. California's BAT for perchlorate specifies fluidized bed biological treatment.

3.1 High Removal Efficiency for Biological Treatment

3.1.1 Have high removal efficiencies that achieve potential MCLs been documented?

Yes. Exhibit 3 summarizes the removal efficiencies and resulting concentrations reported in the literature. It shows that fixed and fluidized bed reactors have consistently achieved removal efficiencies greater than 90 percent, reducing perchlorate to levels that are usually below detection limits of 4 µg/L or lower, even given very high influent perchlorate concentrations. Most of the data in the exhibit are from laboratory-, pilot-, and field-scale tests of biological treatment. Also included, however, are data from several full-scale treatment systems.

Exhibit 3. Perchlorate Effectiveness Results for Biological Treatment

Removal Efficiency	Resulting Concentration (µg/L)	Scale and Reactor Type	Other Analytes (mg/L)	Media / Electron Donor	Data Source(s)
>99%	<4	Bench-scale fixed bed	None	Sand / Acetate	Kim and Logan, 2000
>99%	<4	Bench-scale fixed bed	Nitrate (0.02), sulfate (0.04)	Celite / Acetate	Losi et al., 2002
>98%	<3	Bench-scale fixed bed	Nitrate (13), sulfate (9.3 to16.8)	GAC / Acetic acid or proprietary carbohydrate solution	Upadhyaya et al., 2015
>94%	<4	Bench-scale fixed bed	Nitrate (4)	Sand, plastic media / Acetic acid	Min et al., 2004; Case et al., 2004
>93%	<5	Full-scale fixed bed (a)	Nitrate	GAC / Acetic acid	U.S. DoD, 2008a
>92%	<4	Bench-scale fixed bed	Sulfate (0 to 220)	GAC/ Acetate or ethanol	Brown et al., 2003
92% to 99%	<4	Field-scale fixed bed (d)	Sulfate (140 to 250), Nitrate (6 to 29), DO (4 to 8)	GAC / Acetic acid	Brown et al., 2005; ITRC Team, 2008
>99%	<0.5	Full-scale fluidized bed (a)	Various	GAC / Acetic acid	U.S. DoD, 2009; Webster and Crowley, 2010; 2016; Webster and Litchfield, 2017
>99%	<5	Bench-scale fluidized bed	Nitrate, metals, volatile organics	GAC / Acetic acid	Polk et al., 2001
>99%	220 to 280	Bench-scale fluidized bed	Nitrate (15.4), sulfate (12.5)	GAC / Acetate or proprietary glycerol solution	Kotlarz et al., 2016
>99%	350 to <4	Full-scale fluidized bed (b)	Nitrate (1.9), sulfate (300)	GAC / Acetic acid, ethanol	Polk et al., 2001
>99%	<2	Bench-scale fluidized bed	Sulfate (5 to 10)	GAC, sand / Ethanol, methanol, or mix	Greene and Pitre, 2000
>99%	<4	Full-scale fluidized bed (c)	Not reported	GAC / Ethanol	Greene and Pitre, 2000
>97%	<6	Bench-scale fluidized bed	Nitrate (13), sulfate (9.3 to 16.8)	GAC / Acetic acid or proprietary carbohydrate solution	Upadhyaya et al., 2015
92 to 98%	<4	Field-scale fluidized bed (e)	Various	GAC / Ethanol	Gilbert et al., 2001; Harding Engineering and Environmental Services, 2001

Notes:
a. Rialto Well #2 site in Rialto, California
b. Longhorn Army Ammunition Plant in Karnak, Texas
c. Aerojet facility in Rancho Cordova, California
d. Six-month field test in Santa Clarita, California
e. Eight-month field test in Rancho Cordova, California, supplying water for potable use

3.1.2 Are the effects of water quality parameters on treatment effectiveness and reliability well-known?

Yes. As shown in Exhibit 3, biological treatment remains effective even in the presence of certain co-occurring contaminants. Nitrate and sulfate were present in nearly all of the studies and did not appear to interfere with the removal efficiency of the process. Biological treatment also has been shown effective in the presence of metals, volatile organic compounds, and other contaminants including N-nitrosodimethlamine and 1,4-dioxane (Harding Engineering and Environmental Services, 2001; Polk et al., 2001; U.S. DoD, 2000).

Nevertheless, raw water quality plays a role in the design of a biological treatment system. In identifying design criteria for use in full-scale treatment plant designs, the Harding ESE (2001) authors included expected raw water dissolved oxygen, nitrate, perchlorate, and total phosphorous concentrations as necessary considerations, along with water temperature. In particular, temperature plays an important role in determining the rate of biomass growth. Electron donor dose requirements increase with decreasing temperature. At temperatures below 10 degrees C, biomass growth is inhibited and bioremediation becomes unfeasible (Dugan et al., 2011; Dugan et al., 2009).

3.1.3 Is the technology reliable enough to continuously meet a drinking water MCL?

Continuous destruction of perchlorate in a biological treatment system depends heavily on influent water temperature (see above under Question 3.1.2). Thus, systems with seasonal variation in water temperature such that temperature drops below 10 degrees C in the winter months would not be able to rely on biological treatment year-round. Systems with a constant water temperature or one that remains warm enough year-round, on the other hand, should be able to continuously meet an MCL.

3.1.4 Is additional research needed?

No. Additional research is not required.

3.2 History of Full-Scale Operation for Biological Treatment

3.2.1 Do existing studies include full-scale operations at drinking water treatment facilities?

Yes. Although most of the full-scale systems are part of perchlorate remediation projects in which treated water is not used as drinking water, fluidized bed operations supplying drinking water do exist. For example, one remediation facility conducted an eight-month fluidized bed field test that supplied potable water to local water companies (Gilbert et al., 2001; Harding Engineering and Environmental Services, 2001). Furthermore, the success of several demonstration studies led to the design and installation of a full-scale fluidized bed system supplying drinking water to the West Valley Water District and the City of Rialto. This system completed construction in 2013 and the system underwent extensive testing before receiving its operating permit and beginning to produce drinking water in 2016 (Webster and Crowley, 2010; 2016; Webster and Litchfield, 2017).

3.2.2 Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options?

Yes. Because biological treatment offers complete destruction of the perchlorate ion, the technology does not generate a perchlorate-bearing waste stream. An active bioreactor, however, will have a continuous growth of biomass. Assuming the addition of a sufficient amount of electron donor substrate, the quantity of biomass generated will depend on the concentrations of dissolved oxygen, nitrate, and perchlorate available for consumption. In most bioreactor designs, excess biomass must be removed periodically, which results in one or more residual streams.

In fixed bed bioreactors, biomass removal typically is accomplished using a backwash process, which generates spent backwash water containing the excess biosolids (and some lost media). This backwash water is non-toxic and can typically be discharged to a local sewer (U.S. DoD, 2008a). For facilities without the option of sewer disposal, a clarification and recycle process would be needed.

For fluidized bed reactors, one case study describes the use of a continuously operated separation device that uses supplied air to remove media and biomass from the top of the bed and direct it to a separation chamber. This arrangement was used in combination with an in-bed eductor to intermittently remove biomass growth from deeper within the bed. After treatment through an adsorption clarifier and multimedia filter, the study reports that the remaining residuals were "dilute enough that no special handling or pretreatment requirements should be necessary for most/all POTWs to accept" (U.S. DoD, 2009).

Downstream polishing through filtration, when used as post-treatment (see Question 3.5.1), can also generate residual wastes in the form of backwash water and separated solids. The authors of the Harding ESE (2001) report suggest that clarifier solids could be discharged directly to sewer or filter pressed to reduce volume prior to ultimate disposal. The full-scale drinking water treatment facility in Rialto uses dissolved air floatation, followed by a sludge press, to treat backwash from post-treatment filtration (Webster and Litchfield, 2017). Backwash water from downstream polishing would be expected to have characteristics similar to water from direct backwash of a fixed bed reactor.

3.2.3 Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling?

Yes. Given the experience with full-scale remediation projects, the bench studies, pilot studies, and temporary field tests generally provide sufficient data to represent full-scale drinking water treatment.

3.2.4 Is additional research needed?

No. Additional research is not required.

3.3 General Geographic Applicability for Biological Treatment

3.3.1 What regions do the existing research areas represent?

The studies of biological treatment of perchlorate have been conducted in California and Texas.

3.3.2 Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas?

As discussed above (see Question 3.1.2), water temperature is a critical variable in the ability of biological treatment to continuously destroy perchlorate. Regions not studied may be more likely than California and Texas to have cold water and/or seasonally variable water temperature. Because the effect of temperature is well understood, however, it should be feasible to determine whether biological treatment will be effective for a given system based on a water temperature record.

In addition to external electron donors, bacteria in bioreactors require macro- and micro-nutrients in order to grow and effectively reduce perchlorate. Thus, concentrations of these nutrients in the raw water are a consideration in bioreactor effectiveness. Macro-nutrients include phosphorous and nitrogen, and necessary micro-nutrients include sulfur and iron. While source water typically contains sufficient micro-nutrients, it sometimes has insufficient amounts of phosphorous and nitrogen to allow for bacterial growth. As a result, some full-scale designs have required supplemental addition of one or both of these nutrients (Harding Engineering and Environmental Services, 2001; U.S. DoD, 2008a; 2009).

3.3.3 Are there any regional issues with respect to residuals handling or water resource use?

No. Regional residual handling and water resource needs are not expected to affect technology feasibility.

3.3.4 Is additional research needed?

No. Additional research is not required.

3.4 Compatibility of Biological Treatment with Other Treatment Processes

3.4.1 Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated?

Yes. Biological treatment results in the production of soluble microbial organic products that become part of the treated water. The additional microorganisms increase disinfection demand for the downstream treatment processes. The biological treatment process also depletes the levels of oxygen in the treated water and can add turbidity and sulfides, which can have adverse effects on downstream treatment processes if not managed through post-treatment. Beneficial effects of biological treatment, on the other hand, include the potential to remove nitrate and disinfection byproduct precursors.

3.4.2 Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train?

Yes. Post-treatment will be needed to control the effects on other treatment processes (and also on the distribution system; see Question 3.5.1). In the field study of biological treatment for potable water (Gilbert et al., 2001; Harding Engineering and Environmental Services, 2001), biological treatment was part of a train of seven different unit processes. The train included an aerator and multimedia filter serving as post-treatment for the biological treatment step. Post-treatment was then followed by downstream processes to address other contaminants and water quality concerns. The downstream processes were an air stripper, advanced oxidation, granular activated carbon, and disinfection. Investigators concluded that each of the downstream treatment processes met desired removal efficiencies in a reliable manner (Gilbert et al., 2001). Thus, post-treatment appears able to manage the potential impacts of biological treatment on common downstream treatment processes.

3.4.3 Is additional research needed?

No. Additional research is not required.

3.5 Ability of Biological Treatment to Bring all of the Water System into Compliance

3.5.1 Will the treatment process adversely affect the distribution system or water resource decisions?

Yes, although distribution system impacts might be managed by post-treatment processes. As discussed under Question 3.4.1, biological treatment adds microorganisms, depletes oxygen, and can add turbidity and sulfides. Therefore, post-treatment will typically be required for production of drinking water. Typical post-treatment processes include (Dordelmann, 2009; Harding Engineering and Environmental Services, 2001; U.S. DoD, 2008a; Webster and Crowley, 2016; Webster and Litchfield, 2017):

- reoxygenation or aeration for saturation with oxygen, using hydrogen peroxide addition or an aeration tank
- a polishing filter (using GAC or mixed media) for removal of turbidity, sulfide, and/or dissolved organic content, possibly including coagulant addition before filtration
- disinfection via ultraviolet light or chlorination.

For the full-scale system supplying drinking water, the permit requirements also include instrumentation and controls (chlorine, pH, nitrate, sulfide, total organic carbon, and turbidity) to monitor performance (Webster and Crowley, 2016; Webster and Litchfield, 2017).

In the field study of biological treatment for potable water, which included the post-treatment processes listed above, investigators concluded that bacterial re-growth in the water distribution system would not be significant (Gilbert et al., 2001). They did not, however, address the potential for other distribution systems impacts.

3.5.2 Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns?

Yes. Any of the impacts discussed above under Questions 3.4.1 and 3.5.1, if not adequately managed through post-treatment, could create new environmental quality concerns.

3.5.3 Is additional research needed?

Although Gilbert et al. (2001) concluded that bacterial re-growth in the water distribution system would not be significant after post-treatment, additional research might be needed on the effectiveness of post-treatment processes in mitigating other distribution system impacts.

3.6 Reasonable Cost Basis for Biological Treatment for Large and Medium Systems

3.6.1 Is the technology currently used by medium and large systems (including uses for other treatment purposes)?

Yes. The full-scale system suppling drinking water was initially designed to treat 3 million gallons per day (MGD), with an ultimate capacity of 6 MGD so that water from additional wells might be treated in the future (Webster and Crowley, 2016; Webster and Litchfield, 2017). Fluidized bed reactors also have been used in remedial applications with design flows up to 10 MGD (Greene and Pitre, 2000). This application re-injects treated water into an underlying aquifer; water is not used for drinking water.

3.6.2 Do the treatment studies provide sufficient information on design assumptions to allow cost modeling?

Detailed data are available from the treatment studies for all of the relevant design parameters, including:

- Support media type
- EBCT
- Bed expansion (for fluidized bed reactors)
- Electron donor type and dosage
- Nutrient addition
- Backwash design (for fixed bed reactors)
- Recycle rate (for fluidized bed reactors).

3.6.3 Is additional research needed?

No. Additional research is not required.

4 Best Available Technology Evaluation for Reverse Osmosis

Membrane filtration processes physically remove perchlorate ions from drinking water. These processes separate a solute such as perchlorate ions from a solution by forcing the solvent to flow through a membrane at a pressure greater than the normal osmotic pressure. The membrane is semi-permeable, transporting different molecular species at different rates. Water and low-molecular weight solutes pass through the membrane and are removed as permeate, or filtrate. Dissolved and suspended solids are rejected by the membrane and are removed as concentrate, or reject. This technique does not destroy the perchlorate ion and, therefore, creates a subsequent need for disposal or treatment of perchlorate-contaminated waste (the concentrate).

Membranes may remove ions from feed water by a sieving action (called steric exclusion), or by electrostatic repulsion of ions from the charged membrane surface. Membrane filtration technologies evaluated for perchlorate treatment include RO, nanofiltration (NF), and ultrafiltration (UF). As discussed under Question 4.1.1, bench studies of NF and UF membranes show significant variability in these membranes' ability to remove perchlorate, depending on other constituents of the source water. Therefore, RO is the membrane process most suited for evaluation as BAT for perchlorate.

4.1 High Removal Efficiency for Reverse Osmosis

4.1.1 Have high removal efficiencies that achieve potential MCLs been documented?

Yes. Pilot-scale treatability work at the Metropolitan Water District of Southern California showed that NF and RO membranes consistently removed greater than 80 percent of the perchlorate (up to 98 percent for RO and 92 percent for NF) depending on influent concentration (Liang et al., 1998). Recycling 50 percent of the reject had no effect on overall perchlorate rejection. Exhibit 4 summarizes effectiveness results for this pilot-scale work, along with results from additional, smaller scale bench studies.

Bench-scale studies show the effects of steric/size exclusion and electrostatic exclusion on perchlorate transport through membranes to varying degrees. RO, while removing perchlorate, also removes most other salts, requires high operating pressures, and is prone to significant flux decline. Membrane processes that operate at lower pressures, such as NF or UF, may be effective for perchlorate removal through selectivity based on size and/or charge. However, bench studies show significant variability in these membranes' ability to remove perchlorate, depending on other constituents of the source water. One bench study modified commercial NF membranes using layer-by-layer surface deposition of polyelectrolytes. This study showed that the modified NF membranes could achieve perchlorate removal nearly equal to that of RO membranes. The study, however, did not examine the effect of differing source water quality on the membranes and research on the modified membranes does not yet appear to have progressed beyond the lab (Sanyal et al., 2015).

Exhibit 4. Perchlorate Effectiveness Results for Membranes

Technology/Source	Removal Efficiency	Raw Water Concentration	Location and Source Water	Study Scale
RO and NF (Liang et al., 1998)	RO up to 98% NF up to 92%	20 to 2,000 µg/L (some trials used perchlorate-spiked source water)	Metropolitan Water District of Southern California, La Verne Treatment Plant, CA; Pretreated Colorado River Water	Pilot study (12 gpm)
Surfactant modified UF (Yoon et al., 2003)	Up to 80%	100 µg/L (perchlorate-spiked)	Synthetic water and a blend of Colorado River Water and State Project Water from the Metropolitan Water District, CA	Bench study (225 milliliters per minute)
NF and UF (Yoon et al., 2002)	Up to 75%	100 µg/L (perchlorate-spiked)	Synthetic water with pure component perchlorate, also combined with other salts	Bench study (no flow given)
NF and UF (Y. Yoon et al., 2005)	NF up to 80% (natural water) or 89% (synthetic water) UF up to 5% (natural water) or 66% (synthetic water)	100 µg/L (perchlorate-spiked)	Synthetic water and Colorado River Water from the Metropolitan Water District, CA, spiked with perchlorate	Bench study (100 to 225 milliliters per minute)
RO and NF (Nam et al., 2005)	RO up to 95% NF up to 70%	100 µg/L (perchlorate-spiked)	Ground waters from the Castaic Lake Water Agency, CA	Bench study (no flow given)
RO (USEPA, 2005)	From 125–2,000 µg/L to 5–80 µg/L	125 to 2,000 µg/L	Unspecified perchlorate-contaminated ground water	Bench study (no flow given)
RO and NF (J. Yoon, Yoon, et al., 2005)	RO up to 95% NF up to 55%	100 µg/L (perchlorate-spiked)	Blend of Colorado River Water and State Project Water from the Metropolitan Water District, CA, spiked with perchlorate	Bench study (20 milliliters per minute)
RO, NF, and UF (J. Yoon, Amy, et al., 2005)	RO up to 95% NF up to 78% UF up to 29%	100 µg/L (perchlorate-spiked)	Synthetic water	Bench study (no flow given)
RO, NF, and surface modified NF (Sanyal et al., 2015)	RO up to 95.8% NF up to 70.1% Surface modified NF up to 93%	10,000 µg/L (perchlorate-spiked)	Perchlorate-spiked deionized water	Bench study (0.26 gpm)

4.1.2 Are the effects of water quality parameters on treatment effectiveness and reliability well-known?

Yes. In general, water quality affects the design (e.g., concentrate volume, cleaning frequency, antiscalant selection) of an RO system, but not removal efficiency. The literature specifically for perchlorate removal by membranes supports this conclusion. Higher variability in perchlorate removal with water quality has been found for NF and UF membranes than for RO membranes.

High levels of alkaline earth cations (Ca^{2+} or Mg^{2+}) can cause membrane scaling (Yoon et al., 2003), leading to a decline in product water flux. One study showed that calcium carbonate scaling was also associated with a decline in perchlorate rejection, likely because the scale reduced the surface charge of the membrane (J. Yoon, Amy, et al., 2005). Other substances, such as silica and microbial biomass, may also cause flux decline; however, there are no studies of the resulting effect on perchlorate rejection.

Membrane fouling can be reduced either by reducing the pH of the feed water or by adding an antiscalant chemical. However, for membranes that reject perchlorate electrostatically (primarily NF and UF membranes), studies of several synthetic waters show that a reduced feed pH reduces the rejection of perchlorate (J. Yoon, Amy, et al., 2005; J. Yoon, Yoon, et al., 2005; Y. Yoon et al., 2005). The lower pH has been shown to diminish the negative surface charge of the membranes, inhibiting the electrostatic rejection mechanism. One study (J. Yoon, Amy, et al., 2005) demonstrated that a phosphonate-based antiscalant improved both product water flux and perchlorate rejection. In these studies, perchlorate rejection by RO membranes was much less sensitive to the feed water pH.

The same studies demonstrated that a high concentration of other ions, particularly divalent cations, in the membrane feed water can reduce perchlorate rejection. Again, the studies attributed the reduced rejection to a diminished membrane surface charge. One study that included one natural water and several synthetic waters (Y. Yoon et al., 2005) found that the natural water had worse perchlorate rejection than the most similar synthetic water for NF and UF membranes.

4.1.3 Is the technology reliable enough to continuously meet a drinking water MCL?

Yes. In general, RO is an established, reliable technology that has been used successfully to meet other MCLs. There is nothing unique about perchlorate removal by RO that suggests using it for this contaminant would reduce the technology's reliability.

4.1.4 Is additional research needed?

No. Additional research is not required.

4.2 History of Full-Scale Operation for Reverse Osmosis

4.2.1 Do existing studies include full-scale operations at drinking water treatment facilities?

There are no known full-scale RO facilities specifically for the removal of perchlorate. There are, however, a large number of drinking water treatment facilities that use RO for other contaminants.

4.2.2 Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options?

There are no known full-scale studies of residuals from RO facilities specifically for the removal of perchlorate. In general, however, the characteristics of RO residuals are predictable and handling and treatment options are well understood. RO produces a waste stream called the concentrate (or reject). This waste stream contains all removed dissolved solids. Membrane system designs generally set a recovery rate (i.e., the ratio of permeate to feed flow) based on the scaling potential of the feed water. The presence of a particular target contaminant has little or no effect on the selected recovery rate. Typical recovery rates are 70 to 85 percent, which means that concentrate flows can account for 15 to 30 percent of influent (i.e., 100 percent minus the recovery rate). There is nothing unique about perchlorate removal by RO that suggests recovery rates and concentrate flows would be different. Therefore, it is likely that the concentrate flow from a full-scale RO facility removing perchlorate would represent a substantial share of influent flows, implying a fairly large perchlorate-contaminated waste stream for subsequent treatment or disposal.

For disposal of RO residuals, the majority of systems use surface water discharge or discharge to sanitary sewer, with a small number using deep well injection, evaporation ponds, or spray irrigation (U.S. DoI, 2001). The large volume of residuals is a well-known obstacle to adoption of RO technology, in general. In the case of perchlorate removal by centralized treatment plants, the high perchlorate concentration in the residuals might limit the disposal options or require additional treatment prior to disposal, depending on state and local discharge regulations. Studies of treatment of perchlorate-bearing RO residuals are limited to a few laboratory-scale studies. These include biological (Giblin et al., 2002) and thermal treatment (Applied Research Associates, 2000) of RO concentrate. Urbansky and Schock (1999) note, however, that membrane filtration point-of-use devices can be practical options for homeowners, or other small or remote users. Depending upon the permitted perchlorate discharge levels, the concentrate can often be disposed in the sanitary sewer system, where it will essentially recombine with the raw water in the sewage stream.

4.2.3 Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling?

Yes. As a mature and established technology, the scale-up of RO, in general, from bench- to pilot- to full-scale is well understood.

4.2.4 Is additional research needed?

In general, additional research is not required. In cases where regional or system-specific conditions associated with perchlorate-bearing residuals management present a significant barrier, however, additional research on residuals treatment prior to disposal would be useful.

4.3 General Geographic Applicability for Reverse Osmosis

4.3.1 What regions do the existing research areas represent?

As shown in Exhibit 4, most of the existing pilot- and bench-scale research on RO for perchlorate removal has used water from systems in California.

4.3.2 Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas?

No. Although most of the existing research is for a limited region, there are no data indicating that regional water quality variations will limit effectiveness or reliability. As discussed under Question 4.1.2, water quality affects the design (e.g., concentrate volume, cleaning frequency, antiscalant selection, temperature) of an RO system, but not its effectiveness or reliability.

4.3.3 Are there any regional issues with respect to residuals handling or water resource use?

The large volume of water "lost" as RO residuals can be an issue in regions where water scarcity is a concern. The Small Business Advocacy Review Panel (1999) pointed out that a water rejection rate of 20 to 25 percent can present a problem where water is scarce, such as in the western states. The availability of discharge options for residuals is also a region- and system-specific issue, depending on location, climate, and state and local regulations. The technology is more likely to be feasible when ocean discharge or evaporation ponds are an option.

4.3.4 Is additional research needed?

No. Additional research is not required.

4.4 Compatibility of Reverse Osmosis with Other Treatment Processes

4.4.1 Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated?

Yes. Adverse effects are unlikely. RO might have some effect on treated water chemistry (see Question 4.5.1), which might alter corrosion control or blending requirements. Generally, however, these effluent chemistry changes should not require significant adjustments to downstream treatment processes. With regard to beneficial effects, RO membranes can remove a wide range of contaminants, including inorganic ions, total dissolved solids, nitrate, radionuclides, total organic carbon, some disinfection byproduct precursors, and synthetic organic chemicals. Since RO permeate has a reduced chlorine demand, its finished water requires a low dose of disinfectant.

4.4.2 Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train?

Yes. Post-treatment is typically required to control corrosion impacts (see Question 4.5.1).

4.4.3 Is additional research needed?

No. Additional research is not required.

4.5 Ability of Reverse Osmosis to Bring all of the Water System into Compliance

4.5.1 Will perchlorate treatment affect the distribution system or water resource decisions?

Yes. The permeate from RO filtration is essentially deionized water, and generally requires post treatment for corrosion control before it enters a distribution system (American Water Works Assocation and American Society of Civil Engineers (AWWA/ASCE), 2005). In other drinking water treatment applications, the permeate is often blended with untreated water to produce a less corrosive finished water. If the source water has a sufficiently low concentration of perchlorate and other contaminants, blending may reduce post-treatment requirements. Thus, distribution system effects can be managed by adjusting corrosion control programs or blending practices.

As discussed under Question 4.3.3, the large volume of RO residuals might have an impact on water resource decisions in regions where water scarcity is a concern.

4.5.2 Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns?

Yes. The disposal of large volumes of RO residuals could create an environmental quality concern. As discussed under Question 4.3.3, discharge concerns are region- and system-specific.

4.5.3 Is additional research needed?

No. Additional research is not required.

4.6 Reasonable Cost Basis for Reverse Osmosis for Large and Medium Systems

4.6.1 Is the technology currently used by medium and large systems (including uses for other treatment purposes)?

Yes. Although there are no known full-scale RO facilities specifically for the removal of perchlorate, there are a large number of medium and large systems that use RO for other contaminants.

4.6.2 Do the treatment studies provide sufficient information for design assumptions?

Relevant design parameters for RO include:

- Flux rate
- Membrane type
- Membrane array configuration
- Recovery rate
- Pretreatment requirements
- Cleaning procedures.

Assumptions about these parameters for RO, in general, are determined based on major water quality parameters, such as hardness parameters, chloride, sulfate, silica, pH, silt density index, and total dissolved solids. They typically are not affected by trace contaminant influent concentrations or removal requirements. There is nothing unique about perchlorate removal by RO that suggests a different relationship between the major water quality parameters and typical design requirements.

4.6.3 Is additional research needed?

No. Additional research is not required.

5 Summary of Best Available Technology Evaluation

Exhibit 5 provides a summary of the evaluation results for the three technologies against each of the criteria. Based on this evaluation, the overall conclusions are:

- Ion exchange is a potential BAT. It has been show to achieve high removal efficiency for perchlorate, particularly with the use of perchlorate-selective resin. It is a mature and established technology in general and has been used for full-scale treatment of perchlorate at a large number of facilities. The use of disposable perchlorate-selective resins eliminates concerns about large volumes of liquid residuals in the form of spent regenerant.

- Biological treatment is a potential BAT. It has been shown to achieve high removal efficiency for perchlorate, including at a full-scale fluidized bed drinking water treatment facility. The technology may, however, need to be used in conjunction with post-treatment processes to ensure finished water quality and mitigate distribution system impacts. Water temperatures also may restrict the technology’s applicability on a regional or system-specific basis.

- RO is a potential BAT. It has been shown to achieve high removal efficiency for perchlorate at bench- and pilot-scale. Although no full-scale results are available specifically for perchlorate, RO is a mature and established technology in general. Scale-up of RO systems depends primarily on major water quality parameters and is not dependent on the characteristics of trace contaminants like perchlorate. Large volumes of residual concentrate, however, will likely restrict the technology’s applicability on a system-specific basis. Additional research on treatment of perchlorate-bearing RO residuals could help mitigate this issue in some cases.

Exhibit 5. Perchlorate Technologies Evaluated Against BAT Criteria

Criterion	Ion Exchange	Biological Treatment	Reverse Osmosis
1. High Removal Efficiency			
1.1. Have high removal efficiencies that achieve potential MCLs been documented?	Yes	Yes	Yes
1.2. Are the effects of water quality parameters on treatment effectiveness and reliability well-known?	Yes	Yes	Yes
1.3. Is the technology reliable enough to continuously meet a drinking water MCL?	Yes	Depends on temperature	Yes
1.4. Is additional research needed?	No	No	No
2. History of Full-Scale Operation			
2.1. Do existing studies include full-scale operations at drinking water treatment facilities?	Yes	Yes (using fluidized bed reactors)	Yes (for other treatment purposes)
2.2. Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options?	Yes	Yes	Yes (for other treatment purposes)
2.3. Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling?	Yes	Yes	Yes
2.4. Is additional research needed?	No	No	Maybe
3. General Geographic Applicability			
3.1. What regions do the existing research studies represent?	Primarily California	Primarily California	Primarily California
3.2. Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas?	No	Yes	No
3.3. Are there any regional issues with respect to residuals handling or water resource use?	Not likely	No	Yes
3.4. Is additional research needed?	No	No	No
4. Compatibility with Other Treatment Processes			
4.1. Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated?	Yes	Yes	Yes
4.2. Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train?	Possibly	Yes	Yes
4.3. Is additional research needed?	No	No	No
5. Ability to Bring All of the Water System into Compliance			
5.1. Will the treatment process adversely affect the distribution system or water resource decisions?	Possibly	Yes	Yes
5.2. Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns?	Not likely	Yes	Yes
5.3. Is additional research needed?	No	Maybe	No
6. Reasonable Cost Basis for Large and Medium Systems			
6.1. Is the technology currently used by medium and large systems (including uses for other treatment purposes)?	Yes	Yes	Yes (for other treatment purposes)
6.2. Do the treatment studies provide sufficient information on design assumptions to allow cost modeling?	Yes	Yes	Yes
6.3. Is additional research needed?	No	No	No

6 Small System Compliance Technology Evaluation

6.1 SSCT Analysis Method

A technology must be both effective and affordable to be designated an SSCT. Technologies that meet the effectiveness criterion include those designated as BATs for the proposed rule: anion exchange, biological treatment, and centralized RO. For an MCL greater than or equal to 4 micrograms per liter (µg/L), certified POU RO devices also meet the effectiveness criterion.[3]

To evaluate affordability, EPA compared incremental costs per household for each perchlorate-removal technology against an *expenditure margin*. Exhibit 6 shows the expenditure margins for each system size category. It also shows how EPA derived the expenditure margins, beginning with estimates of MHI, which vary by system size category. The annual affordability threshold for household expenditures on drinking water is 2.5 percent of MHI. EPA deducted estimates of baseline or current water bills from the affordability threshold to obtain the expenditure margin estimates.

Exhibit 6. Expenditure Margins for SSCT Affordability Analysis

System Size (Population Served)	Median Household Income[1] (a)	Affordability Threshold[2] (b) = 2.5% x a	Baseline Water Cost[3] (c)	Expenditure Margin (d) = b - c
25-500	$52,791	$1,320	$341	$979
501-3,300	$51,093	$1,277	$395	$883
3,301-10,000	$55,975	$1,399	$412	$987

Notes:
1. MHI based on U.S. Census 2010 American Community Survey (ACS) 5-year estimates (U.S. Census Bureau, 2010) stated in 2010 dollars, adjusted to 2017 dollars using the CPI (for all items) for areas under 50,000 persons.
2. Affordability threshold equals 2.5 percent of MHI.
3. Household water costs derived from 2006 Community Water System Survey (USEPA, 2009), based on residential revenue per connection within each size category, adjusted to 2017 dollars based on the CPI (for all items) for areas under 50,000 persons.

The cost per household varies by technology and by system size category. EPA used the following method to estimate per-household costs using EPA's work breakdown structure (WBS) technology cost models:

- Estimate system-level costs for capital expenditures and annual operating and maintenance (O&M) costs
- Estimate daily design flow and average flow based on median population
    - Estimate capital cost using a technology-specific WBS cost curve and design flow
    - Estimate O&M costs using a WBS cost curve and average flow
- Calculate annual total costs (annualized capital expenditures plus O&M costs)

[3] POU RO devices that are certified as meeting NSF/ANSI Standard 58 have demonstrated an ability to reduce perchlorate concentrations from 130 µg/L to 4 µg/L or less (http://www.nsf.org/consumer-resources/water-quality/water-filters-testing-treatment/water-treatment-system-certification-process). As of August 2018, there is no standard for POU anion exchange devices.

- Divide total annual costs by the median number of households served.

The WBS models generate capital costs based on equipment that can handle peak production levels or design flows. Annual costs are based on average daily flows. Exhibit 7 shows the design and average flow estimates for the median system in each system size category. It also shows the population served by the median system and the number of households served.

Exhibit 7. Design and Average Flow Estimates and Service Estimates for the 50th Percentile or Median System

System Size (Population Served)	System Population[1] (a)	System Households[2] (b) = a/2.65	Groundwater System Design Flow[3] (MGD)	Groundwater System Average Flow[3] (MGD)	Surface Water System Design Flow[3] (MGD)	Surface Water System Average Flow[3] (MGD)
25-500	110	42	0.049	0.012	0.050	0.015
501-3,300	1,143	431	0.46	0.15	0.46	0.16
3,301-10,000	5,422	2,046	2.0	0.77	2.0	0.74

Notes:
1. Median system populations are from SDWISFED, January 2004.
2. Median system household estimates equal median populations divided by 2.57 persons per household (based on the 2004 U.S. Census mean).
3. Flow estimates are based on regression equations that relate population and design or average flows.

EPA generated costs for each system size category for 38 treatment technology scenarios. There are 12 scenarios for anion exchange comprising all combinations of two source waters (ground and surface), two resin lives (250,000 and 170,000 bed volumes), and three cost levels (low, mid, and high). There are 18 scenarios for biological treatment that are combinations of two source waters, three reactor types (fixed bed pressure vessel, fixed bed gravity basin, and fluidized bed), and three cost levels. There are 6 scenarios for RO utilized as centralized treatment to account for two source waters, and three cost levels, and two design flow ranges. Finally, there are two scenarios for POU RO to account for two source waters. Costs for POU RO do not vary by cost level input (high, mid, low). USEPA (2018) contains the cost curve parameters for all of the treatment technology scenarios. There are separate parameter sets for capital costs and O&M costs and for small, medium, and large system sizes (corresponding to design flows ranges of < 1.0 MGD, ≥ 1.0 MGD to < 10 MGD, and ≥ 10 MGD).

For each scenario, EPA estimated capital and O&M costs for the three system size categories and then calculated total annual costs. For anion exchange, biological, and central RO treatment technologies, EPA annualized capital costs at 7 percent over the expected useful life of centralized treatment equipment and added the result to O&M costs. For POU RO devices, EPA annualized capital costs (i.e., for the devices and installation) over the estimated 10-year life of the POU device. Finally, EPA divided total annual costs by the number of households served to derive per-household incremental costs for perchlorate treatment. EPA assessed affordability by comparing these values with the expenditure margins.

6.2 Results

Exhibit 8 provides ranges of per-household costs for each technology and system size category. The ranges indicate minimum and maximum costs across the scenarios noted in the previous section. For each system size category, the per-household cost range for anion exchange is lower than the corresponding expenditure margin in Exhibit 6. POU RO devices meet the affordability criteria for the two smaller size categories. EPA's WBS model for POU treatment does not cover systems larger than 3,300 people (greater than 1 MGD design flow).

Exhibit 8. Expenditure Margins for SSCT Affordability Analysis

System Size (Population Served)	Ion Exchange	Biological Treatment	Reverse Osmosis	Point-of-Use Reverse Osmosis
25-500	$378 to $610	$2,146 to $3,709	$2,272 to $2,671	$265 to $271
501-3,300	$98 to $148	$324 to $566	$561 to $688	$250 to $251
3,301-10,000	$104 to $153	$211 to $315	$431 to $493	Not applicable[1]

Note:
1. EPA's WBS model for POU treatment does not cover systems larger than 3,300 people (greater than 1 MGD design flow), because implementing and maintaining a large-scale POU program is likely to be impractical.

The results are mixed for biological treatment and RO. For both technologies, the cost range exceeds the expenditure margin for the smallest system size category. The cost range falls below the expenditure margin for the two larger system size categories. Therefore, biological treatment and centralized RO meet the SSCT criteria for the two larger systems size categories, but not the smallest one. Exhibit 9 provides a summary of which technologies meet SSCT criteria for the three system size categories.

Exhibit 9. SSCT Affordability Analysis Results – Technologies that Meet Effectiveness and Affordability Criteria

System Size (Population Served)	Ion Exchange	Biological Treatment	Reverse Osmosis	Point-of-Use Reverse Osmosis
25-500	Yes	No	No	Yes
501-3,300	Yes	Yes	Yes	Yes
3,301-10,000	Yes	Yes	Yes	Not applicable[1]

Note:
1. EPA's WBS model for POU treatment does not cover systems larger than 3,300 people (greater than 1 MGD design flow), because implementing and maintaining a large-scale POU program is likely to be impractical.

7 References

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