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Agency

Technologies and Costs for Treating Perchlorate-Contaminated Waters

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List of Abbreviations and Symbols

ANSI	American National Standards Institute
BAT	best available technology
BPOU	Baldwin Park Operable Unit
BV	bed volumes
CDPH	California Department of Public Health[1]
ClO_4^-	perchlorate anion
DO	dissolved oxygen
EBCT	empty bed contact time
EPA	U.S. Environmental Protection Agency
GAC	granular activated carbon
gfd or gpd/ft^2	gallons per day per square foot
gfd/psi	gallons per day per square foot per pounds per square inch
gpm	gallons per minute
gpm/ft^2	gallons per minute per square foot
gpm/ft^3	gallons per minute per cubic foot
HRT	hydraulic residence time
LSI	Langelier saturation index
MCL	maximum contaminant level
µg/L	micrograms per liter
mg/L	milligrams per liter
MGD	million gallons per day
MWH	Montgomery Watson Harza
NDMA	N-nitrosodimethylamine
NF	nanofiltration
NSF	NSF International, The Public Health and Safety Company
O&M	operation and maintenance
ORNL	Oak Ridge National Laboratory
PNDM	Perchlorate and Nitrate Destruction Module
POTW	publicly-owned treatment works
POU	point-of-use
PRB	perchlorate-reducing bacteria
RO	reverse osmosis
SDI	silt density index
SSCT	small system compliance technology
T&C	technology and costs
TDP	Technology Design Panel
TOC	total organic carbon
UF	ultrafiltration
VOC	volatile organic compound
WBS	work breakdown structure

[1] Formerly, the California Department of Health Services

1 Introduction

1.1 Background

The perchlorate anion (ClO_4^-) is an inorganic ion that consists of a tetrahedral array of oxygen atoms around a central chlorine atom. Perchlorate is primarily an anthropogenic contaminant that generally occurs as a perchlorate salt. These salts are used in a wide range of applications, including pyrotechnics and fireworks, blasting agents, matches, lubricating oils, textile dye fixing, and so on. Common salts of perchlorate ion are ammonium, potassium, and sodium perchlorate. Ammonium perchlorate, used in rocket and missile propellant, accounts for approximately 90 percent of perchlorate salts production (Xu et al., 2003). These salts are highly soluble in water, and dissociate completely to their cations and anions (perchlorate).

Perchlorate can persist in the environment for many decades under typical groundwater and surface water conditions because of its resistance to reaction with other mutually occurring compounds or elements. The physiochemical properties of perchlorate limit its treatment alternatives. For example, conventional treatment (coagulation and filtration) does not remove perchlorate because it is a poor complexing anion and does not form any complexes easily with other chelating ligands or cations, making it harder to remove perchlorate by chemical precipitation or complexation process.

The U.S. Environmental Protection Agency (EPA) is proposing to regulate perchlorate in drinking water distributed by certain public water systems. In 2011, EPA determined that a national primary drinking water regulation for perchlorate would result in a meaningful opportunity to reduce health risks (USEPA, 2011). Based on the best available scientific information on the health effects of perchlorate, EPA is proposing a maximum contaminant level goal of 56 µg/L and an enforceable MCL of 56 µg/L. EPA is also requesting comment on 18 µg/L for the MCL.

To assist in this evaluating the national costs associated with removing perchlorate, this document describes treatment technologies that have the potential to remove or destroy perchlorate in drinking water. It also presents estimated costs associated with the installation and operation of these technologies. The technologies evaluated here can achieve very high perchlorate removal efficiencies (e.g., 95 percent or greater). Given the high efficiencies, EPA assumes systems will blend treated water and untreated water to meet the MCL. Accordingly, the costs presented here reflect systems designed and operated to take advantage of the technologies' high removal effectiveness and the cost curves should be applied to design and average flows adjusted for blending, as discussed in Chapter 7.

1.2 Organization and Overview

This report is organized as follows:

- Evaluation of technologies (or other options) for complying with potential perchlorate standards (Chapters 2 through 6)
- Costs for treatment technologies (Chapter 7).

The technology evaluations in Chapter 2 through 5 describe treatment technologies with the potential to remove or destroy perchlorate in drinking water. Specifically, they address treatment effectiveness for the following:

- ion exchange (Chapter 2)
- biological treatment (Chapter 3)
- membrane technologies (Chapter 4)
- point-of-use (POU) treatment (Chapter 5).

For each technology, the corresponding chapter provides an overview of how the technology operates and summarizes its effectiveness for removal or destruction of perchlorate. Each technology summary also incorporates available findings with respect to variability under different source water conditions. Information on process waste characterization and management is also provided. Each summary concludes with a compilation of the engineering design specifications available from the documents reviewed.

Chapter 6 discusses alternative, nontreatment options that might be used in lieu of treatment to comply with potential perchlorate standards. Chapter 7 (in combination with Appendices B and C) presents estimated costs for installing and operating each of the technologies or options discussed in Chapters 2 through 6. Appendix A presents available information on the potential treatment of residuals from perchlorate removal, a topic that is relevant to several of the technologies. Appendix B provides complete cost equations for the technologies and nontreatment options evaluation. Appendix C presents example cost model outputs for selected flow rates, allowing review of individual cost line items.

1.3 Information Sources

The information presented in this document is a summary of EPA’s literature search to evaluate the state of science with respect to treatment alternatives for perchlorate-contaminated drinking source water. The objectives of the literature review were to:

- identify what technologies are being studied and tested
- summarize the evidence regarding effectiveness
- characterize other factors relevant for drinking water treatment (e.g., pre- and post-treatment requirements and waste characterization and management options)
- identify key research gaps.

2 Ion Exchange

2.1 Operating Principle

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. Feed water passes through a bed of resin in a vessel or column. The operation typically continues until the resin does not have sufficient exchange sites available for perchlorate. At this point, the resin may be disposed and replaced or regenerated. Regeneration occurs when the exhausted resin is rinsed with a concentrated chloride solution. Because of the overwhelming concentration, the chloride in the regenerant replaces the adsorbed ions on the resin, returning the resin to its original state.

The fate of perchlorate treated through ion exchange depends on how the spent resin is managed. If the resin is disposed after exhaustion, the perchlorate remains bound to the spent resin. If the resin is regenerated, the perchlorate becomes concentrated in the spent regenerant solution. Perchlorate will be destroyed only if the spent regenerant is further treated (e.g., through physical, chemical, or biological reduction).

Because it is a large, poorly hydrated, hydrophobic anion (see, for example, Batista et al., 2003; Gu et al., 2001), perchlorate interacts readily with certain types of anion exchange resins, particularly those described as strong-base resins. Several types of resins have the potential to remove perchlorate effectively, at least initially. The key differences among the resins are in their long-term capacity, particularly in the presence of competing anions, and their ease of regeneration. These differences can be significant in terms of the type and quantity of waste generated from the treatment process.

The resin types studied for perchlorate removal include strong-base and weak-base anion resins with polystyrenic, polyacrylic, and polyvinylpyridine matrices, with the most extensive study of strong-base polystyrenic and polyacrylic resins (see, for example, Batista et al., 2000; Tripp et al., 2003). The category of strong-base polystyrenic resins includes those typically used for removal of nitrate (i.e., “nitrate-selective” resins). In addition, in the early 2000s, researchers at the Department of Energy’s Oak Ridge National Laboratory (ORNL) developed a specialized perchlorate-selective resin. Investigators describe this resin as “bifunctional,” because it contains two functional groups, one to enhance selectivity and the other to aid kinetics (Batista et al., 2003; Gu et al., 2002). More recently, a number of new, competing perchlorate-selective resins have become available. These include an updated version of the original bifunctional resin, along with other single functional group (often tributylamine) resin formulations (Blute et al., 2006; Russell et al., 2008; Wu and Blute, 2010).

There are significant differences among the strong-base polyacrylic, strong-base polystyrenic, nitrate-selective, and perchlorate-selective resins in terms of their relative affinity for perchlorate (Batista et al., 2003; Boodoo, 2003; Darracq et al., 2014; Tripp et al., 2003). **Exhibit 2-1** categorizes these resins in order of their perchlorate affinity. Although certain resin types have higher relative affinity than others, all of the types shown in **Exhibit 2-1**, along with weak-base resins, are able to remove perchlorate. The key differences among the resins are in their long-term capacity, particularly in the presence of competing anions, and their ease of regeneration.

Because of these differences, the recent literature indicates a trend toward the increased use of perchlorate-selective resins, which are generally disposed of, rather than regenerated. Section 2.2 discusses the removal rates achieved by different resin types in more detail. Section 2.3 discusses resin capacity in light of raw water quality and Section 2.5 covers regeneration needs.

Exhibit 2-1. Perchlorate Affinity by Resin Type

Perchlorate Affinity	Resin Type
Lowest affinity	Strong-base polyacrylic
Lower affinity	Strong-base polystyrenic
Higher affinity	Nitrate-selective
Highest affinity	Perchlorate-selective

Conventional ion exchange systems use a fixed resin bed where, after exhaustion of the resin, operators will take a vessel out of service temporarily to either remove and dispose of the spent resin or regenerate the resin.

Exhibit 2-2 provides a schematic drawing for a conventional ion exchange system with brine regeneration. With resin disposal, instead of regeneration, as is common for perchlorate-selective resin, the schematic layout becomes simpler. Designs with disposable resin do not require brine storage, eductors, or brine piping. As discussed in Section 2.5, another possible option (instead of disposal) for selective resins is to use a novel procedure involving a tetrachloroferrate solution for regeneration. **Exhibit 2-3** provides a schematic drawing for an ion exchange system using disposable resin (i.e., without regeneration).

Exhibit 2-2. Typical Schematic Layout for Perchlorate Removal by Ion Exchange with Brine Regeneration

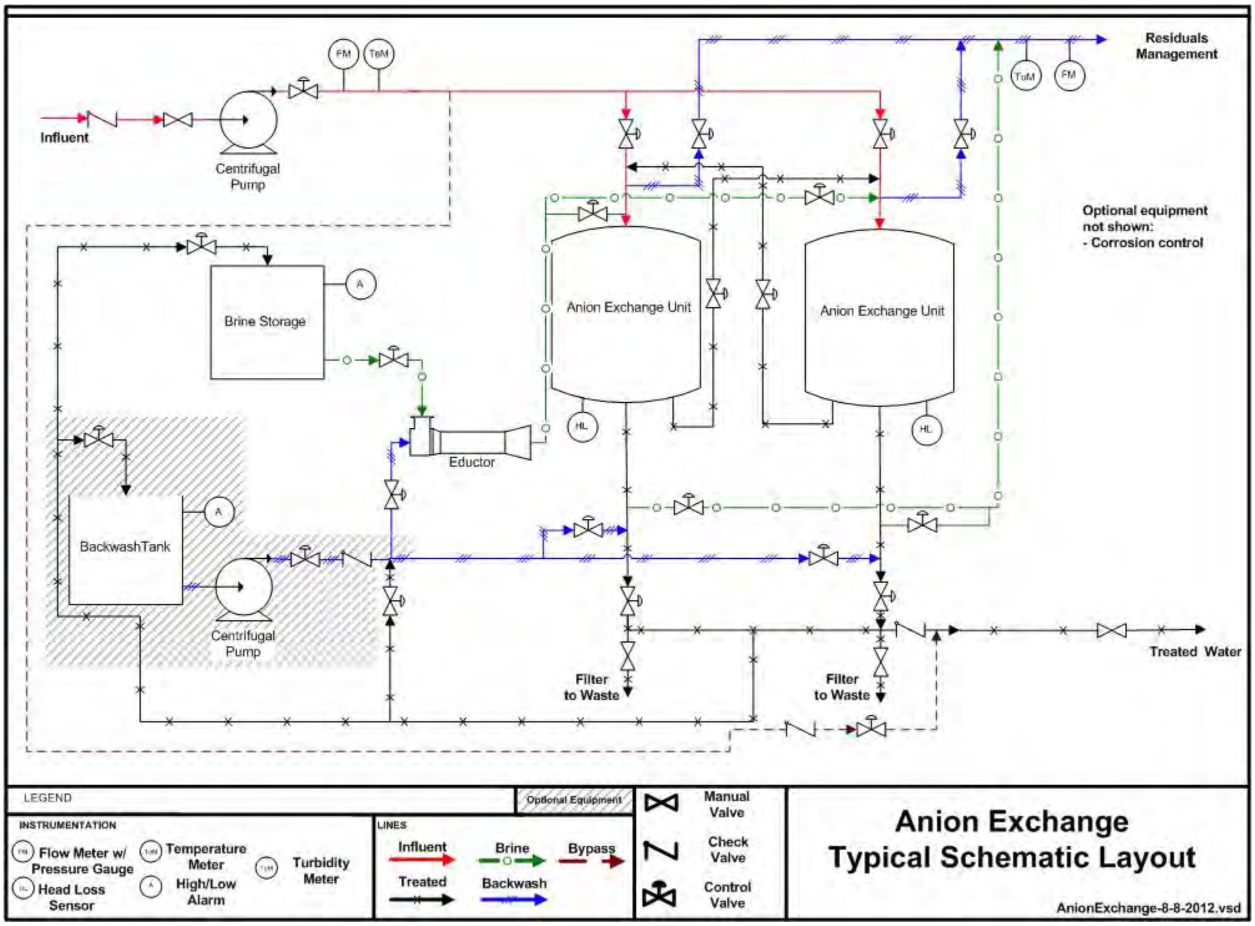
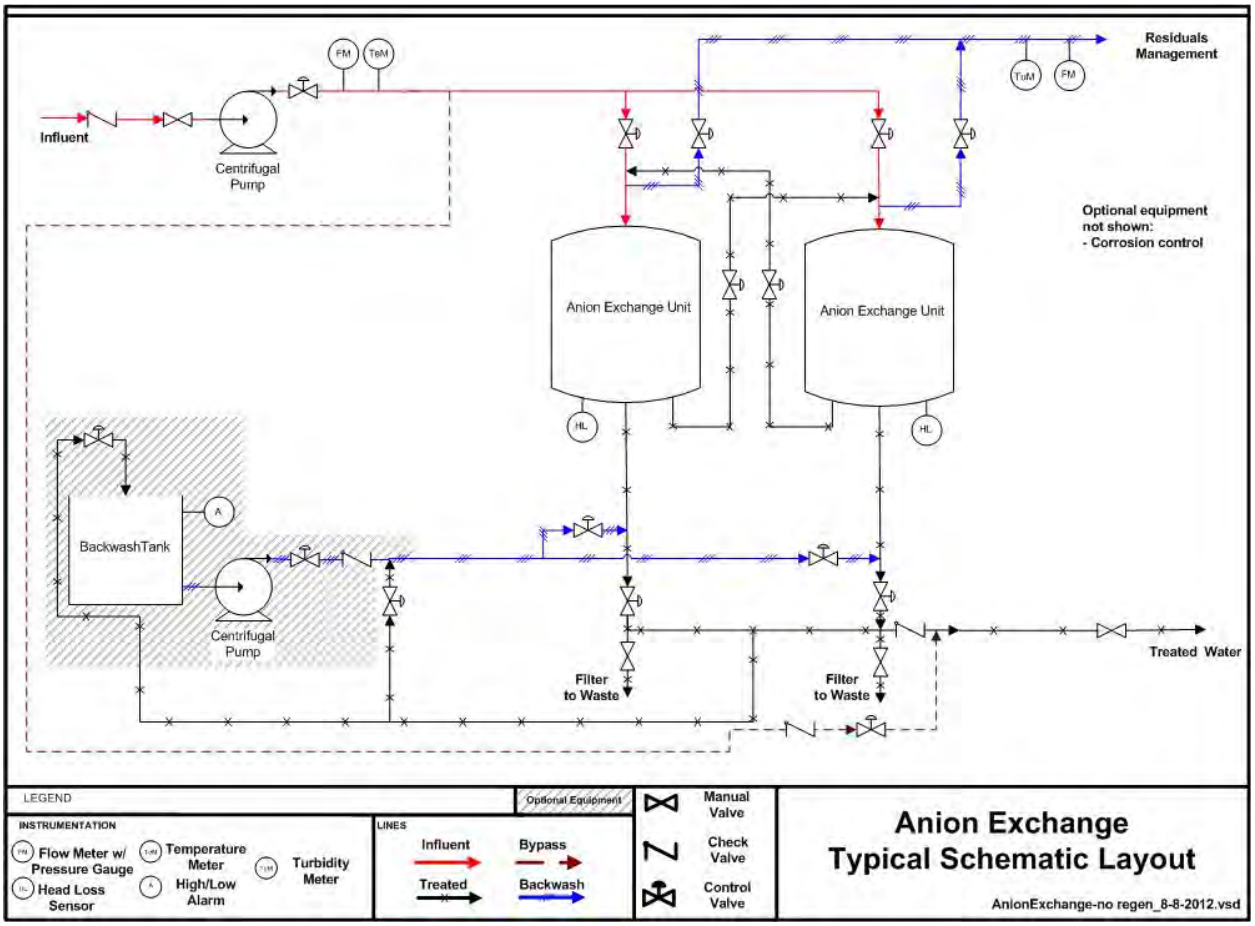


Exhibit 2-3. Typical Schematic Layout for Perchlorate Removal by Ion Exchange with Resin Disposal



2.2 Effectiveness for Perchlorate Removal

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 (California Code of Regulations, Title 22, Chapter 15, Section 64447.2). Researchers have demonstrated that ion exchange is capable of removing perchlorate to levels below 2 to 4 µg/L, even given very high influent perchlorate concentrations. This result corresponds, generally, to a removal efficiency in the 90 percent range, depending on the influent concentration. **Exhibit 2-4** summarizes the removal efficiencies reported in the literature. It includes results from studies conducted in the laboratory, in the field at pilot scale, and in full-scale application.

Exhibit 2-4. 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

Exhibit 2-4 also shows the variety of resin types that 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] All of these resin types can attain very high perchlorate removals, at least initially. While Batista et al. (2003; 2000) have suggested that weak-base resins may have certain advantages in terms of regenerant treatment (see Section 2.5.2 and Appendix A), tests of these resins have been limited, with only a few studies documented in the reviewed literature (Batista et al., 2003; 2000; Boodoo, 2006; U.S. DoD, 2007; 2008b). Furthermore, the use of weak-base resins could require pH adjustment.

Additional support for the effectiveness of ion exchange for perchlorate removal is evident from the number of full-scale facilities that are currently using the technology. As shown in **Exhibit 2-5**, the literature identifies 44 full-scale facilities applying ion exchange for perchlorate removal. **Exhibit 2-5** also demonstrates the increasing use of perchlorate-selective resins. These installations include both remediation sites and facilities producing drinking water.

Currently, the majority of the identified full-scale facilities (18 of 23 facilities where information on resin type is available) currently 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] While Tripp et al. (2003) also examined strong base polyvinylpyridine resins, comparable quantitative data on their removal efficiency are not available.

Exhibit 2-5. Full-scale Ion Exchange Installations for Perchlorate

Location	Flow rate (gallons per minute [gpm])	Resin Type[1]	Resin Fate[2]	Start Date
Kerr-McGee, Henderson, Nevada	300 to 600	--	D	November 1999 [3]
LaPuente Valley County Water District, California	2,500	PS [9]	D [9]	February 2000
Lawrence Livermore National Laboratory, Livermore, California	0.7 to 3.5	NS	R	November 2000
Kerr-McGee, Henderson, Nevada	200 to 560	--	R	March 2002 [4]
California Domestic Water Company, Whittier, California	5,000	PS [8]	D	July 2002
Gage 51-1, City of Riverside, California	2,000	SB-S	D	October 2002
Tippecanoe, City of Riverside, California	5,000	SB-S	D	December 2002
R&H System, La Verne, California	--	--	R	2003 or earlier
City of Pomona, California	10,000	NS [10]	R [10]	2003 or earlier
Baldwin Park, California	7,000 and 7,500	--	R	2003 or earlier
Edwards Air Force Base, Site 285, California	30	PS	R	2003
West San Bernadino Water District, Rialto, California	2,000	PS	D	May 2003
West Valley Water District, San Bernadino, California	2,000	--	D	June 2003
Aerospace Manufacturer, Maryland	20	--	D [7]	October 2003
Wells 15, 17, and 24, City of Colton, California	3,600	PS	D	August 2003
Airport Treatment Plant, City of Rialto, California	2,000	PS	D	August 2003
Delta Treatment Plant, City of Monterey Park, California	4,050	--	D	July 2003
Santa Clara Valley Water District	--	--	D	Prior to December 2003
Colony and County Wells, West San Martin Water Works, West San Martin, California	800	NS	D	2004 or earlier
Texas Street, City of Redlands, California	1,100	PS	D	2004
Fontana Union Water Co., Fontana, California	6,000	PS	D	January 2004
Castaic Lake Water Agency, Whittaker, California	300	PS [11]	D [11]	Prior to March 2004
City of Morgan Hill, California	400 to 1,000	--	D	Prior to March 2004 [5]
Big Dalton Well, San Gabriel Water Quality Association, Baldwin Park, California	3,000	--	--	Prior to March 2004
Camping World, San Martin County Water District, California	2,000	--	--	Prior to March 2004
Southern California Water Co., South San Gabriel, California	750	--	--	Prior to March 2004
Fontana (F17 site), San Gabriel Valley Water Company, El Monte, California	5,000	PS	D	Prior to March 2004
B6 Well Site, San Gabriel Valley Water Company, El Monte, California	7,800	-- [6]	R [6]	May 2004
Valley County Water District, Baldwin Park, California	7,800	-- [6]	R [6]	June 2004
Jet Propulsion Laboratory, Pasadena, California	1,400	--	D	July 2004

Location	Flow rate (gallons per minute [gpm])	Resin Type[1]	Resin Fate[2]	Start Date
Aerojet, Sacramento, California	400 to 2,000	PS	D [7]	August 2004
Lincoln Avenue Water Co., Altadena, California	2,000	PS	D [7]	August 2004
Frank Perkins Road Treatment System, Massachusetts Military Reservation, Cape Cod, Massachusetts	300	--	--	September 2004
B5 Well Site, San Gabriel Valley Water Company, El Monte, California	7,800	PS	D	December 2004
Phoenix Goodyear Airport North, City of Goodyear, Arizona	440	--	D	2005
Aquarion Water Co., Millbury, Massachusetts	1,500	PS	D [7]	June 2005
California Water Services Company, Porterville, California	--	--	D	April 2006
Camp Edwards portion of the Massachusetts Military Reservation, Cape Cod, Massachusetts	1,000	PS	D	2007
Naval Weapons Industrial Reserve Plant, McGregor, Texas	--	--	D	2008 or earlier [3]
Arrowhead Regional Medical Center, Colton, California	600	--	--	January 2010
Saugus Perchlorate Treatment Facility, Castaic Lake Water Agency, Santa Clarita, California	2,200	PS	D	May 2010
Richardson Treatment Plant, Loma Linda, California	1,200	--	--	October 2010
Monk Hill Water Treatment Plant, Pasadena Water and Power, Pasadena, California	7,000	PS	D	July 2011
Golden State Water Service	2,000	PS	D	2011 or earlier

Sources: Berlien, 2003; Blute, 2012; Blute et al., 2006; Bull et al., 2004; California Environmental Protection Agency (CalEPA), 2004; City of Redlands, California, 2004; Coppola, 2003; Croft, 2004; Drago and Leserman, 2011; Faccini et al., 2016; GWRTAC, 2001; Hayward and Gillen, 2005; Min et al., 2003; Lu, 2003; Membrane Technology, 2006; NASA, 2011; Pollack, 2004; Praskins, 2003; Purolite, 2011; Roefer, 2013; Russell et al., 2008; Santschi, 2010; Siemens Water Technologies, 2006; 2009a; 2009b; 2009c; 2009d; 2009d; ITRC Team, 2008; USEPA, 2005; Wagner and Drewry, 2000; Water & Wastes Digest, 2010; Xiong and Zhao, 2004

Notes:

-- = Not reported

1. SB-S = strong-base polystyrenic; SB-A = strong-base polyacrylic; NS = nitrate-selective strong-base polystyrenic; PS = perchlorate-selective
2. D = Disposed; R = Regenerated
3. No longer in operation (replaced with biological reactor).
4. Discontinued after 6 months due to operational issues.
5. Inactive as of March 2004.
6. Reportedly planning to switch to use of perchlorate-selective resin with disposal instead of regeneration (Wu and Blute, 2010).
7. Specifically, spent resin at this facility is incinerated.
8. Switched from strong-base polystyrenic resin to perchlorate-selective resin as of 2011 (Purolite, 2011; Wu and Blute, 2010).
9. Switched from strong-base polyacrylic resin to perchlorate-selective resin with disposal instead of regeneration in July 2010 (Blute, 2012).
10. Currently installing perchlorate-selective resin in addition for part of the treatment train (Blute, 2012).
11. Installed perchlorate-selective resin beginning in 2011 (Blute, 2012).

2.3 Raw Water Quality Considerations

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. Resin capacity (also termed resin life or run length) typically is measured by the number of bed volumes (BV) of water that can be treated before breakthrough of perchlorate. Competing anions take up available exchange sites, reducing perchlorate capacity. In addition, these anions may break through or peak[3] before perchlorate, affecting finished water quality and limiting the practical life of the resin more than perchlorate capacity alone. For example, Case et al. (2004) reported that a strong-base polyacrylic resin could treat 750 BV before perchlorate breakthrough. Nitrate peaking, however, would limit the use of the resin to 425 BV. In practice, however, systems can limit the impact of peaking by using multiple treatment trains in parallel. Also, the full-scale facility studied in Drago and Leserman (2011) eliminated chloride peaking by converting the resin from a chloride to a bicarbonate form prior to installation.

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. **Exhibit 2-6** shows quantitative data from the literature on BV to perchlorate breakthrough for different resin types in the presence of differing concentrations of the major competing anions. The data shown in **Exhibit 2-6** are for initial detection of perchlorate (at detection limits between 1 and 4 µg/L, depending on the specific study) using a single resin column. After perchlorate breakthrough, most resins still have the capacity to continue adsorbing perchlorate before the resin is completely saturated. In practice, using two columns in series (a "lead-lag" configuration) can capture this extra capacity (Boodoo, 2003). For example, Gu et al. (1999) found breakthrough in a lead column after 8,500 BV for a nitrate-selective resin and 40,000 BV for a perchlorate-selective resin. Using a second (lag or polishing) column increased the resins' capacities to approximately 22,000 BV and 104,000 BV, respectively.

Precise, quantitative comparisons of the data in **Exhibit 2-6** are difficult because of variations among studies (e.g., influent concentrations of perchlorate and other constituents, definition of breakthrough, and specific resin manufacturer). The data, however, when combined with general conclusions in the literature, do allow for some general observations about differences among resin types.

[3] Peaking occurs when competing anions adsorbed early in a resins life are displaced by perchlorate, resulting in an effluent concentration of the competing anions greater than the influent concentration. See Boodoo (2003) for an example of peaking behavior.

Exhibit 2-6. Perchlorate Capacity by Resin Type and Competing Anions

Resin Type[1]	Data Source(s)	Perchlorate Capacity (BV to breakthrough)	Competing Anions (mg/L)			
			Sulfate	Nitrate[2]	Bicarbonate	Chloride
SB-A	Batista et al., 2003; 2000	1,800 to 2,100	None	None	None	None
SB-A	Case et al., 2004	750	Present	Present	Present	No data
SB-A	Tripp et al., 2003	700	50	6	122	30
SB-A	Min et al., 2003	700	55	27	155	15
SB-A	Boodoo, 2003	500	44	40	170	13
SB-A	Lehman et al., 2008	650	56	63	300	25
SB-A	Batista et al., 2003; 2000	0[3]	>2,000	>40	No data	No data
SB-S	Batista et al., 2003; 2000	3,750	None	None	None	None
SB-S	Tripp et al., 2003	6,000	50	6	122	30
SB-S	Boodoo, 2003	5,000	44	40	170	13
SB-S	Batista et al., 2003; 2000	600[3]	>2,000	>40	No data	No data
NS	Batista et al., 2000	1,300	None	None	None	None
NS	Gu et al., 2002	14,000	173	3.2	226	356
NS	Tripp et al., 2003	25,000[4]	50	6	122	30
NS	Gu et al., 1999	8,500	14.9	61.2	No data	7.0
PS-Old	Gu et al., 2002	40,000	173	3.2	226	356
PS-Old	Tripp et al., 2003	35,000[3]	50	6	122	30
PS-Old	Min et al., 2003	20,700	266	14	229	40
PS-Old	Gu et al., 1999	40,000	14.9	61.2	No data	7.0
PS-Old	Gu et al., 2007	37,000	16	10	No data	10
PS-Old	Lutes et al., 2010	97,000	14.8	32.8	192	10.7
PS-Old	Blute et al., 2006	~75,000	46.4	1.6	No data	No data
PS-New	Blute et al., 2006	~160,000	46.4	1.6	No data	No data
PS-New	Russell et al., 2008	~130,000 to 170,000	37	25	No data	23
PS-New	Russell et al., 2008	~125,000 to 140,000	44	33	No data	27
PS-New	Russell et al., 2008	~105,000 to 130,000	53	61	No data	47
PS-New	Wu and Blute, 2010	~130,000	45	33	No data	No data
PS-New	Drago and Leserman, 2011	~30,000 to 60,000	130 to 220	18	No data	17 to 29
WB-S	Batista et al., 2000	500	None	None	None	None
WB-S	U.S. DoD, 2007	3,000 to 4,000	3	4	No data	4
WB-S	U.S. DoD, 2008b	9,700	14	31	150	11
WB-S	Boodoo, 2006	15,000	No data	No data	No data	No data
WB-A	Batista et al., 2003; 2000	2,700 to 2,800	None	None	None	None
WB-A	Batista et al., 2003; 2000	800 to 1,000	100	100	None	100

Notes:

1. SB-S = strong-base polystyrenic; SB-A = strong-base polyacrylic; WB-S = weak-base polystyrenic; WB-A = weak-base polyacrylic; WB = weak-base (type not specified); NS = nitrate-selective strong-base polystyrenic; PS-Old = original perchlorate-selective resin developed by ORNL; PS-New = more recently developed perchlorate-selective resins.
2. as NO3.
3. The presence of humic substances caused reduced resin capacity.
4. Column fouling (due to experimental design) may have caused reduced resin capacity.

2.3.1 Strong-base Polyacrylic Resins

The order of affinity of strong-base polyacrylic resins is as follows (Boodoo, 2003; Gu et al., 2001):

sulfate > perchlorate > nitrate > chloride > bicarbonate

Accordingly, Tripp et al. (2003) and Boodoo (2003) conclude that the capacity of strong-base polyacrylic resins is most significantly affected by sulfate concentration. Using computer modeling, Tripp et al. (2003) predicted an 88 percent decrease in strong-base polyacrylic capacity as influent sulfate increased from 1 to 250 milligrams per liter (mg/L). The decrease in capacity was rapid as sulfate increased (see Tripp et al., 2003, Figure 4.61). The cross-study data in **Exhibit 2-6** are consistent with this prediction. For this resin type, Batista et al. (2003; 2000) found a perchlorate capacity of 1,800 to 2,100 BV for a laboratory solution with no sulfate. In comparison, sulfate concentrations in the range of 40 to 60 mg/L reduced capacity to 500 to 700 BV in other studies (Boodoo, 2003; Case et al., 2004; Min et al., 2003; Lehman et al., 2008; Tripp et al., 2003). Batista et al. (2003; 2000) found that very high sulfate concentrations (greater than 2,000 mg/L) prevented a polyacrylic resin from removing any perchlorate (i.e., a capacity of 0 BV), although the investigators suggest fouling of the resin as a contributing factor to the decreased capacity.

Tripp et al. (2003) predicted that strong-base polyacrylic resins are not as sensitive to increasing nitrate concentrations (see Tripp et al., 2003, Figure 4.62). Capacity decreased linearly by 36 percent as influent nitrate increased from 0.1 to 20 mg/L as N (Tripp et al., 2003). Again, the cross-study data support this conclusion, finding similar capacities (500 to 700 BV) for nitrate concentrations from 6 to 63 mg/L as NO_3 (Boodoo, 2003; Case et al., 2004; Min et al., 2003; Lehman et al., 2008; Tripp et al., 2003).

2.3.2 Strong-base Polystyrenic Resins

The order of affinity of strong-base polystyrenic resins is as follows (Boodoo, 2003; Gu et al., 2001):

perchlorate > sulfate > nitrate > chloride > bicarbonate

Therefore, the capacity of strong-base polystyrenic resins should be affected by sulfate concentration, but to a lesser degree than that of polyacrylic resins. Using computer modeling, Tripp et al. (2003) predicted a 94 percent decrease in strong-base polystyrenic capacity as influent sulfate increased from 1 to 250 mg/L. The decrease in capacity, however, was not as rapid as for the polyacrylic resin. Interpolation of Figure 4.61 in Tripp et al. (2003) shows a capacity decrease of approximately 60 percent for the polystyrenic resin at 50 mg/L sulfate, compared to a decrease of nearly 80 percent for the polyacrylic resin. Similarly, the cross-study data in **Exhibit 2-6** show a relatively high perchlorate capacity (5,000 to 6,000 BV) for strong-base polystyrenic resins at moderate sulfate concentrations (40 to 50 mg/L) (Boodoo, 2003; Tripp et al., 2003).

Tripp et al. (2003) predicted that strong-base polystyrenic resins, like polyacrylic resins, are not as sensitive to increasing nitrate concentrations (see Tripp et al., 2003, Figure 4.62). Capacity decreased linearly by 26 percent as influent nitrate increased from 0.1 to 20 mg/L (Tripp et al., 2003). The cross-study data are consistent with this observation, finding similar capacities (5,000 to 6,000 BV) for nitrate concentrations from 6 to 40 mg/L (Boodoo, 2003; Tripp et al., 2003).

2.3.3 Nitrate-Selective Resins

The order of affinity of nitrate-selective resins is as follows (Boodoo, 2003; Burge and Halden, 1999):

perchlorate > nitrate > sulfate > chloride > bicarbonate

Accordingly, computer modeling performed by Tripp et al. (2003) found these resins affected by both sulfate and nitrate, with the greater effect caused by nitrate. Nitrate-selective capacity for perchlorate decreased by 76 percent as nitrate increased from 0.1 to 20 mg/L, compared to 64 percent for a sulfate increase from 1 to 250 mg/L (Tripp et al., 2003). The cross-study data in **Exhibit 2-6** appear consistent, if one ignores an anomalous data point from Batista et al. (2000). Capacities shown are 25,000 BV for moderate sulfate and moderate nitrate (Tripp et al., 2003), 14,000 BV for high sulfate and low nitrate (Gu et al., 2002), and 8,500 BV for low sulfate and high nitrate (Gu et al., 1999)

2.3.4 Perchlorate-Selective Resins

As discussed in Section 2.1, researchers at ORNL developed the first perchlorate-selective resin in the early 2000s. This original, bifunctional resin was known as “BiQuat” and licensed to Purolite for sale under the name Purolite A530E (Boodoo, 2003). More recently, a number of new, competing perchlorate-selective resins have become commercially available. These include (Blute et al., 2006; Darracq et al., 2014; Drago and Leserman, 2011; Russell et al., 2008; U.S. Filter, 2004; Wu and Blute, 2010):

- Purolite A532E (an updated version of the old A530E resin)
- Purolite MCG-P2
- Resin Tech SIR-110-HP
- Rohm & Haas PWA2
- Dow PSR2
- Calgon CalRes 2109.

The order of affinity of the original perchlorate-selective resin was the same as that for nitrate-selective resins (i.e., perchlorate > nitrate > sulfate > chloride), but the perchlorate affinity relative to nitrate affinity was nearly an order of magnitude greater (Boodoo, 2003). Boodoo (2003) suggested that this original resin would be negatively affected by high nitrate concentrations. The cross-study data in **Exhibit 2-6**, however, suggest that the resin was not, in fact, very sensitive to competing anions. Capacity remained high (20,700 to 97,000 BV) for a wide range of nitrate and sulfate concentrations (1.6 to 61.2 mg/L and 14.8 to 266 mg/L, respectively) (Blute et al., 2006; Gu et al., 1999; 2007; 2002; Min et al., 2003; Lutes et al., 2010; Tripp et al., 2003).

For the more recently developed perchlorate-selective resins, the data in **Exhibit 2-6** generally show significantly greater perchlorate capacity than the original resin. In the presence of moderate levels of both sulfate and nitrate, the new resins showed capacities of approximately 105,000 to 170,000 BV (Blute et al., 2006; Russell et al., 2008; Wu and Blute, 2010). Even at higher sulfate levels, at least one of the new resins showed equal or greater capacity than the older resin (Drago and Leserman, 2011). The differences in capacity among the individual new resins appear to be less significant than the difference between the new resins as a group and the old resin. In the studies shown in **Exhibit 2-6** (Blute et al., 2006; Drago and Leserman, 2011; Russell et al., 2008; Wu and Blute, 2010), different resins performed better depending on variations in specific competing anions and other site-specific conditions (i.e., none of the new resins was consistently superior to the others in all of the studies).

2.3.5 Weak-base Resins

As shown in **Exhibit 2-6**, researchers have conducted only limited study on the effect of competing anions on the perchlorate capacity of weak-base resins. Sulfate and nitrate reduce the capacity of weak-base polyacrylic resins when they are present at relatively high levels (100 mg/L each) (Batista et al., 2003; 2000). Data are not available, however, on the effect of more moderate levels of competing anions. Batista el al. (2000) reported that weak-base polystyrenic resins have a relatively low capacity (500 BV) even absent competing anions. Pilot tests at Redstone Arsenal in Alabama used a weak-base polystyrenic resin produced by Purolite. This resin achieved 15,000 BV (Boodoo, 2006), 3,000 to 4,000 BV (U.S. DoD, 2007), or 9,700 BV (U.S. DoD, 2008b) capacity, depending on the test conditions. U.S. DoD (2008b) suggested that competing ions such as nitrate would reduce the capacity of this resin, but data are not available on the magnitude of such competitive effects.

2.3.6 Raw Water Quality Considerations other than Sulfate and Nitrate Competition

Although most investigators identify bicarbonate and chloride as other major competing anions, the affinity of ion exchange 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. Similarly, U.S. DoD (2002) indicates that raw water pH can strongly influence treatment effectiveness, but no quantitative data are available.

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. Accumulation of these contaminants in high concentrations on the resin or in regenerant solution may affect disposal (see Section 2.5), limiting the practical life of a resin. For example, Tripp et al. (2003) suggests that a perchlorate-selective resin would require regeneration every 10,000 BV 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). In some cases, however, incineration facilities have facility-specific restrictions on uranium concentrations that are more stringent that the regulatory thresholds for radioactive waste.

2.4 Pre- and Post-Treatment Needs

Suspended solids and organic substances in source water can cause clogging or fouling of ion exchange resins (Batista et al., 2003; Gu et al., 2002; U.S. DoD, 2002). For example, Batista et al. (2003) found that high concentrations of humic substances (as measured by total organic carbon [TOC]) caused fouling of both strong-base polyacrylic and polystyrenic resins, interfering with perchlorate removal. In spite of earlier conclusions that the perchlorate-selective bifunctional resin would require no pre-treatment (Gu et al., 1999; Oak Ridge National Laboratory, 2002), in pilot testing of the resin, Gu et al. (2002) found that precipitation and/or deposition of iron oxyhydroxides and microbial biomass caused significant clogging and fouling of the resin columns. The addition of a fine in-line filter resolved the problem. Similarly, the full-scale system studied in Drago and Leserman (2011) included pre-treatment bag filters and sulfuric acid addition to minimize scaling. Therefore, the presence of suspended solids and organic matter may require the use of filtration and/or chemical addition as pretreatment. Although the literature reviewed for this report does not identify the specific conditions under which filtration is needed (e.g., concentration of total suspended solids), these conditions are expected to be similar to those documented in application of ion exchange treatment for other contaminants. For perchlorate-selective resins, pre-filtration (bag or cartridge filters) may be required regardless of water quality because the long run lengths (see Section 2.3.4) can result in greater solids accumulation.

Batista et al. (2000) indicates that weak-base resins require carbonation to treat perchlorate. Carbonation can be accomplished by adding carbon dioxide or bicarbonate (generated by feeding sodium bicarbonate through a strong-acid cationic resin) to the feed. Thus, carbonation may constitute a pre-treatment step required for the use of weak-base resins. More information is required on the need for and practicality of this step to evaluate the use of weak-base resins. The weak-base resin piloted in Alabama requires pH reduction with carbon dioxide or acid as a pre-treatment step, carbon dioxide removal as a post-treatment step, and pH adjustment, if needed, as a post-treatment step (Boodoo, 2006; U.S. DoD, 2007; 2008b). An operational pH between 3 and 5, with a target of 4, is required for this resin to operate effectively (U.S. DoD, 2007; 2008b).

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. For applications of weak-base resins where pre-treatment pH adjustment would be required, increasing the pH after treatment would also be necessary for corrosion control.

Tripp et al. (2003) and Min et al. (2003) indicate that N-nitrosodimethylamine (NDMA) may form within certain polystyrenic resins and leach into the treated water. Recent studies of perchlorate-selective resins (Blute et al., 2006; Drago and Leserman, 2011; Russell et al., 2008; Wu and Blute, 2010) have shown leaching of various nitrosamines at first flush or soon after startup, with levels that decline to below detection over time (four hours to one week, depending on the specific resin and nitrosamine). Thus, nitrosamine leaching appears to occur periodically and temporarily (e.g., after installation of new resin). Issues with nitrosamine leaching might be avoided if resins are sufficiently flushed prior to use. For example, the full-scale system studied in Drago and Leserman (2011) minimized nitrosamine leaching with changes to the manufacturer's pre-delivery rinsing and preparation procedures. For one resin, however, Wu and Blute (2010) suggest that rinsing longer than manufacturer recommendations may be required to eliminate leaching concerns. Blute et al. (2006) also hypothesize that nitrosamines could be eliminated by downstream processes such as ultraviolet light treatment, if present.

2.5 Waste Generation and Residuals Management Needs

After a resin reaches its perchlorate capacity (see Section 2.3), the operator must either dispose and replace the resin or regenerate the resin using a chemical solution to remove the adsorbed anions. The former option, commonly termed "throwaway" operation, generates solid waste in the form of spent resin loaded with perchlorate and other anions. The latter option generates a liquid waste in the form of spent regenerant with concentrated perchlorate and other anions. Both options can also generate liquid waste in the form of spent wash water when initial flushing is required upon installation of new resin (e.g., to prevent nitrosamine leaching, see Section 2.4). As shown in **Exhibit 2-5**, almost 79 percent (30 of 38) of full-scale facilities for which waste management data are available dispose of spent resin. 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).

2.5.1 Disposal

In systems using resin disposal without regeneration, calculation of the quantity of solid waste generated would be straightforward, based on the quantity of resin used and the life of the resin. Spent resin characteristics depend on resin type, influent water quality, and the life of the resin. As discussed in Section 2.3, studies of metals build-up in perchlorate-selective resins have found that these resins are not likely to meet regulatory definitions of hazardous waste (Blute et al., 2006; Russell et al., 2008; Wu and Blute, 2010). Because of the shorter life of conventional resins, metals accumulation in these resins likely would be even lower and, thus, the same result should hold true. A typical destination for non-hazardous spent resin would be disposal in an off-site landfill. Based on the data in **Exhibit 2-5**, however, at least four of the full-scale facilities appear to be sending their spent resin to incineration facilities.

2.5.2 Regeneration

In systems using regeneration, the characteristics and quantity of spent regenerant depend on the type of regenerant solution used. The type of regenerant solution selected depends, in turn, on the type of resin used. In addition, the quantity of spent regenerant can be reduced if the regenerant is treated and reused. Appendix A discusses regenerant treatment.

In conventional ion exchange processes using strong-base resins (i.e., for removal of arsenic), operators regenerate spent resin using a brine solution of concentrated sodium chloride or potassium chloride. For resins loaded with perchlorate, however, regeneration with brine is more difficult because of the high relative affinity of most resins for perchlorate. In general, the higher the perchlorate affinity of a resin (see **Exhibit 2-1**), the more difficult it is to regenerate using conventional brine solutions. For example, Tripp et al. (2003) found that regeneration required a significantly greater quantity of brine solution for strong-base polystyrenic resins than for strong-base polyacrylic resins. Similarly, Batista et al. (2000) were able to successfully regenerate a perchlorate-loaded strong-base polyacrylic resin with 12 percent sodium chloride, removing 96 percent of the loaded perchlorate. In comparison, they found regeneration of a nitrate-selective resin using the same solution very ineffective, removing only 17.3 percent of the loaded perchlorate. Investigators, therefore, suggest that highly perchlorate-selective resins cannot be regenerated at all using conventional regenerant solutions (Batista et al., 2000; Boodoo, 2003; Darracq et al., 2014; Gu et al., 2001; 2002).

Regeneration of Non-selective Strong-Base Resins

It appears that, while regeneration of non-selective resins using brine solutions is feasible, large quantities of spent regenerant may result. Although polyacrylic resins regenerate easily, they have relatively short run lengths (see Section 2.3) and, therefore, more frequent regeneration. On the other hand, while polystyrenic resins have longer run lengths, they require more regenerant. Based on computer modeling, Tripp et al. (2003) conclude that the polyacrylic resins are more efficient in terms of quantity of spent regenerant as a percentage of water treated. In practice, regeneration may be accomplished using partial exhaustion-partial regeneration. In this scenario, operators regenerate the resin well before perchlorate breakthrough (e.g., at the point of sulfate or nitrate breakthrough) and regenerate using smaller quantities of brine than would be required for complete perchlorate removal. This practice allows operation for a number of cycles until perchlorate builds up on the resin and complete regeneration is required, and may result in lower overall generation of spent regenerant.

Tripp et al. (2003) suggest partial exhaustion-partial regeneration operation for pilot testing of non-selective resins. Results of tests of this approach reported by Case et al. (2004) suggest that partial exhaustion-partial regeneration is effective, at least for the strong-base polyacrylic resin, with no change in performance for over 20 cycles.

Based on the designs reported in Montgomery Watson Harza (MWH) and University of Houston (2003) and Case et al. (2004), spent regenerant generation in the pilot tests would be 1.5 to 1.6 percent of treated water (6.4 BV of regenerant/400 to 425 BV of treated water) for the polyacrylic resin and 1.4 percent of treated water (9 BV of regenerant/625 BV of treated water) for the polystyrenic resin. Data on spent regenerant generation are not available for the full-scale operations using conventional treatment configurations, although Betts (1998) reports that conventional processes (for contaminants other than perchlorate) typically generate 2 to 5 percent brine waste.

One option for increasing the efficiency of regenerating strong-base polystyrenic resins may be heating the regenerant brine. Based on laboratory experiments, Tripp et al. (2003) found that perchlorate affinity decreases with increasing temperature for these resins. Based on these results and computer modeling, they concluded that heating the brine to 40 degrees centigrade would make the polystyrenic resins equivalent to the polyacrylic resins in terms of quantity of spent regenerant as a percentage of water treated. Heating to 60 degrees centigrade would make the polystyrenic resins more efficient than the polyacrylic resins.

Spent brine generated from the regeneration of perchlorate-loaded resins contains high concentrations of perchlorate. Spent brine might be expected to contain 1.5 to 3.0 mg/L of perchlorate (Case et al., 2004). The high perchlorate concentrations may mean that the waste must be treated prior to disposal. Regenerant treatment can have an additional advantage in that it may allow for reuse of the regenerant multiple times, reducing the quantity of waste generated. Appendix A discusses regenerant treatment in more detail.

Spent brine also contains high levels of the competing anions present in the influent water (nitrate, sulfate, and bicarbonate) (Batista et al., 2003; Berlien, 2003; Montgomery Watson Harza and University of Houston, 2003). The presence of bicarbonate, in particular, can have practical implications for waste management. A full-scale system in LaPuente, California, experienced scaling problems in the waste line due to elevated levels of carbonates and bicarbonates. The operator began adding hydrochloric acid to the line to lower pH from approximately 8.5 to approximately 7 and remedy the problem (Berlien, 2003). Case et al. (2004) also reported that regular maintenance to prevent the build-up of scale was needed in pilot tests.

Regeneration of Selective Resins[4]

Selective resins are difficult to regenerate and are generally disposed of, rather than regenerated. As discussed above and shown in **Exhibit 2-5**, the majority of the full-scale ion exchange systems, including all but one of those using perchlorate-selective resin, operate on a throwaway basis. Because of the difficulty regenerating selective resins using conventional brine solutions, researchers at ORNL have developed a regeneration process for these resins. The process uses tetrachloroferrate anions ($FeCl_4^-$), formed in a ferric chloride solution in the presence of an excess amount of hydrochloric acid or chloride. Because it also has a strong relative affinity, the tetrachloroferrate anion readily displaces perchlorate from the resin. The tetrachloroferrate anion, however, also decomposes rapidly as the chloride concentration in solution decreases, converting to positively charged iron species. The positively charged iron species desorb from the resin by charge repulsion, leaving the resin in its original state with chloride as the counter anion. After tetrachloroferrate regeneration, the resin must be rinsed with dilute hydrochloride acid to wash sorbed ferric ions and excess regenerant off the bed (Gu et al., 2001; 2002). This rinse is necessary to ensure complete removal of the ferric ions to prevent precipitation of iron oxyhydroxides that may clog the bed when the resin is reused for treatment after regeneration (Gu et al., 2001).

Gu et al. (2001; 2002) conducted laboratory-scale and small-scale field pilot tests of this regeneration technology for two types of resin: a commercial nitrate-selective resin and the perchlorate-selective bifunctional resin. They found that nearly complete regeneration could be achieved with as little as two BV of regenerant solution (Gu et al., 2002). They also found no significant deterioration in resin performance after repeated loading and regeneration cycles (Gu et al., 2001). On the basis that the perchlorate-selective bifunctional resin could treat 40,000 BV before breakthrough, they calculated spent regenerant generation at less than 0.005 percent of water treated (Gu et al., 2002). For the nitrate-selective resin, the comparable generation rate would be 0.014 percent (based on the 14,000 BV to breakthrough they reported for this resin). Note that these generation rates do not include the dilute acid rinse required following

[4] Note that, because it is an emerging technology with as yet limited full-scale application, the novel tetrachloroferrate regeneration approach discussed in this section is not among the scenarios modeled for cost estimating purposes in Chapter 7.

regeneration, which the investigators report requires 20 to 30 BV of less than 0.01 percent hydrochloric acid (Gu et al., 2001; 2002).

Like conventional brine solutions, spent tetrachloroferrate regenerant is expected to contain high concentrations of perchlorate. Gu et al. (2002) found that perchlorate concentration peaked at 6,000 mg/L in the regenerant from the nitrate-selective resin and 60,000 mg/L in the regenerant from the perchlorate-selective bifunctional resin. As for conventional brine solutions, these high concentrations indicate that treatment of the spent regenerant may be required before disposal or reuse. Batista et al. (2003) expect that the spent tetrachloroferrate regenerant would also contain other competing anions, low pH, and high concentrations of iron in the form of Fe^{+3}, which could have implications for treatment. Appendix A discusses regenerant treatment. Gu et al. (2002) did not detect perchlorate in the dilute hydrochloric acid rinse solution. They suggest that this solution could be neutralized with dilute sodium hydroxide and readily mixed with the treated water or discharged to a publicly owned treatment works.

The ORNL researchers have examined this novel regeneration technology in small-scale field pilot tests (Gu et al., 2002; 2005). Full-scale application reportedly began at Edwards Air Force Base in January 2003 (U.S. DoD, 2002), but no data are available on results at this installation. More recently, Lutes et al. (2010) reported on a field demonstration of the tetrachloroferrate regeneration approach using full-scale vessel. This study not only involved a larger scale application than the previous work by Gu et al. (2002; 2005), but also slightly different parameters (e.g., more bed volumes of tetrachloroferrate, fewer bed volumes of dilute acid).

More recently, laboratory studies have examined the use of biological treatment to remove perchlorate from exhausted ion exchange resins. Although these studies suggest that bioregeneration has the potential to be effective for selective resins, the research has not yet progressed beyond batch experiments (Faccini et al., 2016; Sharbat and Batista, 2013).

Regeneration of Weak-base Resins

Batista et al. (2003; 2000) state that the primary advantage of weak-base resins is that they can potentially be regenerated using caustic solutions (sodium hydroxide or ammonium hydroxide), instead of conventional brine solutions. They suggest that this is an advantage because such solutions may be more amenable to biological treatment. In laboratory tests, they demonstrated that, while a caustic solution was ineffective in regenerating a weak-base polystyrenic resin, weak-base polyacrylic resins could be regenerated easily using 1 percent sodium hydroxide, removing more than 76.5 percent of loaded perchlorate (Batista et al., 2000). Although Batista et al. (2003) suggest that caustic solutions used for regenerating weak-base resins would have high pH (greater than 11) and high ammonium concentration (if ammonium hydroxide is used), they have not published further data on the quantity or characteristics of these spent regenerant solutions.

Boodoo (2006) indicates that the weak-base resin piloted in Alabama could be regenerated using a caustic solution, followed by neutralization/protonation of the resin bed with an acid solution. The quantity of spent caustic solution was estimated to be less than 0.004 percent of water treated. Later tests showed that the weak-base resins were effectively regenerated using volumes of regenerant equal to less than 0.03 percent to less than 0.05 percent of water treated (U.S. DoD, 2007; 2008b).

2.6 Critical Design Parameters

Critical design parameters that are specific to ion exchange systems removing perchlorate are:

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

Exhibit 2-7 shows values for these parameters used in pilot- and full-scale systems removing perchlorate. Design data are available in the literature for only a few of the many full-scale conventional ion exchange applications. Therefore, much of the data presented in **Exhibit 2-7** are from pilot-scale tests or are for proposed scale-up units.[5]

The paragraphs below discuss each of the parameters listed **Exhibit 2-7** in more detail. Values for other ion exchange design parameters (e.g., resin density, resin expansion during backwash, resin loss during backwash and regeneration), while not specifically addressed in the literature reviewed here, are well documented for ion exchange treatment in general. EPA has no reason to expect a significant difference in these parameters for ion exchange systems treating perchlorate. This section provides a general discussion of the design parameters and the range of values reported in the literature for these parameters. Chapter 7 identifies the specific values for each parameter used in EPA's cost estimates.

[5] The data shown are for conventional (rather than ISEP) treatment configurations only. Because of its proprietary nature, available design data for ISEP are limited. Furthermore, facilities developed since 2004 are not using ISEP for perchlorate removal. Finally, data for ISEP systems would not be applicable in models that simulate conventional ion exchange configurations.

Exhibit 2-7. Critical Design Parameters for Ion Exchange Systems

Ion Exchange Critical Design Parameter	Value from the References
Resin Type	See text.
Vessels Configuration	Lead-lag configuration in all full-scale applications for which data are available (Drago and Leserman, 2011; Fontana Water Company, 2010; Lu, 2003; Siemens Water Technologies, 2009a; 2009b; 2009d). Lead-lag configuration in pilot tests and field demonstrations (Boodoo, 2006; Lehman et al., 2008; ITRC Team, 2008; U.S. DoD, 2007; 2008b). Gu et al. (1999) recommend lead-lag configuration in proposed scale-up unit. Tripp et al. (2003) assume parallel operation in model plant designs for cost estimation, but recommend lead-lag design for nitrate-selective or perchlorate-selective resins.
Empty Bed Contact Time	Conventional Resins: 6 minutes per vessel in full-scale application at the City of Riverside (Lu, 2003). 2.5 to 4.2 minutes per vessel in model plant designs used for cost estimation (Tripp et al., 2003). 1.5 minutes per column in field pilot tests (Lehman et al., 2008; Montgomery Watson Harza and University of Houston, 2003). 4 to 6 minutes per column in laboratory column tests (Batista et al., 2000). Nitrate-selective and Perchlorate-selective Resins: One resin manufacturer recommends 1.5 minutes per vessel for nitrate-selective resin in full-scale applications (Boodoo, F. Personal communication. March 2, 2006). 1 minute per column in small-scale field pilot tests of perchlorate-selective resins (Gu et al., 2002). 45 seconds per vessel in proposed scale-up unit for perchlorate-selective resins (Gu et al., 1999). 1.5 minutes per column in pilot tests of perchlorate-selective resins (Blute et al., 2006; Russell et al., 2008; Wu and Blute, 2010).
Resin bed life	Dependent on resin type and competing anion concentrations. See text.
Surface loading rate	Conventional Resins: Maximum 9 to 15 gpm per square foot (gpm/ft^2) in model plant designs used for cost estimation (Tripp et al., 2003). 19 gpm/ft^2 in field pilot tests (Montgomery Watson Harza and University of Houston, 2003). 9.7 gpm/ft^2 in pilot tests (U.S. DoD, 2008b). Perchlorate-selective Resins: 40 to 50 gpm/ft^2 in proposed scale-up unit (Gu et al., 1999). 12 gpm/ft^2 in pilot tests (Blute et al., 2006; Russell et al., 2008; Wu and Blute, 2010).

Ion Exchange Critical Design Parameter	Value from the References
Regenerant loading rate and application time	Strong-base Polyacrylic Resins: 3 to 6% sodium hydroxide at 25 lbs/ft^3 for 45 minutes followed by 3 BV of rinse in field pilot tests (Montgomery Watson Harza and University of Houston, 2003). 30 lbs/ft^3 in model plant designs used for cost estimation (Tripp et al., 2003). 6% sodium hydroxide at 25 lbs/ft^3 in pilot tests (Lehman et al., 2008). Strong-base Polystyrenic Resins: 6% sodium hydroxide at 35 lbs/ft^3 for 63 minutes followed by 3 BV of rinse in field pilot tests (Montgomery Watson Harza and University of Houston, 2003). 36 lbs/ft^3 for partial regeneration and 400 lbs/ft^3 for full regeneration in model plant designs used for cost estimation (Tripp et al., 2003). Perchlorate-selective Resins: 2 to 4 BV of tetrachloroferrate followed by 20 to 30 BV of dilute hydrochloric acid followed by rinse with water or dilute bicarbonate (no data on loading rates) in small-scale field pilot tests (Gu et al., 2002). 6 BV of tetrachloroferrate, 14 BV of dilute hydrochloric acid, 21 BV rinse with water/ dilute bicarbonate in field demonstration (Lutes et al., 2010).

2.6.1 Resin Type

As discussed in Section 2.1, a variety of resin types have been tested for perchlorate removal. The selection of resin type will affect most other critical design parameter values. **Exhibit 2-7** and the paragraphs below present data for all major resin categories. As discussed in Section 2.2 and shown in **Exhibit 2-5**, however, perchlorate-selective resin appears to have become the technology of choice for modern perchlorate ion exchange facilities when perchlorate is the only contaminant of concern. Thus, where possible, the discussion focuses on parameters specific to perchlorate-selective resins.

2.6.2 Vessel Configuration

Ion exchange vessels can be configured in series or in parallel. In a parallel configuration, one or more vessels are in use, while other vessels are being regenerated or are on standby (Clifford, 1999). Influent water to be treated is divided equally among the operational vessels. Systems set in parallel are generally used to increase throughput. For contaminants that are difficult to remove (such as perchlorate), however, a series configuration can be effective to achieve a greater resin bed life (Boodoo, 2003; Gu et al., 1999). A series configuration allows for operation of the first vessel to a later point on the breakthrough curve because the second vessel can capture the initial breakthrough concentrations from the first vessel, keeping the final treated water from the system below a specified target concentration. As discussed above, series configurations are also known as “lead-lag” designs. As shown in **Exhibit 2-7**, series (lead-lag) operation is generally recommended for perchlorate removal.

2.6.3 Empty Bed Contact Time

EBCT is defined as the volume of resin, including voids, divided by the flow rate. The minimum EBCT required varies depending on the specific contaminant treated, the required contaminant removal percentage, the type of resin used, and other influent water characteristics (e.g., the presence of competing chemical species). In general, the EBCT for ion exchange removal of conventional anions (e.g., sulfates, nitrates, arsenic) usually ranges between 1.5 and 7 minutes per vessel. As shown in **Exhibit 2-7**, recommended EBCTs for perchlorate removal using conventional resins span this range, mostly falling in the middle to upper end of the range. Selective resins (particularly perchlorate-selective resins), however, remain effective at higher flow rates, which correspond to shorter EBCTs. For example, perchlorate-selective resins can be employed at flow rates of 0.5 to 4 BV per minute (Gu et al., 1999; 2001; 2002). Correspondingly, recommended EBCTs for perchlorate-selective resins shown in **Exhibit 2-7** are 1.5 minutes per vessel and less.

2.6.4 Surface Loading Rate

Loading rate is the velocity of flow through the resin measured in units of flow rate per unit area (e.g., gpm/ft^2). The surface area of the treatment pressure vessels must be selected to maintain loading rates within reasonable bounds. As shown in **Exhibit 2-7**, perchlorate-selective resins may have the potential to remain effective at higher maximum loading rates than conventional resins, although the data remain somewhat uncertain.

2.6.5 Resin Bed Life

Section 2.3 provides a detailed discussion of resin capacity (or bed life), which varies depending on resin type and water quality. **Exhibit 2-6** in that section shows detailed data from the literature on resin life. The capacities presented in **Exhibit 2-6** can be extended by series (lead-lag) operation. On the other hand, these capacities can be limited by breakthrough or peaking of co-contaminants.

2.6.6 Regeneration Parameters

Regeneration parameters determine the concentration and quantity of chemicals (i.e., chloride brine or tetrachloroferrate solution) required to restore a resin’s capacity to remove perchlorate. They also determine the quantity of waste regenerant generated. As discussed in Section 2.5, regeneration requirements depend on the type of resin used. **Exhibit 2-7** shows the available data on regeneration parameters that might be applicable if a system chose to regenerate its resin. As discussed in Section 2.5 and shown in **Exhibit 2-5**, however, the majority of full-scale ion exchange systems operate on a throwaway basis.

3 Biological Treatment

3.1 Operating Principle

Biological treatment of perchlorate is the process by which bacteria are used to reduce perchlorate to chlorate, chlorite, chloride, and oxygen. Biological treatment offers complete destruction of the perchlorate ion, eliminating the need for management of perchlorate-bearing waste streams. While there have been a wide variety of laboratory and pilot-scale tests exploring perchlorate treatment using bioreactors, the number of full-scale designs is still very limited.

The fundamental physical and chemical nature of perchlorate complicates the biological treatment process. Common reducing agents do not reduce perchlorate, and common cations do not precipitate it (Urbansky, 1998). Despite its strength as an oxidizing agent, the perchlorate ion is slow to react due to the presence of the highly-oxidized central halogen atom, chlorine (VII). This low reactivity, however, is a matter of kinetics rather that thermodynamics. Urbansky (1998) reports the standard half reactions for reductions to chloride (Eq 1) and chlorate (Eq 2) are favorable processes from a thermodynamic standpoint:

Eq 1 $$\mathrm{ClO_4^-} + 8\,\mathrm{H^+} + 8\,e \leftrightarrow \mathrm{Cl^-} + 4\,\mathrm{H_2O} \quad E^o = 1.287\ \mathrm{V}$$

Eq 2 $$\mathrm{ClO_4^-} + 2\,\mathrm{H^+} + 2\,e \leftrightarrow \mathrm{ClO_3^-} + \mathrm{H_2O} \quad E^o = 1.201\ \mathrm{V}$$

Therefore, the key to reducing perchlorate is finding the right catalyst. Coates et al. (2000) report that the scientific literature has evidence of the microbially-catalyzed reduction of chlorine oxyanions (a group to which perchlorate belongs) dating back over half a century. More recently, Coates et al. (2000), Logan (2001), and others have enumerated perchlorate-reducing bacteria (PRB) in a broad spectrum of environments nationwide, and demonstrated that the microbial reduction of perchlorate is a much more ubiquitous and diverse metabolism than previously considered.

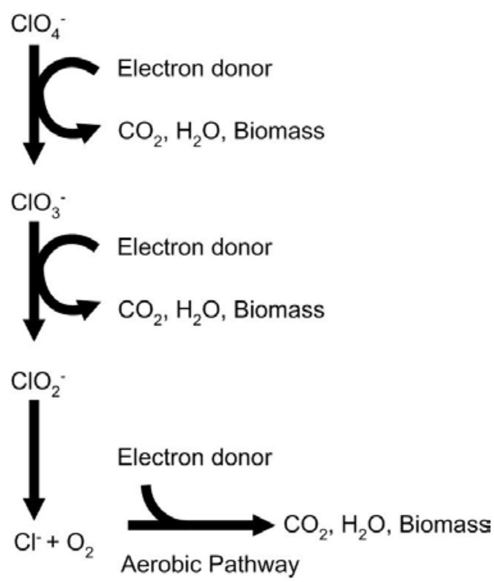
According to Xu et al. (2003), researchers have isolated and characterized many PRB. These microorganisms are all facultative anaerobes and are capable of reducing both perchlorate and chlorate to chloride for energy and growth. Although reduction does not take place (or at least not very quickly) in the presence of a high concentration of dissolved oxygen (DO), most PRB isolates can use oxygen as a terminal electron acceptor. Many PRB partially or completely reduce nitrate. The presence of nitrate usually decreases the rate of perchlorate reduction (until the nitrate is depleted). Most PRB do not reduce sulfate, and none (thus far) use Fe(III), another common component of ground water, as an electron acceptor. Marqusee (2001) presented a summary of electron acceptor use in groundwater samples collected from several locations with varying levels of nitrate (<1.2 to 59 mg/L), perchlorate (9.8 to 666 mg/L), and sulfate (15 to 1,620 mg/L). Generally, the microbial consortia preferred these electron acceptors in the following order:

nitrate > perchlorate > sulfate

Researchers have isolated both heterotrophic and autotrophic PRB (Xu et al., 2003). Many studies have used acetate or ethanol as a single substrate (also referred to as the electron donor or "food") for heterotrophic perchlorate reduction; however, optimal substrate use is straindependent. Many studies have also used supplemented nitrogen and phosphorus as necessary nutrients for the growth of PRB. There is no definitive information on what trace nutrients or metals are needed for growth. In one instance reported in Xu et al. (2003), researchers found iron, molybdenum, and selenium in purified perchlorate reductase. Chaudhuri et al. (2002) established that the PRB *Dechlorosoma suillum* did not reduce perchlorate without the presence of molybdenum. Several field studies presented later in this chapter achieved perchlorate degradation simply through the addition of an oxidizable substrate (e.g. acetate or ethanol) and nitrogen and phosphorous.

Exhibit 3-1 represents the three-step mechanism now widely accepted for bacterial respiration using perchlorate, which sequentially produces chlorate, chlorite, and chloride and oxygen (Xu et al., 2003). While researchers believe *perchlorate reductase* and *chlorite dismutase* are the central enzymes catalyzing the reactions, they are not sure if PRB use these enzymes exclusively or use a broader range of enzymes for perchlorate and chlorate reduction.

Exhibit 3-1. Biological Perchlorate Reduction Pathway



Biological treatment technologies that take advantage of the mechanism shown in **Exhibit 3-1** include:

- heterotrophic fixed bed (or packed bed) reactors
- fluidized bed reactors
- membrane biofilm reactors
- autotrophic hydrogen reactors
- continuously-stirred tank reactors
- *in situ* permeable biological barrier
- *in situ* electron donor delivery
- phytoremediation.

The most promising designs for biological treatment of perchlorate at drinking water facilities are those that operate either in a fixed bed or fluidized bed configuration. The California Department of Public Health (CDPH) also has identified membrane biofilm reactors as a "promising" technology for perchlorate treatment (Meyer, 2012). The first approved, full-scale membrane biofilm system for nitrate removal began operation in California in 2011 (Friese et al., 2013). Full-scale experience with the technology for perchlorate treatment, however, is limited. The literature indicates that *in situ* and other technologies are not currently used with the intent to create potable water supplies. Therefore, the remainder of this chapter focuses on the first two technologies listed above (fixed bed and fluidized bed reactors).

Both fixed bed and fluidized bed designs involve a media bed that provides a surface on which the PRB grows. The PRB can be initially introduced to the reactor with cell cultures, or the system can rely on natural populations of PRB. Drinking water systems typically rely on natural populations. Lab studies have used a variety of media in effectively reducing perchlorate, including granular activated carbon (GAC), anthracite, sand, and plastic media. Full-scale designs for perchlorate treatment have primarily used GAC. 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 is to use a gravity-fed concrete basin to hold the biologically active media. Fluidized bed bioreactor designs use vessels where flow, including a recycled portion, is pumped into the reactor at high rates in an up-flow design, fluidizing the media bed and allowing for more surface area for biomass growth. **Exhibit 3-2** and **Exhibit 3-3** provide schematic drawings for fixed bed and fluidized bed biological treatment, respectively.

Exhibit 3-2. Typical Schematic Layout for Fixed Bed Biological Treatment

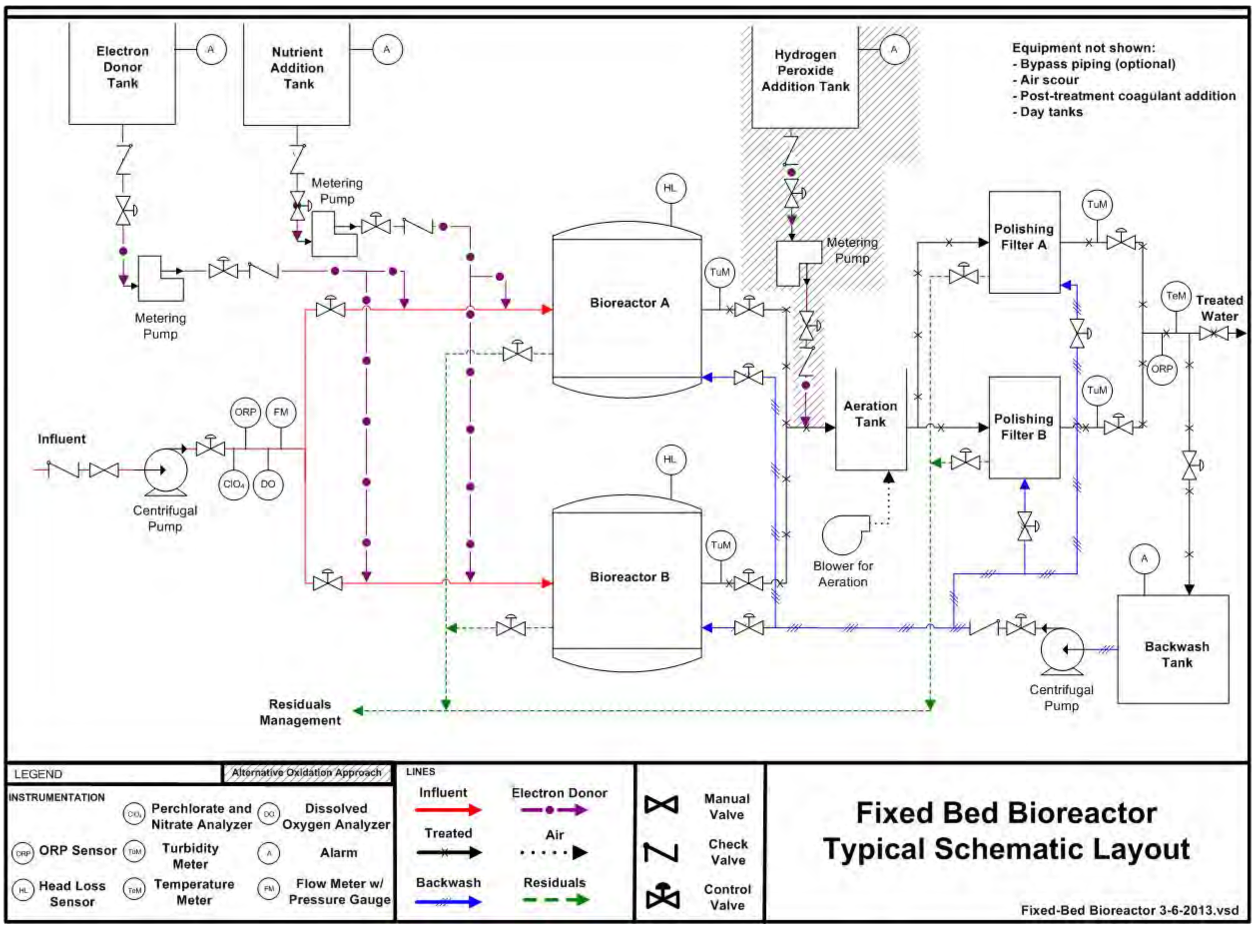
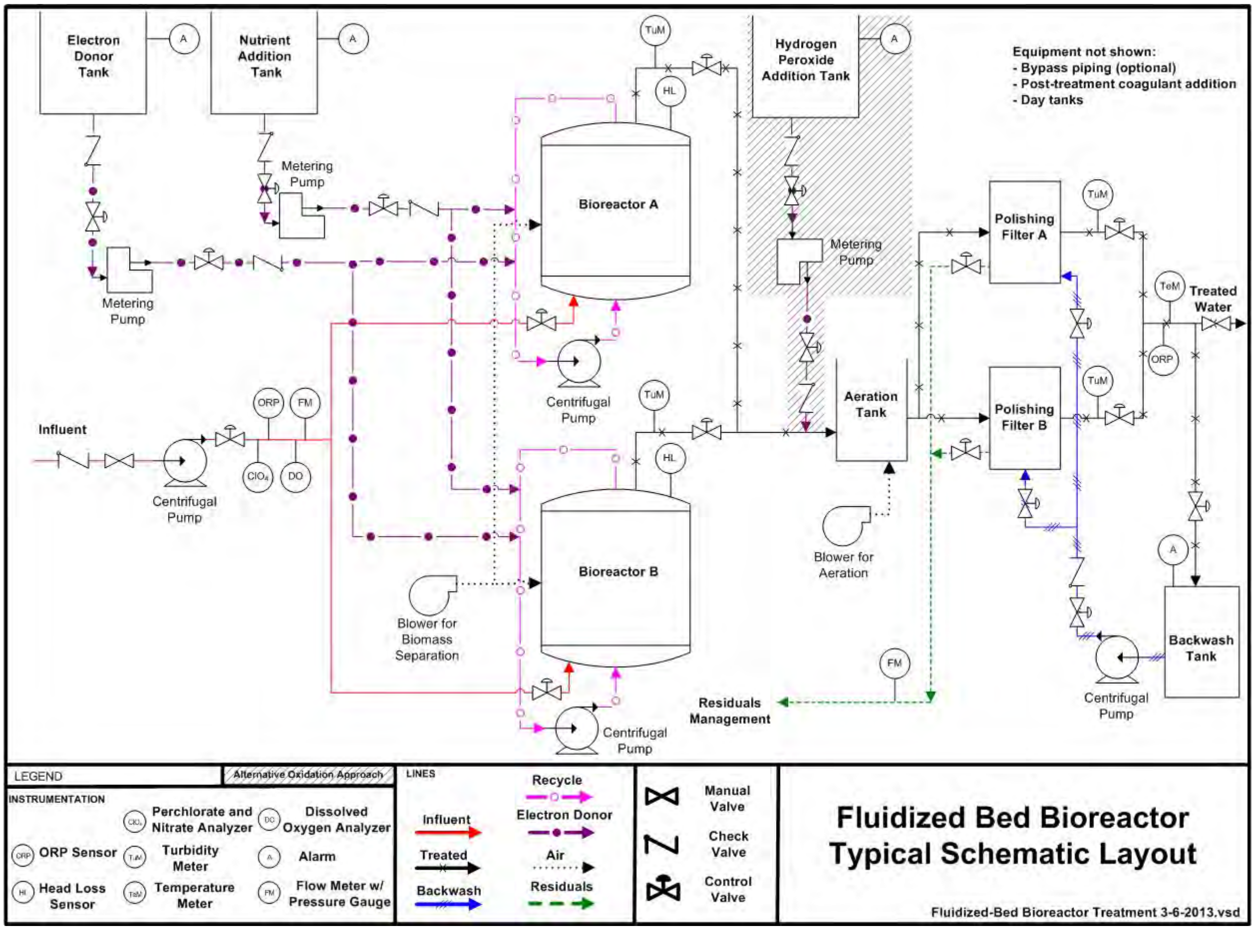


Exhibit 3-3. Typical Schematic Layout for Fluidized Bed Biological Treatment



3.2 Effectiveness for Perchlorate Removal

The State of California has identified fluidized bed biological treatment (along with ion exchange) as one of two BATs for achieving compliance with its standard for perchlorate in drinking water (California Code of Regulations, Title 22, Chapter 15, Section 64447.2). The literature contains substantial evidence of biologically-based technologies capable of reducing perchlorate to low levels in water. **Exhibit 3-4** summarizes the removal efficiencies 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.

Exhibit 3-4. 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

The two full-scale systems identified in **Exhibit 3-4** are perchlorate remediation projects. Treated water from these facilities is not used as drinking water. One of the pilot-scale studies in **Exhibit 3-4**, however, was an eight-month field test that supplied potable water to local water companies (Gilbert et al., 2001; Harding Engineering and Environmental Services, 2001). Furthermore, the success of the demonstration studies in Rialto 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 (Webster and Crowley, 2010; 2016; Webster and Litchfield, 2017). Section 3.2.1 provides additional details regarding the two systems designed to produce municipal drinking water (the permanent full-scale Rialto and West Valley facility and the Aerojet demonstration). Section 3.2.2 discusses several other large-scale treatment systems.

3.2.1 Biological Treatment for Municipal Drinking Water Supply

Rialto Well #6 and West Valley Well #11, Rialto, California. As a result of the successful full-scale demonstration at Rialto Well #2 (see Section 3.2.2), Envirogen installed a full-scale fluidized bed treatment system designed to supply drinking water from two other nearby wells to West Valley Water District and the City of Rialto. The system is sited on a former landfill and 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.

Envirogen completed construction in 2013 and the system underwent extensive testing before receiving its operating permit and beginning to produce drinking water in 2016. The system includes two 14-foot diameter, 24-foot tall bioreactor vessels followed by two 12-foot diameter, 24-foot tall aeration vessels. The bioreactors include a unique system of biomass separators at the surface of the vessels. The separators remove excess biomass that detaches from the media with air scour and agitation.

Additional post-treatment includes two multimedia filters with a dissolved air floatation system for removing solids from filter backwash, followed by chlorination. This additional post-treatment is designed to replicate the surface water treatment process that West Valley Water District operates at another location and satisfy the permit requirement that the biological treatment system meet the Enhanced Surface Water Treatment rule. 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).

Aerojet Field Test, Rancho Cordova, California. Aerojet conducted an eight-month field test at its facility in Rancho Cordova, California (where the company also operates the full-scale fluidized bed-based system described in 3.2.2) of a treatment system that included a fluidized bed biological reactor. The system removed perchlorate, nitrate, volatile organic compounds (VOCs), NDMA, and 1,4-dioxane from contaminated groundwater and supplied the treated water to local water companies for potable use (Harding Engineering and Environmental Services, 2001).

In addition to the fluidized bed reactor (designed to remove perchlorate and nitrate), the other components of the system were a multimedia filter (to remove biomass and GAC fines), an air stripper (for VOC removal), ultraviolet light/chemical oxidation (for other contaminant removal), liquid phase GAC adsorption (for other contaminant removal), disinfection (for potable water supply requirements), and clarification (for filter backwash) (Harding Engineering and Environmental Services, 2001).

The bioreactor component of the treatment system targeted perchlorate and nitrate. The total design flow rate of the fluidized bed reactor used during the field study was 1,800 gpm, which was the flow rate required to maintain the required fluidization of the GAC media. Bioreactor forward flow was variable depending on the desired recycle rate. For example, a forward flow rate of 1,200 gpm results in a recycle rate of 600 gpm (Harding Engineering and Environmental Services, 2001). To control fluidized bed level, a biofilm control system sheared excess biomass from the GAC and discharged cleaned GAC and biomass back into the reactor.

A panel of treatment experts convened by Aerojet to review results from the study concluded the following about the performance of the Aerojet Baldwin Park Operable Unit (BPOU) system (Gilbert et al., 2001):

- This combination of treatment processes removed all target chemicals below regulatory standards needed to meet potable water requirements.
- Each of the treatment processes met desired removal efficiencies in a reliable manner.
- The overall process was stable when the optimum ethanol dosage was maintained.

Investigators sampled water quality throughout the post-treatment process to evaluate the fate of excess biomass leaving the bioreactor. Specifically, they examined assimilable organic carbon, biodegradable dissolved organic carbon, and heterotrophic plate counts. Based on these analyses, they concluded that bacterial re-growth in the water distribution system would not be significant. The expert panel noted, however, that researchers did not solve the problem of cleaning excessive biomass from the GAC media. The episodic nature of the current cleaning process created problems of excessive biosolids loading on the subsequent filter that impacted water quality (Gilbert et al., 2001).

3.2.2 Other Large-Scale Biological Treatment Systems

Rialto Well #2, Rialto, California. Basin Water Inc. and Carollo Engineers Inc. both installed bioreactors as part of a perchlorate treatability field study Rialto, California. These reactors treated water from Well #2, which had been abandoned because of perchlorate contamination (Webster and Litchfield, 2017). Carollo Engineers installed and operated two parallel fixed-bed bioreactors for nitrate and perchlorate removal in a study, conducted over a 10 month period starting in February 2007, with the goal of producing treated water that met all drinking water standards. The treatment process consisted of parallel packed bed bioreactors with a 2 foot diameter and 4.7 foot bed-depth, followed by hydrogen peroxide dosing and biofiltration. The final step of the treatment process included chlorine disinfection. The bioreactor was subjected to various perchlorate spiking tests and consistently was able to treat to below detection limits for perchlorate for spiking concentrations up to 930 µg/L. The study showed that fixed-bed reactors, in combination with post-treatment processes, are a cost-effective way to produce potable water with perchlorate concentrations below detectable levels (U.S. DoD, 2008a).

Basin Water installed a full-size fluidized bed bioreactor at the same Rialto well location and tested the reactor under various operating conditions between 2007 and 2008. The purpose of the study was to test and validate the following items as they pertain to drinking water treatment (U.S. DoD, 2009; Webster and Crowley, 2010; Webster and Litchfield, 2017):

- *ex situ* bioremediation of nitrate and low concentrations of perchlorate though a fluidized bed reactor
- the short-term and long-term performance effects in allowing the system to be self-inoculated with incoming groundwater versus manually inoculating with a non-pathogenic microbial consortium
- short-term performance effects in the simulation of both a feed pump failure and an electrical shutdown
- the use of a post aeration vessel, multimedia filter, and GAC to produce to produce potable-like effluent water stream
- operational effectiveness of on-line nitrate and perchlorate analyzer systems
- long-term monitoring of system robustness and performance under steady-state and spiking perchlorate concentrations.

The Basin Water field study utilized acetic acid as the electron donor for a single fluidized bed reactor. The average flow rate into the reactor was 50 gpm. In steady-state operation, the system consistently treated perchlorate to less than 0.5 µg/L at varying influent concentrations and flow rates (Webster and Litchfield, 2017). Spiking studies showed that the maximum perchlorate concentration that could be consistently treated through the fluidized bed at a flow rate of 25 gpm was 4,000 µg/L of perchlorate, with 99.65 percent removal. The study also examined various system shut-down scenarios and proved that the fluidized bed reactor, in combination with other post-treatment processes, could treat perchlorate-contaminated groundwater to meet drinking water quality standards. The fluidized bed reactor system was able to effectively clean biosolids and maintain a consistent fluidized bed height, though the process was not described in detail (U.S. DoD, 2009). Operating costs were demonstrated to be $125 to $150 per acre foot treated. The success of the study led to the design and installation of the full-scale system producing drinking water from Rialto Well #6 and West Valley Well #11 (see Section 3.2.1) (Webster and Crowley, 2010; Webster and Litchfield, 2017).

Aerojet Facility, Rancho Cordova, California. Aerojet installed four fluidized bed reactors with GAC media designed and supplied by Envirogen, Inc. Envirogen designed the system to treat up to 8 mg/L of perchlorate with a loading rate of 44 pounds per day per 1,000 cubic feet of reactor volume. Each reactor has a design capacity of 1,800 gpm. Since its installation in 1998, Aerojet has operated this system at about 3,500 gpm (less than 900 gpm per reactor), treating concentrations of about 3,500 µg/L perchlorate to non-detect levels (less than 4 µg/L). Aerojet uses ethanol as the electron donor, and they re-inject the treated water into an underlying aquifer. Envirogen selected GAC media (versus sand) on the basis of pilot-testing results (Greene and Pitre, 2000).

Longhorn Army Ammunitions Plant, Karnack, Texas. U.S. Filter/Envirex and Envirogen developed and supplied a full-scale 50 gpm fluidized bed reactor with GAC media and acetic acid/nutrients addition to treat perchlorate-contaminated groundwater. After start up and acclimation, the system treats perchlorate concentrations of up to 35 mg/L (16.5 mg/L on average), reducing them to at least the target goal of 350 µg/L, and routinely to below the 5 µg/L analytical reporting limit. The system discharges treated water to a nearby stream (Polk et al., 2001).

Kerr-McGee and Pepcon Facilities, Henderson, Nevada. Full-scale fluidized bed reactors were installed to remove perchlorate at these two nearby remediation sites. The system at the Kerr-McGee site began operation in 2004, replacing ion exchange systems, and was expanded in 2006 to remove approximately 3,000 pounds per day of perchlorate from groundwater. The system at the Pepcon site began operation in 2012, replacing an *in-situ* bioremediation system. It is designed to remove approximately 1,000 pounds per day of perchlorate (Roefer, 2013).

3.3 Raw Water Quality Considerations

As shown in **Exhibit 3-4**, 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 NDMA 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 Engineering and Environmental Services (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).

In addition, 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 often has insufficient amounts of phosphorous or 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).

3.4 Pre- and Post-Treatment Needs

Although the literature did not contain any studies that examine pre-treatment of source waters prior to biological treatment, certain groundwater conditions require pre-conditioning. For example, acidic ground water is not compatible with either robust microbial growth or common metallic system construction materials. In such cases, operators must raise the pH level prior to treatment. Consequently, some carbonates, sulfides, and oxides less soluble at neutral a pH might precipitate out and require filtration.

To produce drinking water from an impacted source, some form of multi-barrier system, beginning with biological treatment, may be necessary. For example, the treatment train used at the Aerojet BPOU to create potable water consists of seven different unit processes, as described in Section 3.2. Furthermore, biological treatment itself results in the production of soluble microbial organic products that become part of the treated water. Some of this material is biodegradable, and the microorganisms (at least in the case of perchlorate and nitrate reduction) tend to be the normal soil bacteria that are involved in the natural nitrogen cycle and common in all agricultural soils (Gilbert et al., 2001). In addition, the biological treatment process also depletes the levels of oxygen in the treated water. 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.

3.5 Waste Generation and Residuals Management Needs

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 resulting from consumption of dissolved oxygen, nitrates, and perchlorate. In most bioreactor designs, excess biomass must be removed periodically. This removal results in one or more residual streams, the characteristics of which depend on the removal process used.

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. For facilities without the option of sewer disposal, a clarification and recycle process would be needed (U.S. DoD, 2008a). 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 in 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 publicly-owned treatment works (POTWs) to accept” (U.S. DoD, 2009).

Downstream polishing through filtration (see Section 3.4), when used as post-treatment, 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.

In addition, biological treatment can itself be a treatment technology for residuals from other perchlorate removal technologies, such as spent ion exchange regenerant or membrane reject. Appendix A discusses this use of biological treatment.

3.6 Critical Design Parameters

Critical design parameters for biological treatment systems removing perchlorate are:

- Support media type
- EBCT or hydraulic residence time (HRT)
- Bed expansion (for fluidized bed reactors)
- Electron donor type and dosage
- Nutrient addition
- Backwash and biomass separation design
- Recycle rate (for fluidized bed reactors)
- Post-treatment requirements.

The paragraphs below discuss each of these parameters in more detail. As noted in Section 3.1, fixed bed and fluidized bed reactors are the most promising approaches for drinking water treatment. Therefore, this section focuses on design parameters specific to these two types of biological treatment system. Three of the full-scale studies (Harding Engineering and Environmental Services, 2001; U.S. DoD, 2008a; 2009) identified critical design criteria for these types of reactors and were instrumental in guiding the discussion here. This section provides a general discussion of the design parameters and the range of values reported in the literature for these parameters. Chapter 7 identifies the specific values for each parameter used in EPA's cost estimates.

3.6.1 Support Media Type

As discussed in Section 3.1, in both fixed and fluidized bed reactors, PRB require a media surface on which to grow. As shown in **Exhibit 3-4**, studies have used a variety of media in effectively reducing perchlorate, including GAC, anthracite, sand, and plastic media. Full-scale designs for perchlorate treatment, however, have primarily used GAC (Greene and Pitre, 2000; Harding Engineering and Environmental Services, 2001; Polk et al., 2001; U.S. DoD, 2008a; 2009).

3.6.2 Empty Bed Contact Time or Hydraulic Residence Time

EBCT is defined as the volume of support media divided by the flow rate. Minimum EBCT needed in order for perchlorate to be fully reduced is the primary design parameter in sizing fixed bed bioreactor vessels. For fluidized bed bioreactors, HRT is the more accurate term for the primary design parameter. HRT is the time required for treated water to move through the fluidized media bed. For larger flows, multiple bioreactors will be operated in parallel. Typical full-scale bioreactor designs have an EBCT or HRT in the range of 10 to 12 minutes for both fixed bed (U.S. DoD, 2008a) and fluidized bed reactors (Harding Engineering and Environmental Services, 2001).

3.6.3 Bed Expansion

For fluidized bed bioreactors, an additional important vessel sizing consideration is bed expansion. Target bed expansions are used to determine the height of the vessels. Peer review of EPA's biological treatment cost model (see Chapter 7) provided information on typical bed expansion values. Typically, the vessel is filled with a fixed bed depth of media and initially fluidized to 40 to 50 percent. As the biomass grows, the fluidized media bed expands to 70 percent of the initial fixed bed depth. Biomass separation maintains expansion at this target level. Additional space at the top of the vessel provides a safety factor to prevent fluidized media from exiting the reactor.

3.6.4 Electron Donor Type and Dosage

As discussed above, bioreactor designs require the presence of an electron donor (or substrate) for the reduction of perchlorate. For fixed bed bioreactors, electron donors are injected into the influent water prior to entering the bioreactor. In fluidized bed bioreactors, injection typically occurs in the recycle stream. As shown in **Exhibit 3-4**, a wide variety of electron donors have been tested, including acetate, acetic acid, lactate, ethanol, methanol, carbohydrate by-product, hydrogen, propane, and proprietary glycerol- or carbohydrate-based solutions. Full-scale designs for perchlorate treatment, however, have typically used acetic acid or ethanol (Greene and Pitre, 2000; Harding Engineering and Environmental Services, 2001; Polk et al., 2001; U.S. DoD, 2008a; 2009).

Determining the correct electron donor dose is critical in the effectiveness of perchlorate reduction in the bioreactor. Since oxygen and nitrates will be reduced prior to perchlorate reduction, the electron donor dose must be large enough to fully reduce all three. However, the dose cannot be too large or sulfides might form and be present in the effluent along with excess organic carbon, requiring additional post-treatment (Harding Engineering and Environmental Services, 2001).

Electron donor dose is dependent on site-specific conditions, including raw water characteristics. Therefore, determining the dose requirements for the electron donor typically requires pilot study tests, along with stoichiometric and thermodynamic calculations. The following site-specific relationships were developed for two full-scale treatment designs using ethanol and acetic acid:

$$C_e = 0.903\ O_2 + 2.229\ NO_3^- \text{-N} + 0.581\ ClO_4^-$$

(Harding Engineering and Environmental Services, 2001)

$$C_{aa} = O_2 + 2.86\ NO_3^- \text{-N} + 0.64\ ClO_4^-$$

(U.S. DoD, 2008a)

where:
C_e = required ethanol concentration (mg/L)
C_{aa} = required acetic acid concentration (mg/L)
NO_3^--N = influent nitrate-nitrogen concentration (mg/L)
O_2 = influent DO concentration (mg/L)
ClO_4^- = influent perchlorate concentration (mg/L)

As can be seen in these stoichiometric equations, influent concentrations of oxygen, nitrate-nitrogen, and perchlorate need to be available to determine the electron dose. Tests have proven that the electron donor dose is dependent on temperature and that decreasing the water temperature will result in an increase in necessary electron donor dose. However, these small changes are in the range of 3 percent change of dose for a 5 degrees C change (Harding Engineering and Environmental Services, 2001).

3.6.5 Nutrient Addition

As discussed in Section 3.3, bacteria in bioreactors require nutrients. Although these nutrients are sometimes present in source water, full-scale designs have required addition of macro-nutrient such as nitrogen and/or phosphorous. While there are a number of methods for adding nitrogen and phosphorous to the influent, the typical options are addition of ammonium chloride for supplemental nitrogen addition and/or addition of phosphoric acid for supplemental phosphorous (Harding Engineering and Environmental Services, 2001; U.S. DoD, 2008a).

3.6.6 Backwash and Biomass Separation Design

As discussed in Section 3.5, bioreactors require periodic removal of accumulated biomass. Removal of the biomass is achieved in different ways depending on the bioreactor design type. For fixed bed bioreactors, an air scour is used followed by water flush to remove biomass from the media. A backwash basin and pump is needed to supply the water for backwashing. This backwash design is similar to that used in other treatment technologies, such as GAC and greensand filtration. Typical fixed bed bioreactors have a backwash interval in the range of 17 to 24 hours, determined based on target head across the media bed (U.S. DoD, 2008a).

For fluidized bed bioreactors, the expanded bed volume within the fluidized bed reactor will continue to expand as biomass accumulates. This expansion occurs because the specific density of the media plus biomass is less than that of the media alone. It becomes necessary to dislodge biomass growth from the media, thus increasing the specific density and decreasing the fluidized bed volume. Effective methods and equipment for biomass separation include mechanical separation of biomass using eductors or using air scour to sheer the biomass from the media. The amount of air required for biomass separation is around 0.3 cubic feet per hour per gpm of treated water (U.S. DoD, 2009).

3.6.7 Recycle Rate

Designs of fluidized bed reactors use high pumping rates to keep the media in the bioreactor fluidized. A recycle stream is typically used to provide enough water to satisfy these pumping rates. Since feed pumping rates also determine the expansion height of the media bed, the recycle rate must be limited so that the feed pumping rate doesn’t expand the fluidized media past the target height. A typical recycle rate, based on peer review comments on EPA’s biological treatment cost model (see Chapter 7), is 50 percent.

3.6.8 Post-treatment Requirements

Section 3.4 identifies post-treatment processes typically required for biological treatment, which can include reoxygenation, filtration, and disinfection.

4 Membrane Technologies

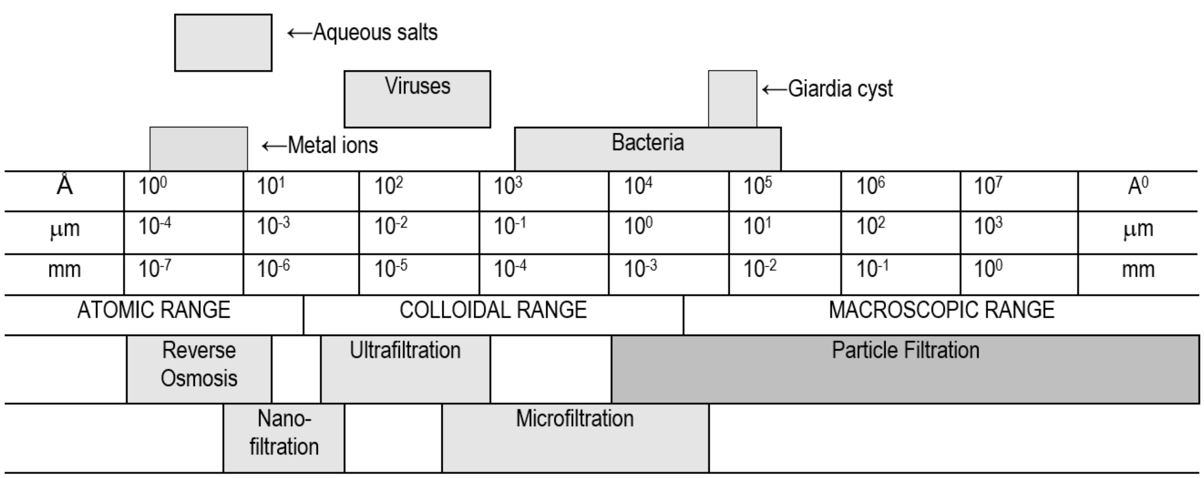
4.1 Operating Principle

Membrane filtration processes physically remove perchlorate ions from drinking water. This technique does not destroy the perchlorate ion and, therefore, creates a subsequent need for disposal or treatment of perchlorate-contaminated waste. Membrane filtration technologies evaluated for perchlorate treatment include reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF).

These processes separate a solute such as perchlorate ions from a solution by forcing the solvent to flow through a membrane at pressure. RO depends on applying high pressures across the membrane in the range of roughly 100 to 1,000 pounds per square inch gauge (psig) in order to overcome the osmotic pressure differential between the saline feed and product waters. The NF process uses pressures in the range of 75 to 150 psig, while pressures for UF typically range from 3 to 40 psig (USEPA, 2003).

In all three processes, 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. Along with a portion of the feed water, these solids are removed as concentrate, or reject. The size range of the rejected solids varies by the type of membrane used, as shown in **Exhibit 4-1**.

Exhibit 4-1. Particle Sizes and Membrane Process Ranges



After Dow (2005) and AWWA (2011)

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. RO membranes, which have an effective pore size of 0.001 microns or less, primarily remove perchlorate by the steric mechanism. UF membranes, with a pore size of roughly 0.01 to 0.1 microns, remove perchlorate primarily by electrostatic repulsion. NF membranes have effective pore sizes of roughly 0.001 to 0.01 microns. Various NF membranes may operate by both mechanisms to varying degrees (Amy et al., 2006; J. Yoon, Amy, et al., 2005; J. Yoon, Yoon, et al., 2005; Nam et al., 2005; USEPA, 2005; Y. Yoon et al., 2005).

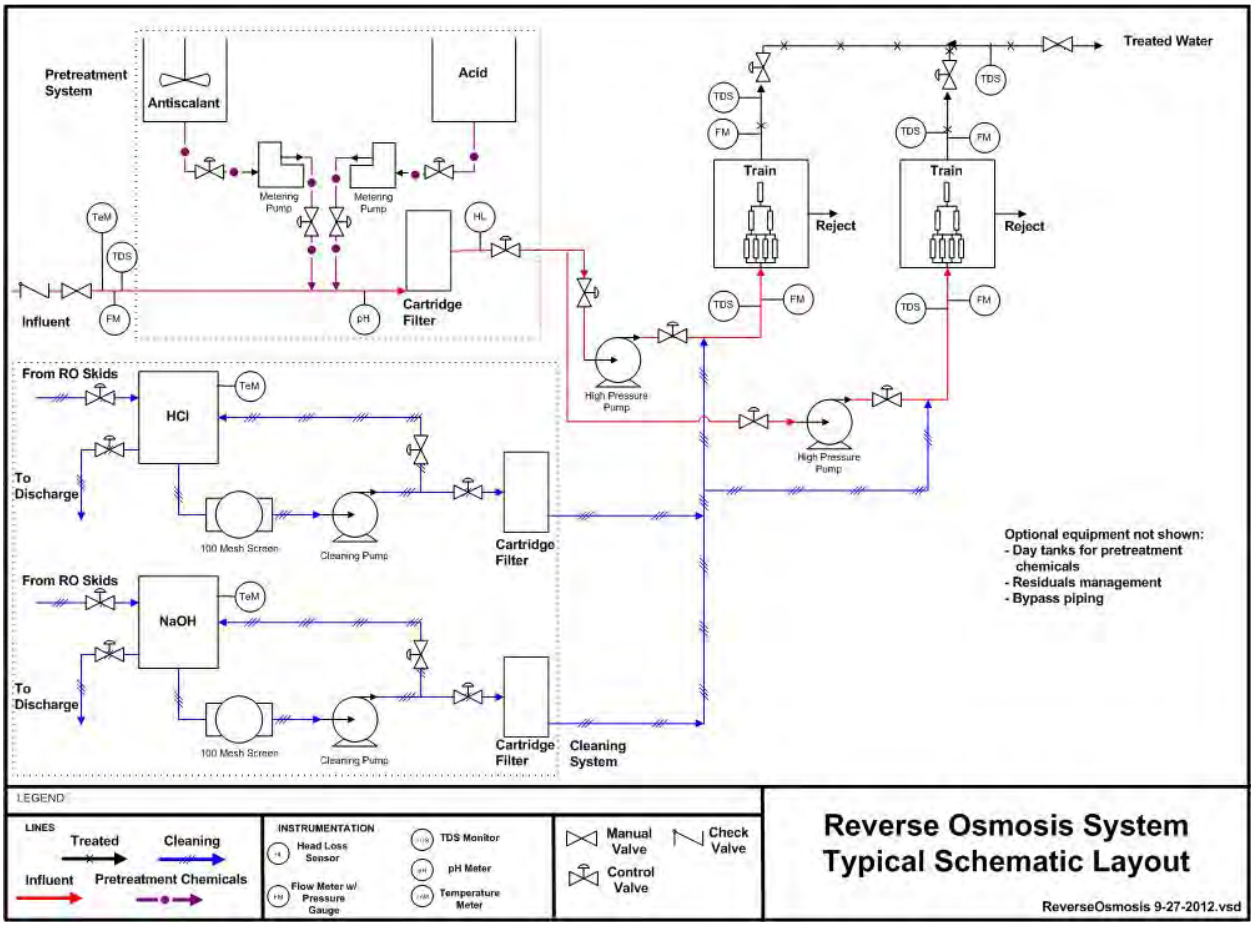
As discussed below in Section 4.2, of the membrane processes, RO has shown the most promise for removing perchlorate. Therefore, this chapter focuses primarily on the technical details of the RO treatment process. It discusses UF and NF mainly in terms of the available data on their effectiveness, with less discussion of their operating principle and relevant design parameters. Note, however, that practical operation of an NF system is very similar to that of an RO system.

For municipal drinking water treatment, RO membranes are most often used in a spiral-wound configuration. A spiral wound membrane consists of several membrane envelopes, layered with feed spacers and rolled together in a spiral around a central permeate collection tube. Each envelope consists of a flat membrane sheet folded in half over a porous membrane permeate carrier, and glued on the remaining three sides to completely enclose the carrier. The envelopes are connected to a central permeate collection tube. After the envelopes and feed spacers are rolled around the tube, the assembly is enclosed in a shell to form a membrane element. Different RO elements are manufactured for different scenarios, including seawater desalination (seawater RO), treatment of brackish water with dissolved solids roughly in the range of thousands of mg/L (brackish water RO), and treatment of less saline water (low-pressure RO). Elements that are intended for higher feed salinity have smaller effective pore sizes. They therefore offer higher rejection of dissolved ions, and require higher pressures for operation.

Multiple RO or NF elements are placed within a pressure vessel. To achieve the target removal efficiency and water recovery, these pressure vessels often are arranged in sequential stages, typically up to three depending on the recovery to be achieved (American Water Works Assocation and American Society of Civil Engineers (AWWA/ASCE), 2005; The Dow Chemical Company, 2005). When multiple stages are used, the number of pressure vessels decreases from stage to stage. Permeate or finished water is collected from each pressure vessel. The concentrate from the first membrane stage serves as the feed to the second and the concentrate from the second stage serves as the feed to the third. Consequently, each successive stage of the process increases the total system recovery. As the feed water travels through the membrane system and becomes more concentrated, its osmotic pressure increases. The feed pressure must overcome this osmotic pressure. The final concentration in the concentrate water therefore has a major effect on the required feed pressure and energy use.

The membrane stages in combination make up an RO treatment train. A treatment system may have multiple trains. **Exhibit 4-2** provides a schematic drawing for an RO treatment facility; each rectangular box within a train represents a pressure vessel that contains multiple membrane elements. An NF treatment facility would be nearly identical, with the primary difference being the type of membranes used and the operating pressures.

Exhibit 4-2. Typical Schematic Layout for a Reverse Osmosis (or Nanofiltration) Treatment Facility



4.2 Effectiveness for Perchlorate Removal

Although the literature pertaining to perchlorate removal using membrane technologies is limited, pilot and bench-scale studies have demonstrated that perchlorate can be substantially removed by RO. The studies also demonstrate widely varying removal of perchlorate with NF and UF processes, and have investigated favorable conditions for its removal (J. Yoon, Amy, et al., 2005; J. Yoon et al., 2003; J. Yoon, Yoon, et al., 2005; Liang et al., 1998; Sanyal et al., 2015; Y. Yoon et al., 2002; 2005). There is no large-scale demonstration study of membrane use for perchlorate removal.

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 concentrate had no effect on overall perchlorate rejection. **Exhibit 4-3** summarizes effectiveness results for this pilot-scale work, along with results from additional, smaller scale bench studies.

Exhibit 4-3. 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 (J. 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 (Y. 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)

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. See Section 4.3 for further discussion. 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).

4.3 Raw Water Quality Considerations

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, may also cause flux decline; however, there are no studies of the resulting effect on perchlorate rejection.

Membrane fouling may 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.

4.4 Pre- and Post-Treatment Needs

In general, pretreatment requirements for membrane technologies depend on influent water quality as well as the type of membrane used. RO and NF membranes are often used after media filtration, or more recently, after UF or microfiltration membranes. Membrane filtration processes often include a prescreen or cartridge filter to remove sediment that could damage the membranes. RO and NF membranes often require pH adjustment or antiscalant.

The pilot study of RO and NF membrane elements (Liang et al., 1998) included prechlorination and conventional filtration (rapid mix, flocculation, sedimentation, and filtration). Pretreatment requirements, however, typically are independent of the specific contaminant targeted for removal. Calculations such as the silt density index (SDI), found in ASTM standard D3739-94, can provide insight into the fouling problems that are inherent in any membrane system. SDI measures the fouling potential of suspended solids. Manufacturers typically specify maximum

SDIs of 3 to 5 for RO and NF elements. In addition, it is important to model and conduct pilot studies to assess the potential for fouling from substances such as calcium carbonate, silica, calcium fluoride, barium sulfate, calcium sulfate, strontium sulfate, and calcium phosphate. The Langelier saturation index (LSI), described in ASTM standard D4189-94, characterizes the potential for $CaCO_3$ scaling. The LSI is used to indicate the tendency of water to precipitate, dissolve, or be in equilibrium with calcium carbonate, and what pH change is required to bring the water back to equilibrium. The scaling potential of other substances may be determined from a saturation calculation.

Although the perchlorate literature does not address post-treatment requirements, 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 using groundwater, 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, higher rates of blending will be possible, likely reducing post-treatment requirements.

4.5 Waste Generation and Residuals Management Needs

Membrane filtration produces a waste stream called the concentrate (or reject). This waste stream contains all removed dissolved and suspended solids, and must be further treated and/or disposed of. Membrane system designs generally set a recovery rate (i.e., the ratio of permeate to feed flow) based on the scaling potential of the resulting concentrate water. The presence of a particular target contaminant has little or no effect on the selected recovery rate. Therefore, it is likely that the concentrate flow would represent a substantial share of influent flows. In other applications, concentrate flows can account for 15 to 30 percent of influent, which implies a fairly large perchlorate-contaminated waste stream for subsequent treatment or disposal.

In general, full-scale RO systems handle concentrate using 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 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, discussed in more detail in Appendix A.

In addition, periodic cleaning of the membrane system is necessary to recover productivity lost to fouling. This cleaning may include cycles of acid and caustic wash, depending on the nature of the fouling. Since the spent cleaning solution is generated infrequently and in small amounts, it is typically diluted by and handled with the concentrate.

4.6 Critical Design Parameters

As discussed in Section 4.2, pilot and bench-scale studies have demonstrated that perchlorate can be substantially removed by RO. The studies demonstrate widely varying removal of perchlorate with NF and UF processes. Therefore, this section focuses on critical design parameters for RO. For comparison, it notes available data for NF, but does not discuss UF.

Critical design parameters for RO systems removing perchlorate are:

- Feed water quality
- Membrane type and feed water pressure
- Recovery rate
- Flux rate
- Pretreatment requirements.

Exhibit 4-4 shows design information from the pilot-scale work performed at the Metropolitan Water District of Southern California, La Verne Treatment Plant, which used RO and NF to remove perchlorate from pretreated Colorado River Water (Liang et al., 1998). The paragraphs below discuss each of the parameters listed above in more detail. Values for other RO design parameters (e.g., cleaning procedures, residuals discharge options), while not specifically addressed in the literature reviewed here, are well documented for RO treatment in general. EPA has no reason to expect a significant difference in these parameters for RO systems treating perchlorate. This section provides a general discussion of the design parameters and the range of values reported in the literature for these parameters. Chapter 7 identifies the specific values for each parameter used in EPA's cost estimates.

Exhibit 4-4. Critical Design Parameters for Reverse Osmosis (and Nanofiltration)

Membrane Filtration Critical Design Parameter	Value from the Reference (Liang et al., 1998)
Feed water quality	TOC = 2.40 – 3.50 mg/L UV^{254} = 0.024 – 0.032 /cm Conductivity = 969 – 1030 micro-ohm/cm Temperature = 26°C pH = 8.09 – 8.24 Turbidity = 0.12 – 0.18 NTU Particle count = 113 – 1590 /milliliter
Membrane type	One membrane element, 4-inch diameter, 40 inches long, thin-film composite with negative surface charge RO: 72 square foot active area, specific flux 0.14 gallons per day per square foot (gpd/ft^2 or gfd) per pound per square inch (gfd/psi) NF: 82 square foot active area, specific flux 0.17 gfd/psi, molecular weight cutoff 300 Daltons
Average feed water pressure	RO: 106 psig NF: 87 psig
Recovery rate	No data is given.
Flux rate	15 gfd for both RO and NF
Pretreatment	The raw water was treated via prechlorination, rapid mix, flocculation, sedimentation, and filtration prior to passing through the membranes. The prechlorination dose was adjusted to maintain an effluent free-chlorine residual of 0.5 to 1.0 mg/L. The coagulation step used 5 mg/L alum and 1 mg/L polymer. Six column-type filters were used: four dual-media filters with 20 inches of anthracite coal and 8 inches of silica sand; and two tri-media filters with 8 inches of silica sand and 3 inches of ilmenite. The filter effluent was passed through a dechlorination unit.

4.6.1 Feed Water Quality

As discussed in Section 4.4, feed water quality can determine pretreatment and cleaning requirements. Furthermore, as discussed below, it affects the values achievable for other relevant design parameters, such as recovery and flux rate. Finally, higher levels of total dissolved solids correspond to higher osmotic pressure in the membrane concentrate, and thus increase energy requirements. Feed water quality parameters that are crucial include temperature, pH, SDI, total dissolved solids, and concentrations of ions that can lead to the oversaturation of scaling salts, such as those listed in Section 4.4.

4.6.2 Membrane Type and Feed Water Pressure

Membrane elements from different manufacturers, and different elements from the same manufacturer, may have widely varying water and ion permeabilities. Effective pore size and maximum feed pressure determine whether a membrane is characterized as RO or NF. As discussed in Section 4.1, RO membranes have pore sizes of 0.001 microns or less and operate at pressures in the range of roughly 100 to 1,000 psig. NF membranes have pore sizes of roughly 0.001 to 0.01 microns and use pressures in the range of 75 to 150 psig. Membrane elements also are characterized by their diameter (usually 4 to 18 inches), active area (in square feet), and specific flux rate (measured in gfd per psi of net driving pressure[6]). Other relevant operating specifications include maximum recovery in one element, minimum concentrate flow, maximum feed SDI, minimum operating pH, maximum operating temperature, and maximum pressure drop permitted in a single element and a complete pressure vessel.

Exhibit 4-4 shows data on the specific membranes tested for perchlorate by Liang et al. (1998). The RO membranes (which showed higher perchlorate removal efficiency than the NF membranes) operated at the low end of the typical range for that technology (106 psig).

4.6.3 Recovery Rate

As discussed above, RO produces a permeate flow (water with most dissolved solids removed) and a concentrate flow (residual water rejected by the membrane). The recovery rate is the percentage of the influent flow that is recovered as permeate. Increasing the recovery rate will increase the concentration of dissolved solids in the membrane reject water, and will thus increase the required feed pressure and the potential for membrane scaling. Thus, the achievable recovery rate depends on the quality of the source water as well as the pretreatment of the water (American Water Works Assocation and American Society of Civil Engineers (AWWA/ASCE), 2005), and systems with high levels of total dissolved solids in their feed water will typically operate at lower recovery rates than systems with lower levels.

For a given membrane and feed water, a higher recovery rate will require the use of more elements in series. The model accomplishes this by increasing the number of elements per pressure vessel and/or by increasing the number of stages in the system. For NF membrane elements, the target recovery will typically be between 80 and 90 percent. For RO elements, the target recovery will typically be between 50 and 85 percent. Although Liang et al. (1998) did not report recovery rates achieved in their pilot studies, recovery rate is driven by overall feed water quality, not the specific contaminant being targeted. Therefore, EPA has no reason to expect a significant difference in recovery rate for RO systems treating perchlorate from the values typically documented for RO systems in general.

4.6.4 Flux Rate

The flux of the system is the rate of permeate water per unit of membrane area, typically measured in gfd. While each stage of a membrane system will have a different flux, the average flux over all elements is a fundamental design parameter. In general, the higher the quality of the feed water, the higher the flux that may be achieved. Operating with excessively high flux, however, leads to fouling of the membrane elements. Depending on the nature of the fouling, it may be reversed by cleaning, or may require replacement of the elements.

For many ground waters, systems can operate successfully with fluxes between 16 and 20 gfd. Surface waters require lower fluxes, typically between 12 and 17 gfd, depending on the SDI of the source water. Pretreatment will usually permit the use of a higher flux. The pilot studies by Liang et al. (1998) used a flux rate of 15 gfd, in the typical range for surface water.

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[6] Net driving pressure is equal to the feed pressure at a particular point in the pressure vessel minus the osmotic pressure of the feed water.

4.6.5 Pretreatment Requirements

As discussed in Section 4.4, to reduce fouling of the membrane, some type of pretreatment is usually required. The pilot studies by Liang et al. (1998) used extensive pretreatment, the equivalent of conventional filtration. Conventional filtration, however, would likely already be present at surface water sources that require additional treatment to remove perchlorate. The types of pretreatment that would more likely need to be added to an existing treatment train for implementation of RO include those identified in Section 4.4, such as cartridge filtration and acid and/or antiscalant addition.

5 Point-of-Use Treatment

5.1 Operating Principle

A POU device uses a miniaturized version of a centralized treatment process to meet water quality standards for consumption at individual taps (e.g., a kitchen sink). When a system installs, controls (i.e., owns), and maintains POU devices at all customer locations where water is consumed (e.g., residences), it can forego centralized treatment (USEPA, 2006b). Because POU devices treat a small fraction of the water delivered by a system, a compliance program that relies on POU devices may be more cost-effective for smaller systems.

For perchlorate removal, the NSF Joint Committee on Drinking Water Treatment Units has added a protocol to *NSF/ American National Standards Institute (ANSI) Standard 58: Reverse Osmosis Drinking Water Treatment Systems* that requires an RO unit to be able to reduce perchlorate from a challenge level of 130 µg/L to a target level of 4 µg/L (NSF International, 2019). Several organizations (e.g., NSF International, Underwriters Laboratories, Water Quality Association) provide third-party testing and certification that POU devices meet drinking water treatment standards. There are no perchlorate certification standards for other types of POU devices such as those using ion exchange media. Therefore, the discussion in this section focuses on POU RO devices.

The operating principle for POU RO devices is the same as centralized RO: steric exclusion and electrostatic repulsion of ions from the charged membrane surface. In addition to an RO membrane for dissolved ion removal, POU RO devices often have a sediment pre-filter and a carbon filter in front of the RO membrane, a 3- to 5-gallon treated water storage tank, and a carbon filter between the tank and the tap.

To meet a perchlorate drinking water standard, a system would need to purchase, install, and maintain certified POU RO devices for all customers. Usually, a system would install a single POU RO device at the kitchen tap for each residential customer. Nonresidential customers might require multiple devices (e.g., for drinking fountains). Installation requires retrofitting the device into existing plumbing fixtures (e.g., tapping into the water supply line to insert a treated water line with a dedicated tap and adding a wastewater connection for the RO membrane concentrate or reject). Maintenance primarily consists of filter replacement, often on a fixed schedule that varies by filter type. Monitoring water quality at individual treated water taps will also be necessary to demonstrate compliance with a perchlorate drinking water standard.

5.2 Effectiveness for Perchlorate Removal

There are no perchlorate removal case studies that use POU RO. Nevertheless, bench-scale and pilot testing indicates that RO membranes should be able to effectively remove perchlorate ions. Furthermore, devices certified under *NSF/ANSI Standard 58* have a demonstrated 97 percent perchlorate reduction capability based on reducing perchlorate from challenge level of 130 µg/L to a target level of 4 µg/L.

Boodoo (2003) provides an assessment of possible configurations for POU or point-of-entry ion exchange devices that achieve high removal rates. There are, however, no certification standards for such devices.

5.3 Raw Water Quality Considerations

Because the POU RO devices will be installed at service taps that are downstream of a system's entry point to the distribution system, EPA assumes that the raw water entering a POU RO device will be water that is suitable for consumption except for an exceedance of the proposed perchlorate regulatory standard. As noted in the next section, POU RO devices include pre-filters to address potential interference of delivered water quality with RO performance.

5.4 Pre- and Post-Treatment Needs

POU RO devices include various filters to address pre- and post-treatment concerns. Most devices include a sediment filter for solids removal to prevent membrane fouling and a pre-RO carbon filter to remove chlorine and organic compounds that could impair membrane function. They also include a carbon filter after the membrane and storage tank to remove any organics that may remain or bacterial growth that occurs during storage. Because the POU device is installed at the tap, there are no potential adverse impacts on the distribution system.

5.5 Waste Generation and Residuals Management Needs

The treatment process waste comprises wastewater and used filter cartridges. Waste disposal methods must comply with state and local requirements. The wastewater connection is generally plumbed to the household sewer system, which uses either an on-site septic system or a centralized wastewater collection system for disposal. Depending on state and local regulations, the used cartridge filters may be included in household solid waste (USEPA, 2006b).

5.6 Critical Design Parameters

In addition to the POU devices themselves, there are several components to the design of a POU program that are primary cost drivers. These include the following:

- POU RO device installation
- Public education program development
- POU device monitoring
- POU device maintenance.

Chapter 7 discusses each of these parameters in more detail and identifies the specific values for each used in EPA's cost estimates.

6 Nontreatment Alternatives

6.1 Application Principle

For small water utilities that lack the financial and/or technical capacity to implement a new treatment-based compliance strategy, nontreatment options may offer a more cost-effective path to compliance. Nontreatment options essentially replace the contaminated water source with water that meets drinking water standards, including a new standard for perchlorate.

Nontreatment solutions for drinking water compliance include the following: well rehabilitation; contaminant source elimination; new well construction; and interconnecting with another system to purchase water (USEPA, 2006c). The feasible nontreatment options will depend on site-specific circumstances such as system size, source water type, contaminant reduction needs, and proximity to alternative water sources. For small systems, neither well rehabilitation for contaminated ground water sources nor source elimination (e.g., remediation of perchlorate-contaminated sediments or ground water) is likely to be feasible and cost-effective solutions. Another option – blending water from existing wells – may be a feasible, low-cost option for systems with multiple wells including some for which perchlorate does not exceed the proposed perchlorate standard. For systems that cannot blend source water to comply with the proposed standard, two feasible nontreatment options include a new well to replace the contaminated source water and an interconnection to purchase water from a supplier. These two options (new wells and interconnection) are likely to have higher costs than the other options (well rehabilitation and source elimination) (USEPA, 2006c)..

The costs associated with drilling a new well include the initial hydrological assessment, pilot hole drilling, developing the final well design, drilling the well bore, installing well casings, screens, and filters, development of the well, and installation of the pump and power source (Harter, 2003). A hydrological assessment identifies ground water sources of suitable quality and adequate long-term supply. When replacing an existing well, the costs will also include connecting the well to the existing water distribution system.

The interconnection option involves laying a pipeline to connect the affected system to the distribution network of a neighboring system that can provide adequate water that meets all applicable drinking water standards. Costs include the cost of purchased water as well as construction and maintenance of the interconnection pipeline. Pipeline costs will depend on proximity of the neighboring system, topography of the distance to be covered, and right-of-way requirements for pipes and booster pump stations.

6.2 Compliance Effectiveness

Nontreatment options achieve compliance by replacing a perchlorate-contaminated water source with an alternative water source that meets a perchlorate standard. This strategy is inherently compliant as long as the new water source is not at risk for perchlorate contamination. If the wholesale supplier of purchased water has perchlorate contamination, it must implement an effective treatment process because the water it sells must comply with the perchlorate standard before it can be distributed to the purchasing system.

6.3 Raw Water Quality Considerations

A system will need to determine whether the change in source water may affect other existing treatment processes (e.g., chlorination), or if changes in water quality may affect the distribution system (e.g., purchased water has a different pH). Changes in delivered water chemistry that result in major process additions or changes could diminish the cost-effectiveness of nontreatment options.

6.4 Pre- and Post-Treatment Needs

By definition, there are no pre-treatment needs to consider with a change in source water. All treatment adjustments to account for differences in source water quality would necessarily occur after the point of source water connection. If the alternative water source has chemical parameters that differ substantially from the original source water and may affect water quality elsewhere in the system, then there may be "post-treatment" needs to adjust water chemistry.

6.5 Waste Generation and Residuals Management Needs

An interconnection or new well should not have incremental wastes or residuals requiring management.

6.6 Critical Design Parameters

For new wells, key design parameters are the following:

- Total flow rate requirements and flow per well
- Well depth (and screened depth)
- Pump type
- Distance from well to distribution system.

For an interconnection option, key design parameters include:

- Flow rate requirements
- Distance to interconnection water supply
- Pressure at water supply source
- Cost of purchased water.

Chapter 7 discusses each of these parameters in more detail and identifies the specific values for each used in EPA's cost estimates.

7 Costs for Treatment Technologies and Nontreatment Options

Note: The technologies evaluated here can achieve very high perchlorate removal efficiencies (e.g., 95 percent or greater). Given the high efficiencies, EPA assumes systems will blend treated water and untreated water to meet the MCL. Accordingly, the costs presented here reflect systems designed and operated to take advantage of the technologies' high removal effectiveness and the cost curves should be applied to design and average flows adjusted to account for the blending rate, as discussed in the following paragraphs.

A blending rate is the proportion of influent water that has to be treated. For example, a blending rate of 0.6 means 60 percent of the water is treated and then blended with 40 percent untreated water. This rate depends on baseline perchlorate concentration, the treatment target concentration, and the removal efficiency of the treatment process (i.e., the percent of baseline perchlorate removed during treatment). For a treatment efficiency of 95 percent (or 0.95), the following equation defines the treatment target concentration of perchlorate (P_t) as a weighted average of the baseline concentration (P_b) and the treated water concentration [P_b x (1-0.95)] where the weights – based on the blending rate, B – are (1-B) for the untreated water and B for the treated water:

$$P_t = (1 - B) \times P_b + \ B \times (P_b \times (1 - 0.95)).$$

Rearranging terms to solve for B (the blending rate) shows that the blending rate increases when the baseline concentration increases or the treatment target concentration decreases.

$$B = \frac{(P_b - P_t)}{P_b \times 0.95}$$

The cost curves presented here use the <u>treatment process flow</u> as the independent variable. Treatment process flow can be calculated from entry point flow by incorporating the blending rate (B) as follows:

$$Treatment\ Process\ Flow = B \times Entry\ Point\ Flow.$$

7.1 Introduction

7.1.1 Overview and Cost Modeling Approach

This chapter presents estimated costs for installing and operating the technologies and nontreatment options discussed in Chapters 2 through 6. Based on the information in those chapters, particularly the data on engineering design specifications, EPA developed work breakdown structure (WBS) cost estimating models for each of the perchlorate treatment technologies. The WBS models are spreadsheet-based engineering models for individual treatment technologies, linked to a central database of component unit costs. EPA developed the WBS model approach as part of an effort to address recommendations made by the Technology Design Panel (TDP), which convened in 1997 to review the Agency's methods for estimating drinking water compliance costs (USEPA, 1997).[7] In general, the WBS approach involves breaking a process down into discrete components for the purpose of estimating unit costs. The WBS models represent improvements over past EPA cost estimating methods by increasing comprehensiveness, flexibility, and transparency. By adopting a WBS-based approach to identify the components that should be included in a cost analysis, the models produce a more comprehensive assessment of the capital and operating requirements for a treatment system. The documentation for the individual WBS models (USEPA, 2007; 2017a; 2017b; 2017c; 2019) provides complete details on the structure, content, and use of the models. EPA used the WBS models to develop the costs presented in this chapter. The models and their documentation can be accessed at: https://www.epa.gov/dwregdev/drinking-water-treatment-technology-unit-cost-models-and-overview-technologies.

The remainder of this section provides a brief overview of the common elements of all the WBS models and information on the anticipated accuracy of the resulting cost estimates. Subsequent sections describe how EPA used each individual technology-specific WBS model to estimate costs for perchlorate treatment and present the resulting cost estimates.

7.1.2 Work Breakdown Structure Models

Each WBS model contains the work breakdown for a particular treatment process and preprogrammed engineering criteria and equations that estimate equipment requirements for user-specified design requirements (e.g., system size and influent water quality). Each model also provides unit and total cost information by component (e.g., individual items of capital equipment) and totals the individual component costs to obtain a direct capital cost. Additionally, the models estimate add-on costs (permits, pilot study, and land acquisition costs for each technology), indirect capital costs, and annual operation and maintenance (O&M) costs, thereby producing a complete compliance cost estimate.

Primary inputs common to all of the WBS models include design flow and average flow in MGD. Each WBS model has default designs (input sets) that correspond to the eight standard flow sizes in EPA's flow characterization paradigm for public water systems (see **Exhibit 7-1**), but the models can generate designs for many other combination of flows. To estimate costs for perchlorate compliance, EPA fit cost curves to the WBS estimates for up to 49 different flow rates.[8] Thus, the cost estimates in Sections 7.2 through 7.6 and Appendix B are in the form of equations.

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[7] The TDP consisted of nationally recognized drinking water experts from U.S. EPA, water treatment consulting companies, public and private water utilities and suppliers, equipment vendors, and Federal and State regulators in addition to cost estimating professionals.

[8] Specifically, for each scenario modeled and separately for total capital and for O&M costs, EPA fit up to three curves: one covering small systems (less than 1 MGD design flow), one covering medium systems (1 MGD to less than 10 MGD design flow), and one covering large systems (10 MGD design flow and greater). For each curve fit, EPA chose from among several possible equation forms: linear, quadratic, cubic, power, exponential, and logarithmic. EPA chose the form that resulted in the best correlation coefficient (R^2), subject to the requirement that the equation must be monotonically increasing over the appropriate range of flow rates (i.e., within the flow rate category, the equation must always result in higher estimated costs for higher flow systems than for lower flow systems).

Exhibit 7-1. Model Size Categories Based on EPA's Flow Characterization Paradigm

Size Category	Population Served	Design Flow (MGD)	Average Flow (MGD)
1	25 to 100	0.030	0.007
2	101 to 500	0.124	0.035
3	501 to 1,000	0.305	0.094
4	1,001 to 3,300	0.740	0.251
5	3,301 to 10,000	2.152	0.819
6	10,001 to 50,000	7.365	3.200
7	50,001 to 100,000	22.614	11.087
8	Greater than 100,000	75.072	37.536

Another input common to all of the WBS models is "component level" or "cost level." This input drives the selection of materials for items of equipment that can be constructed of different materials. For example, a low cost system might include fiberglass pressure vessels and PVC piping. A high cost system might include stainless steel pressure vessels and stainless steel piping. The component level input also drives other model assumptions that can affect the total cost of the system, such as building quality and heating and cooling. The component level input has three possible values: low cost, mid cost, and high cost. To estimate costs for perchlorate compliance, EPA generated separate cost curves for each of the three component levels, thus creating a range of cost estimates for use in national compliance cost estimates.

The third input common at all of the WBS models is system automation, which allows the design of treatment systems that are operated manually or with varying degrees of automation (i.e., with control systems that reduce the need for operator intervention). The cost estimates in the technology-specific sections below are for systems that are fully automated, minimizing the need for operator intervention and reducing operator labor costs.

The WBS models generate cost estimates that include a consistent set of capital, add-on, indirect, and O&M costs. **Exhibit 7-2** identifies these cost elements, which are common to all of the WBS models and included in the cost estimates below. The exhibit also provides references for further information on the methods and assumptions used in the WBS models to estimate the costs for each of these cost elements.

7.1.3 WBS Model Accuracy

Costs for a given system can vary depending on site-specific conditions (e.g., raw water quality, climate, local labor rates, and location relative to equipment suppliers). The costs presented here are based on national average assumptions and include a range (represented by low, mid, and high cost curves) intended to encompass the variation in costs that systems would incur to remove perchlorate. To validate the engineering design methods used by the WBS models and increase the accuracy of the resulting cost estimates, EPA has subjected the individual models to a process of external peer review by nationally recognized technology experts.

The anion exchange model underwent peer review in 2005, during an early stage of its development. One peer reviewer responded that resulting cost estimates were in the range of budget estimates (+30 to -15 percent). The other two reviewers thought anion exchange estimates were order of magnitude estimates (+50 to -30 percent), with an emphasis on the estimates being high. The anion exchange model has since undergone extensive revision, both in response to the peer review and to adapt it for perchlorate treatment (see Section 7.2, below).

The RO/NF model underwent peer review in 2007. The majority of peer reviewers who evaluated the model expressed the opinion that resulting cost estimates would be in the range of budget estimates (+30 to -15 percent). The RO/NF model has since undergone substantial revision in response to the peer review comments.

The biological treatment model underwent peer review in early 2012. One reviewer thought the model underestimated O&M costs by 20 to 30 percent (which would be in the range of an order of magnitude estimate), but overestimated capital costs by about 25 percent (which would be in the range of a budget estimate). A second reviewer responded that direct capital costs were at the fringes of a budget estimate (+30 to -15 percent), while total capital costs were in the order of magnitude range (+50 to -30 percent) or possibly even better, in the budget estimate range. This reviewer’s conclusions about total capital costs were based on comparison to preliminary costs for a plant currently under construction, for which the model underestimated costs. The final reviewer responded that costs were budget estimates (+30 to -15 percent). The biological treatment model has since undergone revision in response to the peer review comments.

The POU model underwent peer review in 2006. Reviewers felt that the default assumptions may tend to overstate “out-of-pocket” costs to systems because very small systems could use volunteers to perform some tasks. While this may be true, EPA’s model is designed to estimate the opportunity costs for a successful POU program that is consistent with EPA POU Guidance, which does not include volunteers. The POU model has since been revised in response to the peer review comments.

EPA received peer review comments on the nontreatment model in May 2012. The first reviewer responded that cost estimates resulting from the nontreatment model were in the range of budget estimates (+30 to -15 percent). The second reviewer thought the cost estimates were order of magnitude estimates (+50 to -30 percent). The third reviewer felt the cost estimates were definitive (+15 to -5 percent), except for land costs, which were difficult to assess due to regional variations. Revision of the nontreatment model in response to the peer review comments was recently completed.

Exhibit 7-2. Cost Elements Included in All WBS Models

Cost Category and Components Included	For Further Information
Direct Capital Costs	
• Technology-specific equipment (e.g., vessels, basins, pumps, blowers, treatment media, piping, valves)	Technology-specific sections below
• Instrumentation and system controls	USEPA (2017a; 2017b; 2017c; 2019), Appendix A
• Buildings	USEPA (2017a; 2017b; 2017c; 2019), Appendix B
• Residuals management equipment	USEPA (2017a; 2017b; 2017c; 2019), Appendix C
Add-on Costs	
• Land • Permits • Pilot testing	USEPA (2017a; 2017b; 2017c; 2019), Chapter 2
Indirect Capital Costs	
• Mobilization and demobilization • Architectural fees for treatment building • Equipment delivery, equipment installation, and contractor's overhead and profit • Sitework • Yard piping • Geotechnical • Standby power • Electrical infrastructure • Process engineering • Contingency • Miscellaneous allowance • Legal, fiscal, and administrative • Sales tax • Financing during construction • Construction management	USEPA (2017a; 2017b; 2017c; 2019) Appendix D
O&M Costs	
• Operator labor for technology-specific tasks (e.g., managing regeneration, backwash, or media replacement) • Materials for maintenance and operation of technology-specific equipment • Replacement of technology-specific equipment that occurs on an annual basis (e.g., treatment media) • Energy for operation of technology-specific items of equipment (e.g., blowers, mixers)	Technology-specific sections below
• Operator labor for operation and maintenance of process equipment • Operator labor for building maintenance • Managerial and clerical labor • Materials for maintenance of booster or influent pumps • Materials for building maintenance • Energy for operation of booster or influent pumps • Energy for lighting, ventilation, cooling, and heating	USEPA (2017a; 2017b; 2017c; 2019), Appendix E
• Residuals management operator labor, materials, and energy • Residuals disposal and discharge costs	USEPA (2017a; 2017b; 2017c; 2019), Appendix C

7.2 Costs for Ion Exchange

7.2.1 Model Components and Assumptions

USEPA (2017b) provides a complete description of the engineering design process used by the WBS model for perchlorate ion exchange. The perchlorate ion exchange model can estimate costs for removing perchlorate using any of the following resin types described Chapter 2: strong-base polyacrylic, strong-base polystyrenic, nitrate-selective, and perchlorate-selective.[9] In addition to the common WBS direct capital cost items listed in **Exhibit 7-2**, the ion exchange model for perchlorate includes the following technology-specific equipment:

- Booster pumps for influent water
- Pressure vessels that contain the anion resin bed
- Tanks and pumps for backwashing the vessels
- Tanks, mixers, and eductors for delivering the solution used in regenerating the resin (if regeneration is used)
- Pre-treatment cartridge filters
- Tanks and pumps for post-treatment corrosion control (optional)
- Equipment for managing residuals (spent backwash, spent resin, and, potentially, spent regenerant)
- Associated piping, valves, and instrumentation.

The ion exchange model for perchlorate also adds the following technology-specific O&M elements:

- Operator labor for resin changeouts
- Operator labor for regeneration (if regeneration is used)
- Spent resin replacement and disposal
- Labor and replacement cartridges for pre-treatment filters
- Chemical usage (if corrosion control or regeneration is used).

For small systems (less than 1 MGD), the ion exchange model for perchlorate assumes the use of package treatment systems that are pre-assembled in a factory, mounted on a skid, and transported to the site. The model estimates costs for package systems by costing all individual equipment line items (e.g., vessels, interconnecting piping and valves, instrumentation, and system controls) in the same manner as custom-engineered systems. This approach is based on vendor practices of partially engineering these types of package plants for specific systems (e.g., selecting vessel size to meet flow and treatment criteria). The model applies a variant set of design inputs and assumptions that are intended to simulate the use of a package plant and that reduce the size and cost of the treatment system. USEPA (2017b) provides complete details on the variant design assumptions used for package plants.

The paragraphs below describe the specific inputs and assumptions that EPA used to generate the costs in Section 7.2.2. These inputs assume treatment with perchlorate breakthrough defined so

[9] The input also allows for selection of an alternative resin type, by entering appropriate design assumptions for their resin and selecting “Alternative resin (user defined)” for this input.

that the treatment process maintains a minimum of 95 percent removal. Other inputs and assumptions not discussed below (e.g., number of booster pumps, treated water corrosion control, bed expansion) remained as described in USEPA (2017b).

Resin Type

As noted above, the perchlorate ion exchange model can estimate costs for removing perchlorate using several different resin types. Based on the information in Section 2.2 and **Exhibit 2-5**, however, EPA believes that any new ion exchange facilities removing perchlorate will use perchlorate-selective resin. Therefore, the cost estimates below assume the use of perchlorate-selective resin and, accordingly, the paragraphs below describe the inputs and assumptions associated with perchlorate-selective resins only.

Regeneration or Throwaway Operation

The perchlorate ion exchange model has an option to design and estimate costs for a system either with or without regeneration capability. As discussed in Section 2.5, nearly all of the full-scale facilities using perchlorate-selective resin rely on disposal instead of regeneration. Therefore, the cost estimates below assume throwaway operation.

Number of Bed Volumes before Regeneration/Throwaway

The perchlorate ion exchange model requires entry of the number of bed volumes before perchlorate breakthrough. System configuration (i.e., parallel or series operation) can have a significant effect on bed volumes to breakthrough. As discussed below, the model default assumption is series (lead-lag) operation. The data shown in **Exhibit 2-6** are for initial perchlorate breakthrough using a single resin column. Studies of the capacity of the older perchlorate-selective resin (Gu et al., 1999) found breakthrough in a lead column after 40,000 BV. Using a second (lag or polishing) column increased the resin's capacity to approximately 104,000 BV. Similar studies of the performance of the new resins in a lead-lag configuration are not available.

Given the lack of precise data on the performance of the new resins in a lead-lag configuration and given expected site-specific variations in water quality (e.g., concentrations of competing anions), the cost estimates below consider two scenarios for bed life. Although one of the scenarios assumes a longer bed life than the other (meaning better performance and lower costs), both scenarios are designed to be conservative (erring on the site of higher costs).

The first scenario assumes an increase in capacity of the new resins from lead-lag operation similar to that observed for the older resin. This scenario starts from the <u>lowest</u> single-column capacity (about 100,000 BV) observed for any of the new resins in several pilot studies (Blute et al., 2006; Russell et al., 2008; Wu and Blute, 2010). It multiplies this capacity by 2.5 (the approximate increase observed for the older resin in Gu et al., 1999) to account for lead-lag operation. This calculation results in 250,000 BV to breakthrough. The second scenario starts from the highest single-column capacity (about 170,000 BV) observed for any of the new resins the pilot studies, but assumes <u>no increase in capacity from lead-lag operation</u>. Thus, the second scenario assumes 170,000 BV to breakthrough.

Number of Vessels in Series (parallel or series operation)

As discussed in Section 2.6, series (lead-lag) operation is generally recommended for perchlorate removal. Therefore, the cost estimates below assume two vessels in series.

Theoretical Total Empty Bed Contact Time

As discussed in Section 2.6, recommended EBCTs for perchlorate-selective resins are 1.5 minutes per vessel and less. Therefore, the cost estimates below assume a total EBCT of 3 minutes (which corresponds to 1.5 minutes per vessel, given two vessels in series).

Backwash System Design

The perchlorate ion exchange model assumes that periodic backwashing during operation is not required when throwaway operation is chosen. It does, however, assume an initial rinse is required during resin installation. Therefore, for systems of 1 MGD design flow and larger the cost estimates below include the cost of equipment (pumps and storage tanks) to accomplish this initial rinse. For small systems, the cost estimates assume the initial rinse can be accomplished using existing equipment.

Residuals Management

The perchlorate ion exchange model includes the option to dispose of spent resin by incineration.[10] As discussed in Section 2.5.1, a number of full-scale facilities dispose of their spent perchlorate-selective resin by incineration. Although incineration is a more expensive option than landfill disposal, the overall impact on operating costs is small. Incineration increases model cost estimates by approximately $0.01 per thousand gallons of treated water produced, which is less than 3 percent of the total cost of treatment even for the largest systems. Therefore, the cost estimates below assume disposal by incineration, although some systems might have the slightly cheaper option of landfill disposal available. They assume that spent rinse water from the initial resin rinse is discharged to a POTW.

Surface Loading Rate

As discussed in Section 2.6, maximum surface loading rates vary by resin type. Based on the data presented in Section 2.6 and comments from the experts who reviewed initial drafts of this document (Blute, 2012; Drago, 2012; Meyer, 2012), EPA chose a maximum surface loading rate of 12 gpm/ft^2 for perchlorate-selective resin. The cost estimates below incorporate this assumption.

Regeneration Solution Type and Assumptions

The perchlorate ion exchange model incorporates the option to regenerate selective resins using the novel tetrachloroferrate regeneration solution discussed in Section 2.5.2. Specifically, when regeneration is chosen for nitrate- or perchlorate-selective resins, the model assumes the use of

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[10] This option is activated by entering the cost of incineration under “Alternate media disposal cost (including transportation)” in the O&M assumptions module of the perchlorate version of the ion exchange model. When a value is present for this assumption, the model uses this unit cost in estimating total non-hazardous waste disposal cost. If this assumption is left blank, the model uses the default unit cost from the central WBS database, which reflects disposal in an off-site non-hazardous waste landfill.

tetrachloroferrate solution. When regeneration is chosen for non-selective strong-base polyacrylic or polystyrenic resins, the model assumes the use of conventional brine solution. The selection of resin type also controls the values of a number of critical design assumptions relevant to each regeneration process (e.g., brine concentration, tetrachloroferrate solution strength, regeneration time). The cost estimates below, however, assume throwaway operation and, therefore, do not incorporate these assumptions.

7.2.2 Cost Estimates

The graphs below plot WBS cost model results in 2017 dollars at the mid cost level for removal of perchlorate from groundwater using perchlorate-selective ion exchange, assuming 250,000 BV to breakthrough (**Exhibit 7-3**) and 170,000 BV to breakthrough (**Exhibit 7-4**). The costs assume treatment with perchlorate breakthrough defined so that the treatment process maintains a minimum of 95 percent removal. The flow rates shown on the x-axes and as independent variables in the equations are treatment process flows. To account for blending, treatment process flows should be calculated from entry point flows by incorporating a blending rate as discussed in the introduction to this chapter.

In these exhibits, note that costs increase at 1 MGD design flow (0.355 MGD average flow) because of the transition from package systems (used by small systems) to custom-engineered systems (used by large systems). Appendix B provides complete cost equations for both bed life scenarios, including the high, mid, and low cost levels and for treatment of groundwater and surface water. Appendix C presents example WBS model outputs at selected flow rates, allowing review of individual cost line items.

Exhibit 7-3. Mid Cost Results for Removal of Perchlorate from Groundwater Using Perchlorate-Selective Ion Exchange with 250,000 BV to Breakthrough (2017 dollars)

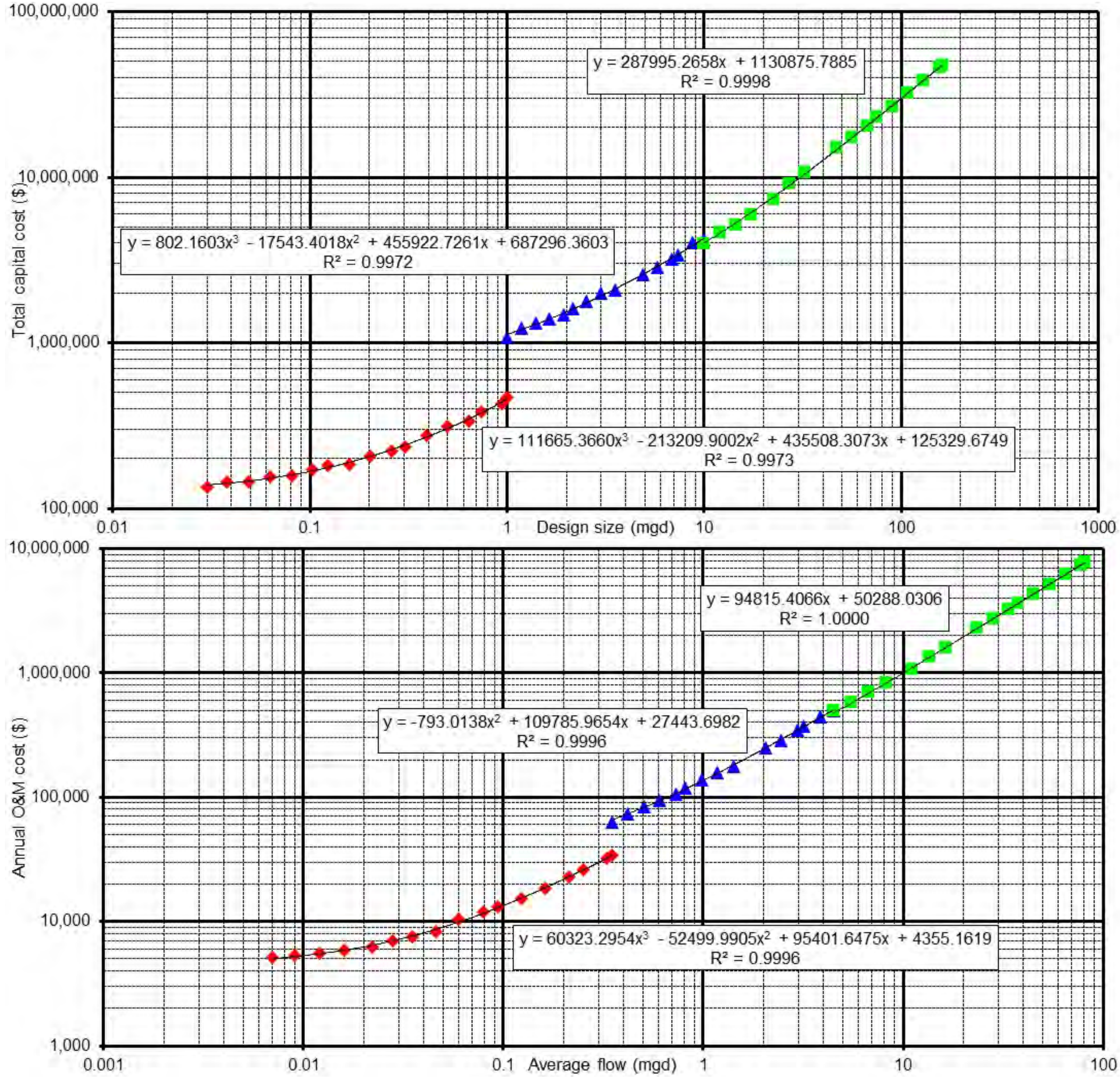
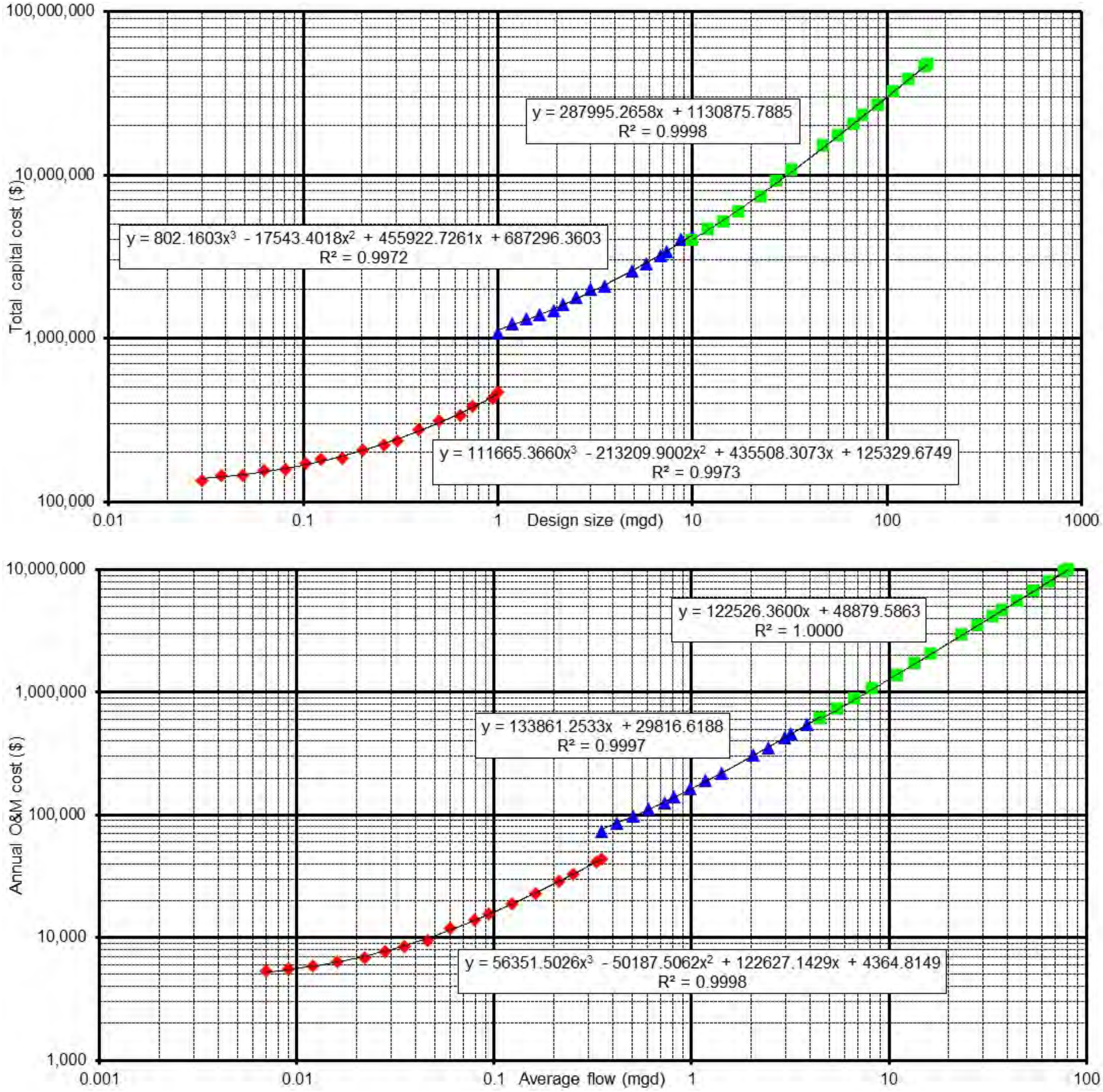


Exhibit 7-4. Mid Cost Results for Removal of Perchlorate from Groundwater Using Perchlorate-Selective Ion Exchange with 170,000 BV to Breakthrough (2017 dollars)



7.3 Costs for Biological Treatment

7.3.1 Model Components and Assumptions

USEPA (2017a) provides a complete description of the engineering design process used by the WBS model for biological treatment. The biological treatment model can estimate costs for three types of bioreactor designs:

- Fixed media bed pressure vessels
- Fixed media bed gravity basin
- Fluidized bed pressure vessels.

In addition to the common WBS direct capital cost items listed in **Exhibit 7-2**, the biological treatment model includes the following technology-specific equipment:

- Booster pumps for influent water
- Equipment (e.g., tanks, pumps) for electron donor addition
- Equipment (e.g., tanks, pumps) for nutrient addition
- Bioreactors (either pressure vessels or concrete basins) that contain the GAC media bed
- Tanks, pumps, and blowers for backwashing the bioreactors (fixed bed designs only) and post-treatment filters (if used)
- Pumps for recycled water (fluidized designs only)
- Blowers for biomass separation (fluidized designs only)
- Equipment for post-treatment aeration or hydrogen peroxide addition (optional)
- Post-treatment coagulant addition and mixed media filtration (optional)
- Equipment for managing residuals (spent backwash)
- Associated piping, valves, and instrumentation (including online perchlorate and nitrate analysis instruments).

The biological treatment model also adds the following technology-specific O&M elements:

- Operator labor for managing backwashes
- Operator labor and materials for maintaining concrete basins (gravity designs only)
- Operator labor and materials for maintaining backwash pumps and air scour blowers (and biomass removal blowers for fluidized bed designs)
- Chemical usage for electron donor and nutrient addition (and post-treatment hydrogen peroxide addition, if used)
- Coagulant and polymer usage for spent backwash treatment (and post-treatment filtration, if used)
- Attrition loss replacement for bioreactor media (and post-treatment filter media, if used)
- Consumables used in online perchlorate and nitrate analysis.

For small systems (less than 1 MGD), the biological treatment model applies a set of design inputs and assumptions that reduce the size and cost of the treatment system relative to larger systems. Some of these small system assumptions are similar to those used for package plants in the ion exchange model (e.g., skid-mounted pressure vessels, reduced need for booster pumping). Because package plants are not currently available for biological treatment, however, the biological treatment model assumptions do not differ as greatly between small and large systems. USEPA (2017a) provides complete details on the variant design assumptions used for small systems.

The paragraphs below describe specific inputs and assumptions that EPA used to generate the costs in Section 8.3.2. Other inputs and assumptions not discussed below (e.g., number of booster pumps, bioreactor dimensions) were as described in USEPA (2017a).

Electron Donor Type

The biological treatment model allows the user to select between acetic acid and ethanol as the electron donor type. As discussed in Section 3.6, these are the most common electron donors used in full-scale biological systems treating perchlorate. The cost estimates below assume acetic acid as the electron donor.

Electron Donor Dose

As discussed in Section 3.6, electron donor dose is typically determined using pilot studies along with stoichiometric calculations. The biological treatment model requires the user to input the electron donor dose. For comparison purposes, the user can enter raw waster quantities of perchlorate, nitrate, and dissolved oxygen and the model will display the results of stoichiometric calculations using the site-specific equations discussed in Section 3.6. The cost estimates below assume 10 mg/L of acetic acid.

Nutrient Requirements

The biological treatment model includes four options for nutrient addition:

- no additional nutrients required
- additional nitrogen required
- additional phosphorous required
- both nitrogen and phosphorous required.

For designs that require additional nutrients, the model prompts the user to input doses for ammonium chloride and/or phosphoric acid. Based on comments from the peer review of the biological treatment model, the cost estimates below assume additional phosphorous is required and achieved using 1 mg/L (measured as phosphorus) of phosphoric acid.

Empty Bed Contact Time/Hydraulic Residence Time

The biological treatment model uses EBCT in sizing fixed bed bioreactors and HRT in sizing fluidized bed bioreactors. As discussed in Section 3.6, typical full-scale bioreactor designs have an EBCT/HRT in the range of 10 to 12 minutes for both fixed bed (U.S. DoD, 2008a) and fluidized bed reactors (Harding Engineering and Environmental Services, 2001). The cost estimates below assume an EBCT/HRT value of 12 minutes.

Interval between Backwashes

For fixed bed bioreactors, the biological treatment model requires the user to input the interval between backwashes.[11] For designs that include post-treatment filters (see below), the model requires a separate backwash interval for these filters. The cost estimates below assume backwash intervals of 24 hours for fixed bed bioreactors and 36 hours for post-treatment filters.

Post-Treatment Options

Biological treatment results in the production of soluble microbial organic products that become part of the treated water. The biological treatment process also depletes the levels of oxygen in the treated water. Therefore, based on peer review comments, post-treatment will be required for production of drinking water. The biological treatment model allows users to choose whether to include post-treatment coagulant addition and filtration for removal of turbidity, sulfide, and/or dissolved organic content. It also allows users to choose from aeration or hydrogen peroxide addition for post-treatment oxidation. The cost estimates below include post-treatment filtration with coagulant addition and aeration for post-treatment oxidation.

Although post-treatment disinfection typically is needed following biological treatment, disinfection is required for most water systems regardless of whether perchlorate treatment is present. Therefore, the costs of disinfection are not attributable exclusively to perchlorate compliance. Accordingly, the cost estimates below do not include post-treatment disinfection; they assume that existing disinfection facilities are sufficient and located appropriately.

Fluidized Bed Expansion

Based on peer review comments on the biological treatment model, the cost estimates below assume bed expansion of 70 percent for fluidized beds. They also include freeboard above the expanded bed of 4 feet for small systems (less than 1 MGD design flow) and 7 feet for larger systems (1 MGD and greater).

Fluidized Bed Recycle Rate

Based on peer review comments on the biological treatment model, the cost estimates below assume a recycle rate of 50 percent for fluidized beds.

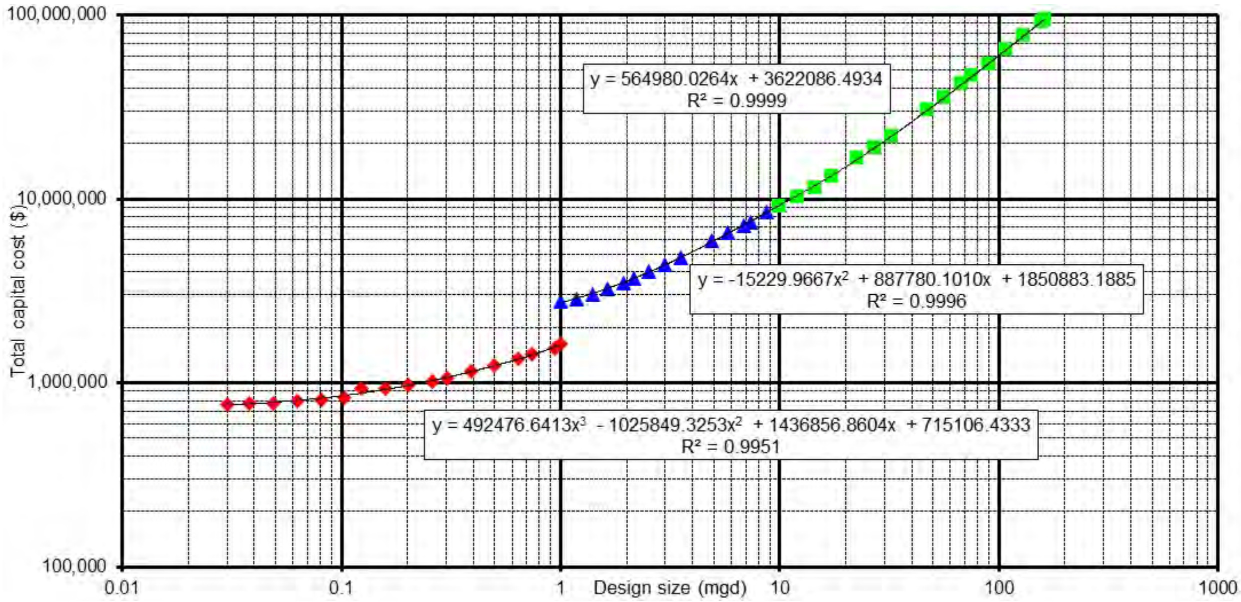
7.3.2 Cost Estimates

The graphs below plot WBS cost model results in 2017 dollars at the mid cost level for removal of perchlorate from groundwater using biological treatment with fixed bed pressure vessels (**Exhibit 7-5**), fixed bed gravity basins (**Exhibit 7-6**), and fluidized bed pressure vessels (**Exhibit 7-7**). In the exhibits, note that costs increase at 1 MGD design flow (0.355 MGD average flow) because of the change in assumptions used for small systems versus those for large systems. Appendix B provides complete cost equations for all three design types, including the high, mid, and low cost levels and for treatment of groundwater and surface water. Appendix C

[11] For fluidized bed bioreactors, the model uses a continuous biomass separation device consisting of a blower to agitate excess biomass and send it out of the bioreactor in the effluent, so no such interval is needed.

presents example WBS model outputs for selected flow rates, allowing review of individual cost line items.

Exhibit 7-5. Mid Cost Results for Removal of Perchlorate from Groundwater Using Biological Treatment with Fixed Bed Pressure Vessels (2017 dollars)



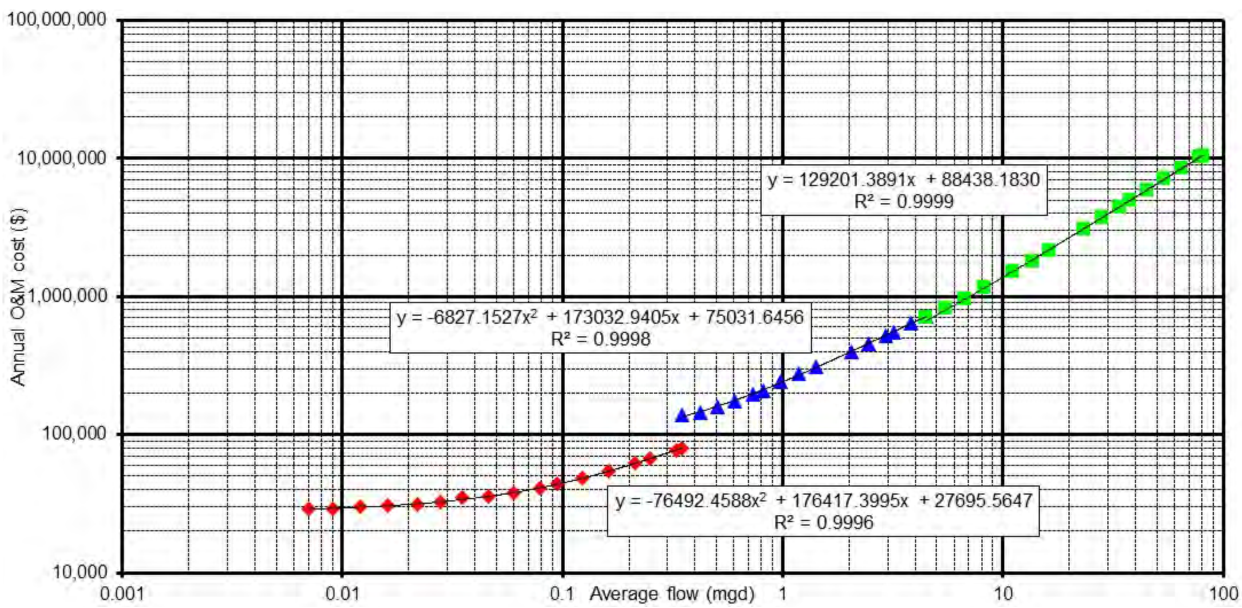


Exhibit 7-6. Mid Cost Results for Removal of Perchlorate from Groundwater Using Biological Treatment with Fixed Bed Gravity Basins (2017 dollars)

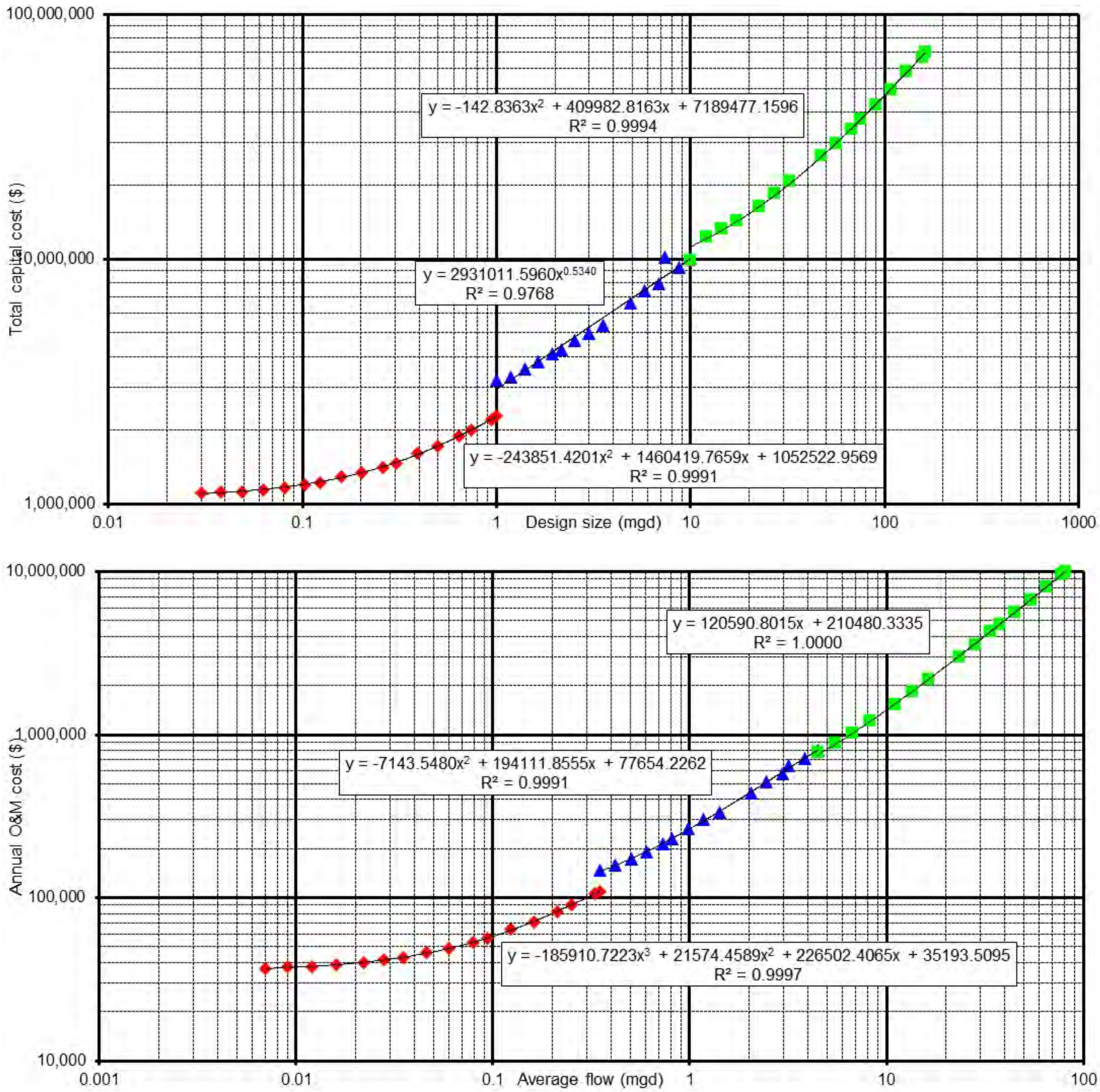
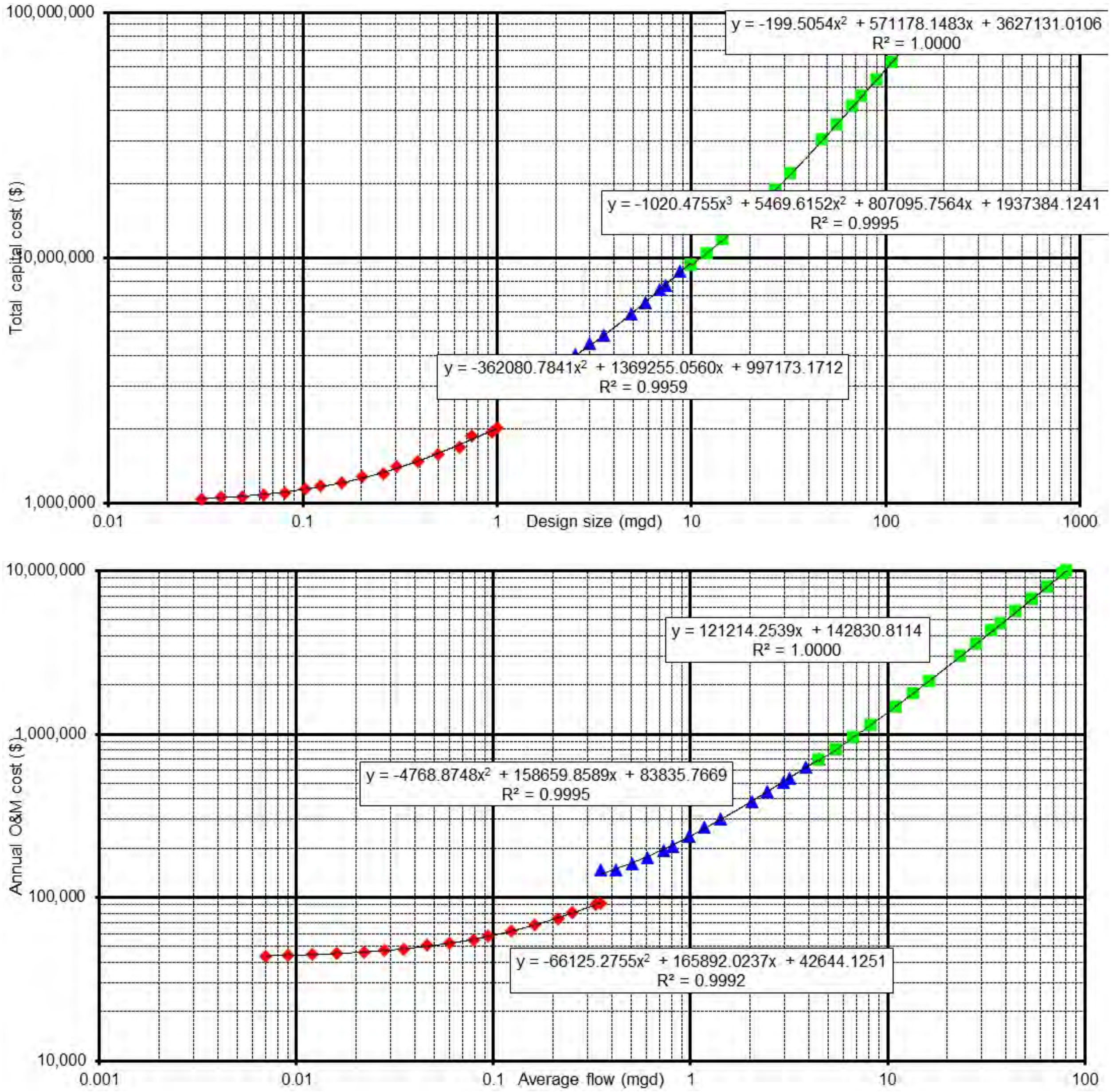


Exhibit 7-7. Mid Cost Results for Removal of Perchlorate from Groundwater Using Biological Treatment with Fluidized Bed Pressure Vessels (2017 dollars)



7.4 Costs for Reverse Osmosis

7.4.1 Model Components and Assumptions

USEPA (2019) provides a complete description of the engineering design process used by the WBS model for RO/NF. The model can estimate costs for a multistage RO installation, based on an input water quality analysis and treatment parameters. Although it is also capable of estimating costs for NF, the model was used here specifically for RO, because that membrane technology showed the most promise for removing perchlorate. As discussed in Chapter 4, NF (and UF) demonstrated widely varying removal of perchlorate.

In addition to the common WBS direct capital cost items listed in **Exhibit 7-2**, the RO model includes the following technology-specific equipment:

- Pressure vessels, membrane elements, piping, valves, connectors, and steel structure for the membrane racks
- High-pressure pumps for influent water and (optionally) interstage pressure boost
- Valves for concentrate control and (optionally) per-stage throttle
- Cartridge filters for pretreatment
- Tanks, pumps, and mixers for pretreatment chemicals
- Tanks, pumps, screens, cartridge filters, and heaters for membrane cleaning
- Equipment for managing RO concentrate and spent cleaning chemicals
- Associated pipes, valves, and instrumentation.

The RO model also includes the following technology-specific O&M elements:

- Operator labor and replacement elements for pretreatment cartridge filters
- Chemical usage for pretreatment
- Labor and materials for routine operation and maintenance of membrane units
- Energy for high-pressure pumping
- Replacement of membrane elements
- Labor, materials, and chemical usage for membrane cleaning
- Disposal costs for spent cartridge filters and membrane elements
- Fee for disposal of concentrate at a POTW (if POTW disposal is selected).

The paragraphs below describe specific inputs and assumptions that EPA used to generate the costs in Section 8.4.2. Other inputs and assumptions not discussed below (e.g., cleaning interval, permeate throttling and interstage boost, membrane life) were as described in USEPA (2019).

Water Type

As described in Section 4.6, the composition of the feed water affects pretreatment and cleaning requirements, the range of permissible RO train design parameters, and energy usage for pumping. The WBS model includes three default ground waters and three default surface waters, ranging from high to low quality (i.e., from low to high total dissolved solids and scaling potential). The particular water parameters are based on a survey of membrane feed water characteristics in the literature. The cost estimates below and in Appendix B are intended to reflect the incremental cost of removing perchlorate from otherwise deliverable water using RO. Therefore, they use the default high quality water parameters built in to the WBS model. Total dissolved solids for the high quality surface water is approximately 360; for high quality ground water, total dissolved solids is approximately 500 mg/L. USEPA (2019) documents the other relevant characteristics of these default waters.

Membrane Element

The WBS model includes the option of NF, low-pressure RO, or brackish water RO membrane elements, with a diameter of 4 inches, 8 inches, or 16 to 18 inches. (Not all manufacturers use the same size for their largest diameter elements, but the model is independent of the exact diameter.) Since not all NF membranes are effective for perchlorate treatment, the cost estimates below assume use of low-pressure RO membrane elements, consistent with the type of elements shown to be effective by Liang et al. (1998). For very small systems, the cost estimates use 4-inch diameter elements; above that point they use 8-inch elements. The switch from 4-inch to 8-inch elements takes place at about 75,000 gallons per day.

Recovery and Flux Rates

The WBS model takes target recovery and flux rates, and designs the reverse osmosis train to come as close as possible to them. The flux rate, in combination with the system design flow, determines the total membrane area in the system, and therefore the total number of membrane elements to be used. The recovery rate affects the number of membrane elements in series. For instance, two stages of seven elements each would give fourteen elements in series, while three stages of six elements each would give eighteen. To maintain adequate crossflow, each individual element is limited in the recovery it can achieve. Therefore, a higher recovery rate requires more elements in series.

In general, the cost estimates use recovery rates of 80 to 85 percent. At small flows, the small number of membrane elements limits flexibility in the system design; therefore, estimates up to about 500,000 gallons per day may use recovery rates as low as 70 percent.

Flux rates are based on the recommendations of various manufacturers for waters of different challenge. For ground water, the estimates use flux rates of 19 gfd. For surface water, the rates are 15 to 16 gfd.

Pretreatment

The RO model always includes 5-micron cartridge filters to protect the membrane elements from suspended solids. The cost estimates also include the addition of sulfuric acid and scale inhibitor to prevent fouling of the membrane elements.

The cost estimates include the addition of enough sulfuric acid to ensure that at least 1.5 mol/L of inorganic carbon is present in the RO permeate, to be available for alkalinity recovery; the resulting dose ranges from 16 to 45 mg/L.

While there are many scale inhibitors available, the model includes two general classes, which it calls basic antiscalant (to address calcium carbonate scaling) and premium antiscalant (to address sulfate salts and silica scaling). The cost estimates below include the addition of basic antiscalant. The antiscalant doses are sufficient to provide a dose of 15 mg/L in the concentrate, assuming that all antiscalant is retained on the feed/concentrate side of the membrane. This requirement corresponds to a feed water dose from 2.25 to 4.5 mg/L.

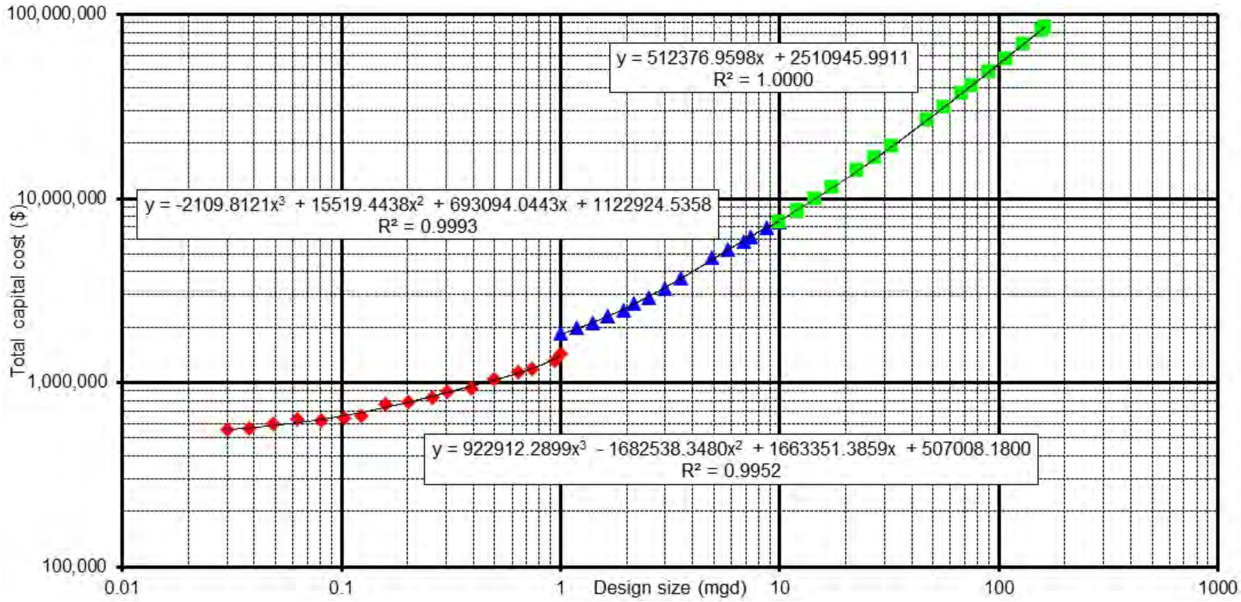
Residuals Discharge

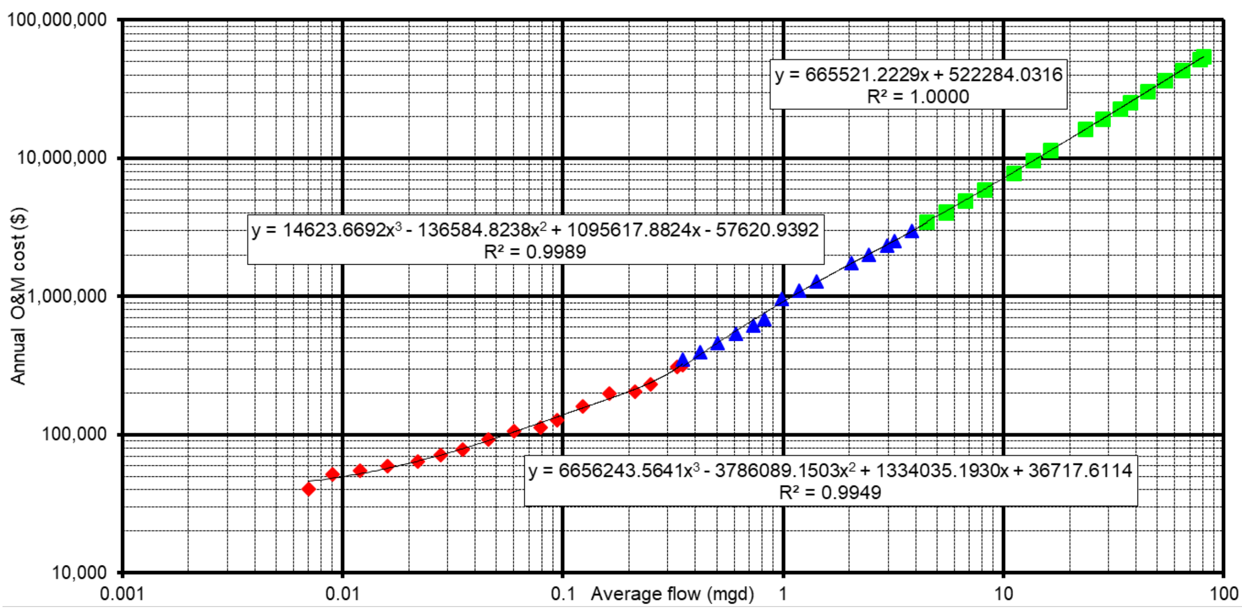
Residuals discharge is usually a major contributor to the cost of an RO facility. The RO/NF process generates two residuals streams: the membrane concentrate and spent cleaning solution. Since the spent cleaning solution is generated infrequently and in small amounts, the model assumes that it will be diluted and discharged with membrane concentrate. The cost estimates below assume the combined residuals are sent to a POTW. Although it might be impractical for most POTWs to treat very large concentrate flows, this scenario results in more conservative estimates (i.e., erring on the side of higher costs) than surface water (ocean) discharge or deep well injection.

7.4.2 Cost Estimates

The graphs below plot WBS cost model results in 2017 dollars at the mid cost level for removal of perchlorate from groundwater using RO (**Exhibit 7-8**). Appendix B provides complete cost equations, including the high, mid, and low cost levels and for treatment of groundwater and surface water. Appendix C presents example WBS model outputs for selected flow rates, allowing review of individual cost line items.

Exhibit 7-8. Mid Cost Results for Removal of Perchlorate from Groundwater Using Reverse Osmosis (2017 dollars)





7.5 Costs for Point-of-use Technologies

7.5.1 Model Components and Assumptions

The document *Cost Evaluation of Point-of-Use and Point-of-Entry Treatment Units for Small Systems: Cost Estimating Tool and User Guide* (USEPA, 2007) provides a complete description of the WBS model for POU technologies. The POU model is capable of estimating equipment costs for a variety of POU devices, including POU RO devices and replacement filters. The POU model also includes the cost of the following other components of a complete POU program:

- POU RO device installation
- Public education program development
- POU device monitoring
- POU device maintenance.

Because only small systems would be expected to use POU programs, the POU model covers only the first four size categories shown in **Exhibit 7-1**. Also, the POU model does not include assumptions or materials of construction that vary based on a "component level" or "cost level" input. Therefore, unlike the other models, it does not generate separate estimates for low-, mid-, and high-cost scenarios.

To use the POU model in estimating costs for perchlorate, EPA selected a program using RO devices. **Exhibit 7-9** identifies the values used for parameters (other than equipment costs) that drive the costs of a POU RO program. EPA developed these assumptions based on EPA Guidance (USEPA, 2006b) and case study data, as discussed in detail in the paragraphs below.

Exhibit 7-9. POU Model Assumptions for Perchlorate

Parameter Category	Value
Installation labor time	Plumber installation time: 2 hours per POU device (NSF International, 2005) Scheduling time: 0.5 hours per household (USEPA, 2006b)
Public education program	Public meeting-related time: 20 hours Other outreach time (e.g., program updates in a billing mailer): 4 hours
Monitoring requirements	Initial monitoring for all units; annual monitoring for 1/3 of units (USEPA, 2006b) Sampling time: 0.25 hours per sampling event (NSF International, 2005)
Filter replacement	Replacement schedule: RO element (3 years); post-RO carbon filter (1 year); pre-RO filters (9 months) (manufacturer recommendations) Filter replacement time: 0.5 hour per change-out (NSF International, 2005) Scheduling time: 0.5 hours per household (USEPA, 2006b)

POU RO Device Installation

Installation of the POU RO devices will be the responsibility of the water system. The utility can, however, hire a licensed plumber or representative of the product manufacturer to install the devices. Based on the variety of plumbing issues encountered among older housing units in a rural community, NSF International (2005) recommends using an experienced plumber to perform the installations.

The POU model contains a default estimate of two hours per household to install the POU RO. A variety of factors such as existing plumbing conditions and travel distance will affect installation times across sites. The estimate is consistent with case study data. In a Grimes, California, arsenic demonstration program (NSF International, 2005), POU adsorptive filter installation times ranged from 15 minutes to 3 hours depending on the accessibility of piping and the need for additional lines (e.g., to provide treated water to ice-makers). The mean device installation time was one hour, but total plumber billing records indicated that twice as much time was spent on all installation-related activities (e.g., additional time to obtain special plumbing fittings and return visits to homes when residents missed their appointments).

Installation costs also include administrative time for system staff to contact homeowners to schedule an installation appointment. EPA assumed an average of 30 minutes (0.5 hours) per household to schedule an appointment. Scheduling effort is likely to vary across customers, with some being relatively easy to schedule while others may require multiple calls to identify and contact the correct homeowners or to handle situations such as homeowner reluctance to participate or language barriers (USEPA, 2006b).

Public Education Program

EPA Guidance (2006b) recommends that systems implement a public education program to obtain and maintain customer participation and long-term customer satisfaction with the POU program. The two main program elements recommended in USEPA (2006b) are: public meetings prior to installing any POU devices to educate customers about the regulatory compliance requirements and the role of the POU devices; and POU program updates in billing mailers and on information flyers posted in public locations such as a post office, a public library, or a website. The POU model includes labor costs for the following program elements:

- preparing information for one public meeting
- attending the meeting
- preparing an additional billing mailer with program updates.

Public education program costs are not available from POU case studies. USEPA (2007) provides a detailed breakdown of the assumptions used to generate the time estimates shown in **Exhibit 7-9.** It also describes the costs for materials such as information flyers for the public meeting, meeting announcements, and billing mailers.

POU Device Monitoring

A system that implements a POU compliance strategy will need to monitor the quality of water produced by the treatment devices to demonstrate compliance with a perchlorate standard. The system will need to work with the appropriate regulatory agency to establish an approved compliance-monitoring schedule (USEPA, 2006b). The resulting monitoring schedule may have sampling rates in initial year that differ from sampling rates in subsequent years. EPA Guidance (2006b) provides an example of a monitoring schedule in which samples are taken from every unit during the first year to confirm that the units are working properly, and then monitoring frequency declines to one-third of units each subsequent year. EPA's cost estimates incorporate these monitoring frequencies.

Monitoring costs include sampling time, shipping fees, and laboratory analysis fees. The average sampling is 15 minutes (0.25 hours). To minimize the burden on households as well as system resources, EPA assumes that sampling occurs during installation or maintenance trips. The assumption is consistent with the Grimes case study cost analysis (NSF International, 2005) used an estimate of 15 minutes per sampling event.

POU Device Maintenance

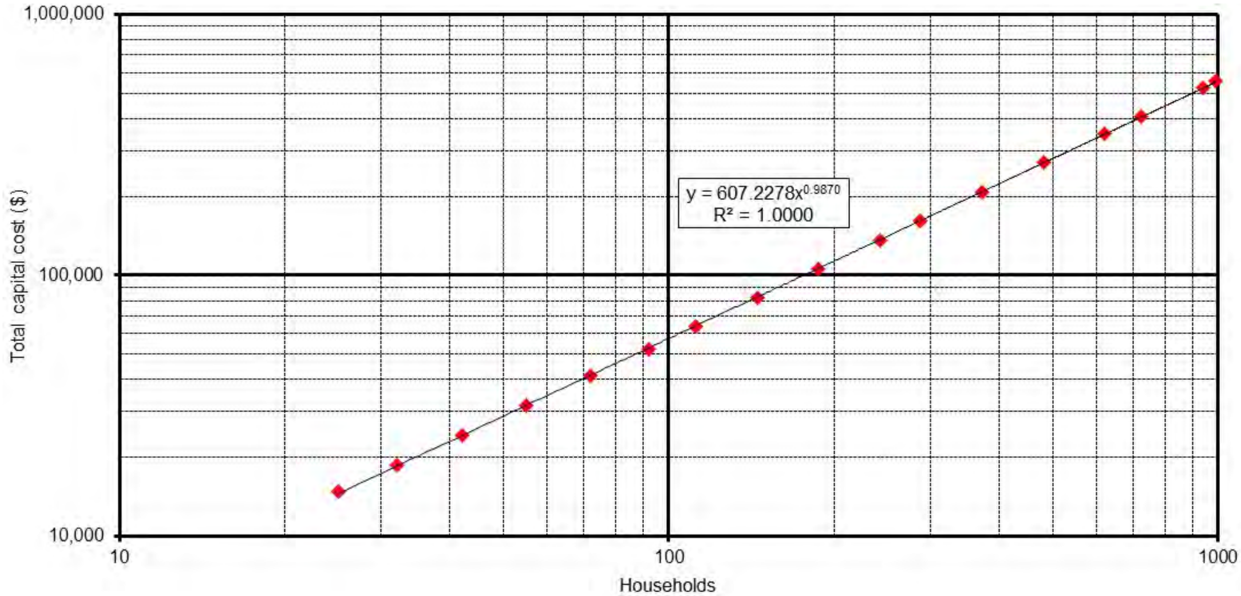
Maintenance for the POU RO device primarily includes replacing the four filters: RO membrane, two carbon filters, and the sediment filter. Replacement schedules reflect average useful lives based on vendor recommendations. On average, the RO membrane is replaced once every three years based on average replacement schedules across vendors, and the other filter cartridges are changed once per year.

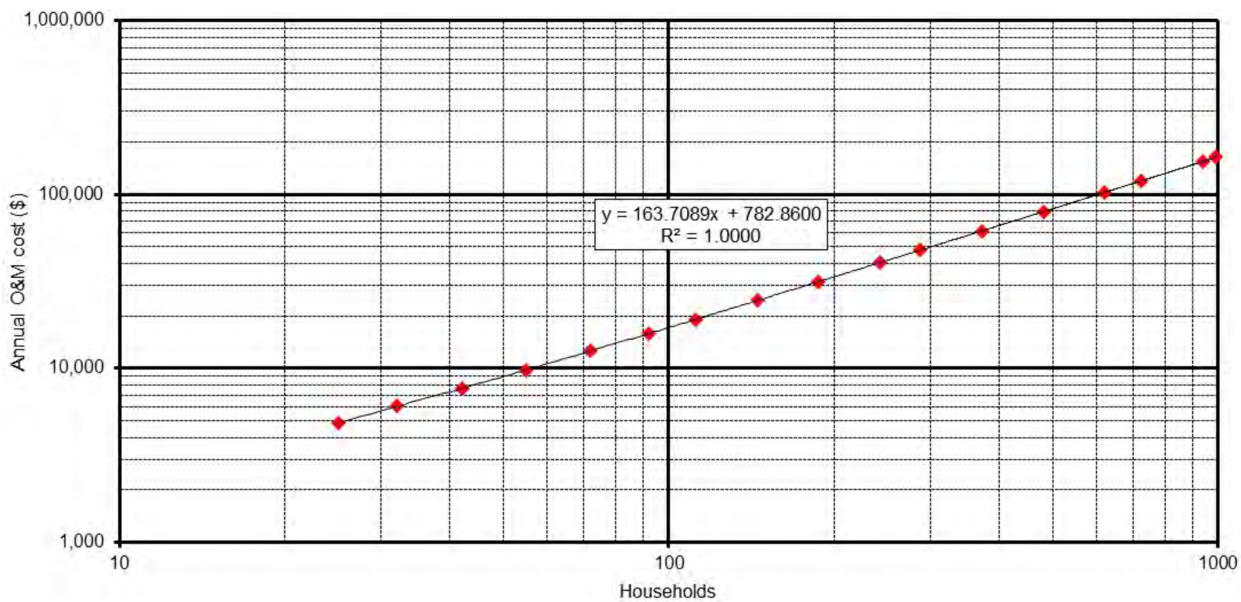
In addition to replacement filter costs, maintenance costs include scheduling time and time to change filters. The Grimes case study cost analysis (NSF International, 2005) used an estimate of 15 minutes per filter change out. EPA assumed the average length of a maintenance call 30 minutes (0.5 hours) because the most frequent type of visit involves changing two filters. EPA used the same 30-minute scheduling time assumption that it used for initial installation.

7.5.2 Cost Estimates

Exhibit 7-10 plots WBS cost model results in 2017 dollars for removal of perchlorate from groundwater using POU treatment. Note that this exhibit is plotted based on the number of households served, rather than the system flow, because number of households is the more relevant parameter for POU treatment. EPA limits the POU model to a maximum of approximately 1,000 households served because implementing and maintaining a POU program for a greater number of households is likely to be impractical. Therefore, the exhibit does not extend beyond this maximum. As discussed above, the POU model also does not generate separate high, mid, and low cost estimates. Appendix B contains complete cost equations for POU treatment, including for groundwater and surface water. For use in national cost estimating, it also contains equations on the basis of design and average flow, in addition to those on the basis of households served. Appendix C presents example WBS model outputs for selected flow rates, allowing review of individual cost line items.

Exhibit 7-10. Cost Results for Removal of Perchlorate from Groundwater Using POU Treatment (2017 dollars)





7.6 Costs for Nontreatment Options

7.6.1 Overview

USEPA (2017c) provides a complete description of the engineering design process used by the WBS model for nontreatment options. The model can estimate costs for two nontreatment options: interconnection with another system and drilling a new well to replace a contaminated one. EPA based the model components, design parameters, and default user input values on information available for nontreatment case studies and cost analyses for prior regulations (American Water Works Association, 2005; Lucey, 2008; USEPA, 1995; 2006a; 2006c). These studies involved compliance via nontreatment options for contaminants such as arsenic, volatile organic contaminants, and radionuclides. The case studies are for systems that range in size from serving small communities with fewer than 100 connections to systems distributing 2.5 MGD. Although EPA does not have nontreatment case studies specific to perchlorate, the design and cost information contained in the case studies for other contaminants is transferable. Nontreatment options are less likely to be available for larger systems because of the quantity of water required. Therefore, EPA's WBS nontreatment cost model generates costs only for systems serving less than 10,000 people.

As discussed in Section 7.1, the two options covered by the WBS nontreatment model (new wells or interconnection) are likely to have higher costs than other nontreatment options available for perchlorate. The sections below identify the specific cost elements included under each option. They also describe the specific inputs and assumptions that EPA used to generate the costs for each option in Section 8.6.4. For both options, the cost estimates assume that systems choosing a nontreatment option do so because they have an alternative source that will not require additional water treatment to address changes in raw water quality (i.e., no post-treatment). Because of this, they further assume no incremental waste or residuals management costs.

7.6.2 Model Components and Assumptions for New Wells

In addition to the common WBS direct capital cost items listed in **Exhibit 7-2**, the WBS nontreatment model includes the following direct capital cost items specific to the new well option:

- Well casing, screens, and plugs
- Well installation costs including drilling, development, gravel pack, and surface seals
- Well pumps
- Piping (buried) and valves to connect the new well to the system.

It includes the following option-specific O&M elements:

- Operator labor for operating and maintaining well pumps and valves
- Materials for maintaining well pumps
- Energy for operating well pumps.

The option includes a small shed or other low cost building at the well site along with materials and labor for maintenance of this building. In calculating land costs, it incorporates a 100 foot buffer on all sides of the new well building to allow for a sanitary control area around the well, as recommended in the peer review comments on the model. For new wells, the model includes all of the indirect capital costs shown in **Exhibit 7-2**, except for yard piping. The paragraphs below describe specific inputs and assumptions used to generate costs for perchlorate under the new well nontreatment option.

Total Flow Rate Requirements and Flow per Well

As with other WBS models, design and average flow are inputs to the nontreatment model. In the case of nontreatment approaches, however, "design" flow is actually the peak flow required by the system, rather than the design capacity of a treatment plant. In the new well nontreatment option, the flow rate requirements determine the number of new wells required. The cost estimates below assume one new well would be installed per 500 gpm of water production capacity required.

Well Depth

Well depth will vary for each site depending on the geological formations and aquifer depths. Geophysical studies prior to well installation will provide guidance on optimum well depths. The model has pumps available to serve wells up to 1,350 feet in depth. The cost estimates below assume a 250-foot well depth. The estimates assume 50 percent of this depth is screened, allowing for sections of casing both above and below the well screen.

Pump Type

The size of the well will depend on the diameter of the pump used to draw water from the aquifer. The model contains three sizes of submersible pumps: 4-, 6-, and 8-inch diameter. Each size can serve a range of flows and depths, so the default size varies across system flows. The cost estimates below assume 4-inch pumps for systems in the smallest size category (25 to 100 people) and 6-inch pumps for larger systems.

Distance from Well to Distribution System

The distance between a new well and the distribution system affects pipe installation costs. No case studies provided distance information. The cost estimates below assume a default value of 500 feet.

7.6.3 Model Components and Assumptions for Interconnection

In addition to the common WBS direct capital cost items listed in **Exhibit 7-2**, the WBS nontreatment model includes the following direct capital cost items specific to the interconnection option:

- Booster pumps or pressure reducing valves (depending on pressure at supply source)
- Concrete vaults (buried) for booster pumps or pressure reducing valves
- Interconnecting piping (buried) and valves.

It includes the following option-specific O&M elements:

- Cost of purchased water
- Operator labor for operating and maintaining booster pumps or pressure reducing valves (depending on pressure at supply source) and interconnecting valves

- Materials for maintaining booster pumps (if required by pressure at supply source)
- Energy for operating booster pumps (if required by pressure at supply source).

The option does not include any buildings. It includes all of the indirect capital costs shown in **Exhibit 7-2**, except for yard piping, site work, and architectural fees. The paragraphs below describe specific inputs and assumptions used to generate costs for perchlorate under the interconnection nontreatment option.

Flow Rate Requirements

As with other WBS models, design and average flow are inputs to the nontreatment model. In the case of nontreatment approaches, however, “design” flow is actually the peak flow required by the system, rather than the design capacity of a treatment plant. In the interconnection nontreatment option, the flow rate requirements determine a number of system and equipment parameters, including pipeline and valve size and pump capacity and energy use (if required by pressure at the supply source).

Distance to Interconnection Water Supply

For utilities that have the ability to purchase water from a neighboring system, the capital cost of the interconnection project will depend on the distance between the two systems. If the systems are far apart geographically, the cost of installing a pipeline may be too high to make an interconnection project feasible. Also, a larger booster pump will be required to overcome friction losses along longer pipelines. The cost estimates below assume an average interconnection distance of 10,000 feet, based on comments from the peer review of the nontreatment model.

Pressure at Supply Water Source

The water pressure of purchased water may require adjustment prior to entering the purchasing system’s distribution network (e.g., to account for elevation differences). If the wholesale supplier does not have enough pressure to meet the distribution needs of the interconnection project, then booster pumps are needed to move water from the supply source into the distribution system. The booster pump size is based on flow rate as well as distance and grade to the distribution system. If the supply source has more pressure than necessary then pressure reducing valves are needed. Based on comments from the peer review, the cost estimates below assume that differences in pressure between the supplier and the purchasing system are minimal, so that neither booster pumps nor pressure reducing valves are needed.

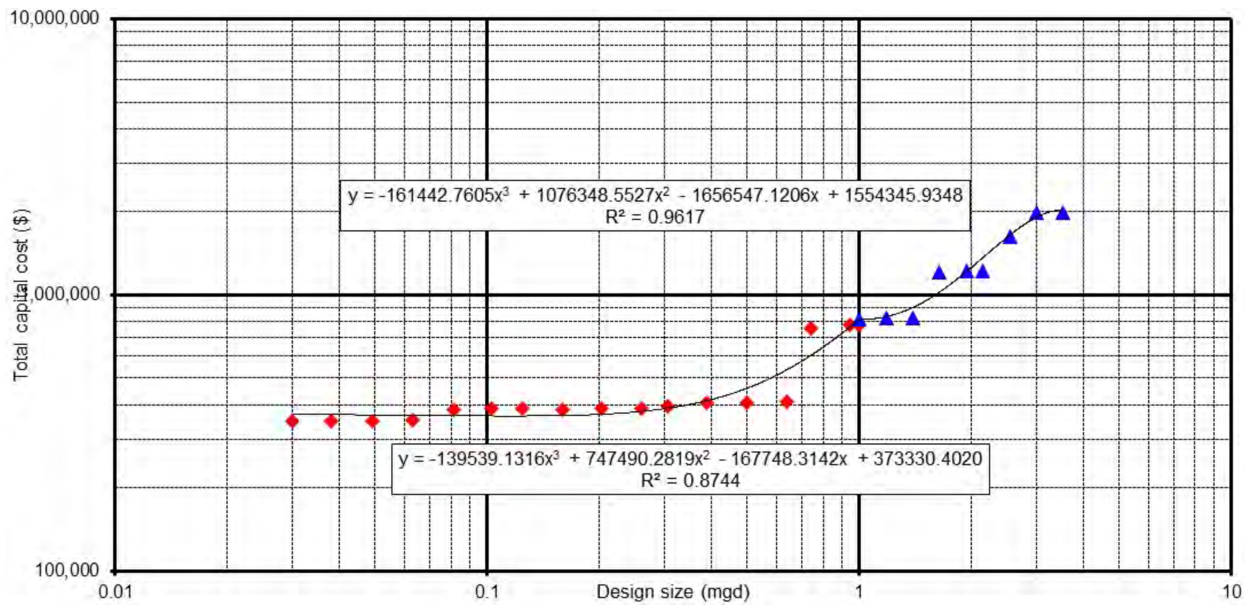
Cost of Purchased Water

An interconnection project will include one or more water rates paid to the wholesale system by the purchasing system. The model assumption is a single water rate for the average cost in dollars per thousand gallons of purchased water. Based on data in USEPA (2009), the mean revenue per thousand gallons among all wholesale systems is $1.85. The cost estimates below assume a higher cost of purchased water of $2.00 per thousand gallons, based on comments from the peer review.

7.6.4 Cost Estimates

The graphs below plot WBS cost model results in 2017 dollars at the mid cost level for the two nontreatment options for systems using groundwater: new wells (**Exhibit 7-11**) and interconnection (**Exhibit 7-12**). The exhibits do not extend beyond 3.536 MGD design flow, because the nontreatment model does not generate costs for larger systems. Appendix B provides complete cost equations for both nontreatment options, including the high, mid, and low cost levels and for interconnection of groundwater and surface water systems. Appendix C presents example WBS model outputs for selected flow rates, allowing review of individual cost line items.

Exhibit 7-11. Mid Cost Results for New Wells at Groundwater Systems (2017 dollars)



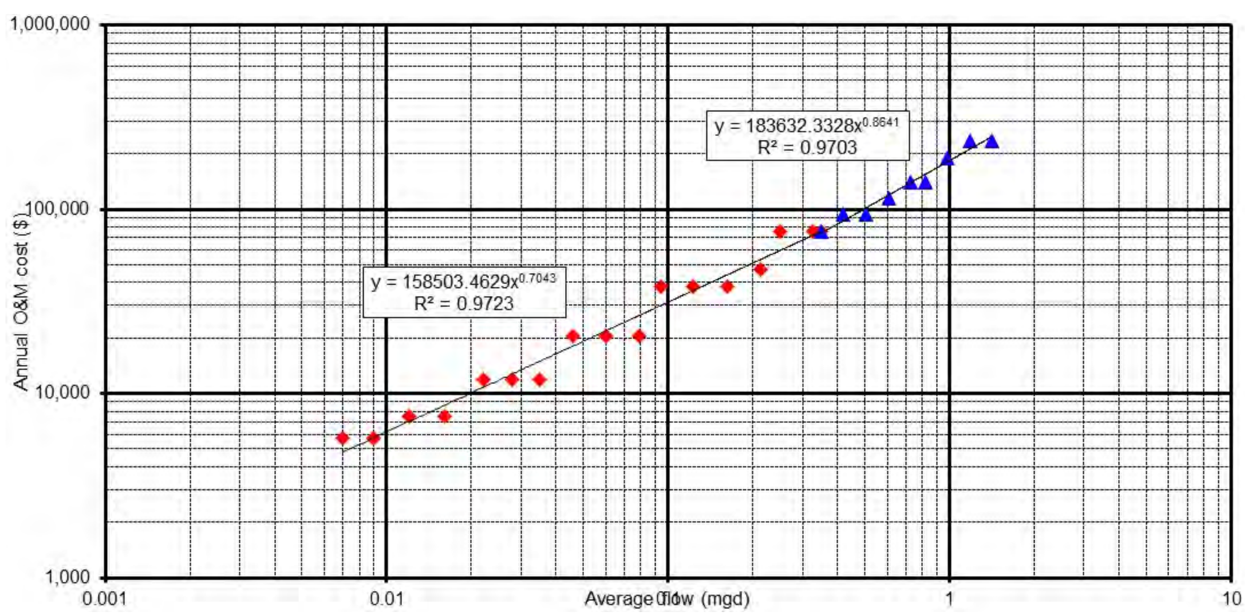
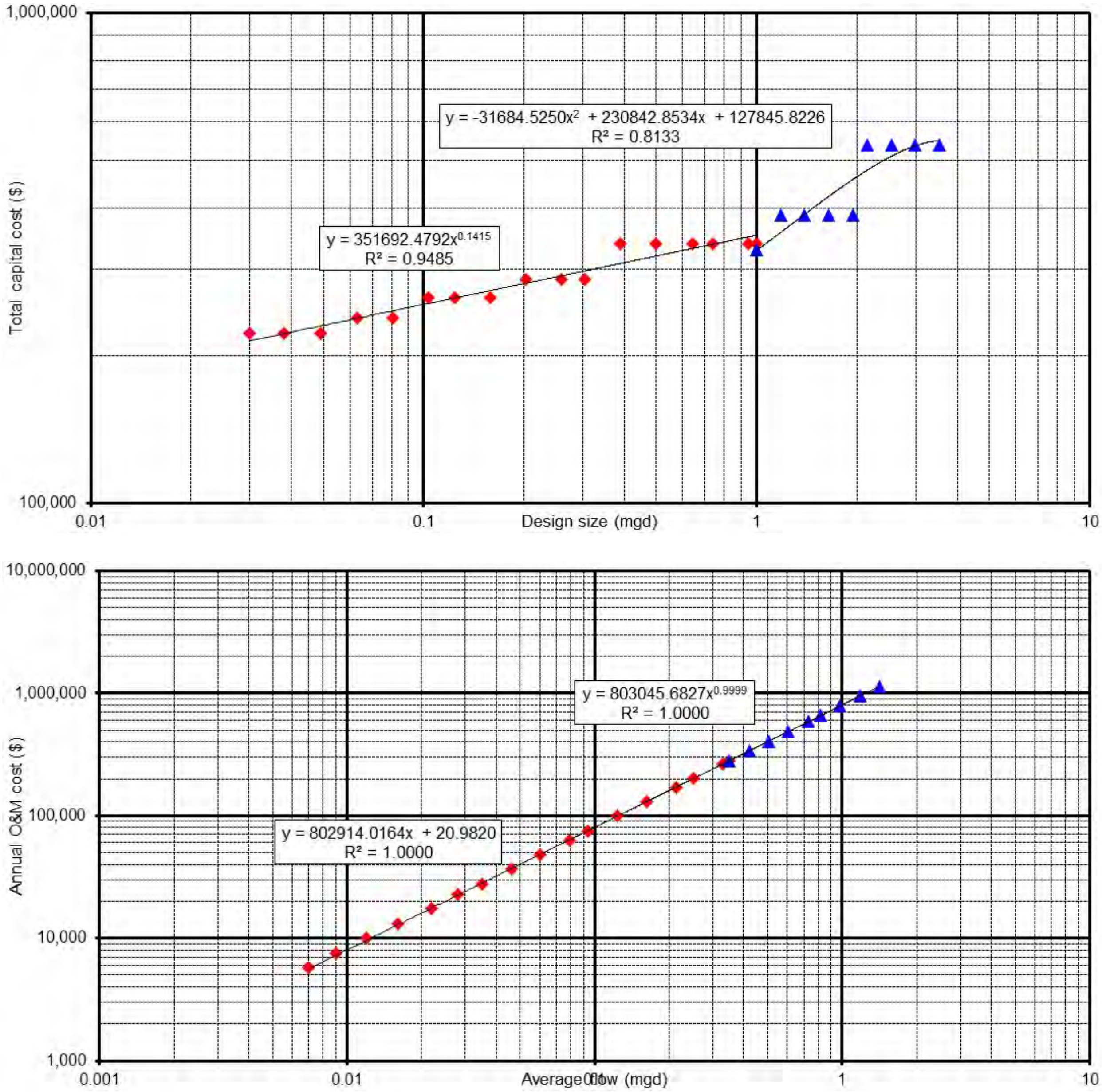


Exhibit 7-12. Mid Cost Results for Interconnection of Groundwater Systems (2017 dollars)



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Appendix A: Residuals Treatment

For certain residuals from technologies removing perchlorate from drinking water, additional treatment may be desirable or required. Specifically, residuals from both ion exchange (see Chapter 2) and membrane technologies (see Chapter 4) may be amenable to treatment prior to their disposal, discharge, or reuse. One form of residuals treatment that has received considerable research attention uses biological treatment (see Chapter 3). Thus, the topic of residuals treatment is relevant to several of the technologies discussed in this document. Because of its cross-technology applicability, residuals treatment research is summarized here in an appendix.

Treatment technologies for residuals from technologies removing perchlorate from drinking water include biological treatment and physical/chemical reduction.[12] This appendix provides an overview of the status of each residuals treatment technology.

A.1 Biological Treatment of Residuals

Biological treatment of concentrated waste streams from ion exchange processes can be difficult due the microbial toxicity associated with the high salt content of the brine. In the case of an anion exchange process, the regeneration of the resin typically generates a 7 to 12 percent sodium hydroxide brine solution enriched in perchlorate. Gingras and Batista (2002) were unable to adapt a PRB culture to degrade perchlorate in an ion exchange brine. As little as 1 percent sodium hydroxide reduced perchlorate reduction rates by their perchlorate-degrading culture by half (Gingras and Batista, 2002). Batista et al. (2003) indicate that the use of halotolerant microbes that can reduce perchlorate in the presence of high levels of salinity would be required for effective biological brine treatment.

Pilot tests conducted by MWH and the University of Houston, however, evaluated biological treatment of spent brines with promising initial results. A biological system based on a marine sediment inoculum was shown to successfully and consistently remove perchlorate at concentrations of 1.5 to 3.0 mg/L from the brine to below 0.2 mg/L, the goal established for effective reuse of the brine. Investigators observed that as the treated brine was recycled to regenerate the exhausted ion exchange resin, the resin maintained its ability to remove perchlorate to less than 4 µg/L. After 30 reuse cycles, various constituents accumulated within the brine, including bicarbonate, sulfate, uranium, arsenic, chromium, fluoride, barium, and silica. These accumulated chemicals are site specific and depend upon raw water quality. Control of this accumulation through additional treatment might be required depending on site-specific concentrations. The researchers identified mixing and maintaining an anoxic environment as key operational requirements. Regular maintenance to remove scale build-up prevents system clogging. The researchers noted that the potential for precipitation and clogging is high under standard operating conditions (Case et al., 2004).

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[12] In addition, several sources (Boodoo, 2006; U.S. DoD, 2007; 2008b) present information on a potential treatment approach for spent caustic regenerant from an ion exchange system using weak-base resin. This approach uses a small, strong-base resin scavenger bed, with the spent resin from the scavenger bed ultimately disposed by incineration. Because study of this approach has been limited to weak-base resin regenerant, this appendix does not include further discussion of this residuals treatment method.

The literature does not include any detailed evaluation of the feasibility of biological treatment of spent tetrachloroferrate regenerant. Batista et al. (2003) suggest that such a system could be used if pH adjustment were applied to raise the pH of the regenerant. Recent studies of tetrachloroferrate regeneration (Gu et al., 2007; Lutes et al., 2010) do not include examination of biological treatment of spent regenerant.

Batista et al. (2003; 2000) have suggested that a primary advantage of weak-base resins is that caustic solutions used to regenerate these resins may be more amenable to biological treatment than conventional brine solutions. Instead of containing sodium chloride, which can be toxic to some microorganisms, these solutions could contain ammonium hydroxide, which can be used as a nutrient by microbes (Batista et al., 2000). On the other hand, the caustic solutions would require pH adjustment to lower the pH. Also, high levels of ammonium (greater than 0.3 percent) could be toxic to anaerobic biological systems. Ammonium might need to be air stripped or biologically oxidized to nitrate (Batista et al., 2003). Recent studies of regenerated weak-base resins (U.S. DoD, 2007; 2008b) do not include examination of biological treatment of spent regenerant.

Xu et al. (2003) notes that the waste stream containing perchlorate produced from a RO process contains much lower amount of salts (less than 1 percent) than the sodium hydroxide brine generated using an ion exchange process. Giblin et al. (2002) inoculated a PBR with the pure culture perc1ace and tested its ability to remove perchlorate from a simulated RO rejectate. The researchers found that this system removed 98 percent of perchlorate from a twice-concentrated rejectate (total dissolved solids of 0.4 percent) with an influent perchlorate concentration of 8 mg/L and a residence time of 2 hours. The system removed nitrate simultaneously with perchlorate from an initial concentration as high as 900 mg/L to below 4 mg/L. Despite the efficiency of perchlorate removal, the system suffered from clogging due to precipitation of the high total dissolved solids of the twice-concentrated rejectate.

A.2 Physical/Chemical Reduction of Residuals

Calgon Carbon has developed a proprietary physical/chemical brine treatment system called the Perchlorate and Nitrate Destruction Module (PNDM). The PNDM is a high-pressure and high-temperature catalytic process that uses ammonia as a chemical reductant to reduce the nitrate and perchlorate in spent brine (Montgomery Watson Harza and University of Houston, 2003). In pilot tests that incorporated a nanofiltration unit to remove sulfate from the brine after PNDM treatment, Venkatesh et al. (2000) found that the PNDM system was able to reduce perchlorate in the spent brine from 60,000 to 70,000 µg/L to less than the detection limit of 125 µg/L. This reduction allowed reuse of the brine and reduced overall waste generation from 1.75 percent of water treated to 0.17 percent of water treated. The remaining waste consisted of the sulfate-laden reject from the nanofiltration step. With 70 mg/L chloride and 50 mg/L sulfate in this reject, the study suggests that blending with treated water is a feasible option (Venkatesh et al., 2000).

The pilot tests conducted by MWH and the University of Houston evaluated the PNDM system for treatment of spent brine from a conventional ion exchange configuration. The biological treatment initial results were promising. PNDM was able to reduce perchlorate in brine to below 0.2 mg/L and allowed reuse of the brine for up to 30 cycles (Case et al., 2004).

The MWH and University of Houston pilot tests also evaluated an electrolytic treatment process to reduce perchlorate in brine. This process, developed by Ionex for the treatment of nitrate contaminated water, is called IXL (Montgomery Watson Harza and University of Houston, 2003). Initial results, however, demonstrated minimal perchlorate reduction with this system (Case et al., 2004).

Applied Research Associates has proposed an Integrated Thermal Treatment Process for treating spent brine. This process would concentrate the spent brine using reverse osmosis, thereby rejecting sulfate and nitrate salts, and concentrating the perchlorate. The concentrated perchlorate would then be thermally destroyed. The treated brine would be suitable for reuse and Applied Research Associates estimates that the quantity of brine waste for disposal would be reduced by 95 to 99 percent. This thermal treatment approach, however, has been tested only in the laboratory for synthetic spent brine (Applied Research Associates, 2000).

The Oak Ridge National Laboratory researchers have developed a proprietary methodology for reducing perchlorate in spent tetrachloroferrate regenerant solution. Reportedly, in this methodology, perchlorate decomposes into chloride under certain catalytic conditions within a few hours to one day with an initial perchlorate concentration of about 7,000 mg/L. The process does not otherwise alter the properties of the regenerant solution and allows it to be reused (Gu et al., 2002). More recently, Lutes et al. (2010) reported on a process in which tetrachloroferrate regenerant is reduced with ferrous chloride in a thermoreactor. In this process, they observed perchlorate destruction efficiency from 73.6 to greater than 99.7 percent, a median efficiency of greater than 99.2 percent. The process has been patented and licensed exclusively to Calgon Carbon (Lutes et al., 2010).

Appendix B: Cost Equations

Notes:

- Cost equations presented here take one of the following forms, identified by which coefficients (C1 through C10) are nonzero:

  Cost $= C1\ Q^{C2}$
  or $= C3\ \mathrm{Ln}(Q) + C4$
  or $= C5\ e^{(C6\ Q)}$
  or $= C7\ Q^3 + C8\ Q^2 + C9\ Q + C10$

  where Q is design flow in MGD for total capital costs, or average flow in MGD for annual O&M costs.

- Equations are designated as for small, medium, or large systems. These equations apply as follows:
  Small system equations apply where design flow (Q) is less than 1 MGD
  Medium system equations apply where design flow (Q) is 1 MGD or greater, but less than 10 MGD
  Large system equations apply where design flow (Q) is 10 MGD or greater

- For Point of Use/Point of Entry, alternative equations also are included where:

  Cost $= C1\ H^{C2}$
  or $= C3\ \mathrm{Ln}(H) + C4$
  or $= C5\ e^{(C6\ H)}$
  or $= C7\ H^3 + C8\ H^2 + C9\ H + C10$

  where H is number of households served for both total capital costs and annual O&M costs.

- EPA developed each equation using the method described in Section 8.1.2.

- Equations are derived from the following data files, with columns rearranged for ease of reference:

  - Results_Summary_GW_082817 for groundwater systems
  - Results_Summary_SW_082817 for surface water systems.

- For Anion Exchange for Perchlorate, the Perchlorate-selective 170,000 BV scenario corresponds to the Alternative resin (user defined) option in the source data files.

- For Point of Use/Point of Entry, costs do not vary by component level input (high, mid, low); equations are not presented for medium and large systems.

- For Non-treatment, medium system size curves are valid only up to 3.536 MGD design flow (1.417 MGD groundwater average flow and 1.345 MGD surface water average flow); equations are not presented for systems of greater size.

- For Non-treatment, equations are not presented for New Wells for surface water systems, because this option is not likely to be available for surface water systems.

B.1 Capital and O&M Cost Curve Parameters for Anion Exchange Treatment Scenarios

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Perchlorate-selective 250,000 BV	GW	Small	Low	Total Capital	0	0	0	0	0	0	165188.3006	-319172.535	472901.5875	81055.1941	17.74117647
Perchlorate-selective 250,000 BV	GW	Medium	Low	Total Capital	0	0	0	0	0	0	814.5718	-15685.9444	419749.9937	596924.4296	32.34
Perchlorate-selective 250,000 BV	GW	Large	Low	Total Capital	0	0	0	0	0	0	0	0	281010.0818	993827.2688	33.97647059
Perchlorate-selective 250,000 BV	GW	Small	Mid	Total Capital	0	0	0	0	0	0	111665.366	-213209.9	435508.3073	125329.6749	17.69411765
Perchlorate-selective 250,000 BV	GW	Medium	Mid	Total Capital	0	0	0	0	0	0	802.1603	-17543.4018	455922.7261	687296.3603	31.74
Perchlorate-selective 250,000 BV	GW	Large	Mid	Total Capital	0	0	0	0	0	0	0	0	287995.2658	1130875.789	33.95882353
Perchlorate-selective 250,000 BV	GW	Small	High	Total Capital	0	0	0	0	0	0	186840.2446	-375907.224	708990.975	171244.269	20.24705882
Perchlorate-selective 250,000 BV	GW	Medium	High	Total Capital	0	0	0	0	0	0	2804.3789	-52743.211	810631.6507	852108.8158	33.78
Perchlorate-selective 250,000 BV	GW	Large	High	Total Capital	0	0	0	0	0	0	0	0	444429.0529	1729726.784	34.71764706
Perchlorate-selective 250,000 BV	GW	Small	Low	Annual O&M	0	0	0	0	0	0	60323.2954	-52499.9905	95401.6475	4355.1619	17.74117647
Perchlorate-selective 250,000 BV	GW	Medium	Low	Annual O&M	0	0	0	0	0	0	0	-749.5103	107314.0049	25199.9683	32.34
Perchlorate-selective 250,000 BV	GW	Large	Low	Annual O&M	0	0	0	0	0	0	0	0	94348.8299	54918.7765	33.97647059
Perchlorate-selective 250,000 BV	GW	Small	Mid	Annual O&M	0	0	0	0	0	0	60323.2954	-52499.9905	95401.6475	4355.1619	17.69411765
Perchlorate-selective 250,000 BV	GW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	-793.0138	109785.9654	27443.6982	31.74
Perchlorate-selective 250,000 BV	GW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	0	94815.4066	50288.0306	33.95882353
Perchlorate-selective 250,000 BV	GW	Small	High	Annual O&M	0	0	0	0	0	0	0	-22144.6512	92551.7336	4510.6253	20.24705882
Perchlorate-selective 250,000 BV	GW	Medium	High	Annual O&M	0	0	0	0	0	0	0	-864.5234	111139.9758	27196.8415	33.78
Perchlorate-selective 250,000 BV	GW	Large	High	Annual O&M	0	0	0	0	0	0	0	27.2244	93568.467	64877.4787	34.71764706
Perchlorate-selective 170,000 BV	GW	Small	Low	Total Capital	0	0	0	0	0	0	165188.3006	-319172.535	472901.5875	81055.1941	17.74117647
Perchlorate-selective 170,000 BV	GW	Medium	Low	Total Capital	0	0	0	0	0	0	814.5718	-15685.9444	419749.9937	596924.4296	32.34

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Perchlorate-selective 170,000 BV	GW	Large	Low	Total Capital	0	0	0	0	0	0	0	0	281010.0818	993827.2688	33.97647059
Perchlorate-selective 170,000 BV	GW	Small	Mid	Total Capital	0	0	0	0	0	0	111665.366	-213209.9	435508.3073	125329.6749	17.69411765
Perchlorate-selective 170,000 BV	GW	Medium	Mid	Total Capital	0	0	0	0	0	0	802.1603	-17543.4018	455922.7261	687296.3603	31.74
Perchlorate-selective 170,000 BV	GW	Large	Mid	Total Capital	0	0	0	0	0	0	0	0	287995.2658	1130875.789	33.95882353
Perchlorate-selective 170,000 BV	GW	Small	High	Total Capital	0	0	0	0	0	0	186840.2446	-375907.224	708990.975	171244.269	20.24705882
Perchlorate-selective 170,000 BV	GW	Medium	High	Total Capital	0	0	0	0	0	0	2804.3789	-52743.211	810631.6507	852108.8158	33.78
Perchlorate-selective 170,000 BV	GW	Large	High	Total Capital	0	0	0	0	0	0	0	0	444429.0529	1729726.784	34.71764706
Perchlorate-selective 170,000 BV	GW	Small	Low	Annual O&M	0	0	0	0	0	0	56351.5026	-50187.5062	122627.1429	4364.8149	17.74117647
Perchlorate-selective 170,000 BV	GW	Medium	Low	Annual O&M	0	0	0	0	0	0	0	0	131580.5513	27443.0764	32.34
Perchlorate-selective 170,000 BV	GW	Large	Low	Annual O&M	0	0	0	0	0	0	0	0	122034.7577	53803.0803	33.97647059
Perchlorate-selective 170,000 BV	GW	Small	Mid	Annual O&M	0	0	0	0	0	0	56351.5026	-50187.5062	122627.1429	4364.8149	17.69411765
Perchlorate-selective 170,000 BV	GW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	0	133861.2533	29816.6188	31.74
Perchlorate-selective 170,000 BV	GW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	0	122526.36	48879.5863	33.95882353
Perchlorate-selective 170,000 BV	GW	Small	High	Annual O&M	0	0	0	0	0	0	57937.7322	-51428.4226	123700.2943	4441.0268	20.24705882
Perchlorate-selective 170,000 BV	GW	Medium	High	Annual O&M	0	0	0	0	0	0	-751.2236	4495.5752	128358.2051	31778.107	33.78
Perchlorate-selective 170,000 BV	GW	Large	High	Annual O&M	0	0	0	0	0	0	0	0	123508.7003	38942.7634	34.71764706
Perchlorate-selective 250,000 BV	SW	Small	Low	Total Capital	0	0	0	0	0	0	165274.688	-319329.202	472978.9565	81058.2965	17.74117647
Perchlorate-selective 250,000 BV	SW	Medium	Low	Total Capital	0	0	0	0	0	0	839.1878	-16075.29	421154.5885	595626.0307	32.34
Perchlorate-selective 250,000 BV	SW	Large	Low	Total Capital	0	0	0	0	0	0	0	0	280265.6113	1007900.297	33.98823529
Perchlorate-selective 250,000 BV	SW	Small	Mid	Total Capital	0	0	0	0	0	0	111750.4602	-213363.524	435584.8953	125332.7918	17.69411765
Perchlorate-selective 250,000 BV	SW	Medium	Mid	Total Capital	0	0	0	0	0	0	830.5377	-17999.3282	457555.6503	685792.943	31.74

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Perchlorate-selective 250,000 BV	SW	Large	Mid	Total Capital	0	0	0	0	0	0	0	0	287250.061	1144962.062	33.97058824
Perchlorate-selective 250,000 BV	SW	Small	High	Total Capital	0	0	0	0	0	0	186942.4138	-376095.796	709087.0242	171247.8793	20.24705882
Perchlorate-selective 250,000 BV	SW	Medium	High	Total Capital	0	0	0	0	0	0	2838.7252	-53286.93	812529.4756	850397.7787	33.78
Perchlorate-selective 250,000 BV	SW	Large	High	Total Capital	0	0	0	0	0	0	0	0	443634.4238	1743834.45	34.72941176
Perchlorate-selective 250,000 BV	SW	Small	Low	Annual O&M	0	0	0	0	0	0	0	-18741.0467	90566.6107	4395.0332	17.74117647
Perchlorate-selective 250,000 BV	SW	Medium	Low	Annual O&M	0	0	0	0	0	0	0	-598.7219	109065.4542	24276.2342	32.34
Perchlorate-selective 250,000 BV	SW	Large	Low	Annual O&M	0	0	0	0	0	0	0	0	95522.9118	71724.5663	33.98823529
Perchlorate-selective 250,000 BV	SW	Small	Mid	Annual O&M	0	0	0	0	0	0	0	-18741.0467	90566.6107	4395.0332	17.69411765
Perchlorate-selective 250,000 BV	SW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	0	109075.9181	28101.0967	31.74
Perchlorate-selective 250,000 BV	SW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	0	96019.7175	67473.7023	33.97058824
Perchlorate-selective 250,000 BV	SW	Small	High	Annual O&M	0	0	0	0	0	0	0	-19036.6668	91488.2917	4470.8681	20.24705882
Perchlorate-selective 250,000 BV	SW	Medium	High	Annual O&M	0	0	0	0	0	0	-1039.9695	6031.209	101107.6527	31206.5711	33.78
Perchlorate-selective 250,000 BV	SW	Large	High	Annual O&M	0	0	0	0	0	0	0	0	97012.5603	58878.3927	34.72941176
Perchlorate-selective 170,000 BV	SW	Small	Low	Total Capital	0	0	0	0	0	0	165274.688	-319329.202	472978.9565	81058.2965	17.74117647
Perchlorate-selective 170,000 BV	SW	Medium	Low	Total Capital	0	0	0	0	0	0	839.1878	-16075.29	421154.5885	595626.0307	32.34
Perchlorate-selective 170,000 BV	SW	Large	Low	Total Capital	0	0	0	0	0	0	0	0	280265.6113	1007900.297	33.98823529
Perchlorate-selective 170,000 BV	SW	Small	Mid	Total Capital	0	0	0	0	0	0	111750.4602	-213363.524	435584.8953	125332.7918	17.69411765
Perchlorate-selective 170,000 BV	SW	Medium	Mid	Total Capital	0	0	0	0	0	0	830.5377	-17999.3282	457555.6503	685792.943	31.74
Perchlorate-selective 170,000 BV	SW	Large	Mid	Total Capital	0	0	0	0	0	0	0	0	287250.061	1144962.062	33.97058824
Perchlorate-selective 170,000 BV	SW	Small	High	Total Capital	0	0	0	0	0	0	186942.4138	-376095.796	709087.0242	171247.8793	20.24705882
Perchlorate-selective 170,000 BV	SW	Medium	High	Total Capital	0	0	0	0	0	0	2838.7252	-53286.93	812529.4756	850397.7787	33.78

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Perchlorate-selective 170,000 BV	SW	Large	High	Total Capital	0	0	0	0	0	0	0	0	443634.4238	1743834.45	34.72941176
Perchlorate-selective 170,000 BV	SW	Small	Low	Annual O&M	0	0	0	0	0	0	0	-18636.7959	118095.4167	4401.0983	17.74117647
Perchlorate-selective 170,000 BV	SW	Medium	Low	Annual O&M	0	0	0	0	0	0	0	-594.8003	136645.3404	24283.6711	32.34
Perchlorate-selective 170,000 BV	SW	Large	Low	Annual O&M	0	0	0	0	0	0	0	0	123198.8697	70820.6621	33.98823529
Perchlorate-selective 170,000 BV	SW	Small	Mid	Annual O&M	0	0	0	0	0	0	0	-18636.7959	118095.4167	4401.0983	17.69411765
Perchlorate-selective 170,000 BV	SW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	0	136673.7625	28097.7332	31.74
Perchlorate-selective 170,000 BV	SW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	0	123719.8582	66316.3849	33.97058824
Perchlorate-selective 170,000 BV	SW	Small	High	Annual O&M	0	0	0	0	0	0	0	-18919.6285	119009.5802	4477.345	20.24705882
Perchlorate-selective 170,000 BV	SW	Medium	High	Annual O&M	0	0	0	0	0	0	-1038.7155	6027.6327	128706.7892	31207.6465	33.78
Perchlorate-selective 170,000 BV	SW	Large	High	Annual O&M	0	0	0	0	0	0	0	0	124761.0668	57213.3622	34.72941176

Cost = C1 * Q ^ C2 + C3 * Ln(Q) + C4 + C5 * Exp (C6 * Q) + C7 * Q^3 + C8 * Q^2 + C9 * Q + C10
Where Q is design flow in MGD for total capital costs and average flow in MGD for annual O&M costs

B.2 Capital and O&M Cost Curve Parameters for Biological Treatment Scenarios

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Fixed Bed Pressure Vessel	GW	Small	Low	Total Capital	0	0	0	0	0	0	360664.2489	-719515.71	1107604.628	643541.8543	24.46470588
Fixed Bed Pressure Vessel	GW	Medium	Low	Total Capital	0	0	0	0	0	0	-1230.8188	4236.7079	740451.7857	1652605.61	31.79333333
Fixed Bed Pressure Vessel	GW	Large	Low	Total Capital	0	0	0	0	0	0	0	-33.3723	558954.1451	2437567.235	31.31764706
Fixed Bed Pressure Vessel	GW	Small	Mid	Total Capital	0	0	0	0	0	0	492476.6413	-1025849.33	1436856.86	715106.4333	23.12941176
Fixed Bed Pressure Vessel	GW	Medium	Mid	Total Capital	0	0	0	0	0	0	0	-15229.9667	887780.101	1850883.189	31.34
Fixed Bed Pressure Vessel	GW	Large	Mid	Total Capital	0	0	0	0	0	0	0	0	564980.0264	3622086.493	31.35882353
Fixed Bed Pressure Vessel	GW	Small	High	Total Capital	0	0	0	0	0	0	770133.6573	-1683703.84	2371838.543	836853.9079	25.47647059
Fixed Bed Pressure Vessel	GW	Medium	High	Total Capital	0	0	0	0	0	0	-2465.7652	13844.2369	1241563.686	2576024.887	33.52
Fixed Bed Pressure Vessel	GW	Large	High	Total Capital	0	0	0	0	0	0	7.225	-1535.1083	1011253.121	3406280.863	33.12352941
Fixed Bed Pressure Vessel	GW	Small	Low	Annual O&M	0	0	0	0	0	0	0	-45961.3314	158156.0739	27926.5161	24.46470588
Fixed Bed Pressure Vessel	GW	Medium	Low	Annual O&M	0	0	0	0	0	0	1184.1123	-14333.9198	180043.52	62255.524	31.79333333
Fixed Bed Pressure Vessel	GW	Large	Low	Annual O&M	0	0	0	0	0	0	0	0	126538.9848	104543.6316	31.31764706
Fixed Bed Pressure Vessel	GW	Small	Mid	Annual O&M	0	0	0	0	0	0	0	-76492.4588	176417.3995	27695.5647	23.12941176

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Fixed Bed Pressure Vessel	GW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	-6827.1527	173032.9405	75031.6456	31.34
Fixed Bed Pressure Vessel	GW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	0	129201.3891	88438.183	31.35882353
Fixed Bed Pressure Vessel	GW	Small	High	Annual O&M	0	0	0	0	0	0	91643.6805	-120401.753	185483.6022	28225.6213	25.47647059
Fixed Bed Pressure Vessel	GW	Medium	High	Annual O&M	0	0	0	0	0	0	0	-7136.1131	175890.2434	75595.8595	33.52
Fixed Bed Pressure Vessel	GW	Large	High	Annual O&M	0	0	0	0	0	0	-2.6058	349.0829	122625.9002	143270.435	33.12352941
Fixed Bed Gravity Basin	GW	Small	Low	Total Capital	0	0	0	0	0	0	-199338.503	108033.2323	1102079.756	943520.528	28.67058824
Fixed Bed Gravity Basin	GW	Medium	Low	Total Capital	2610057.586	0.5365	0	0	0	0	0	0	0	0	32.84
Fixed Bed Gravity Basin	GW	Large	Low	Total Capital	0	0	0	0	0	0	0	0	369737.988	7037405.771	31.62352941
Fixed Bed Gravity Basin	GW	Small	Mid	Total Capital	0	0	0	0	0	0	0	-243851.42	1460419.766	1052522.957	27.42941176
Fixed Bed Gravity Basin	GW	Medium	Mid	Total Capital	2931011.596	0.534	0	0	0	0	0	0	0	0	32.36666667
Fixed Bed Gravity Basin	GW	Large	Mid	Total Capital	0	0	0	0	0	0	0	-142.8363	409982.8163	7189477.16	31.61764706
Fixed Bed Gravity Basin	GW	Small	High	Total Capital	0	0	0	0	0	0	202978.9468	-743201.86	2218774.508	1232771.998	29.86470588
Fixed Bed Gravity Basin	GW	Medium	High	Total Capital	3735296.534	0.5134	0	0	0	0	0	0	0	0	33.99333333
Fixed Bed Gravity Basin	GW	Large	High	Total Capital	0	0	0	0	0	0	0	-127.9367	472526.5562	9035136.284	32.77058824

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Fixed Bed Gravity Basin	GW	Small	Low	Annual O&M	0	0	0	0	0	0	-244584.565	45607.9876	217316.197	33588.7142	28.67058824
Fixed Bed Gravity Basin	GW	Medium	Low	Annual O&M	0	0	0	0	0	0	0	-6559.4032	186687.2639	75555.8157	32.84
Fixed Bed Gravity Basin	GW	Large	Low	Annual O&M	0	0	0	0	0	0	0	0	118304.6266	225492.918	31.62352941
Fixed Bed Gravity Basin	GW	Small	Mid	Annual O&M	0	0	0	0	0	0	-185910.722	21574.4589	226502.4065	35193.5095	27.42941176
Fixed Bed Gravity Basin	GW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	-7143.548	194111.8555	77654.2262	32.36666667
Fixed Bed Gravity Basin	GW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	0	120590.8015	210480.3335	31.61764706
Fixed Bed Gravity Basin	GW	Small	High	Annual O&M	0	0	0	0	0	0	0	-76893.7765	246083.0756	36218.5012	29.86470588
Fixed Bed Gravity Basin	GW	Medium	High	Annual O&M	0	0	0	0	0	0	0	-7101.1547	196805.7999	79557.3458	33.99333333
Fixed Bed Gravity Basin	GW	Large	High	Annual O&M	0	0	0	0	0	0	-1.6021	227.8999	115719.1797	264822.2223	32.77058824
Fluidized Bed Pressure Vessel	GW	Small	Low	Total Capital	0	0	0	0	0	0	-165867.923	-28166.6787	1025869.936	861046.6691	27.07647059
Fluidized Bed Pressure Vessel	GW	Medium	Low	Total Capital	0	0	0	0	0	0	-1758.0291	18962.1919	649400.0564	1694269.883	31.5
Fluidized Bed Pressure Vessel	GW	Large	Low	Total Capital	0	0	0	0	0	0	0	-184.9186	540273.6829	2881509.567	30.98823529

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Fluidized Bed Pressure Vessel	GW	Small	Mid	Total Capital	0	0	0	0	0	0	0	-362080.784	1369255.056	997173.1712	25.97058824
Fluidized Bed Pressure Vessel	GW	Medium	Mid	Total Capital	0	0	0	0	0	0	-1020.4755	5469.6152	807095.7564	1937384.124	31
Fluidized Bed Pressure Vessel	GW	Large	Mid	Total Capital	0	0	0	0	0	0	0	-199.5054	571178.1483	3627131.011	30.94705882
Fluidized Bed Pressure Vessel	GW	Small	High	Total Capital	0	0	0	0	0	0	0	-575922.439	2258409.846	1191761.253	28.81764706
Fluidized Bed Pressure Vessel	GW	Medium	High	Total Capital	0	0	0	0	0	0	-2245.5247	23231.221	1173986.54	2689612.461	33.32
Fluidized Bed Pressure Vessel	GW	Large	High	Total Capital	0	0	0	0	0	0	2.0713	-750.9524	958369.9281	4502384.894	33.18823529
Fluidized Bed Pressure Vessel	GW	Small	Low	Annual O&M	0	0	0	0	0	0	0	-61439.932	156677.6914	37218.503	27.07647059
Fluidized Bed Pressure Vessel	GW	Medium	Low	Annual O&M	0	0	0	0	0	0	0	-4273.302	151726.0086	77431.6855	31.5
Fluidized Bed Pressure Vessel	GW	Large	Low	Annual O&M	0	0	0	0	0	0	0	0	118931.5849	156492.319	30.98823529
Fluidized Bed Pressure Vessel	GW	Small	Mid	Annual O&M	0	0	0	0	0	0	0	-66125.2755	165892.0237	42644.1251	25.97058824

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Fluidized Bed Pressure Vessel	GW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	-4768.8748	158659.8589	83835.7669	31
Fluidized Bed Pressure Vessel	GW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	0	121214.2539	142830.8114	30.94705882
Fluidized Bed Pressure Vessel	GW	Small	High	Annual O&M	0	0	0	0	0	0	0	-69019.5329	173487.8271	46943.947	28.81764706
Fluidized Bed Pressure Vessel	GW	Medium	High	Annual O&M	0	0	0	0	0	0	0	-5090.8845	161873.9793	83364.5317	33.32
Fluidized Bed Pressure Vessel	GW	Large	High	Annual O&M	0	0	0	0	0	0	0	0	125753.2694	116080.0404	33.18823529
Fixed Bed Pressure Vessel	SW	Small	Low	Total Capital	0	0	0	0	0	0	376530.23	-743505.873	1116042.748	643296.522	24.46470588
Fixed Bed Pressure Vessel	SW	Medium	Low	Total Capital	0	0	0	0	0	0	-1306.1553	5435.3388	734513.1972	1657773.704	31.79333333
Fixed Bed Pressure Vessel	SW	Large	Low	Total Capital	0	0	0	0	0	0	-1.3562	301.9828	536580.3031	2719357.571	31.31764706
Fixed Bed Pressure Vessel	SW	Small	Mid	Total Capital	0	0	0	0	0	0	376530.23	-743505.873	1116042.748	643296.522	24.46470588
Fixed Bed Pressure Vessel	SW	Medium	Mid	Total Capital	0	0	0	0	0	0	-1306.1553	5435.3388	734513.1972	1657773.704	31.79333333
Fixed Bed Pressure Vessel	SW	Large	Mid	Total Capital	0	0	0	0	0	0	-1.3562	301.9828	536580.3031	2719357.571	31.31764706
Fixed Bed Pressure Vessel	SW	Small	High	Total Capital	0	0	0	0	0	0	787557.8629	-1711551.3	2382625.539	836532.0821	25.47647059

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Fixed Bed Pressure Vessel	SW	Medium	High	Total Capital	0	0	0	0	0	0	-2509.418	14699.0305	1235969.914	2580751.403	33.52
Fixed Bed Pressure Vessel	SW	Large	High	Total Capital	0	0	0	0	0	0	7.2587	-1541.3548	1010264.132	3400477.674	33.11764706
Fixed Bed Pressure Vessel	SW	Small	Low	Annual O&M	0	0	0	0	0	0	0	-30006.0913	151948.7891	27786.4856	24.46470588
Fixed Bed Pressure Vessel	SW	Medium	Low	Annual O&M	0	0	0	0	0	0	0	-6472.2083	171959.0723	65214.7013	31.79333333
Fixed Bed Pressure Vessel	SW	Large	Low	Annual O&M	0	0	0	0	0	0	0	-50.0737	133952.7487	116880.3955	31.31764706
Fixed Bed Pressure Vessel	SW	Small	Mid	Annual O&M	0	0	0	0	0	0	0	-47426.4264	167113.6865	27582.7544	23.11764706
Fixed Bed Pressure Vessel	SW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	-7571.6831	182100.1207	70400.4121	31.33333333
Fixed Bed Pressure Vessel	SW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	-48.638	136680.3001	104187.003	31.35882353
Fixed Bed Pressure Vessel	SW	Small	High	Annual O&M	0	0	0	0	0	0	0	-54988.4534	172649.2074	28155.967	25.47647059
Fixed Bed Pressure Vessel	SW	Medium	High	Annual O&M	0	0	0	0	0	0	0	-7944.4304	185272.3046	70814.7398	33.52
Fixed Bed Pressure Vessel	SW	Large	High	Annual O&M	0	0	0	0	0	0	0	-47.6434	142797.7639	76278.2943	33.11764706
Fixed Bed Gravity Basin	SW	Small	Low	Total Capital	0	0	0	0	0	0	-194555.784	103163.0231	1100879.375	944940.1123	28.66470588
Fixed Bed Gravity Basin	SW	Medium	Low	Total Capital	2611597.865	0.5352	0	0	0	0	0	0	0	0	32.84
Fixed Bed Gravity Basin	SW	Large	Low	Total Capital	0	0	0	0	0	0	0	-97.4647	385856.916	6442653.679	31.6

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Fixed Bed Gravity Basin	SW	Small	Mid	Total Capital	0	0	0	0	0	0	0	-241076.609	1455779.615	1054413.219	27.42941176
Fixed Bed Gravity Basin	SW	Medium	Mid	Total Capital	2932533.852	0.5325	0	0	0	0	0	0	0	0	32.36666667
Fixed Bed Gravity Basin	SW	Large	Mid	Total Capital	0	0	0	0	0	0	1.4957	-485.1302	428334.3343	6915717.611	31.59411765
Fixed Bed Gravity Basin	SW	Small	High	Total Capital	0	0	0	0	0	0	0	-437897.61	2100725.869	1242829.494	29.86470588
Fixed Bed Gravity Basin	SW	Medium	High	Total Capital	3737297.463	0.5121	0	0	0	0	0	0	0	0	33.98666667
Fixed Bed Gravity Basin	SW	Large	High	Total Capital	0	0	0	0	0	0	-2.2055	429.0556	433942.163	9481048.78	32.74117647
Fixed Bed Gravity Basin	SW	Small	Low	Annual O&M	0	0	0	0	0	0	-295094.821	107422.9682	200339.6042	33528.7699	28.66470588
Fixed Bed Gravity Basin	SW	Medium	Low	Annual O&M	0	0	0	0	0	0	0	-7078.7184	196694.4742	70481.3509	32.84
Fixed Bed Gravity Basin	SW	Large	Low	Annual O&M	0	0	0	0	0	0	0	-53.1455	125332.4549	225578.8415	31.6
Fixed Bed Gravity Basin	SW	Small	Mid	Annual O&M	0	0	0	0	0	0	0	-39781.1639	225091.591	34770.0602	27.42941176
Fixed Bed Gravity Basin	SW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	-7922.9458	205415.3033	71952.8472	32.36666667
Fixed Bed Gravity Basin	SW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	-49.281	127203.5984	221133.0458	31.59411765
Fixed Bed Gravity Basin	SW	Small	High	Annual O&M	0	0	0	0	0	0	-265504.07	96891.6626	214451.7462	36419.1032	29.86470588
Fixed Bed Gravity Basin	SW	Medium	High	Annual O&M	0	0	0	0	0	0	0	-7678.6964	207592.0873	74095.0996	33.98666667

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Fixed Bed Gravity Basin	SW	Large	High	Annual O&M	0	0	0	0	0	0	0	0	127770.6593	245595.9535	32.74117647
Fluidized Bed Pressure Vessel	SW	Small	Low	Total Capital	0	0	0	0	0	0	-175859.574	-15604.5734	1022532.417	861605.1699	27.08235294
Fluidized Bed Pressure Vessel	SW	Medium	Low	Total Capital	0	0	0	0	0	0	-1853.4978	20390.6304	642914.6996	1699906.968	31.5
Fluidized Bed Pressure Vessel	SW	Large	Low	Total Capital	0	0	0	0	0	0	0	-184.3819	539381.2799	2877427.798	30.99411765
Fluidized Bed Pressure Vessel	SW	Small	Mid	Total Capital	0	0	0	0	0	0	97225.5085	-508869.031	1424987.278	993856.3133	25.97647059
Fluidized Bed Pressure Vessel	SW	Medium	Mid	Total Capital	0	0	0	0	0	0	0	-11461.5583	883976.9293	1850411.667	30.99333333
Fluidized Bed Pressure Vessel	SW	Large	Mid	Total Capital	0	0	0	0	0	0	0	-197.1765	569947.5394	3626369.958	30.95294118
Fluidized Bed Pressure Vessel	SW	Small	High	Total Capital	0	0	0	0	0	0	0	-579364.841	2261637.972	1192128.15	28.81764706
Fluidized Bed Pressure Vessel	SW	Medium	High	Total Capital	0	0	0	0	0	0	-2497.6049	26750.0461	1159072.431	2703008.262	33.32
Fluidized Bed Pressure Vessel	SW	Large	High	Total Capital	0	0	0	0	0	0	0	-236.2879	924354.1605	4920097.242	33.19411765

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Fluidized Bed Pressure Vessel	SW	Small	Low	Annual O&M	0	0	0	0	0	0	0	-48119.3527	151722.3833	37060.3885	27.08235294
Fluidized Bed Pressure Vessel	SW	Medium	Low	Annual O&M	0	0	0	0	0	0	683.1623	-8992.2086	166147.0816	70692.5368	31.5
Fluidized Bed Pressure Vessel	SW	Large	Low	Annual O&M	0	0	0	0	0	0	0	-77.7363	127503.5199	136708.2479	30.99411765
Fluidized Bed Pressure Vessel	SW	Small	Mid	Annual O&M	0	0	0	0	0	0	0	-51241.3715	160339.9151	42473.2257	25.97647059
Fluidized Bed Pressure Vessel	SW	Medium	Mid	Annual O&M	0	0	0	0	0	0	0	-5128.5574	165688.954	80177.5823	30.99333333
Fluidized Bed Pressure Vessel	SW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	-76.4289	129834.5381	126303.1959	30.95294118
Fluidized Bed Pressure Vessel	SW	Small	High	Annual O&M	0	0	0	0	0	0	0	-52938.0151	167468.4034	46763.9136	28.81764706
Fluidized Bed Pressure Vessel	SW	Medium	High	Annual O&M	0	0	0	0	0	0	0	-5503.3764	169209.2828	79563.3081	33.32
Fluidized Bed Pressure Vessel	SW	Large	High	Annual O&M	0	0	0	0	0	0	0	-69.7757	134187.4415	107314.9692	33.19411765

Cost = C1 * Q ^ C2 + C3 * Ln(Q) + C4 + C5 * Exp (C6 * Q) + C7 * Q^3 + C8 * Q^2 + C9 * Q + C10
Where Q is design flow in MGD for total capital costs and average flow in MGD for annual O&M costs

B.3 Capital and O&M Cost Curve Parameters for Reverse Osmosis Treatment Scenarios

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
High Qual GW	GW	Small	Low	Total Capital	0	0	0	0	0	0	419730.7281	-788209.698	1051419.014	442510.3593	24.25882353
High Qual GW	GW	Medium	Low	Total Capital	0	0	0	0	0	0	-2786.1614	27165.9297	609019.2816	834956.3855	30.08666667
High Qual GW	GW	Large	Low	Total Capital	0	0	0	0	0	0	0	0	501464.6241	2255690.684	29.34117647
High Qual GW	GW	Small	Mid	Total Capital	0	0	0	0	0	0	922912.2899	-1682538.35	1663351.386	507008.18	21.88823529
High Qual GW	GW	Medium	Mid	Total Capital	0	0	0	0	0	0	-2109.8121	15519.4438	693094.0443	1122924.536	28.22
High Qual GW	GW	Large	Mid	Total Capital	0	0	0	0	0	0	0	0	512376.9598	2510945.991	29.54705882
High Qual GW	GW	Small	High	Total Capital	0	0	0	0	0	0	766189.679	-1380227.98	1525573.733	570809.2307	24.37058824
High Qual GW	GW	Medium	High	Total Capital	0	0	0	0	0	0	-2107.3138	14031.7866	729255.4764	1165183.835	29.69333333
High Qual GW	GW	Large	High	Total Capital	0	0	0	0	0	0	0	43.302	528875.1103	2776676.683	29.88823529
High Qual GW	GW	Small	Low	Annual O&M	0	0	0	0	0	0	6656243.564	-3786089.15	1334035.193	36717.6114	24.25882353
High Qual GW	GW	Medium	Low	Annual O&M	0	0	0	0	0	0	14623.6692	-136584.824	1095617.882	-57620.9392	30.08666667
High Qual GW	GW	Large	Low	Annual O&M	0	0	0	0	0	0	0	0	665521.2229	522284.0316	29.34117647
High Qual GW	GW	Small	Mid	Annual O&M	0	0	0	0	0	0	6656243.564	-3786089.15	1334035.193	36717.6114	21.88823529
High Qual GW	GW	Medium	Mid	Annual O&M	0	0	0	0	0	0	14623.6692	-136584.824	1095617.882	-57620.9392	28.22
High Qual GW	GW	Large	Mid	Annual O&M	0	0	0	0	0	0	0	0	665521.2229	522284.0316	29.54705882
High Qual GW	GW	Small	High	Annual O&M	0	0	0	0	0	0	6656243.564	-3786089.15	1334035.193	36717.6114	24.37058824
High Qual GW	GW	Medium	High	Annual O&M	0	0	0	0	0	0	14623.6692	-136584.824	1095617.882	-57620.9392	29.69333333
High Qual GW	GW	Large	High	Annual O&M	0	0	0	0	0	0	0	0	665521.2229	522284.0316	29.88823529
High Qual SW	SW	Small	Low	Total Capital	0	0	0	0	0	0	149193.1749	-494226.186	1100191.755	425799.664	24.38235294
High Qual SW	SW	Medium	Low	Total Capital	0	0	0	0	0	0	0	-20031.7053	832358.7573	712738.9352	30.41333333

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
High Qual SW	SW	Large	Low	Total Capital	0	0	0	0	0	0	0	0	471323.5873	2660282.067	30.1
High Qual SW	SW	Small	Mid	Total Capital	0	0	0	0	0	0	710187.6349	-1479543.01	1773005.169	482742.038	22.09411765
High Qual SW	SW	Medium	Mid	Total Capital	0	0	0	0	0	0	992.0306	-36548.5993	935963.6527	986641.0663	28.54666667
High Qual SW	SW	Large	Mid	Total Capital	0	0	0	0	0	0	0	0	482545.7284	2941963.972	30.31764706
High Qual SW	SW	Small	High	Total Capital	0	0	0	0	0	0	521778.1744	-1165763.6	1665430.871	535877.9142	24.41764706
High Qual SW	SW	Medium	High	Total Capital	0	0	0	0	0	0	0	-22177.6296	904905.0085	1106566.125	30.02666667
High Qual SW	SW	Large	High	Total Capital	0	0	0	0	0	0	0	0	506185.1909	3060324.078	30.66470588
High Qual SW	SW	Small	Low	Annual O&M	0	0	0	0	0	0	6589736.981	-3985129.69	1508433.457	36750.2247	24.38235294
High Qual SW	SW	Medium	Low	Annual O&M	0	0	0	0	0	0	57128.2822	-406859.935	1486200.795	-119209.519	30.41333333
High Qual SW	SW	Large	Low	Annual O&M	0	0	0	0	0	0	11.5056	-1617.309	643746.394	390169.1403	30.1
High Qual SW	SW	Small	Mid	Annual O&M	0	0	0	0	0	0	6589736.981	-3985129.69	1508433.457	36750.2247	22.09411765
High Qual SW	SW	Medium	Mid	Annual O&M	0	0	0	0	0	0	57128.2822	-406859.935	1486200.795	-119209.519	28.54666667
High Qual SW	SW	Large	Mid	Annual O&M	0	0	0	0	0	0	11.5056	-1617.309	643746.394	390169.1403	30.31764706
High Qual SW	SW	Small	High	Annual O&M	0	0	0	0	0	0	6589736.981	-3985129.69	1508433.457	36750.2247	24.41764706
High Qual SW	SW	Medium	High	Annual O&M	0	0	0	0	0	0	57128.2822	-406859.935	1486200.795	-119209.519	30.02666667
High Qual SW	SW	Large	High	Annual O&M	0	0	0	0	0	0	11.5056	-1617.309	643746.394	390169.1403	30.66470588

Cost = C1 * Q ^ C2 + C3 * Ln(Q) + C4 + C5 * Exp (C6 * Q) + C7 * Q^3 + C8 * Q^2 + C9 * Q + C10
Where Q is design flow in MGD for total capital costs and average flow in MGD for annual O&M costs

B.4 Capital and O&M Cost Curve Parameters for Point-of-Use Treatment Scenarios (Flow Basis)

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
POU Reverse Osmosis	GW	Small	n/a	Total Capital	552638.6724	1.0352	0	0	0	0	0	0	0	0	10
POU Reverse Osmosis	GW	Small	n/a	Annual O&M	0	0	0	0	0	0	0	-99260.9973	496421.4345	1775.6587	10
POU Reverse Osmosis	SW	Small	n/a	Total Capital	555487.2438	1.0462	0	0	0	0	0	0	0	0	10
POU Reverse Osmosis	SW	Small	n/a	Annual O&M	0	0	0	0	0	0	0	0	460080.1825	688.6075	10

Cost = C1 * Q ^ C2 + C3 * Ln(Q) + C4 + C5 * Exp (C6 * Q) + C7 * Q^3 + C8 * Q^2 + C9 * Q + C10
Where Q is design flow in MGD for total capital costs and average flow in MGD for annual O&M costs

B.5 Capital and O&M Cost Curve Parameters for Point-of-Use Treatment Scenarios (Household Basis)

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
POU Reverse Osmosis	GW	Small	n/a	Total Capital	607.2278	0.987	0	0	0	0	0	0	0	0	10
POU Reverse Osmosis	GW	Small	n/a	Annual O&M	0	0	0	0	0	0	0	0	163.7089	782.86	10
POU Reverse Osmosis	SW	Small	n/a	Total Capital	608.0877	0.9868	0	0	0	0	0	0	0	0	10
POU Reverse Osmosis	SW	Small	n/a	Annual O&M	0	0	0	0	0	0	0	0	163.7627	788.7267	10

Cost = C1 * H ^ C2 + C3 * Ln(H) + C4 + C5 * Exp (C6 * H) + C7 * H^3 + C8 * H^2 + C9 * H + C10
Where H is number of households served

B.6 Capital and O&M Cost Curve Parameters for Non-Treatment Scenarios

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
Interconnection	GW	Small	Low	Total Capital	338077.9484	0.1356	0	0	0	0	0	0	0	0	17
Interconnection	GW	Medium	Low	Total Capital	0	0	0	0	0	0	0	-31084.5197	227314.1808	118001.2476	21.98888889
Interconnection	GW	Small	Mid	Total Capital	351692.4792	0.1415	0	0	0	0	0	0	0	0	16.92941176
Interconnection	GW	Medium	Mid	Total Capital	0	0	0	0	0	0	0	-31684.525	230842.8534	127845.8226	21.74444444
Interconnection	GW	Small	High	Total Capital	353452.9305	0.1363	0	0	0	0	0	0	0	0	17
Interconnection	GW	Medium	High	Total Capital	0	0	0	0	0	0	0	-32984.1112	240477.5383	121870.7095	21.9
Interconnection	GW	Small	Low	Annual O&M	0	0	0	0	0	0	0	0	802914.0164	20.982	17
Interconnection	GW	Medium	Low	Annual O&M	803045.6827	0.9999	0	0	0	0	0	0	0	0	21.98888889
Interconnection	GW	Small	Mid	Annual O&M	0	0	0	0	0	0	0	0	802914.0164	20.982	16.92941176
Interconnection	GW	Medium	Mid	Annual O&M	803045.6827	0.9999	0	0	0	0	0	0	0	0	21.74444444
Interconnection	GW	Small	High	Annual O&M	0	0	0	0	0	0	0	0	802914.0164	20.982	17
Interconnection	GW	Medium	High	Annual O&M	803045.6827	0.9999	0	0	0	0	0	0	0	0	21.9
New Well Construction	GW	Small	Low	Total Capital	0	0	0	0	0	0	0	293739.0823	-56575.0209	187426.9077	17.1
New Well Construction	GW	Medium	Low	Total Capital	0	0	0	0	0	0	0	-7446.9958	329941.3709	82930.8255	22.41111111
New Well Construction	GW	Small	Mid	Total Capital	0	0	0	0	0	0	-139539.132	747490.2819	-167748.314	373330.402	33.86470588
New Well Construction	GW	Medium	Mid	Total Capital	0	0	0	0	0	0	-161442.761	1076348.553	-1656547.12	1554345.935	39.21111111
New Well Construction	GW	Small	High	Total Capital	0	0	0	0	0	0	-186326.987	850714.244	-198767.813	384792.9094	34.31764706
New Well Construction	GW	Medium	High	Total Capital	0	0	0	0	0	0	-170156.492	1136151.351	-1756631.22	1640223.951	39.38888889
New Well Construction	GW	Small	Low	Annual O&M	158503.4629	0.7043	0	0	0	0	0	0	0	0	17.1
New Well Construction	GW	Medium	Low	Annual O&M	183632.3328	0.8641	0	0	0	0	0	0	0	0	22.41111111

Design	GW/ SW	Size Category	Comp Level	Cost Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Useful Life
New Well Construction	GW	Small	Mid	Annual O&M	158503.4629	0.7043	0	0	0	0	0	0	0	0	33.86470588
New Well Construction	GW	Medium	Mid	Annual O&M	183632.3328	0.8641	0	0	0	0	0	0	0	0	39.21111111
New Well Construction	GW	Small	High	Annual O&M	158503.4629	0.7043	0	0	0	0	0	0	0	0	34.31764706
New Well Construction	GW	Medium	High	Annual O&M	183632.3328	0.8641	0	0	0	0	0	0	0	0	39.38888889
Interconnection	SW	Small	Low	Total Capital	338077.9484	0.1356	0	0	0	0	0	0	0	0	17
Interconnection	SW	Medium	Low	Total Capital	0	0	0	0	0	0	0	-31084.5197	227314.1808	118001.2476	21.98888889
Interconnection	SW	Small	Mid	Total Capital	351692.4792	0.1415	0	0	0	0	0	0	0	0	16.92941176
Interconnection	SW	Medium	Mid	Total Capital	0	0	0	0	0	0	0	-31684.525	230842.8534	127845.8226	21.74444444
Interconnection	SW	Small	High	Total Capital	353452.9305	0.1363	0	0	0	0	0	0	0	0	17
Interconnection	SW	Medium	High	Total Capital	0	0	0	0	0	0	0	-32984.1112	240477.5383	121870.7095	21.9
Interconnection	SW	Small	Low	Annual O&M	0	0	0	0	0	0	0	0	802695.4	116.2102	17
Interconnection	SW	Medium	Low	Annual O&M	803045.4022	0.9999	0	0	0	0	0	0	0	0	21.98888889
Interconnection	SW	Small	Mid	Annual O&M	0	0	0	0	0	0	0	0	802695.4	116.2102	16.92941176
Interconnection	SW	Medium	Mid	Annual O&M	803045.4022	0.9999	0	0	0	0	0	0	0	0	21.74444444
Interconnection	SW	Small	High	Annual O&M	0	0	0	0	0	0	0	0	802695.4	116.2102	17
Interconnection	SW	Medium	High	Annual O&M	803045.4022	0.9999	0	0	0	0	0	0	0	0	21.9

Cost = C1 * Q ^ C2 + C3 * Ln(Q) + C4 + C5 * Exp (C6 * Q) + C7 * Q^3 + C8 * Q^2 + C9 * Q + C10
Where Q is design flow in MGD for total capital costs and average flow in MGD for annual O&M costs

Appendix C: Example WBS Model Outputs

Notes:

- Example outputs presented here correspond to treatment of groundwater.
- To show the variations among both system size and cost level, the examples chosen for each scenario modeled typically include a low cost small system, a mid cost medium system, and a high cost large system.
- Each of the examples is among the individual flow rate-specific estimates used to generate the cost equations presented in Appendix B (see Section 8.1.2 for details on the method used to develop the equation).

Anion Exchange for Perchlorate, design 0.500 mgd, average 0.162 mgd, Low-Cost Components, Resin type: Perchlorate-selective 250,000 BV

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1	Pressure Vessels - Carbon Steel - Plastic Internals	35,590	30
2.1	Ion Exchange Resin - Perchlorate-selective	40,858	N/A
3.4.1	Caustic Storage Tanks - Plastic/XLPE	844	7
3.4.2	Caustic Storage Tanks - Heat Tracing	1,454	7
3.4.3	Caustic Storage Tanks - Insulation	163	7
4.1	Cartridge Filters - Cartridge Filters	24,784	30
5.1.1	Backwash Piping - PVC	205	17
5.3.1	Process Piping - PVC	311	17
5.5.1	Inlet and Outlet Piping - PVC	311	17
5.7.1	Caustic Piping - PVC	60	17
5.8.1	Residuals Piping - PVC	198	17
5.8.2	Residuals Piping - Excavation	1,064	17
5.8.3	Residuals Piping - Bedding	61	17
5.8.4	Residuals Piping - Backfill and Compaction	493	17
5.8.5	Residuals Piping - Thrust Blocks	96	17
6.1.1	Valves and Fittings - Motor/Air Operated (on/off) - Process - Polypropylene/PVC	9,580	20
6.1.2	Valves and Fittings - Motor/Air Operated (on/off) - Backwash - Polypropylene/PVC	4,218	20
6.2.1	Valves and Fittings - Manual - Inlet and outlet - Polypropylene/PVC	1,282	20
6.2.2	Valves and Fittings - Manual - Process - Polypropylene/PVC	1,282	20
6.3.2	Valves and Fittings - Check Valves - Inlet and Outlet - Polypropylene/PVC	2,705	20
6.3.7	Valves and Fittings - Check Valves - Residuals - Polypropylene/PVC	243	20
8.2.1	Mixers for Caustic Storage Tanks - Mounted	1,656	22
11.1.1	Instrumentation and Controls - Flow Meters - Inlet and Outlet - Propeller	4,141	14
11.3.1	Instrumentation and Controls - Flow Meters - Backwash - Propeller	3,227	14
11.4.1	Instrumentation and Controls - Flow Meters - Residuals - Propeller	2,625	14
11.9	Instrumentation and Controls - High/Low Alarm (for caustic tanks)	593	14
11.12	Instrumentation and Controls - Head loss sensors	4,242	14
11.13.1	Instrumentation and Controls - Sampling Ports - Stainless Steel	250	30
12.1.1	System Controls - PLC Units - PLC racks/power supplies	340	8
12.1.2	System Controls - PLC Units - CPUs	1,256	8
12.1.3	System Controls - PLC Units - I/O discrete input modules	307	8
12.1.4	System Controls - PLC Units - I/O discrete output modules	375	8
12.1.5	System Controls - PLC Units - I/O combination analog modules	1,958	8
12.1.6	System Controls - PLC Units - Ethernet modules	1,730	8
12.1.9	System Controls - PLC Units - UPSs	563	8
12.2.1	System Controls - Operator Equipment - Drive controllers	1,072	14
12.2.2	System Controls - Operator Equipment - Operator interface units	3,911	8
13.1.1	Building Structures and HVAC - Building 1 - Small Low Cost Shed	11,961	20
13.3	Building Structures and HVAC - Concrete Pad	2,592	37
Indirect	Indirect and Add-On Costs (contingency from model)	96,284	20
	Process Cost	**168,600**	
	System Cost	**264,884**	
	O&M Cost	**18,351**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Construction Management	4,102
Process Engineering	33,720
Site Work	3,332
Yard Piping	2,810
Geotechnical	0
Standby Power	0
Electrical (including yard wiring)	15,405
Mobilization and Demobilization	0
Architectural Fees for Treatment Building	0
Permits	24
Pilot Study	15,573
Land Cost	1,086
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Contingency (0.0%)	0
Miscellaneous Allowance (10.0%)	16,860
Legal, Fiscal, and Administrative (2.0%)	3,372
Sales Tax (0.0%)	0
Financing during Construction (0.0%)	0

Breakdown of O&M costs	Annual Cost ($/year)
Manager (8 hrs/yr @ $45.2396/hr)	371
Clerical (8 hrs/yr @ $30.4776/hr)	250
Operator (82 hrs/yr @ $31.9149/hr)	2,616
Cartridge filter replacement (7 filters/yr @ $191.6015/sf/yr)	1,380
Facility maintenance (materials and labor) (260 sf @ $5.7866/sf/yr)	1,505
Sodium Hydroxide - Small Qty (5268 lbs/yr @ $0.302/lb)	1,591
Perchlorate-selective (32 cf/yr @ $256.5165/cf)	8,111
Energy for backwash/rinse pumps (0 Mwh/yr @ $0.1212/kwh)	0
Energy for lighting (0 Mwh/yr @ $0.1212/kwh)	3
Energy for ventilation (0 Mwh/yr @ $0.1212/kwh)	7
POTW discharge fees (953 gal/yr @ $0.3881/gal)	370
Spent resin disposal (1 ton/yr @ $697.6744/ton)	474
Spent cartridge filter disposal (0 ton/yr @ $74.9152/ton)	6
Miscellaneous Allowance (0 @ $)	1,668

Anion Exchange for Perchlorate, design 5.809 mgd, average 2.455 mgd, Mid-Cost Components, Resin type: Perchlorate-selective 250,000 BV

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1	Pressure Vessels - Carbon Steel - Plastic Internals	264,172	35
2.1	Ion Exchange Resin - Perchlorate-selective	487,390	N/A
3.1.1	Backwash/Rinse Tanks - Fiberglass	11,822	25
3.4.1	Caustic Storage Tanks - Fiberglass	5,578	10
3.4.2	Caustic Storage Tanks - Heat Tracing	1,573	10
3.4.3	Caustic Storage Tanks - Insulation	947	10
3.5.1	Caustic Day Tanks - Fiberglass	4,749	10
3.5.2	Caustic Day Tanks - Heat Tracing	1,455	10
3.5.3	Caustic Day Tanks - Insulation	182	10
4.1	Cartridge Filters - Cartridge Filters	166,640	35
5.1.1	Backwash Piping - CPVC	7,502	22
5.3.1	Process Piping - CPVC	9,549	22
5.5.1	Inlet and Outlet Piping - CPVC	19,446	22
5.7.1	Caustic Piping - CPVC	1,119	22
5.8.1	Residuals Piping - CPVC	2,590	22
5.8.2	Residuals Piping - Excavation	1,187	22
5.8.3	Residuals Piping - Bedding	70	22
5.8.4	Residuals Piping - Backfill and Compaction	550	22
5.8.5	Residuals Piping - Thrust Blocks	409	22
6.1.1	Valves and Fittings - Motor/Air Operated (on/off) - Process - Cast Iron	53,747	25
6.1.2	Valves and Fittings - Motor/Air Operated (on/off) - Backwash - Cast Iron	44,639	25
6.1.6	Valves and Fittings - Motor/Air Operated (on/off) - Caustic - Stainless Steel	2,072	25
6.2.1	Valves and Fittings - Manual - Inlet and outlet - Cast Iron	5,215	25
6.2.2	Valves and Fittings - Manual - Process - Cast Iron	11,357	25
6.3.1	Valves and Fittings - Check Valves - Backwash - Cast Iron	3,857	25
6.3.2	Valves and Fittings - Check Valves - Inlet and Outlet - Cast Iron	10,467	25
6.3.7	Valves and Fittings - Check Valves - Residuals - Cast Iron	1,082	25
7.1	Pumps - Booster	69,732	20
7.2	Pumps - Backwash/Rinse	23,885	20
8.2.1	Mixers for Caustic Storage Tanks - Mounted	1,802	25
8.3.1	Mixers for Caustic Day Tanks - Mounted	1,658	25
11.1.1	Instrumentation and Controls - Flow Meters - Inlet and Outlet - Venturi	17,176	15
11.3.1	Instrumentation and Controls - Flow Meters - Backwash - Venturi	12,496	15
11.4.1	Instrumentation and Controls - Flow Meters - Residuals - Venturi	9,686	15
11.6	Instrumentation and Controls - High/Low Alarm (for backwash tanks)	593	15
11.9	Instrumentation and Controls - High/Low Alarm (for caustic tanks)	1,185	15
11.11	Instrumentation and Controls - Temperature meters	593	15
11.12	Instrumentation and Controls - Head loss sensors	23,332	15
11.13.1	Instrumentation and Controls - Sampling Ports - Carbon Steel	500	25
11.17	Instrumentation and Controls - Turbidity meters	5,223	15
12.1.1	System Controls - PLC Units - PLC racks/power supplies	680	10
12.1.2	System Controls - PLC Units - CPUs	1,256	10
12.1.3	System Controls - PLC Units - I/O discrete input modules	614	10
12.1.4	System Controls - PLC Units - I/O discrete output modules	375	10
12.1.5	System Controls - PLC Units - I/O combination analog modules	5,221	10
12.1.6	System Controls - PLC Units - Ethernet modules	1,730	10
12.1.7	System Controls - PLC Units - Base expansion modules	118	10
12.1.8	System Controls - PLC Units - Base expansion controller modules	86	10
12.1.9	System Controls - PLC Units - UPSs	563	10
12.2.1	System Controls - Operator Equipment - Drive controllers	6,435	15
12.2.2	System Controls - Operator Equipment - Operator interface units	920	10
12.2.3	System Controls - Operator Equipment - PC Workstations	1,006	10
12.2.4	System Controls - Operator Equipment - Printers - laser jet	627	10

WBS #	Item	Total Cost ($)	Useful Life (yrs)
12.2.5	System Controls - Operator Equipment - Printers - dot matrix	642	10
12.3.1	System Controls - Controls Software - Operator interface software	366	10
12.3.2	System Controls - Controls Software - PLC programming software	474	10
12.3.3	System Controls - Controls Software - PLC data collection software	690	10
12.3.4	System Controls - Controls Software - Plant intelligence software	11,480	10
13.1.1	Building Structures and HVAC - Building 1 - Medium Quality	390,703	40
13.1.3.1	Building Structures and HVAC - Building 1 - Heating and Cooling System - Heat pump	5,957	25
13.3	Building Structures and HVAC - Concrete Pad	53,134	40
Indirect	Indirect and Add-On Costs (contingency from model)	1,073,196	40
	Process Cost	**1,770,308**	
	System Cost	**2,843,504**	
	O&M Cost	**284,473**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Construction Management	115,738
Process Engineering	212,437
Site Work	60,232
Yard Piping	26,287
Geotechnical	0
Standby Power	21,078
Electrical (including yard wiring)	132,051
Mobilization and Demobilization	87,480
Architectural Fees for Treatment Building	35,984
Permits	24
Pilot Study	69,717
Land Cost	11,216
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Contingency (0.0%)	0
Miscellaneous Allowance (10.0%)	177,031
Legal, Fiscal, and Administrative (2.0%)	35,406
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	88,515

Breakdown of O&M costs	Annual Cost ($/year)
Manager (47 hrs/yr @ $57.6375/hr)	2,733
Clerical (47 hrs/yr @ $39.3563/hr)	1,866
Operator (474 hrs/yr @ $35.9445/hr)	17,043
Materials for booster pumps (calculated as a percentage of capital)	697
Materials for backwash/rinse pumps (calculated as a percentage of capital)	239
Cartridge filter replacement (58 filters/yr @ $197.9583/sf/yr)	11,402
Facility maintenance (materials and labor) (4700 sf @ $5.9929/sf/yr)	28,166
Sodium Hydroxide - Small Qty (79132 lbs/yr @ $0.302/lb)	23,895
Perchlorate-selective (479 cf/yr @ $256.5165/cf)	122,919
Energy for booster pumps (216 Mwh/yr @ $0.1212/kwh)	26,226
Energy for backwash/rinse pumps (0 Mwh/yr @ $0.1212/kwh)	0
Energy for lighting (4 Mwh/yr @ $0.1212/kwh)	540
Energy for ventilation (4 Mwh/yr @ $0.1212/kwh)	444
Heat pump (cooling mode) (39 Mwh/yr @ $0.1212/kwh)	4,732
Heat pump (62 Mwh/yr @ $0.1212/kwh)	7,516
POTW discharge fees (16757 gal/yr @ $0.1762/gal)	2,953
Spent resin disposal (10 ton/yr @ $697.6744/ton)	7,188
Spent cartridge filter disposal (1 ton/yr @ $74.9152/ton)	52
Miscellaneous Allowance (0 @ $)	25,861

Anion Exchange for Perchlorate, design 56.271 mgd, average 28.136 mgd, High-Cost Components, Resin type: Perchlorate-selective 250,000 BV

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1	Pressure Vessels - Stainless Steel	6,247,920	35
2.1	Ion Exchange Resin - Perchlorate-selective	4,672,704	N/A
3.4.1	Caustic Storage Tanks - Stainless Steel	20,040	35
3.4.2	Caustic Storage Tanks - Heat Tracing	2,341	10
3.4.3	Caustic Storage Tanks - Insulation	4,613	10
3.5.1	Caustic Day Tanks - Stainless Steel	5,461	35
3.5.2	Caustic Day Tanks - Heat Tracing	1,544	10
3.5.3	Caustic Day Tanks - Insulation	794	10
4.1	Cartridge Filters - Cartridge Filters	1,280,742	35
5.1.1	Backwash Piping - Stainless Steel	68,948	45
5.3.1	Process Piping - Stainless Steel	65,361	45
5.5.1	Inlet and Outlet Piping - Stainless Steel	127,977	45
5.7.1	Caustic Piping - Stainless Steel	27,579	45
5.8.1	Residuals Piping - Stainless Steel	29,507	45
5.8.2	Residuals Piping - Excavation	1,334	45
5.8.3	Residuals Piping - Bedding	79	45
5.8.4	Residuals Piping - Backfill and Compaction	618	45
5.8.5	Residuals Piping - Thrust Blocks	1,070	45
6.1.1	Valves and Fittings - Motor/Air Operated (on/off) - Process - Stainless Steel	1,247,412	25
6.1.2	Valves and Fittings - Motor/Air Operated (on/off) - Backwash - Stainless Steel	405,104	25
6.1.6	Valves and Fittings - Motor/Air Operated (on/off) - Caustic - Stainless Steel	8,267	25
6.2.1	Valves and Fittings - Manual - Inlet and outlet - Cast Iron	22,996	25
6.2.2	Valves and Fittings - Manual - Process - Stainless Steel	337,430	25
6.3.1	Valves and Fittings - Check Valves - Backwash - Stainless Steel	9,128	25
6.3.2	Valves and Fittings - Check Valves - Inlet and Outlet - Stainless Steel	75,474	25
6.3.7	Valves and Fittings - Check Valves - Residuals - Stainless Steel	3,068	25
7.1	Pumps - Booster	412,163	20
7.2	Pumps - Backwash/Rinse	42,669	20
8.2.1	Mixers for Caustic Storage Tanks - Mounted	3,221	25
8.3.1	Mixers for Caustic Day Tanks - Mounted	1,765	25
11.1.1	Instrumentation and Controls - Flow Meters - Inlet and Outlet - Orifice Plate	12,366	15
11.3.1	Instrumentation and Controls - Flow Meters - Backwash - Magnetic	8,824	15
11.4.1	Instrumentation and Controls - Flow Meters - Residuals - Magnetic	6,832	15
11.9	Instrumentation and Controls - High/Low Alarm (for caustic tanks)	1,185	15
11.11	Instrumentation and Controls - Temperature meters	593	15
11.12	Instrumentation and Controls - Head loss sensors	95,449	15
11.13.1	Instrumentation and Controls - Sampling Ports - Carbon Steel	1,300	25
11.17	Instrumentation and Controls - Turbidity meters	5,223	15
12.1.1	System Controls - PLC Units - PLC racks/power supplies	1,361	10
12.1.2	System Controls - PLC Units - CPUs	1,256	10
12.1.3	System Controls - PLC Units - I/O discrete input modules	1,227	10
12.1.4	System Controls - PLC Units - I/O discrete output modules	375	10
12.1.5	System Controls - PLC Units - I/O combination analog modules	14,359	10
12.1.6	System Controls - PLC Units - Ethernet modules	1,730	10
12.1.7	System Controls - PLC Units - Base expansion modules	355	10
12.1.8	System Controls - PLC Units - Base expansion controller modules	257	10
12.1.9	System Controls - PLC Units - UPSs	563	10
12.2.1	System Controls - Operator Equipment - Drive controllers	9,652	15
12.2.2	System Controls - Operator Equipment - Operator interface units	920	10
12.2.3	System Controls - Operator Equipment - PC Workstations	1,006	10
12.2.4	System Controls - Operator Equipment - Printers - laser jet	627	10
12.2.5	System Controls - Operator Equipment - Printers - dot matrix	642	10

WBS #	Item	Total Cost ($)	Useful Life (yrs)
12.3.1	System Controls - Controls Software - Operator interface software	366	10
12.3.2	System Controls - Controls Software - PLC programming software	474	10
12.3.3	System Controls - Controls Software - PLC data collection software	690	10
12.3.4	System Controls - Controls Software - Plant intelligence software	11,480	10
13.1.1	Building Structures and HVAC - Building 1 - High Quality	1,555,399	40
13.1.2.1	Building Structures and HVAC - Building 1 - Heating System - Natural gas condensing furnace	64,314	25
13.1.3.1	Building Structures and HVAC - Building 1 - Cooling System - Air conditioner	25,745	25
13.2.1	Building Structures and HVAC - Building 2 - High Quality	412,924	40
13.2.3.1	Building Structures and HVAC - Building 2 - Heating and Cooling System - Heat pump	34,649	25
13.3	Building Structures and HVAC - Concrete Pad	236,511	40
Indirect	Indirect and Add-On Costs (contingency from model)	9,150,973	40
	Process Cost	**17,635,986**	
	System Cost	**26,786,959**	
	O&M Cost	**2,713,642**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Construction Management	749,880
Process Engineering	1,410,879
Site Work	262,459
Yard Piping	195,489
Geotechnical	32,795
Standby Power	147,274
Electrical (including yard wiring)	1,530,645
Mobilization and Demobilization	431,365
Architectural Fees for Treatment Building	144,432
Permits	1,731
Pilot Study	69,717
Land Cost	91,577
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Contingency (6.2%)	1,084,613
Miscellaneous Allowance (10.0%)	1,763,599
Legal, Fiscal, and Administrative (2.0%)	352,720
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	881,799

Breakdown of O&M costs	Annual Cost ($/year)
Manager (195 hrs/yr @ $71.8488/hr)	14,034
Clerical (195 hrs/yr @ $39.3563/hr)	7,688
Operator (1953 hrs/yr @ $43.8427/hr)	85,639
Materials for booster pumps (calculated as a percentage of capital)	4,122
Materials for backwash/rinse pumps (calculated as a percentage of capital)	427
Cartridge filter replacement (960 filters/yr @ $207.2477/sf/yr)	198,958
Facility maintenance (materials and labor) (20480 sf @ $5.9929/sf/yr)	122,734
Sodium Hydroxide - Large Qty (906405 lbs/yr @ $0.1254/lb)	113,672
Perchlorate-selective (5492 cf/yr @ $256.5165/cf)	1,408,734
Energy for booster pumps (2480 Mwh/yr @ $0.1212/kwh)	300,573
Energy for backwash/rinse pumps (0 Mwh/yr @ $0.1212/kwh)	3
Energy for lighting (160 Mwh/yr @ $0.1212/kwh)	19,397
Energy for ventilation (28 Mwh/yr @ $0.1212/kwh)	3,376
Air conditioning (67 Mwh/yr @ $0.1212/kwh)	8,167
Heat pump (cooling mode) (283 Mwh/yr @ $0.1212/kwh)	34,319
Heat pump (82 Mwh/yr @ $0.1212/kwh)	9,947
Natural gas condensing furnace (25251 therms/yr @ $0.7941/therm)	20,051
POTW discharge fees (189467 gal/yr @ $0.1682/gal)	31,868
Spent resin disposal (118 ton/yr @ $697.6744/ton)	82,377
Spent cartridge filter disposal (12 ton/yr @ $74.9152/ton)	863
Miscellaneous Allowance (0 @ $)	246,695

Biological Treatment, design 0.500 mgd, average 0.162 mgd, Low-Cost Components, Design Type: Fixed Bed Pressure Vessel

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1.1	Bioreactors - Pressure Vessels - Carbon Steel - Plastic Internals	61,436	30
1.3.1	Bioreactors - Media - GAC	30,950	N/A
2.1.1	Post-Treatment Filters - Filter Basins - Concrete	14,675	37
2.1.2	Post-Treatment Filters - Filter Basins - Internals (Underdrain/Backwash System)	121,148	37
2.1.3	Post-Treatment Filters - Filter Basins - Aluminum Railing	1,795	35
2.1.4	Post-Treatment Filters - Filter Basins - Aluminum Stairs	8,435	35
2.1.5	Post-Treatment Filters - Filter Basins - Excavation	8,987	37
2.1.6	Post-Treatment Filters - Filter Basins - Backfill and Compaction	3,334	37
2.3.1	Post-Treatment Filters - Media - Anthracite	7,920	8.5
2.3.2	Post-Treatment Filters - Media - Sand	3,608	20
3.2.1	Tanks - Electron Donor Storage Tanks - Plastic/XLPE	1,171	7
3.5.1	Tanks - Electron Donor Day Tanks - Plastic/XLPE	911	7
3.8.1	Tanks - Residuals Holding Tanks/Basins - Plastic/XLPE Tanks	12,401	20
3.11.1	Tanks - Aeration Tanks - Plastic/XLPE	1,596	20
3.11.2	Tanks - Aeration Tanks - Diffusers	53	10
3.12.1	Tanks - Polymer Storage Tanks - Plastic/XLPE	1,045	7
3.13.1	Tanks - Coagulant Mix Tank - Plastic/XLPE Tanks	1,571	20
4.1.1	Piping - Backwash Piping - PVC	1,134	17
4.2.1	Piping - Electron Donor Piping - PVC	101	17
4.4.1	Piping - Phosphoric Acid Piping - PVC	101	17
4.5.1	Piping - Process Piping - PVC	408	17
4.7.1	Piping - Inlet and Outlet Piping - PVC	622	17
4.8.1	Piping - Residuals Piping - PVC	219	17
4.11.1	Piping - Polymer Addition Piping - PVC	101	17
5.1.1	Valves and Fittings - Motor/Air Operated (on/off) - Process - Polypropylene/PVC	10,434	20
5.1.2	Valves and Fittings - Motor/Air Operated (on/off) - Backwash - Polypropylene/PVC	21,987	20
5.1.3	Valves and Fittings - Motor/Air Operated (on/off) - Electron Donor - Polypropylene/PVC	3,470	20
5.1.5	Valves and Fittings - Motor/Air Operated (on/off) - Phosphoric Acid - Polypropylene/PVC	2,974	20
5.1.7	Valves and Fittings - Motor/Air Operated (on/off) - Residuals - Polypropylene/PVC	1,654	20
5.1.8	Valves and Fittings - Motor/Air Operated (on/off) - Air Scour- Polypropylene/PVC	2,087	20
5.1.12	Valves and Fittings - Motor/Air Operated (on/off) - Aeration- Polypropylene/PVC	2,531	20
5.1.13	Valves and Fittings - Motor/Air Operated (on/off) - Polymer- Polypropylene/PVC	2,478	20
5.2.1	Valves and Fittings - Manual - Inlet and outlet - Polypropylene/PVC	1,282	20
5.2.2	Valves and Fittings - Manual - Process - Polypropylene/PVC	905	20
5.3.1	Valves and Fittings - Check Valves - Backwash - Polypropylene/PVC	2,262	20
5.3.2	Valves and Fittings - Check Valves - Residuals - Polypropylene/PVC	227	20
5.3.3	Valves and Fittings - Check Valves - Inlet and outlet - Polypropylene/PVC	1,353	20
5.3.5	Valves and Fittings - Check Valves - Electron Donor - Polypropylene/PVC	283	20
5.3.7	Valves and Fittings - Check Valves - Phosphoric Acid - Polypropylene/PVC	424	20
5.3.8	Valves and Fittings - Check Valves - Polymer - Polypropylene/PVC	141	20
6.4	Pumps and Blowers - Residuals Pump	13,958	17
6.5.1	Pumps and Blowers - Electron Donor Metering - PVC - Electric	1,850	15
6.7.1	Pumps and Blowers - Phosphoric Acid Metering - PVC - Electric	777	15
6.8.1	Pumps and Blowers - Blowers - Air Scour - Positive Displacement	23,134	20

WBS #	Item	Total Cost ($)	Useful Life (yrs)
6.8.3	Pumps and Blowers - Blowers - Aeration - Positive Displacement	20,390	20
6.10.1	Pumps and Blowers - Polymer Metering - PVC - Electric	5,165	15
7.1.1	Mixers - Mixers for Electron Donor Storage Tanks - Mounted	1,720	22
7.2.1	Mixers - Mixers for Electron Donor Day Tanks - Mounted	1,669	22
7.5.1	Mixers - Mixers for Phosphoric Acid Storage Tanks - Mounted	1,650	22
7.11.1	Mixers - Mixers for Polymer Storage Tanks - Mounted	1,695	22
7.12.1	Mixers - Coagulant Mix Tank Mixers - Mounted	1,752	22
8.1	Solids Transfer - Eductors for Holding Tanks	1,690	40
8.2.1	Solids Transfer - Dry Feeders for Filter Coagulant Addition - Volumetric Feeder	15,177	20
9.1.1	Instrumentation - Flow Meters - Inlet and Outlet - Propeller	4,141	14
9.3.1	Instrumentation - Flow Meters - Backwash - Propeller	4,544	14
9.4.1	Instrumentation - Flow Meters - Residuals - Propeller	1,786	14
9.7	Instrumentation - High/Low Alarm (for holding tanks)	593	14
9.8	Instrumentation - Temperature meters	2,373	14
9.9	Instrumentation - Head loss sensors	4,242	14
9.10.1	Instrumentation - Sampling Ports - Stainless Steel	350	30
9.12	Instrumentation - ORP sensor	5,265	14
9.14	Instrumentation - Turbidity meters	20,893	14
9.15	Instrumentation - Perchlorate/Nitrate Analyzer	24,574	14
9.17	Instrumentation - Dissolved Oxygen Analyzer	2,941	14
10.1.1	System Controls - PLC Unit(s) - PLC racks/power supplies	680	8
10.1.2	System Controls - PLC Unit(s) - CPUs	1,256	8
10.1.3	System Controls - PLC Unit(s) - I/O discrete input modules	614	8
10.1.4	System Controls - PLC Unit(s) - I/O discrete output modules	375	8
10.1.5	System Controls - PLC Unit(s) - I/O combination analog modules	5,874	8
10.1.6	System Controls - PLC Unit(s) - Ethernet modules	1,730	8
10.1.7	System Controls - PLC Unit(s) - Base expansion modules	118	8
10.1.8	System Controls - PLC Unit(s) - Base expansion controller modules	86	8
10.1.9	System Controls - PLC Unit(s) - UPSs	563	8
10.2.1	System Controls - Operator Equipment - Drive controllers	15,014	14
10.2.2	System Controls - Operator Equipment - Operator interface units	3,911	8
11.1.1	Building Structures and HVAC - Building 1 - Low Quality	86,721	37
11.3	Building Structures and HVAC - Concrete Pad	9,072	37
14.1	Solids drying pad	1,296	37
Indirect	Indirect and Add-On Costs (contingency from model)	425,303	37
	Process Cost	**627,852**	
	System Cost	**1,053,155**	
	O&M Cost	**52,275**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Mobilization and Demobilization	0
Architectural Fees for Treatment Building	0
Site Work	15,507
Yard Piping	3,375
Geotechnical	4,736
Standby Power	0
Electrical (including yard wiring)	53,206
Contingency	0
Process Engineering	125,570
Construction Management and GC Overhead	11,913
Permits	903
Pilot Study	132,669
Land Cost	2,082
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	62,785
Legal, Fiscal, and Administrative (2.0%)	12,557
Sales Tax (0.0%)	0
Financing during Construction (0.0%)	0

Breakdown of O&M costs	Annual Cost ($/year)
Manager (45 hrs/yr @ $45.2396/hr)	2,049
Administrative (45 hrs/yr @ $31.9149/hr)	1,446
Operator (321 hrs/yr @ $30.4776/hr)	9,776
Materials for residuals pumps (calculated as a percentage of capital)	140
Materials for backwash air scour blowers (calculated as a percentage of capital)	231
Materials for aeration blowers (calculated as a percentage of capital)	204
Materials for filter basins (calculated as a percentage of capital)	1,404
Facility maintenance (materials and labor) (1100 sf @ $5.7866/sf/yr)	6,365
Acetic Acid (24657 lbs/yr @ $0.0978/lb)	2,412
Phosphoric Acid - Small Qty (2086 lbs/yr @ $0.5492/lb)	1,145
Ferric Chloride - Small Qty (4931 lbs/yr @ $0.9961/lb)	4,912
Polymers - Large Qty (2521 lbs/yr @ $0.8113/lb)	2,045
GAC annual attrition replacement - Bioreactor (1701 lbs/yr @ $1.9176/lb)	3,262
Sand annual attrition replacement- Filter (15 cuft/yr @ $23.5561/cuft)	361
Anthracite annual attrition replacement- Filter (1555 lbs/yr @ $0.5093/lb)	792
Consumables for online perchlorate analysis (NA)	10,117
Energy for backwash pumps (2 Mwh/yr @ $0.1212/kwh)	230
Energy for residuals pumps (0 Mwh/yr @ $0.1212/kwh)	15
Energy for blowers (1 Mwh/yr @ $0.1212/kwh)	100
Energy for lighting (0 Mwh/yr @ $0.1212/kwh)	60
Energy for ventilation (1 Mwh/yr @ $0.1212/kwh)	74
Holding basins solids disposal (5 ton/yr @ $74.9152/ton)	381
Miscellaneous Allowance (0 @ $)	4,752

Biological Treatment, design 5.809 mgd, average 2.455 mgd, Mid-Cost Components, Design Type: Fixed Bed Gravity Basin

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.2.1	Bioreactors - Gravity Basins - Concrete	106,224	40
1.2.2	Bioreactors - Gravity Basins - Internals (Underdrain/Backwash System)	492,141	40
1.2.3	Bioreactors - Gravity Basins - Aluminum Railing	8,526	40
1.2.4	Bioreactors - Gravity Basins - Aluminum Stairs	8,435	40
1.2.5	Bioreactors - Gravity Basins - Excavation	48,763	40
1.2.6	Bioreactors - Gravity Basins - Backfill and Compaction	11,850	40
1.3.1	Bioreactors - Media - GAC	406,254	N/A
2.1.1	Post-Treatment Filters - Filter Basins - Concrete	96,486	40
2.1.2	Post-Treatment Filters - Filter Basins - Internals (Underdrain/Backwash System)	413,581	40
2.1.3	Post-Treatment Filters - Filter Basins - Aluminum Railing	7,068	40
2.1.4	Post-Treatment Filters - Filter Basins - Aluminum Stairs	8,435	40
2.1.5	Post-Treatment Filters - Filter Basins - Excavation	41,825	40
2.1.6	Post-Treatment Filters - Filter Basins - Backfill and Compaction	10,826	40
2.3.1	Post-Treatment Filters - Media - Anthracite	110,417	10
2.3.2	Post-Treatment Filters - Media - Sand	50,308	20
3.1.1	Tanks - Backwash Tanks - Fiberglass	57,627	25
3.2.1	Tanks - Electron Donor Storage Tanks - Fiberglass	10,837	10
3.4.1	Tanks - Phosphoric Acid Storage Tanks - Fiberglass	4,705	10
3.5.1	Tanks - Electron Donor Day Tanks - Fiberglass	5,874	10
3.7.1	Tanks - Phosphoric Acid Day Tanks - Fiberglass	4,705	10
3.8.1	Tanks - Residuals Holding Tanks/Basins - Concrete Basins (includes Excavation, Backfill, and Compaction)	150,286	40
3.11.1	Tanks - Aeration Tanks - Fiberglass	12,202	25
3.11.2	Tanks - Aeration Tanks - Diffusers	413	10
3.12.1	Tanks - Polymer Storage Tanks - Fiberglass	9,932	10
3.13.1	Tanks - Coagulant Mix Tank - Fiberglass Tanks	11,769	25
4.1.1	Piping - Backwash Piping - CPVC	32,516	22
4.2.1	Piping - Electron Donor Piping - CPVC	352	22
4.4.1	Piping - Phosphoric Acid Piping - CPVC	352	22
4.5.1	Piping - Process Piping - CPVC	17,733	22
4.7.1	Piping - Inlet and Outlet Piping - CPVC	36,114	22
4.8.1	Piping - Residuals Piping - CPVC	4,003	22
4.11.1	Piping - Polymer Addition Piping - CPVC	480	22
5.1.1	Valves and Fittings - Motor/Air Operated (on/off) - Process - Cast Iron	231,488	25
5.1.2	Valves and Fittings - Motor/Air Operated (on/off) - Backwash - Cast Iron	114,008	25
5.1.3	Valves and Fittings - Motor/Air Operated (on/off) - Electron Donor - Stainless Steel	4,163	25
5.1.5	Valves and Fittings - Motor/Air Operated (on/off) - Phosphoric Acid - Stainless Steel	4,163	25
5.1.7	Valves and Fittings - Motor/Air Operated (on/off) - Residuals - Cast Iron	5,311	25
5.1.8	Valves and Fittings - Motor/Air Operated (on/off) - Air Scour- Cast Iron	6,822	25
5.1.12	Valves and Fittings - Motor/Air Operated (on/off) - Aeration- Cast Iron	7,440	25
5.1.13	Valves and Fittings - Motor/Air Operated (on/off) - Polymer- Polypropylene/PVC	2,614	25
5.2.1	Valves and Fittings - Manual - Inlet and outlet - Cast Iron	5,215	25
5.3.1	Valves and Fittings - Check Valves - Backwash - Cast Iron	7,911	25
5.3.2	Valves and Fittings - Check Valves - Residuals - Cast Iron	2,164	25
5.3.3	Valves and Fittings - Check Valves - Inlet and outlet - Cast Iron	5,234	25
5.3.5	Valves and Fittings - Check Valves - Electron Donor - Stainless Steel	1,032	25
5.3.7	Valves and Fittings - Check Valves - Phosphoric Acid - Stainless Steel	1,547	25
5.3.8	Valves and Fittings - Check Valves - Polymer - Polypropylene/PVC	180	25
6.1	Pumps and Blowers - Booster Pump	69,732	20

WBS #	Item	Total Cost ($)	Useful Life (yrs)
6.3	Pumps and Blowers - Backwash Pump	83,511	20
6.4	Pumps and Blowers - Residuals Pump	20,314	20
6.5.1	Pumps and Blowers - Electron Donor Metering - Stainless Steel - Electric	5,993	20
6.7.1	Pumps and Blowers - Phosphoric Acid Metering - PVC - Electric	1,612	20
6.8.1	Pumps and Blowers - Blowers - Air Scour - Positive Displacement	58,928	25
6.8.3	Pumps and Blowers - Blowers - Aeration - Positive Displacement	34,152	25
6.10.1	Pumps and Blowers - Polymer Metering - Stainless Steel - Motor Driven	14,614	20
7.1.1	Mixers - Mixers for Electron Donor Storage Tanks - Mounted	2,681	25
7.2.1	Mixers - Mixers for Electron Donor Day Tanks - Mounted	1,853	25
7.5.1	Mixers - Mixers for Phosphoric Acid Storage Tanks - Mounted	1,706	25
7.6.1	Mixers - Mixers for Phosphoric Acid Day Tanks - Mounted	1,651	25
7.11.1	Mixers - Mixers for Polymer Storage Tanks - Mounted	2,534	25
7.12.1	Mixers - Coagulant Mix Tank Mixers - Mounted	2,781	25
8.1	Solids Transfer - Eductors for Holding Tanks	9,084	45
8.2.1	Solids Transfer - Dry Feeders for Filter Coagulant Addition - Volumetric Feeder	15,180	25
9.1.1	Instrumentation - Flow Meters - Inlet and Outlet - Venturi	17,176	15
9.3.1	Instrumentation - Flow Meters - Backwash - Venturi	15,837	15
9.4.1	Instrumentation - Flow Meters - Residuals - Venturi	9,686	15
9.5	Instrumentation - Level Switch/Alarm (for vessels)	2,963	15
9.6	Instrumentation - High/Low Alarm (for backwash tanks)	593	15
9.7	Instrumentation - High/Low Alarm (for holding tanks)	593	15
9.8	Instrumentation - Temperature meters	5,933	15
9.9	Instrumentation - Head loss sensors	10,605	15
9.10.1	Instrumentation - Sampling Ports - Carbon Steel	700	25
9.12	Instrumentation - ORP sensor	5,265	15
9.14	Instrumentation - Turbidity meters	57,455	15
9.15	Instrumentation - Perchlorate/Nitrate Analyzer	24,574	15
9.17	Instrumentation - Dissolved Oxygen Analyzer	2,941	15
10.1.1	System Controls - PLC Unit(s) - PLC racks/power supplies	1,361	10
10.1.2	System Controls - PLC Unit(s) - CPUs	1,256	10
10.1.3	System Controls - PLC Unit(s) - I/O discrete input modules	921	10
10.1.4	System Controls - PLC Unit(s) - I/O discrete output modules	375	10
10.1.5	System Controls - PLC Unit(s) - I/O combination analog modules	11,748	10
10.1.6	System Controls - PLC Unit(s) - Ethernet modules	1,730	10
10.1.7	System Controls - PLC Unit(s) - Base expansion modules	355	10
10.1.8	System Controls - PLC Unit(s) - Base expansion controller modules	257	10
10.1.9	System Controls - PLC Unit(s) - UPSs	563	10
10.2.1	System Controls - Operator Equipment - Drive controllers	20,376	15
10.2.2	System Controls - Operator Equipment - Operator interface units	920	10
10.2.3	System Controls - Operator Equipment - PC Workstations	1,006	10
10.2.4	System Controls - Operator Equipment - Printers - laser jet	627	10
10.2.5	System Controls - Operator Equipment - Printers - dot matrix	642	10
10.3.1	System Controls - Controls Software - Operator interface software	366	10
10.3.2	System Controls - Controls Software - PLC programming software	474	10
10.3.3	System Controls - Controls Software - PLC data collection software	690	10
10.3.4	System Controls - Controls Software - Plant intelligence software	11,480	10
11.1.1	Building Structures and HVAC - Building 1 - Medium Quality	479,622	40
11.1.3.1	Building Structures and HVAC - Building 1 - Heating and Cooling System - Heat pump	3,812	25
11.2.1	Building Structures and HVAC - Building 2 - Medium Quality	748,150	40
11.2.3.1	Building Structures and HVAC - Building 2 - Heating and Cooling System - Heat pump	13,213	25
11.3	Building Structures and HVAC - Concrete Pad	183,377	40
14.1	Solids drying pad	7,128	40

WBS #	Item	Total Cost ($)	Useful Life (yrs)
Indirect	Indirect and Add-On Costs (contingency from model)	2,835,055	40
	Process Cost	**4,551,427**	
	System Cost	**7,386,482**	
	O&M Cost	**511,935**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Mobilization and Demobilization	226,694
Architectural Fees for Treatment Building	88,547
Site Work	206,712
Yard Piping	51,461
Geotechnical	62,238
Standby Power	28,054
Electrical (including yard wiring)	312,325
Contingency	0
Process Engineering	546,171
Construction Management and GC Overhead	286,932
Permits	7,622
Pilot Study	212,082
Land Cost	32,474
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	455,143
Legal, Fiscal, and Administrative (2.0%)	91,029
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	227,571

Breakdown of O&M costs	Annual Cost ($/year)
Manager (199 hrs/yr @ $57.6375/hr)	11,493
Administrative (199 hrs/yr @ $35.9445/hr)	7,167
Operator (1365 hrs/yr @ $39.3563/hr)	53,734
Materials for booster pumps (calculated as a percentage of capital)	697
Materials for backwash pumps (calculated as a percentage of capital)	835
Materials for residuals pumps (calculated as a percentage of capital)	203
Materials for backwash air scour blowers (calculated as a percentage of capital)	589
Materials for aeration blowers (calculated as a percentage of capital)	342
Materials forbioreactor basins (calculated as a percentage of capital)	6,153
Materials for filter basins (calculated as a percentage of capital)	4,709
Facility maintenance (materials and labor) (15560 sf @ $5.9929/sf/yr)	93,249
Acetic Acid (373663 lbs/yr @ $0.0978/lb)	36,551
Phosphoric Acid - Small Qty (31607 lbs/yr @ $0.5492/lb)	17,359
Ferric Chloride - Small Qty (74733 lbs/yr @ $0.9961/lb)	74,442
Polymers - Large Qty (48210 lbs/yr @ $0.8113/lb)	39,113
GAC annual attrition replacement - Bioreactor (19440 lbs/yr @ $1.8038/lb)	35,065
Sand annual attrition replacement- Filter (178 cuft/yr @ $23.5561/cuft)	4,192
Anthracite annual attrition replacement- Filter (18067 lbs/yr @ $0.5093/lb)	9,201
Consumables for online perchlorate analysis (NA)	10,117
Energy for booster pumps (216 Mwh/yr @ $0.1212/kwh)	26,226
Energy for backwash pumps (14 Mwh/yr @ $0.1212/kwh)	1,754
Energy for residuals pumps (9 Mwh/yr @ $0.1212/kwh)	1,108
Energy for blowers (10 Mwh/yr @ $0.1212/kwh)	1,188
Energy for lighting (62 Mwh/yr @ $0.1212/kwh)	7,522
Energy for ventilation (6 Mwh/yr @ $0.1212/kwh)	698
Heat pump (cooling mode) (54 Mwh/yr @ $0.1212/kwh)	6,509
Heat pump (99 Mwh/yr @ $0.1212/kwh)	12,003
Holding basins solids disposal (42 ton/yr @ $74.9152/ton)	3,175
Miscellaneous Allowance (0 @ $)	46,540

Biological Treatment, design 56.271 mgd, average 28.136 mgd, High-Cost Components, Design Type: Fluidized Bed Pressure Vessel

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1.1	Bioreactors - Pressure Vessels - Stainless Steel	16,981,071	35
1.3.1	Bioreactors - Media - GAC	2,776,373	N/A
2.1.1	Post-Treatment Filters - Filter Basins - Concrete	509,517	40
2.1.2	Post-Treatment Filters - Filter Basins - Internals (Underdrain/Backwash System)	1,692,172	40
2.1.3	Post-Treatment Filters - Filter Basins - Aluminum Railing	25,802	40
2.1.4	Post-Treatment Filters - Filter Basins - Aluminum Stairs	8,435	40
2.1.5	Post-Treatment Filters - Filter Basins - Excavation	236,337	40
2.1.6	Post-Treatment Filters - Filter Basins - Backfill and Compaction	41,320	40
2.3.1	Post-Treatment Filters - Media - Anthracite	1,039,884	10
2.3.2	Post-Treatment Filters - Media - Sand	473,789	20
3.2.1	Tanks - Electron Donor Storage Tanks - Stainless Steel	115,623	35
3.4.1	Tanks - Phosphoric Acid Storage Tanks - Fiberglass	4,944	10
3.5.1	Tanks - Electron Donor Day Tanks - Stainless Steel	19,303	35
3.7.1	Tanks - Phosphoric Acid Day Tanks - Fiberglass	4,944	10
3.8.1	Tanks - Residuals Holding Tanks/Basins - Steel Tanks	139,334	35
3.11.1	Tanks - Aeration Tanks - Steel	87,651	35
3.11.2	Tanks - Aeration Tanks - Diffusers	3,636	10
3.12.1	Tanks - Polymer Storage Tanks - Stainless Steel	25,447	35
3.13.1	Tanks - Coagulant Mix Tank - Steel Tanks	84,632	35
4.1.1	Piping - Backwash Piping - Stainless Steel	141,470	45
4.2.1	Piping - Electron Donor Piping - Stainless Steel	3,657	45
4.4.1	Piping - Phosphoric Acid Piping - Stainless Steel	3,657	45
4.5.1	Piping - Process Piping - Stainless Steel	88,253	45
4.7.1	Piping - Inlet and Outlet Piping - Stainless Steel	204,762	45
4.8.1	Piping - Residuals Piping - Stainless Steel	9,102	45
4.9.1	Piping - Fluidized Bed Recycle Piping - Stainless Steel	70,544	45
4.11.1	Piping - Polymer Addition Piping - Stainless Steel	7,801	45
5.1.1	Valves and Fittings - Motor/Air Operated (on/off) - Process - Stainless Steel	1,355,857	25
5.1.2	Valves and Fittings - Motor/Air Operated (on/off) - Backwash - Stainless Steel	785,358	25
5.1.3	Valves and Fittings - Motor/Air Operated (on/off) - Electron Donor - Stainless Steel	27,895	25
5.1.5	Valves and Fittings - Motor/Air Operated (on/off) - Phosphoric Acid - Stainless Steel	27,895	25
5.1.7	Valves and Fittings - Motor/Air Operated (on/off) - Residuals - Stainless Steel	2,012	25
5.1.8	Valves and Fittings - Motor/Air Operated (on/off) - Air Scour- Stainless Steel	16,535	25
5.1.9	Valves and Fittings - Motor/Air Operated (on/off) - Fluidized Bed Recycle - Stainless Steel	269,670	25
5.1.11	Valves and Fittings - Motor/Air Operated (on/off) - Air Biomass Removal- Stainless Steel	6,007	25
5.1.12	Valves and Fittings - Motor/Air Operated (on/off) - Aeration- Stainless Steel	70,204	25
5.1.13	Valves and Fittings - Motor/Air Operated (on/off) - Polymer- Stainless Steel	3,353	25
5.2.1	Valves and Fittings - Manual - Inlet and outlet - Cast Iron	22,996	25
5.2.2	Valves and Fittings - Manual - Process - Stainless Steel	459,469	25
5.3.1	Valves and Fittings - Check Valves - Backwash - Stainless Steel	26,164	25
5.3.2	Valves and Fittings - Check Valves - Residuals - Stainless Steel	868	25
5.3.3	Valves and Fittings - Check Valves - Inlet and outlet - Stainless Steel	37,737	25
5.3.5	Valves and Fittings - Check Valves - Electron Donor - Stainless Steel	1,032	25
5.3.7	Valves and Fittings - Check Valves - Phosphoric Acid - Stainless Steel	1,547	25
5.3.8	Valves and Fittings - Check Valves - Polymer - Stainless Steel	868	25

WBS #	Item	Total Cost ($)	Useful Life (yrs)
6.1	Pumps and Blowers - Booster Pump	412,163	20
6.2	Pumps and Blowers - Recycle Pump	302,373	20
6.3	Pumps and Blowers - Backwash Pump	158,883	20
6.4	Pumps and Blowers - Residuals Pump	30,540	20
6.5.1	Pumps and Blowers - Electron Donor Metering - Stainless Steel - Motor Driven	11,689	20
6.7.1	Pumps and Blowers - Phosphoric Acid Metering - PVC - Motor Driven	5,938	20
6.8.1	Pumps and Blowers - Blowers - Air Scour - Positive Displacement	59,261	25
6.8.2	Pumps and Blowers - Blowers - Biomass Removal - Positive Displacement	15,178	25
6.8.3	Pumps and Blowers - Blowers - Aeration - Positive Displacement	143,920	25
6.10.1	Pumps and Blowers - Polymer Metering - Stainless Steel - Motor Driven	15,347	20
7.1.1	Mixers - Mixers for Electron Donor Storage Tanks - Impeller	24,687	25
7.2.1	Mixers - Mixers for Electron Donor Day Tanks - Mounted	3,156	25
7.5.1	Mixers - Mixers for Phosphoric Acid Storage Tanks - Mounted	2,309	25
7.6.1	Mixers - Mixers for Phosphoric Acid Day Tanks - Mounted	1,692	25
7.11.1	Mixers - Mixers for Polymer Storage Tanks - Mounted	3,668	25
7.12.1	Mixers - Coagulant Mix Tank Mixers - Impeller	18,263	25
8.1	Solids Transfer - Eductors for Holding Tanks	15,000	45
8.2.1	Solids Transfer - Dry Feeders for Filter Coagulant Addition - Volumetric Feeder	15,205	25
9.1.1	Instrumentation - Flow Meters - Inlet and Outlet - Orifice Plate	12,366	15
9.3.1	Instrumentation - Flow Meters - Backwash - Magnetic	21,398	15
9.4.1	Instrumentation - Flow Meters - Residuals - Magnetic	3,868	15
9.7	Instrumentation - High/Low Alarm (for holding tanks)	593	15
9.8	Instrumentation - Temperature meters	73,569	15
9.9	Instrumentation - Head loss sensors	131,508	15
9.10.1	Instrumentation - Sampling Ports - Carbon Steel	3,950	25
9.12	Instrumentation - ORP sensor	5,265	15
9.14	Instrumentation - Turbidity meters	396,960	15
9.15	Instrumentation - Perchlorate/Nitrate Analyzer	24,574	15
9.17	Instrumentation - Dissolved Oxygen Analyzer	2,941	15
10.1.1	System Controls - PLC Unit(s) - PLC racks/power supplies	4,082	10
10.1.2	System Controls - PLC Unit(s) - CPUs	1,256	10
10.1.3	System Controls - PLC Unit(s) - I/O discrete input modules	2,455	10
10.1.4	System Controls - PLC Unit(s) - I/O discrete output modules	750	10
10.1.5	System Controls - PLC Unit(s) - I/O combination analog modules	49,604	10
10.1.6	System Controls - PLC Unit(s) - Ethernet modules	1,730	10
10.1.7	System Controls - PLC Unit(s) - Base expansion modules	1,302	10
10.1.8	System Controls - PLC Unit(s) - Base expansion controller modules	942	10
10.1.9	System Controls - PLC Unit(s) - UPSs	563	10
10.2.1	System Controls - Operator Equipment - Drive controllers	30,028	15
10.2.2	System Controls - Operator Equipment - Operator interface units	920	10
10.2.3	System Controls - Operator Equipment - PC Workstations	1,006	10
10.2.4	System Controls - Operator Equipment - Printers - laser jet	627	10
10.2.5	System Controls - Operator Equipment - Printers - dot matrix	642	10
10.3.1	System Controls - Controls Software - Operator interface software	366	10
10.3.2	System Controls - Controls Software - PLC programming software	474	10
10.3.3	System Controls - Controls Software - PLC data collection software	690	10
10.3.4	System Controls - Controls Software - Plant intelligence software	11,480	10
11.1.1	Building Structures and HVAC - Building 1 - High Quality	3,785,520	40
11.1.2.1	Building Structures and HVAC - Building 1 - Heating System - Natural gas condensing furnace	186,719	25
11.1.3.1	Building Structures and HVAC - Building 1 - Cooling System - Air conditioner	127,120	25
11.2.1	Building Structures and HVAC - Building 2 - High Quality	927,051	40

WBS #	Item	Total Cost ($)	Useful Life (yrs)
11.2.2.1	Building Structures and HVAC - Building 2 - Heating System - Natural gas condensing furnace	97,694	25
11.2.3.1	Building Structures and HVAC - Building 2 - Cooling System - Air conditioner	280,408	25
11.3	Building Structures and HVAC - Concrete Pad	664,821	40
14.1	Solids drying pad	9,720	40
Indirect	Indirect and Add-On Costs (contingency from model)	19,972,073	40
	Process Cost	**36,019,163**	
	System Cost	**55,991,236**	
	O&M Cost	**3,636,058**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Mobilization and Demobilization	880,869
Architectural Fees for Treatment Building	321,675
Site Work	730,092
Yard Piping	255,323
Geotechnical	203,370
Standby Power	238,619
Electrical (including yard wiring)	2,994,983
Contingency	3,243,958
Process Engineering	2,881,533
Construction Management and GC Overhead	1,510,943
Permits	32,593
Pilot Study	347,913
Land Cost	206,944
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	3,601,916
Legal, Fiscal, and Administrative (2.0%)	720,383
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	1,800,958

Breakdown of O&M costs	Annual Cost ($/year)
Manager (540 hrs/yr @ $71.8488/hr)	38,763
Administrative (540 hrs/yr @ $43.8427/hr)	23,653
Operator (4578 hrs/yr @ $39.3563/hr)	180,188
Materials for booster pumps (calculated as a percentage of capital)	4,122
Materials for backwash pumps (calculated as a percentage of capital)	1,589
Materials for recycle pumps (calculated as a percentage of capital)	3,024
Materials for residuals pumps (calculated as a percentage of capital)	305
Materials for backwash air scour blowers (calculated as a percentage of capital)	744
Materials for aeration blowers (calculated as a percentage of capital)	1,439
Materials for filter basins (calculated as a percentage of capital)	19,627
Facility maintenance (materials and labor) (56180 sf @ $5.9929/sf/yr)	336,679
Acetic Acid (4282440 lbs/yr @ $0.0978/lb)	418,894
Phosphoric Acid - Small Qty (362238 lbs/yr @ $0.5492/lb)	198,943
Ferric Chloride - Small Qty (856488 lbs/yr @ $0.9961/lb)	853,160
Polymers - Large Qty (123761 lbs/yr @ $0.8113/lb)	100,407
GAC annual attrition replacement - Bioreactor (83034 lbs/yr @ $1.6718/lb)	138,819
Sand annual attrition replacement- Filter (1724 cuft/yr @ $23.5561/cuft)	40,610
Anthracite annual attrition replacement- Filter (175011 lbs/yr @ $0.5093/lb)	89,133
Consumables for online perchlorate analysis (NA)	10,117
Energy for booster pumps (2480 Mwh/yr @ $0.1212/kwh)	300,573
Energy for recycle pumps (1240 Mwh/yr @ $0.1212/kwh)	150,286
Energy for backwash pumps (36 Mwh/yr @ $0.1212/kwh)	4,343
Energy for blowers (150 Mwh/yr @ $0.1212/kwh)	18,183
Energy for lighting (1212 Mwh/yr @ $0.1212/kwh)	146,962
Energy for ventilation (117 Mwh/yr @ $0.1212/kwh)	14,167
Air conditioning (685 Mwh/yr @ $0.1212/kwh)	82,991
Natural gas condensing furnace (142420 therms/yr @ $0.7941/therm)	113,090
Holding basins solids disposal (196 ton/yr @ $74.9152/ton)	14,695
Miscellaneous Allowance (0 @ $)	330,551

Reverse Osmosis / Nanofiltration, design 0.500 mgd, average 0.162 mgd, Low-Cost Components, Feed Water: High Quality GW

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1	Membrane Process - Membrane Elements	42,359	N/A
1.2	Membrane Process - RO Pressure Vessels	15,339	17
1.3.1	Membrane Process - Feed Line Connectors - Victaulic, Painted	1,341	20
1.5.1	Membrane Process - Piping On Rack - Feed - Stainless Steel	7,454	40
1.5.2	Membrane Process - Piping On Rack - Permeate - PVC	245	40
1.5.3	Membrane Process - Piping On Rack - Concentrate - Stainless Steel	5,573	40
1.6	Membrane Process - Vessel Support Rack - Steel Beams	13,663	20
1.7	Membrane Process - Markup for Rack Assembly	30,343	22
2.1.1	Pretreatment Acid Tanks - Plastic (HXLPE)	1,015	7
2.2.1	Pretreatment Antiscalant Tanks - Plastic (XLPE)	823	7
2.3.1	Cleaning Solution Makeup Tanks - Plastic (XLPE)	2,274	7
2.4.1	Cleaning Chemical Storage Tanks - Acid storage - Plastic (XLPE)	799	7
2.4.2	Cleaning Chemical Storage Tanks - High pH storage - Plastic (XLPE)	799	7
2.8.1	Acid Day Tanks - Plastic/XLPE	814	7
2.10.1	Mixers for Antiscalant Storage Tanks - Mounted	1,652	22
3.1.1	Inlet and Outlet Piping - PVC	622	17
3.2.1	Cleaning System Piping - PVC	204	17
3.3.1	Residuals Piping - PVC	612	17
3.3.2	Residuals Piping - Excavation	1,187	17
3.3.3	Residuals Piping - Bedding	70	17
3.3.4	Residuals Piping - Backfill and Compaction	550	17
3.3.5	Residuals Piping - Thrust Blocks	409	17
4.1.1	Motor/Air Operated (on/off) Valves - Pretreatment acid - Polypropylene/PVC	1,983	20
4.1.2	Motor/Air Operated (on/off) Valves - Antiscalant - Polypropylene/PVC	1,983	20
4.1.3	Motor/Air Operated (on/off) Valves - Feed line - Polypropylene/PVC	4,174	20
4.1.4	Motor/Air Operated (on/off) Valves - Concentrate control - Cast Iron	2,770	20
4.1.10	Motor/Air Operated (on/off) Valves - Cleaning - Polypropylene/PVC	25,042	20
4.2.1	Manual Valves - Inlet and outlet - Polypropylene/PVC	1,282	20
4.3.1	Check Valves - Residuals - Polypropylene/PVC	680	20
4.3.2	Check Valves - Inlet - Polypropylene/PVC	1,353	20
4.3.4	Check Valves - Feed pumps - Polypropylene/PVC	1,360	20
4.3.5	Check Valves - Cleaning - Polypropylene/PVC	2,040	20
5.1.1	Acid Metering Pumps for Pretreatment - PVC - Electric	1,582	15
5.2.1	Antiscalant Metering Pumps for Pretreatment - PVC - Electric	887	15
5.4	Pumps - Feed Water	34,730	17
5.7	Pumps - Cleaning Pumps (separate for acid and caustic)	2,901	17
6.1	Screens and Filters - Cartridge Filters for Feed	32,089	30
6.2.1	Screens and Filters - Security Screens for Cleaning - Simplex Basket Screens	11,080	30
6.3	Screens and Filters - Cartridge Filters for Cleaning	16,481	30
8.1	Teflon Immersion Heaters for Cleaning Tanks	3,321	14
9.1.1	Instrumentation - Flow Meters - Inlet and Outlet - Propeller	8,283	14
9.2.1	Instrumentation - Flow Meters - Membrane Trains - Feed Line - Propeller	7,289	14
9.3.1	Instrumentation - Flow Meters - Membrane Trains - Permeate Line - Propeller	7,289	14
9.3.1	Instrumentation - Flow Meters - Membrane Trains - Concentrate Line - Propeller	5,905	14
9.4.1	Instrumentation - Flow Meters - Cleaning - Propeller	12,424	14
9.5.1	Instrumentation - Propeller	3,645	14
9.6	Instrumentation - Level Switches/Alarms (for cleaning tanks)	1,185	14
9.7	Instrumentation - High/Low Alarms (for pretreatment chemical tanks)	1,185	14
9.8	Instrumentation - High/Low Alarms (for cleaning chemical storage tanks)	1,185	14
9.1	Instrumentation - pH meters	10,530	14

WBS #	Item	Total Cost ($)	Useful Life (yrs)
9.11	Instrumentation - Temperature meters	1,780	14
9.12	Instrumentation - Conductivity meters	12,927	14
9.13	Instrumentation - Head loss sensors	8,484	14
9.14.1	Instrumentation - Sampling ports - Carbon Steel	900	22
10.1.1	System Controls - PLC Units - PLC racks/power supplies	680	8
10.1.2	System Controls - PLC Units - CPUs	1,256	8
10.1.3	System Controls - PLC Units - I/O discrete input modules	614	8
10.1.4	System Controls - PLC Units - I/O discrete output modules	375	8
10.1.5	System Controls - PLC Units - I/O combination analog modules	5,874	8
10.1.6	System Controls - PLC Units - Ethernet modules	1,730	8
10.1.7	System Controls - PLC Units - Base expansion modules	118	8
10.1.8	System Controls - PLC Units - Base expansion controller modules	86	8
10.1.9	System Controls - PLC Units - UPSs	563	8
10.2.1	System Controls - Operator Equipment - Drive controllers	9,652	14
10.2.2	System Controls - Operator Equipment - Operator interface units	3,911	8
11.1.1	Building Structures and HVAC - Building 1 - Low Quality	118,890	37
11.4	Building Structures and HVAC - Concrete Pad	18,143	37
Indirect	Indirect and Add-On Costs (contingency from model)	305,971	37
	Process Cost	**518,789**	
	System Cost	**824,760**	
	O&M Cost	**198,657**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	**Total Cost ($)**
Mobilization and Demobilization	31,613
Construction Management and GC Overhead	41,579
Contingency	0
Process Engineering	103,758
Site Work	19,992
Yard Piping	3,418
Geotechnical	0
Standby Power	0
Electrical (including yard wiring)	38,176
Architectural Fees for Treatment Building	0
Pilot Study	1,330
Land Cost	2,444
Permits	1,407
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	51,879
Legal, Fiscal, and Administrative (2.0%)	10,376
Sales Tax (0.0%)	0
Financing during Construction (0.0%)	0

Breakdown of O&M costs	**Annual Cost ($/year)**
Manager (116 hrs/yr @ $45.2396/hr)	5,269
Administrative (116 hrs/yr @ $30.4776/hr)	3,550
Operator (1165 hrs/yr @ $31.9149/hr)	37,173
Materials for pretreatment (calculated as a percentage of capital)	346
Cartridge filter replacement (19 filters/yr @ $173.693/filter)	3,275
Materials for membrane process (calculated as a percentage of capital)	424
Membrane replacement (10 element/yr @ $564.7907/element)	5,809
Materials for cleaning (calculated as a percentage of capital)	305
Materials for feed water and booster pumps (calculated as a percentage of capital)	347

Breakdown of O&M costs	Annual Cost ($/year)
Facility maintenance (materials and labor) (1560 sf @ $5.7866/sf/yr)	9,027
Sulfuric Acid - Small Qty (23565 lbs/yr @ $0.3087/lb)	7,274
Antiscalant - Basic (2468 lbs/yr @ $1.8447/lb)	4,552
Membrane Cleaner - Low pH Sulfate Control (13 gal/yr @ $27.5474/gal)	349
Membrane Cleaner - High pH Detergent (13 gal/yr @ $31.6028/gal)	400
Energy for feed water and booster pumps (119 Mwh/yr @ $0.1212/kwh)	14,385
Energy for lighting (2 Mwh/yr @ $0.1212/kwh)	220
Energy for ventilation (3 Mwh/yr @ $0.1212/kwh)	363
POTW discharge fees (19757898 gal/yr @ $0.0044/gal)	87,493
Spent cartridge filter disposal (0 ton/yr @ $74.9152/ton)	23
Spent membrane element disposal (0 ton/yr @ $74.9152/ton)	14
Miscellaneous Allowance (0 @ $)	18,060

Reverse Osmosis / Nanofiltration, design 5.809 mgd, average 2.455 mgd, Mid-Cost Components, Feed Water: High Quality GW

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1	Membrane Process - Membrane Elements	679,514	N/A
1.2	Membrane Process - RO Pressure Vessels	224,291	22
1.3.1	Membrane Process - Feed Line Connectors - Victaulic, Galvanized	23,514	25
1.5.1	Membrane Process - Piping On Rack - Feed - Stainless Steel	121,348	45
1.5.2	Membrane Process - Piping On Rack - Permeate - PVC	5,132	45
1.5.3	Membrane Process - Piping On Rack - Concentrate - Stainless Steel	102,499	45
1.6	Membrane Process - Vessel Support Rack - Steel Beams	56,866	25
1.7	Membrane Process - Markup for Rack Assembly	299,601	29
2.1.1	Pretreatment Acid Tanks - Fiberglass	7,338	10
2.2.1	Pretreatment Antiscalant Tanks - Fiberglass	5,085	10
2.3.1	Cleaning Solution Makeup Tanks - Fiberglass	17,704	10
2.4.1	Cleaning Chemical Storage Tanks - Acid storage - Fiberglass	4,785	10
2.4.2	Cleaning Chemical Storage Tanks - High pH storage - Fiberglass	4,785	10
2.8.1	Acid Day Tanks - Fiberglass	4,891	10
2.9.1	Antiscalant Day Tanks - Fiberglass	4,710	10
2.10.1	Mixers for Antiscalant Storage Tanks - Mounted	1,717	25
2.11.1	Mixers for Antiscalant Day Tanks - Mounted	1,651	25
3.1.1	Inlet and Outlet Piping - CPVC	29,641	22
3.2.1	Cleaning System Piping - CPVC	3,430	22
3.3.1	Residuals Piping - CPVC	13,641	22
3.3.2	Residuals Piping - Excavation	1,508	22
3.3.3	Residuals Piping - Bedding	89	22
3.3.4	Residuals Piping - Backfill and Compaction	699	22
3.3.5	Residuals Piping - Thrust Blocks	2,153	22
4.1.1	Motor/Air Operated (on/off) Valves - Pretreatment acid - Stainless Steel	1,665	25
4.1.2	Motor/Air Operated (on/off) Valves - Antiscalant - Stainless Steel	1,665	25
4.1.3	Motor/Air Operated (on/off) Valves - Feed line - Cast Iron	36,483	25
4.1.4	Motor/Air Operated (on/off) Valves - Concentrate control - Stainless Steel	15,983	25
4.1.10	Motor/Air Operated (on/off) Valves - Cleaning - Stainless Steel	202,457	25
4.2.1	Manual Valves - Inlet and outlet - Cast Iron	6,852	25
4.3.1	Check Valves - Residuals - Cast Iron	2,870	25
4.3.2	Check Valves - Inlet - Cast Iron	6,754	25
4.3.4	Check Valves - Feed pumps - Cast Iron	15,822	25
4.3.5	Check Valves - Cleaning - Cast Iron	5,786	25
5.1.1	Acid Metering Pumps for Pretreatment - PVC - Electric	2,963	20
5.2.1	Antiscalant Metering Pumps for Pretreatment - Stainless Steel - Electric	3,304	20
5.4	Pumps - Feed Water	213,062	20
5.7	Pumps - Cleaning Pumps (separate for acid and caustic)	8,294	20
6.1	Screens and Filters - Cartridge Filters for Feed	203,680	35
6.2.1	Screens and Filters - Security Screens for Cleaning - Simplex Basket Screens	53,718	35
6.3	Screens and Filters - Cartridge Filters for Cleaning	123,757	35
8.1	Teflon Immersion Heaters for Cleaning Tanks	23,304	15
9.1.1	Instrumentation - Flow Meters - Inlet and Outlet - Venturi	37,666	15
9.2.1	Instrumentation - Flow Meters - Membrane Trains - Feed Line - Venturi	47,512	15
9.3.1	Instrumentation - Flow Meters - Membrane Trains - Permeate Line - Venturi	43,235	15
9.3.1	Instrumentation - Flow Meters - Membrane Trains - Concentrate Line - Venturi	37,488	15
9.4.1	Instrumentation - Flow Meters - Cleaning - Venturi	56,499	15
9.5.1	Instrumentation - Venturi	14,412	15
9.6	Instrumentation - Level Switches/Alarms (for cleaning tanks)	1,185	15
9.7	Instrumentation - High/Low Alarms (for pretreatment chemical tanks)	1,185	15

WBS #	Item	Total Cost ($)	Useful Life (yrs)
9.8	Instrumentation - High/Low Alarms (for cleaning chemical storage tanks)	1,185	15
9.1	Instrumentation - pH meters	10,530	15
9.11	Instrumentation - Temperature meters	1,780	15
9.12	Instrumentation - Conductivity meters	17,775	15
9.13	Instrumentation - Head loss sensors	14,848	15
9.14.1	Instrumentation - Sampling ports - Stainless Steel	8,700	35
10.1.1	System Controls - PLC Units - PLC racks/power supplies	1,020	10
10.1.2	System Controls - PLC Units - CPUs	1,256	10
10.1.3	System Controls - PLC Units - I/O discrete input modules	2,455	10
10.1.4	System Controls - PLC Units - I/O discrete output modules	375	10
10.1.5	System Controls - PLC Units - I/O combination analog modules	7,832	10
10.1.6	System Controls - PLC Units - Ethernet modules	1,730	10
10.1.7	System Controls - PLC Units - Base expansion modules	237	10
10.1.8	System Controls - PLC Units - Base expansion controller modules	171	10
10.1.9	System Controls - PLC Units - UPSs	563	10
10.2.1	System Controls - Operator Equipment - Drive controllers	16,087	15
10.2.2	System Controls - Operator Equipment - Operator interface units	920	10
10.2.3	System Controls - Operator Equipment - PC Workstations	2,013	10
10.2.4	System Controls - Operator Equipment - Printers - laser jet	627	10
10.2.5	System Controls - Operator Equipment - Printers - dot matrix	642	10
10.3.1	System Controls - Controls Software - Operator interface software	366	10
10.3.2	System Controls - Controls Software - PLC programming software	947	10
10.3.3	System Controls - Controls Software - PLC data collection software	1,380	10
10.3.4	System Controls - Controls Software - Plant intelligence software	22,960	10
11.1.1	Building Structures and HVAC - Building 1 - Medium Quality	419,822	40
11.1.2.1	Building Structures and HVAC - Building 1 - Heating System - Natural gas condensing furnace	61,640	25
11.4	Building Structures and HVAC - Concrete Pad	73,869	40
Indirect	Indirect and Add-On Costs (contingency from model)	1,857,320	40
	Process Cost	**3,455,924**	
	System Cost	**5,313,244**	
	O&M Cost	**2,017,479**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Mobilization and Demobilization	150,269
Construction Management and GC Overhead	192,949
Contingency	0
Process Engineering	360,983
Site Work	65,230
Yard Piping	13,803
Geotechnical	0
Standby Power	115,996
Electrical (including yard wiring)	252,677
Architectural Fees for Treatment Building	38,513
Pilot Study	64,004
Land Cost	11,857
Permits	3,530
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	345,592
Legal, Fiscal, and Administrative (2.0%)	69,118
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	172,796

Breakdown of O&M costs	Annual Cost ($)
Manager (634 hrs/yr @ $57.6375/hr)	36,534
Administrative (634 hrs/yr @ $39.3563/hr)	24,946
Operator (6338 hrs/yr @ $35.9445/hr)	227,834
Materials for pretreatment (calculated as a percentage of capital)	2,083
Cartridge filter replacement (130 filters/yr @ $203.4792/filter)	26,510
Materials for membrane process (calculated as a percentage of capital)	6,795
Membrane replacement (165 element/yr @ $529.4913/element)	87,366
Materials for cleaning (calculated as a percentage of capital)	1,858
Materials for feed water and booster pumps (calculated as a percentage of capital)	2,131
Facility maintenance (materials and labor) (5090 sf @ $5.9193/sf/yr)	30,129
Sulfuric Acid - Small Qty (253899 lbs/yr @ $0.3087/lb)	78,367
Antiscalant - Basic (28052 lbs/yr @ $1.8447/lb)	51,749
Membrane Cleaner - Low pH Sulfate Control (203 gal/yr @ $27.5474/gal)	5,592
Membrane Cleaner - High pH Detergent (203 gal/yr @ $31.6028/gal)	6,415
Energy for feed water and booster pumps (1872 Mwh/yr @ $0.1212/kwh)	226,892
Energy for lighting (32 Mwh/yr @ $0.1212/kwh)	3,911
Energy for ventilation (13 Mwh/yr @ $0.1212/kwh)	1,547
Natural gas condensing furnace (23911 therms/yr @ $0.7941/therm)	18,987
POTW discharge fees (224932839 gal/yr @ $0.0044/gal)	994,106
Spent cartridge filter disposal (2 ton/yr @ $74.9152/ton)	154
Spent membrane element disposal (2 ton/yr @ $74.9152/ton)	165
Miscellaneous Allowance (0 @ $)	183,407

Reverse Osmosis / Nanofiltration, design 56.271 mgd, average 28.136 mgd, High-Cost Components, Feed Water: High Quality GW

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1	Membrane Process - Membrane Elements	4,612,457	N/A
1.2	Membrane Process - RO Pressure Vessels	1,522,459	22
1.3.1	Membrane Process - Feed Line Connectors - Victaulic, Galvanized	159,611	25
1.5.1	Membrane Process - Piping On Rack - Feed - Stainless Steel	823,697	45
1.5.2	Membrane Process - Piping On Rack - Permeate - PVC	34,835	45
1.5.3	Membrane Process - Piping On Rack - Concentrate - Stainless Steel	695,752	45
1.6	Membrane Process - Vessel Support Rack - Steel Beams	379,103	25
1.7	Membrane Process - Markup for Rack Assembly	2,026,759	29
2.1.1	Pretreatment Acid Tanks - Fiberglass	28,524	10
2.2.1	Pretreatment Antiscalant Tanks - Stainless Steel	11,510	35
2.3.1	Cleaning Solution Makeup Tanks - Stainless Steel	22,264	35
2.4.1	Cleaning Chemical Storage Tanks - Acid storage - Fiberglass	4,878	10
2.4.2	Cleaning Chemical Storage Tanks - High pH storage - Stainless Steel	4,710	35
2.8.1	Acid Day Tanks - Fiberglass	6,716	10
2.9.1	Antiscalant Day Tanks - Stainless Steel	4,880	35
2.10.1	Mixers for Antiscalant Storage Tanks - Mounted	2,412	25
2.11.1	Mixers for Antiscalant Day Tanks - Mounted	1,700	25
3.1.1	Inlet and Outlet Piping - Stainless Steel	136,508	45
3.2.1	Cleaning System Piping - Stainless Steel	24,848	45
3.3.1	Residuals Piping - Steel	74,713	35
3.3.2	Residuals Piping - Excavation	2,871	22
3.3.3	Residuals Piping - Bedding	144	22
3.3.4	Residuals Piping - Backfill and Compaction	1,331	22
3.3.5	Residuals Piping - Thrust Blocks	15,674	22
4.1.1	Motor/Air Operated (on/off) Valves - Pretreatment acid - Stainless Steel	1,665	25
4.1.2	Motor/Air Operated (on/off) Valves - Antiscalant - Stainless Steel	1,665	25
4.1.3	Motor/Air Operated (on/off) Valves - Feed line - Stainless Steel	685,694	25
4.1.4	Motor/Air Operated (on/off) Valves - Concentrate control - Stainless Steel	106,556	25
4.1.10	Motor/Air Operated (on/off) Valves - Cleaning - Stainless Steel	745,892	25
4.2.1	Manual Valves - Inlet and outlet - Cast Iron	22,996	25
4.3.1	Check Valves - Residuals - Stainless Steel	15,845	25
4.3.2	Check Valves - Inlet - Stainless Steel	37,737	25
4.3.4	Check Valves - Feed pumps - Stainless Steel	195,726	25
4.3.5	Check Valves - Cleaning - Stainless Steel	9,203	25
5.1.1	Acid Metering Pumps for Pretreatment - PVC - Motor Driven	8,099	20
5.2.1	Antiscalant Metering Pumps for Pretreatment - PVC - Motor Driven	6,078	20
5.4	Pumps - Feed Water	2,900,895	20
5.7	Pumps - Cleaning Pumps (separate for acid and caustic)	8,352	20
6.1	Screens and Filters - Cartridge Filters for Feed	1,569,824	35
6.2.1	Screens and Filters - Security Screens for Cleaning - Simplex Basket Screens	54,857	35
6.3	Screens and Filters - Cartridge Filters for Cleaning	126,670	35
8.1	Teflon Immersion Heaters for Cleaning Tanks	23,855	15
9.1.1	Instrumentation - Flow Meters - Inlet and Outlet - Orifice Plate	24,731	15
9.2.1	Instrumentation - Flow Meters - Membrane Trains - Feed Line - Magnetic	225,534	15
9.3.1	Instrumentation - Flow Meters - Membrane Trains - Permeate Line - Magnetic	225,534	15
9.3.1	Instrumentation - Flow Meters - Membrane Trains - Concentrate Line - Magnetic	136,649	15
9.4.1	Instrumentation - Flow Meters - Cleaning - Orifice Plate	13,941	15
9.5.1	Instrumentation - Magnetic	25,692	15
9.6	Instrumentation - Level Switches/Alarms (for cleaning tanks)	1,185	15
9.7	Instrumentation - High/Low Alarms (for pretreatment chemical tanks)	1,185	15

WBS #	Item	Total Cost ($)	Useful Life (yrs)
9.8	Instrumentation - High/Low Alarms (for cleaning chemical storage tanks)	1,185	15
9.1	Instrumentation - pH meters	10,530	15
9.11	Instrumentation - Temperature meters	1,780	15
9.12	Instrumentation - Conductivity meters	100,186	15
9.13	Instrumentation - Head loss sensors	99,691	15
9.14.1	Instrumentation - Sampling ports - Stainless Steel	58,450	35
10.1.1	System Controls - PLC Units - PLC racks/power supplies	4,422	10
10.1.2	System Controls - PLC Units - CPUs	1,256	10
10.1.3	System Controls - PLC Units - I/O discrete input modules	13,195	10
10.1.4	System Controls - PLC Units - I/O discrete output modules	750	10
10.1.5	System Controls - PLC Units - I/O combination analog modules	35,897	10
10.1.6	System Controls - PLC Units - Ethernet modules	1,730	10
10.1.7	System Controls - PLC Units - Base expansion modules	1,420	10
10.1.8	System Controls - PLC Units - Base expansion controller modules	1,028	10
10.1.9	System Controls - PLC Units - UPSs	563	10
10.2.1	System Controls - Operator Equipment - Drive controllers	45,042	15
10.2.2	System Controls - Operator Equipment - Operator interface units	920	10
10.2.3	System Controls - Operator Equipment - PC Workstations	4,026	10
10.2.4	System Controls - Operator Equipment - Printers - laser jet	627	10
10.2.5	System Controls - Operator Equipment - Printers - dot matrix	642	10
10.3.1	System Controls - Controls Software - Operator interface software	366	10
10.3.2	System Controls - Controls Software - PLC programming software	1,895	10
10.3.3	System Controls - Controls Software - PLC data collection software	2,761	10
10.3.4	System Controls - Controls Software - Plant intelligence software	45,920	10
10.3.5	System Controls - Controls Software - Early warning software	13,395	10
11.1.1	Building Structures and HVAC - Building 1 - High Quality	640,174	40
11.1.2.1	Building Structures and HVAC - Building 1 - Heating System - Natural gas condensing furnace	170,293	25
11.1.3.1	Building Structures and HVAC - Building 1 - Heating and Cooling System - Air conditioner	1,104,140	25
11.2.1	Building Structures and HVAC - Building 2 - High Quality	362,372	40
11.2.3.1	Building Structures and HVAC - Building 2 - Heating and Cooling System - Heat pump	4,053	25
11.3.1	Building Structures and HVAC - Building 3 - High Quality	1,286,225	40
11.3.2.1	Building Structures and HVAC - Building 3 - Heating System - Natural gas condensing furnace	27,051	25
11.3.3.1	Building Structures and HVAC - Building 3 - Cooling System - Air conditioner	7,126	25
11.4	Building Structures and HVAC - Concrete Pad	384,249	40
Indirect	Indirect and Add-On Costs (contingency from model)	10,347,182	40
	Process Cost	**22,207,784**	
	System Cost	**32,554,965**	
	O&M Cost	**19,273,680**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Mobilization and Demobilization	508,239
Construction Management and GC Overhead	858,411
Contingency	0
Process Engineering	1,620,601
Site Work	291,037
Yard Piping	88,455
Geotechnical	0
Standby Power	1,039,493
Electrical (including yard wiring)	1,709,688
Architectural Fees for Treatment Building	195,959
Pilot Study	132,875
Land Cost	110,762
Permits	16,337
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	2,220,778
Legal, Fiscal, and Administrative (2.0%)	444,156
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	1,110,389

Breakdown of O&M costs	Annual Cost ($/year)
Manager (2379 hrs/yr @ $71.8488/hr)	170,939
Administrative (2379 hrs/yr @ $39.3563/hr)	93,634
Operator (23791 hrs/yr @ $43.8427/hr)	1,043,082
Materials for pretreatment (calculated as a percentage of capital)	15,790
Cartridge filter replacement (885 filters/yr @ $207.2116/filter)	183,293
Materials for membrane process (calculated as a percentage of capital)	46,125
Membrane replacement (1120 element/yr @ $529.4913/element)	593,030
Materials for cleaning (calculated as a percentage of capital)	1,899
Materials for feed water and booster pumps (calculated as a percentage of capital)	29,009
Facility maintenance (materials and labor) (22710 sf @ $5.9929/sf/yr)	136,098
Sulfuric Acid - Large Qty (2902863 lbs/yr @ $0.1107/lb)	321,406
Antiscalant - Basic (320728 lbs/yr @ $1.8447/lb)	591,654
Membrane Cleaner - Low pH Sulfate Control (1378 gal/yr @ $27.5474/gal)	37,958
Membrane Cleaner - High pH Detergent (1378 gal/yr @ $31.6028/gal)	43,546
Energy for feed water and booster pumps (21420 Mwh/yr @ $0.1212/kwh)	2,596,501
Energy for lighting (199 Mwh/yr @ $0.1212/kwh)	24,115
Energy for ventilation (90 Mwh/yr @ $0.1212/kwh)	10,902
Air conditioning (1878 Mwh/yr @ $0.1212/kwh)	227,680
Heat pump (15 Mwh/yr @ $0.1212/kwh)	1,760
Heat pump (43 Mwh/yr @ $0.1212/kwh)	5,236
Natural gas condensing furnace (80713 therms/yr @ $0.7941/therm)	64,091
POTW discharge fees (2553033230 gal/yr @ $0.0044/gal)	11,281,363
Spent cartridge filter disposal (11 ton/yr @ $74.9152/ton)	832
Spent membrane element disposal (21 ton/yr @ $74.9152/ton)	1,585
Miscellaneous Allowance (0 @ $)	1,752,153

Point of Use/Point of Entry, design 0.500 mgd, average 0.162 mgd, Contaminant: Perchlorate, Treatment Technology: POU Reverse Osmosis

WBS #	Item	Total Cost ($)	Useful Life (yrs)
23.1.1	Installed Treatment Equipment - POU/POE Unit Purchase	116,781	10
23.1.2	Installed Treatment Equipment - POU/POE Installation	41,270	10
23.1.3	Installed Treatment Equipment - Scheduling Time	7,330	N/A
23.2.1.1	Public Education - Technical Labor - Develop materials	319	N/A
23.2.1.3	Public Education - Technical Labor - Meetings	64	N/A
23.2.1.4	Public Education - Technical Labor - Post-meeting	64	N/A
23.2.2.1	Public Education - Clerical Labor - Develop materials	183	N/A
23.2.2.3	Public Education - Clerical Labor - Meetings	61	N/A
23.2.2.4	Public Education - Clerical Labor - Post-meeting	61	N/A
23.2.3.1	Public Education - Printed Material - Meeting flyers	8	N/A
23.2.3.2	Public Education - Printed Material - Meeting ads	60	N/A
23.2.3.4	Public Education - Printed Material - Meeting handouts	173	N/A
23.2.3.5	Public Education - Printed Material - Billing mailers	115	N/A
23.3.1	Initial Year Monitoring 1 - Sampling time	2,561	N/A
23.3.3	Initial Year Monitoring 1 - Analysis	35,074	N/A
23.3.4	Initial Year Monitoring 1 - Analysis (total coliform)	8,780	N/A
23.3.5	Initial Year Monitoring 1 - Shipping	598	N/A
Indirect	Indirect and Add-On Costs (contingency from model)	56,229	10
	Process Cost	**213,501**	
	System Cost	**269,730**	
	O&M Cost	**79,513**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Permitting	4,961
Pilot Testing	4,961
Legal	4,961
Engineering	24,807
Contingency	16,538

Breakdown of O&M costs	Annual Cost ($/year)
POU/POE Maintenance	9,978
Information updates	383
Maintenance Scheduling	9,529
Information updates	366
Sediment Pre-Filter	4,541
Pre-GAC Filter Cartridge	11,742
Post-GAC Filter Cartridge	6,785
RO Membrane	12,577
Billing mailers	173
Sampling time	1,277
Analysis	17,483
Shipping	304

Non-Treatment, design 0.500 mgd, average 0.162 mgd, Low-Cost Components, Design Type: Interconnection

WBS #	Item	Total Cost ($)	Useful Life (yrs)
3.1.1	Piping - Interconnect - PVC	59,800	17
3.1.2	Piping - Interconnect - Excavation	91,114	17
3.1.3	Piping - Interconnect - Backfill and Compaction	42,241	17
3.1.4	Piping - Interconnect - Asphalt Patch	12,713	17
4.1.1	Valves - Isolation (PRV) and Street - Ductile Iron	8,217	20
6.1.1	Instrumentation - Flow Meters - Interconnect - Propeller	4,141	14
Indirect	Indirect and Add-On Costs (contingency from model)	106,490	17
	Process Cost	**218,225**	
	System Cost	**324,716**	
	O&M Cost	**130,125**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Contingency	0
Process Engineering	43,645
Construction Management and GC Overhead	24,656
Site Work	0
Yard Piping	0
Geotechnical	0
Standby Power	0
Electrical (including yard wiring)	0
Mobilization and Demobilization	12,002
Architectural Fees for Treatment Building	0
Permits	0
Pilot Study	0
Land Cost	0
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	21,823
Legal, Fiscal, and Administrative (2.0%)	4,365
Sales Tax (0.0%)	0
Financing during Construction (0.0%)	0

Breakdown of O&M costs	Annual Cost ($/year)
Manager (0 hrs/yr @ $45.2396/hr)	4
Administrative (0 hrs/yr @ $31.9149/hr)	3
Operator (1 hrs/yr @ $30.4776/hr)	28
Purchased Water (59130 K gal @ $2K gal)	118,260
Miscellaneous Allowance (0 @ $)	11,830

Non-Treatment, design 0.500 mgd, average 0.162 mgd, Low-Cost Components, Design Type: New Well Construction

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1.1	Well Items - Well Casing - PVC	9,383	17
1.2.1	Well Items - Well screen - PVC Schedule 40	8,354	17
1.3.1	Well Items - Plugs - PVC	172	17
1.4	Well Items - Well Drilling	22,988	N/A
1.5	Well Items - Gravel Pack	14,275	N/A
1.6	Well Items - Well Development	875	N/A
1.7	Well Items - Surface seal well, concrete fill	5,125	N/A
3.2.1	Piping - Well - PVC	615	17
3.2.2	Piping - Well - Excavation	4,556	17
3.2.3	Piping - Well - Backfill and Compaction	2,112	17
4.2.2	Valves - Motor/Air Operated (on/off) - Well Pump - Polypropylene/PVC	1,282	20
5.2	Pumps - Well Pump	14,343	17
6.2.1	Instrumentation - Flow Meters - Well - Propeller	4,141	14
8.1.1	Building Structures - Building 1 - Small Low Cost Shed	9,200	20
Indirect	Indirect and Add-On Costs (contingency from model)	110,111	17
	Process Cost	**97,419**	
	System Cost	**207,530**	
	O&M Cost	**38,061**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Contingency	0
Process Engineering	19,484
Construction Management and GC Overhead	12,509
Site Work	2,563
Yard Piping	0
Geotechnical	27,008
Standby Power	0
Electrical (including yard wiring)	8,822
Mobilization and Demobilization	7,278
Architectural Fees for Treatment Building	0
Permits	0
Pilot Study	0
Land Cost	20,757
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	9,742
Legal, Fiscal, and Administrative (2.0%)	1,948
Sales Tax (0.0%)	0
Financing during Construction (0.0%)	0

Breakdown of O&M costs	Annual Cost ($/year)
Manager (4 hrs/yr @ $45.2396/hr)	193
Administrative (4 hrs/yr @ $31.9149/hr)	136
Operator (43 hrs/yr @ $30.4776/hr)	1,298
Facility maintenance (materials and labor) (200 sf @ $5.7866/sf/yr)	1,157
Well pump (calculated as a percentage of capital)	143
Energy for well pumps (261 Mwh/yr @ $0.1212/kwh)	31,674
Miscellaneous Allowance (0 @ $)	3,460

Non-Treatment, design 1.000 mgd, average 0.350 mgd, Mid-Cost Components, Design Type: Interconnection

WBS #	Item	Total Cost ($)	Useful Life (yrs)
3.1.1	Piping - Interconnect - PVC	59,800	22
3.1.2	Piping - Interconnect - Excavation	91,114	22
3.1.3	Piping - Interconnect - Backfill and Compaction	42,241	22
3.1.4	Piping - Interconnect - Asphalt Patch	12,713	22
4.1.1	Valves - Isolation (PRV) and Street - Ductile Iron	8,217	25
6.1.1	Instrumentation - Flow Meters - Interconnect - Venturi	12,496	15
Indirect	Indirect and Add-On Costs (contingency from model)	101,239	22
	Process Cost	**226,580**	
	System Cost	**327,819**	
	O&M Cost	**281,089**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Contingency	0
Process Engineering	27,190
Construction Management and GC Overhead	25,561
Site Work	0
Yard Piping	0
Geotechnical	0
Standby Power	0
Electrical (including yard wiring)	0
Mobilization and Demobilization	9,970
Architectural Fees for Treatment Building	0
Permits	0
Pilot Study	0
Land Cost	0
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	22,658
Legal, Fiscal, and Administrative (2.0%)	4,532
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	11,329

Breakdown of O&M costs	Annual Cost ($/year)
Manager (0 hrs/yr @ $51.7408/hr)	5
Administrative (0 hrs/yr @ $34.0506/hr)	3
Operator (1 hrs/yr @ $30.4776/hr)	28
Purchased Water (127750 K gal @ $2K gal)	255,500
Miscellaneous Allowance (0 @ $)	25,554

Non-Treatment, design 1.000 mgd, average 0.350 mgd, Mid-Cost Components, Design Type: New Well Construction

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1.1	Well Items - Well Casing - Stainless Steel	246,420	45
1.2.1	Well Items - Well screen - PVC Schedule 40	16,708	22
1.3.1	Well Items - Plugs - PVC	343	22
1.4	Well Items - Well Drilling	45,975	N/A
1.5	Well Items - Gravel Pack	28,550	N/A
1.6	Well Items - Well Development	1,750	N/A
1.7	Well Items - Surface seal well, concrete fill	10,250	N/A
3.2.1	Piping - Well - PVC	1,230	22
3.2.2	Piping - Well - Excavation	9,111	22
3.2.3	Piping - Well - Backfill and Compaction	4,224	22
4.2.2	Valves - Motor/Air Operated (on/off) - Well Pump - Cast Iron	9,920	25
5.2	Pumps - Well Pump	28,686	20
6.2.1	Instrumentation - Flow Meters - Well - Venturi	12,496	15
8.1.1	Building Structures - Building 1 - Small Low Cost Shed	18,401	25
Indirect	Indirect and Add-On Costs (contingency from model)	380,036	45
	Process Cost	**434,064**	
	System Cost	**814,100**	
	O&M Cost	**76,202**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Contingency	0
Process Engineering	52,088
Construction Management and GC Overhead	35,031
Site Work	5,126
Yard Piping	0
Geotechnical	54,017
Standby Power	51,369
Electrical (including yard wiring)	41,566
Mobilization and Demobilization	25,182
Architectural Fees for Treatment Building	1,656
Permits	0
Pilot Study	0
Land Cost	40,210
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	43,406
Legal, Fiscal, and Administrative (2.0%)	8,681
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	21,703

Breakdown of O&M costs	Annual Cost ($/year)
Manager (9 hrs/yr @ $51.7408/hr)	441
Administrative (9 hrs/yr @ $34.0506/hr)	290
Operator (85 hrs/yr @ $30.4776/hr)	2,596
Facility maintenance (materials and labor) (400 sf @ $5.7866/sf/yr)	2,315
Well pump (calculated as a percentage of capital)	287
Energy for well pumps (523 Mwh/yr @ $0.1212/kwh)	63,347
Miscellaneous Allowance (0 @ $)	6,927

Non-Treatment, design 3.536 mgd, average 1.417 mgd, High-Cost Components, Design Type: Interconnection

WBS #	Item	Total Cost ($)	Useful Life (yrs)
3.1.1	Piping - Interconnect - PVC	177,500	22
3.1.2	Piping - Interconnect - Excavation	103,262	22
3.1.3	Piping - Interconnect - Backfill and Compaction	47,873	22
3.1.4	Piping - Interconnect - Asphalt Patch	14,408	22
4.1.1	Valves - Isolation (PRV) and Street - Ductile Iron	20,394	25
6.1.1	Instrumentation - Flow Meters - Interconnect - Magnetic	11,277	15
Indirect	Indirect and Add-On Costs (contingency from model)	173,295	22
	Process Cost	**374,714**	
	System Cost	**548,009**	
	O&M Cost	**1,137,900**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Contingency	17,763
Process Engineering	44,966
Construction Management and GC Overhead	30,378
Site Work	0
Yard Piping	0
Geotechnical	0
Standby Power	0
Electrical (including yard wiring)	0
Mobilization and Demobilization	16,487
Architectural Fees for Treatment Building	0
Permits	0
Pilot Study	0
Land Cost	0
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	37,471
Legal, Fiscal, and Administrative (2.0%)	7,494
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	18,736

Breakdown of O&M costs	Annual Cost ($/year)
Manager (0 hrs/yr @ $57.6375/hr)	5
Administrative (0 hrs/yr @ $35.9445/hr)	3
Operator (1 hrs/yr @ $39.3563/hr)	36
Purchased Water (517205 K gal @ $2K gal)	1,034,410
Miscellaneous Allowance (0 @ $)	103,445

Non-Treatment, design 3.536 mgd, average 1.417 mgd, High-Cost Components, Design Type: New Well Construction

WBS #	Item	Total Cost ($)	Useful Life (yrs)
1.1.1	Well Items - Well Casing - Stainless Steel	616,050	45
1.2.1	Well Items - Well screen - PVC Schedule 40	41,769	22
1.3.1	Well Items - Plugs - PVC	858	22
1.4	Well Items - Well Drilling	114,938	N/A
1.5	Well Items - Gravel Pack	71,375	N/A
1.6	Well Items - Well Development	4,375	N/A
1.7	Well Items - Surface seal well, concrete fill	25,625	N/A
3.2.1	Piping - Well - PVC	3,075	22
3.2.2	Piping - Well - Excavation	22,778	22
3.2.3	Piping - Well - Backfill and Compaction	10,560	22
4.2.2	Valves - Motor/Air Operated (on/off) - Well Pump - Stainless Steel	53,278	25
5.2	Pumps - Well Pump	85,420	20
6.2.1	Instrumentation - Flow Meters - Well - Magnetic	6,832	15
8.1.1	Building Structures - Building 1 - Low Quality	79,569	40
Indirect	Indirect and Add-On Costs (contingency from model)	948,179	45
	Process Cost	**1,136,501**	
	System Cost	**2,084,680**	
	O&M Cost	**236,470**	
	Totals are computed before component costs are rounded		

Breakdown of indirect and add-on costs	Total Cost ($)
Contingency	58,752
Process Engineering	136,380
Construction Management and GC Overhead	75,554
Site Work	12,815
Yard Piping	0
Geotechnical	135,042
Standby Power	101,216
Electrical (including yard wiring)	105,693
Mobilization and Demobilization	64,197
Architectural Fees for Treatment Building	7,161
Permits	854
Pilot Study	0
Land Cost	57,309
Installation, Transportation, and O&P (0.0%)	0
Instrumentation and Control (0.0%)	0
Miscellaneous Allowance (10.0%)	113,650
Legal, Fiscal, and Administrative (2.0%)	22,730
Sales Tax (0.0%)	0
Financing during Construction (5.0%)	56,825

Breakdown of O&M costs	Annual Cost ($/year)
Manager (21 hrs/yr @ $57.6375/hr)	1,227
Administrative (21 hrs/yr @ $35.9445/hr)	765
Operator (213 hrs/yr @ $39.3563/hr)	8,380
Facility maintenance (materials and labor) (1000 sf @ $5.7866/sf/yr)	5,787
Well pump (calculated as a percentage of capital)	854
Energy for well pumps (1633 Mwh/yr @ $0.1212/kwh)	197,960
Miscellaneous Allowance (0 @ $)	21,497