Technologies and Costs Document for the Final Long Term 2 Enhanced Surface Water Treatment Rule and Final Stage 2 Disinfectants and Disinfection Byproducts Rule

Table of Contents

Executive Summary

Chapter 1: Introduction

Chapter 2: Technologies for DBP and Microbial Contaminant Control

Chapter 3: Technology Design and Criteria

Chapter 4: Technology Costs

List of Exhibits

List of Appendices

List of Acronyms

AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
AWWSC	American Water Works Service Company
BAT	Best Available Technology
BCI	building cost index
BDOC	biodegradable organic carbon
BLS	Bureau of Labor Statistics
BV	bed volume
˚C	degrees Celsius
CAP	total capital costs
CDC	Centers for Disease Control and Prevention
CFE	combined filter effluent
CFR	Code of Federal Regulations
CIP	clean-in-place
cm	centimeter
CT	measured disinfectant residual × contact time
CWS	community water system
D/DBP	disinfectant/disinfection byproduct
DBP	disinfection byproduct
DBPR	Disinfectants and Disinfection Byproducts Rule
DES	designated flow
DNA	deoxyribonucleic acid
DOC	dissolved organic carbon
E&I	electrical and instrumentation
EA	economic analysis
EA	environmental assessment
EBCT	empty bed contact time

EIS	environmental impact statement
ENR	Engineering News Record
EPA	United States Environmental Protection Agency
ES	effective size
ESWTR	Enhanced Surface Water Treatment Rule
FACA	Federal Advisory Committee Act
FBRR	Filter Backwash Recycling Rule
fps	feet per second
ft	feet
ft^2 (sf or sq ft)	square feet
FTW	filter to waste
GAC	granular activated carbon
gfd	gallons of filtrate per day per square foot of membrane area
gpd	gallons per day
gpm	gallons per minute
GWUDI	ground water under the direct influence of surface water
HAA	haloacetic acid
HAA5	sum of five haloacetic acids
HAA6	sum of six haloacetic acids
HIV	human immunodeficiency virus
Hp	horsepower
HPC	heterotrophic plate count
hr	hour
HVAC	heating, ventilation, and air conditioning
i	discount rate
I&C	instrumentation and controls
ICR	Information Collection Rule
IESWTR	Interim Enhanced Surface Water Treatment Rule
in	inch

kgal	thousand gallons
kgpd	thousand gallons per day
kW	kilowatt
kWh	kilowatt hour
lb	pound
LOX	liquid oxygen
LP	low pressure
LPHO	low pressure high output
LPUV	low pressure ultraviolet light
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
M-DBP	microbial-disinfection Byproduct
MF	microfiltration
mg/kg	milligrams per kilogram
µg/L	micrograms per liter
mg/L	milligrams per liter
mgal	million gallons
MGD or mgd	million gallons per day
mJ	milliJoules
mJ/cm^2	milliJoules per square centimeter
µm	micrometer
mm	millimeter
MP	medium pressure
MRDL	maximum residual disinfectant level
MRDLG	maximum residual disinfectant level goal
MWCO	molecular weight cut-off
MWDSC	Metropolitan Water District of Southern California

N	number of years
NDWAC	National Drinking Water Advisory Council
NF	nanofiltration
NIPDWR	National Interim Primary Drinking Water Regulation
nm	nanometers
NOM	natural organic matter
NPDWR	National Primary Drinking Water Regulation
NSF	National Science Foundation
NTNCWS	nontransient noncommunity water system
NTU	nephelometric turbidity units
O&M	operations and maintenance
OGWDW	Office of Ground Water and Drinking Water
OH&P	overhead and profit
OSHA	Occupational Safety and Health Administration
P&V	pipes and valves
PAC	powder activated carbon
PLC	programmable logic controller
POTW	publicly owned treatment works
ppb	parts per billion
ppm	parts per million
PPI	Producer Price Index (for Finished Goods)
PSA	pressure swing absorption
psi	pounds per square inch
psig	pounds per square inch gauge
PUV	pulsed ultraviolet
PVC	polyvinyl chloride
PWS	public water supply
RIA	regulatory impact analysis
RNA	ribonucleic acid

RO	reverse osmosis
SAB	Science Advisory Board
SCADA	Supervisory Control and Data Acquisition
scf	standard cubic feet
SDS	simulated distribution system
SDWA	Safe Drinking Water Act
sf (ft^2 or sq ft)	square feet
SOC	soluble organic carbon
SOC	synthetic organic chemical
sq ft (or sf or ft^2)	square feet
SWAT	surface water analytical tool
SWTR	Surface Water Treatment Rule
TDH	total dynamic head
TDP	Technology Design Panel
TDS	total dissolved solids
THM	trihalomethane
THMFP	trihalomethane formation potential
TMP	transmembrane pressure
TNCWS	transient noncommunity water system
TOC	total organic carbon
TOX	total organic halide
TOXFP	total organic halide formation potential
TSS	total suspended solids
TTHM	total trihalomethane
TWG	Technical Work Group
UC	uniformity coefficient
UF	ultrafiltration
UPS	uninterrupted power supply
UV	ultraviolet

UVT	ultraviolet transmittance
UV_{254}	ultraviolet absorbance at 254 nm
VSS	Very Small Systems Best Available Technology Cost Document
wk	week
WTP	water treatment plant
W/W	water and wastewater
yr	year

Executive Summary

ES.1 Introduction

This document provides information on costs and performance characteristics of treatment technologies that EPA projects public water systems (PWSs) will use to comply with the Stage 2 Disinfectants and Disinfection Byproducts Rule (Stage 2 DBPR) and the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). The unit costs are based on design criteria relevant to compliance with these rules. EPA developed these costs as part of making a regulatory impact assessment.

The Stage 2 DBPR will require PWSs that produce high concentrations of trihalomethanes (THMs) and haloacetic acids (HAAs) to reduce the levels of those species. Specifically, PWSs would have to comply with a locational running annual average (LRAA) of 80 and 60 μg/L for TTHM and HAAs, respectively. THMs and HAAs form primarily through reactions between chlorine, which is applied as a disinfectant, and natural organic matter in water. Systems can reduce the formation of THMs and HAAs by either of two general approaches: (1) reduce the concentration of dissolved organic carbon prior to disinfection through processes like enhanced coagulation, activated carbon, or nanofiltration, or (2) use pathogen removal/inactivation processes that do not form, or form low concentrations of, THMs and HAAs. Such processes include disinfection via chloramines, ozone, chlorine dioxide, ultraviolet (UV) light, and the use of membranes.

The LT2ESWTR will require certain PWSs to provide additional removal or inactivation of *Cryptosporidium*. The amount of required additional treatment for a PWS is dependent upon the results of source water *Cryptosporidium* monitoring and the existing level of treatment. Systems can treat for *Cryptosporidium* by: (1) removing *Cryptosporidium* through filtration processes, like granular media filtration, cartridge filters, or membranes; or (2) using disinfectants that are effective against *Cryptosporidium*, such as chlorine dioxide, UV, and ozone. Chlorine and chloramines are largely ineffective at inactivating *Cryptosporidium*.

Because many of the technologies systems can use to treat for *Cryptosporidium* are also effective in reducing formation of THMs and HAAs, EPA has chosen to address technologies for both the Stage 2 DBPR and LT2ESWTR in a single document. Chapter 1 of this document provides a brief overview of the microorganisms and DBPs of concern, along with a synopsis of existing regulatory requirements. Chapter 2 describes the technologies that were evaluated in this document for pathogen removal/inactivation and DBP control. Chapter 3 contains design criteria for these technologies, and Chapter 4 presents unit costs. Additional cost information is provided in the appendices.

ES.2 Alternative Disinfection and Precursor Reduction Strategies

This document evaluates the following pathogen removal and inactivation strategies—

- Chlorine dioxide
- Chloramines
- UV light
- Ozone
- Micro/Ultrafiltration
- Bag/cartridge filtration

- Pre-sedimentation
- Second Stage Filtration
- Watershed Management

As noted above, chlorine dioxide, UV light, ozone, micro/ultrafiltration, and bag/cartridge filtration are considered as available technologies for systems needing additional treatment for *Cryptosporidium*. Chlorine dioxide, chloramines, UV light, ozone, micro/ultrafiltration, bag/cartridge filtration, pre-sedimentation, second stage filtration, and watershed management are all disinfection strategies considered for systems to reduce THM and HAA formation.

While most of these alternative disinfection strategies are feasible for a wide range of system sizes, many considerations affect the choice of appropriate strategy for an individual system. While ozone, chlorine dioxide, and chloramines form lower concentrations of THMs and HAAs than free chlorine, these disinfectants form other regulated disinfection byproducts. Ozone reacts with naturally occurring bromide to form bromate, and can potentially increase formation of brominated THMs and HAAs. Chlorine dioxide is reduced to form chlorite. Chloramination increases the risk of nitrification in the distribution system. UV, and physical processes used for microbial treatment like microfiltration and cartridge filtration, do not result in DBP formation. However, verifying adequate process performance with these technologies may be a concern. Moreover, UV and these physical processes are less effective against viruses than chlorine, and do not have the oxidizing properties of chemical disinfectants. The alternative disinfection strategies also differ substantially with regard to how they are impacted by water quality; how they can fit into existing infrastructure; their use of materials, energy, and labor; their impact on other unit processes and treatment goals; and cost.

Many of these considerations also apply to selection of technologies for reducing DBP precursors. This document evaluates the following DBP precursors removal options—

- Granular activated carbon adsorption
- Nanofiltration

Economical use of granular activated carbon may necessitate on-site thermal reactivation (particularly at large facilities), which has multi-media impacts (e.g., air emissions). Nanofiltration is expensive, particularly for small systems, and disposal of residuals can be an issue. Further, nanofiltration may produce a reject stream of as much as 30 percent of the daily plant flow. These issues illustrate a few of the many factors that a system must consider when determining whether these technologies are feasible.

ES.3 Development of Design Criteria and Upgrade Costs

Process design criteria were developed for alternative disinfection strategies and DBP precursor removal technologies using water quality data gathered under the Information Collection Rule (ICR) and best engineering judgment. The ICR data were used to generate water quality statistics for parameters (e.g., turbidity, alkalinity, total organic carbon) that affect technology performance. Generally, 10^{th}, 50^{th} and 90^{th} percentile data were evaluated and design criteria are developed for these scenarios to provide low, medium, and high estimates of cost. When ICR data were not appropriate, engineering judgment and practical experience are used to develop a range of design criteria for which costs were estimated. The design criteria and methodology used to determine the criteria are discussed in detail in Chapter 3.

The Federal Advisory Committee convened a Technical Work Group (TWG) to assist with the regulatory development process. The TWG consisted of consulting engineers, scientists, utility representatives, EPA personnel, representatives of water equipment manufacturers, and other experts. One of the goals of the TWG was to ensure that the many inputs to the regulatory development process were reasonable, both scientifically and practically. As a result the TWG played a significant role in reviewing the design criteria and upgrade costs presented in this document.

Capital and operations and maintenance (O&M) costs are provided for each of the alternative disinfection strategies and DBP precursor removal technologies discussed in this document. Costs are provided for design flows ranging from 0.007 to 520 mgd. Previous drafts of this and similar EPA technology cost documents relied on various cost models. However, costs presented in this document were primarily developed using manufacturer quotations and cost estimating guides, though cost models were used for a few technologies.

Capital costs are presented in 2003 dollars. Appropriate *Engineering News Record* (ENR) and Bureau of Labor Statistics (BLS) cost indices were used for capital cost computation. The Producer's Price Index for Finished Goods was used in adjusting operations and maintenance (O&M) cost estimates. Capital and O&M costs are presented in Chapter 4 for each technology discussed in Chapter 2.

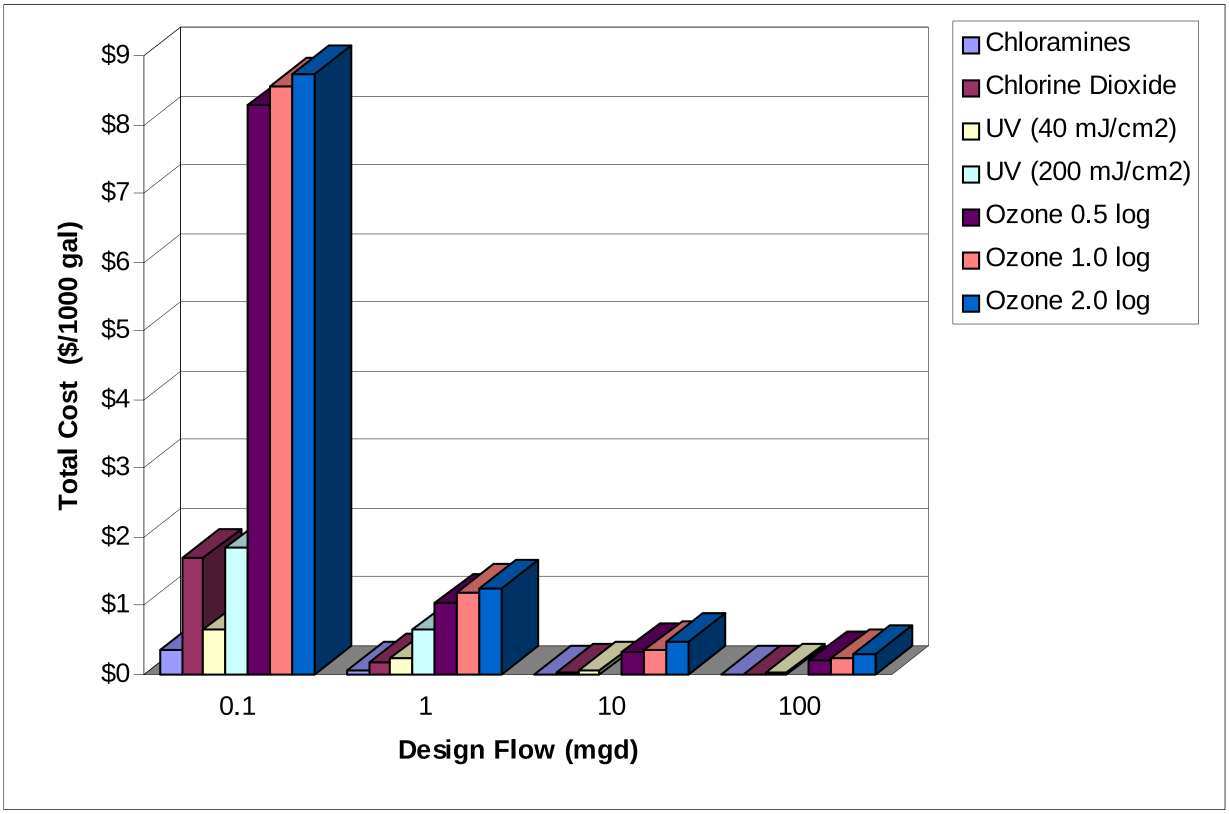
ES.4 Summary of Technology Cost Estimates

This document presents total capital ($) and total annual O&M ($/year) costs for each of the alternative disinfection strategies and precursor removal technologies discussed. These costs are presented in tabular format in Chapter 4.

There can be a significant disparity in costs from technology to technology for a given plant capacity. As plant flows become larger, though, the differences in cost between technologies tend to decrease. Figure ES.1 compares total costs (discounted at 3 percent over 20 years) for alternative chemical (and UV) disinfection strategies. Figure ES.2 compares total costs (discounted at 3 percent over 20 years) for disinfection technologies involving physical removal of microbial contaminants. Depending on the technology, either inactivation or physical removal can be the more economical option. In these cases, other factors, such as formation of other DBPs (e.g., bromate) and ease of operation, may ultimately influence the final technology decision. Figure ES.3 compares total costs (discounted at 3 percent over 20 years) for DBP precursor removal technologies. Collectively, these costs are comparable with alternative disinfectants and microbial removal technology costs presented in Figures ES.1 and ES.2. However, these technologies may involve more significant plant modifications. Costs for all technologies are summarized in tabular format in Table ES.1.

It should be noted that many systems have more than one treatment plant. For those systems the total cost impact will be the sum of the costs for each treatment plant, a cost which is generally greater than if the system had only one plant.

Figure ES.1 Cost Comparison for Alternative Chemical Disinfection Strategies[1]



Note: Chloramines are costed at two different doses; however, because the difference in costs between the two doses is insignificant on the scale shown, only the 0.55 mg/L dose is shown in Figure ES.1.

[1] EPA updated the 40 mJ/cm2 UV unit costs based on data obtained for recent installations of this technology. Similar data for 200 mJ/cm2 UV systems were not available within the time frame required to include in this analysis.

Figure ES.2 Cost Comparison for Alternative Physical Removal Technologies

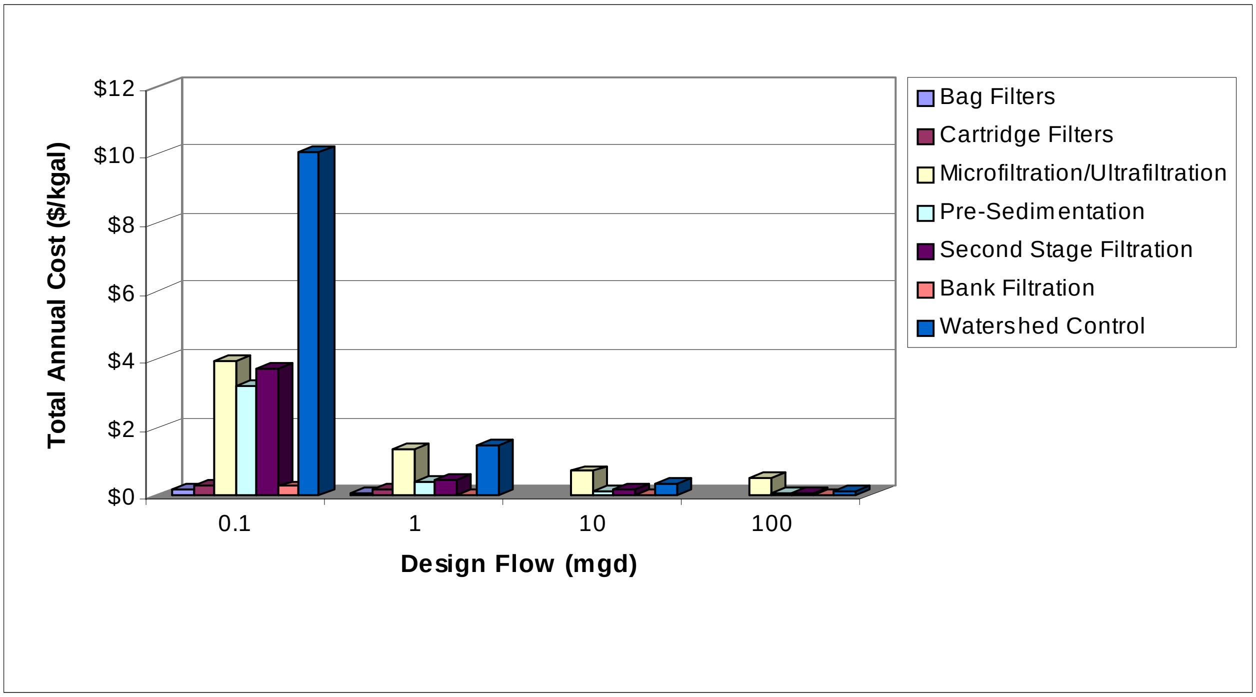


Figure ES.3 Cost Comparison for DBP Precursor Removal Technologies

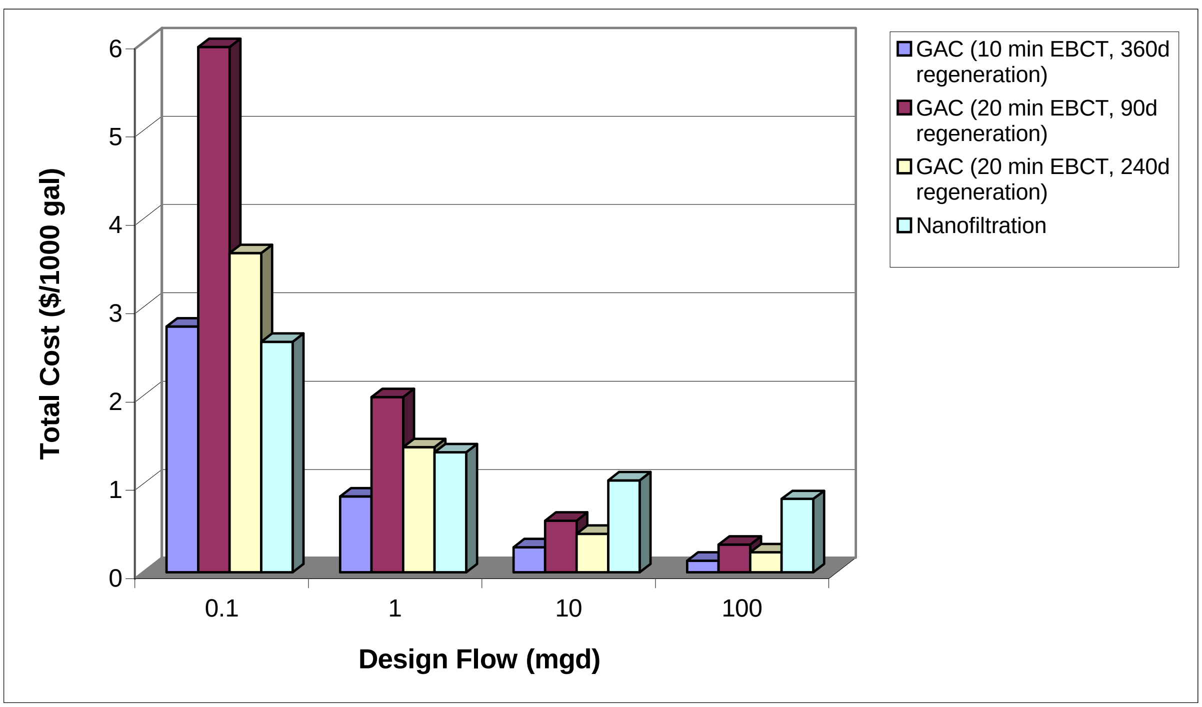


Table ES.1 Technology Total Annual Costs ($/kgal) for the Stage 2 D/DBP and LT2ESWT Rules

Technology	Design Flow (mgd)			
	0.1	1	10	100
Alternative Chemical Disinfection Strategies[2]				
Chloramines (NH4 dose = 0.55mg/l)	$0.36	$0.06	$0.01	$0.01
Chlorine Dioxide	$1.69	$0.17	$0.03	$0.01
UV (40 mJ/cm2)	$0.66	$0.23	$0.05	$0.02
UV (200 mJ/cm2)*	$1.84	$0.64		
Ozone (0.5-log *Cryptosporidium* inactivation)	$8.30	$1.05	$0.32	$0.21
Ozone (1.0-log *Cryptosporidium* inactivation)	$8.55	$1.20	$0.37	$0.23
Ozone (2.0-log *Cryptosporidium* inactivation)	$8.72	$1.25	$0.47	$0.31
Alternative Physical Disinfection Strategies				
Bag Filters*	$0.17	$0.07		
Cartridge Filters*	$0.28	$0.17		
Microfiltration/Ultrafiltration	$3.96	$1.38	$0.72	$0.52
Pre-sedimentation	$3.22	$0.41	$0.14	$0.10
Second stage filtration	$3.74	$0.48	$0.17	$0.07
Bank filtration	$0.28	$0.04	$0.04	$0.03
Watershed control	$10.05	$1.50	$0.36	$0.14
DBP Precursor Removal Technologies				
GAC (EBCT = 10, 360 day regeneration)	$2.78	$0.86	$0.28	$0.13
GAC (EBCT = 20, 90 day regeneration)	$5.95	$1.99	$0.59	$0.32
GAC (EBCT = 20, 240 day regeneration)	$3.61	$1.42	$0.44	$0.23
Nanofiltration	$2.61	$1.36	$1.04	$0.83

Note: * considered options only for small systems.

[2] EPA updated the 40 mJ/cm2 UV unit costs based on data obtained for recent installations of this technology. Similar data for 200 mJ/cm2 UV systems were not available within the time frame required to include in this analysis.

1. Introduction

1.1 Purpose of Technology and Cost Document

This document provides information on costs and treatment effectiveness of technologies and treatment strategies available to public water systems (PWSs) to remove or inactivate pathogenic microorganisms, specifically *Cryptosporidium*, and/or reduce the formation of disinfection byproducts (DBPs). This information is developed solely for use in conducting Economic Analyses (EAs) for the Stage 2 Disinfectants and Disinfection Byproducts Rule (DBPR) and Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). Please note that the information provided by this document is of a general nature. It is not intended to guide PWSs in selecting or designing technologies for compliance with existing or proposed rules.

The LT2ESWTR will require systems to provide additional *Cryptosporidium* treatment if *Cryptosporidium* concentrations in their source waters exceed specified levels. *Cryptosporidium* is resistant to chlorine but can be inactivated with certain alternative disinfectants or can be physically removed through filtration processes.

The Stage 2 DBPR will require PWSs to reduce the formation of trihalomethanes (THMs) or haloacetic acids (HAAs) if they exceed specified levels. THMs and HAAs form primarily through reactions between chlorine and natural organic matter (NOM). Their formation can be reduced with alternative disinfectants or disinfection practices or through increases in NOM removal prior to chlorine application.

Issues associated with microbial disinfection and the formation of DBPs are interwoven; PWSs should not undercut microbial protection in their efforts to reduce DBP levels. Several of the alternative disinfectants that systems could choose to reduce the formation of THMs and HAAs can provide increased protection against chlorine-resistant pathogens like *Cryptosporidium*. For these reasons, PWSs should have the ability to make decisions regarding compliance strategies for the Stage 2 DBPR and LT2ESWTR at the same time. Consequently, the United States Environmental Protection Agency (EPA) is developing these regulations as a paired rulemaking and is addressing compliance technologies for both rules in a single document.

The EAs for the LT2ESWTR and Stage 2 DBPR evaluate the total impact of a regulation in terms of costs associated with additional treatment requirements and benefits associated with reduced risk. This evaluation requires the following types of information:

- National occurrence of the regulated contaminant(s)
- Existing level of treatment for the contaminant provided by PWSs
- Unit costs and efficacy of treatment strategies available for compliance with the regulation
- Number and sizes of PWSs that will select a particular treatment strategy for regulatory compliance
- Benefits and costs resulting from changes to existing treatment

This document supports the EA by describing the design criteria necessary for a technology to achieve a desired level of treatment and the cost associated with that technology as a function of the design criteria.

Information on unit costs and treatment performance is critical to projecting technology usage stemming from a regulation and to evaluating national compliance costs and benefits. No information is given here on the national compliance costs (that information is provided in the EA) or on the numbers of PWSs that will adopt various treatment strategies to comply with the regulations.

Process design criteria for alternative disinfection strategies and DBP precursor removal technologies were developed in large part using water quality data gathered under the Information Collection Rule (ICR) and best engineering judgement. Where appropriate, EPA used ICR data to generate statistics regarding water quality parameters that affect technology performance. These water quality statistics were used to estimate costs for technology options presented in this document. Costs were developed using EPA cost models, manufacturer price data, and recent literature. Unit prices and cost indices for model input were based upon vendor information, prevailing rates, and published values in the trade literature (e.g., *Engineering News Record*, Bureau of Labor Statistics). These costs were reviewed by the Technical Work Group (TWG), a group of industry experts convened during the M/DBP FACA process. The TWG reviewed the costs and provided suggestions for design parameters. Subsequent revisions have also been made to respond to comments from outside reviewers, particularly the National Drinking Water Advisory Council (NDWAC) and EPA's Science Advisory Board (SAB).

1.2 Existing Regulations

The following are existing regulations that address risks posed by microorganisms and DBPs in public water systems.

1.2.1 Surface Water Treatment Rule

Under the Surface Water Treatment Rule (SWTR), finalized in 1989, EPA set Maximum Contaminant Level Goals (MCLGs) of zero for *Giardia lamblia*, viruses, and *Legionella*; and promulgated National Primary Drinking Water Regulations (NPDWRs) for all PWSs using surface water or ground water under the direct influence of surface water (GWUDI). Unfiltered systems were required to comply with the SWTR by 1991 and filtered systems by 1993. The SWTR includes treatment technique requirements for filtered and unfiltered systems that are intended to protect against the adverse health effects of exposure to *Giardia*, viruses, and *Legionella*, as well as other pathogenic microorganisms (63 FR 69478 December 1998b). Briefly, those requirements include the following:

- Maintenance of a disinfectant residual in the distribution system
- Removal/inactivation of 3 log (99.9 percent) for *Giardia* and 4 log (99.99 percent) for viruses
- Combined filter effluent turbidity performance standards
- Watershed protection and raw water quality requirements for unfiltered systems

1.2.2 Information Collection Rule

The ICR is a monitoring and data reporting rule that was promulgated in 1996. The purpose of the ICR was to collect occurrence and treatment information to help evaluate the need for possible changes to the SWTR and microbial treatment practices and to help evaluate the need for future regulation of DBPs. The ICR provided EPA with information on the occurrence of pathogenic microorganisms, including *Cryptosporidium, Giardia,* and viruses, as well as the occurrence of DBPs and water quality parameters that impact DBP formation. The ICR also provided engineering data on how PWSs control such contaminants (65 FR 19046 April 2000).

1.2.3 Interim Enhanced Surface Water Treatment Rule

The Interim Enhanced Surface Water Treatment Rule (IESWTR) was finalized in December 1998 and applies only to surface water and GWUDI PWSs serving 10,000 or more people. The purposes of the IESWTR were to improve control of microbial pathogens, specifically *Cryptosporidium* and to address risk trade-offs between pathogens and disinfection byproducts (65 FR 19046 April 2000). Key provisions of the rule include the following:

- MCLG of zero for *Cryptosporidium*
- 2 log (99 percent) *Cryptosporidium* removal requirements for systems that filter
- Strengthened combined filter effluent turbidity standards
- Requirements for individual filter turbidity monitoring
- Disinfection benchmark provisions to ascertain the level of microbial protection provided as systems take steps to comply with new DBP standards
- Inclusion of *Cryptosporidium* in the definition of GWUDI and in the watershed control requirements for unfiltered systems
- Requirements for covers on new finished water reservoirs
- Requirements for sanitary surveys for *all* surface water and GWUDI systems, even those serving fewer than 10,000 people

1.2.4 Stage 1 Disinfectants and Disinfection Byproducts Rule

The Stage 1 Disinfectants and Disinfection Byproducts Rule was promulgated in December 1998. The Stage 1 DBPR applies to all PWSs that are community water systems (CWSs) or non-transient non-community water systems (NTNCWSs) and that treat their water with a chemical disinfectant for either primary or secondary disinfection. In addition, certain requirements for chlorine dioxide apply to transient non-community water systems (TNCWSs). Surface water and GWUDI systems serving at least 10,000 people were required to comply with the Stage 1 DBPR by January 2002. All ground water systems, as well as surface water and GWUDI systems serving fewer than 10,000 people, were required to comply with the Stage 1 DBPR by January 2004.

The Stage 1 DBPR established the following provisions:

- Maximum residual disinfectant level goals (MRDLGs) for chlorine, chloramines, and chlorine dioxide
- MCLGs for three trihalomethanes (bromodichloromethane, dibromochloromethane, and bromoform), two haloacetic acids (dichloroacetic acid and trichloroacetic acid), bromate, and chlorite
- Maximum residual disinfectant levels (MRDL) for chlorine, chloramines, and chlorine dioxide
- MCLs for total trihalomethanes (TTHM), five haloacetic acids (HAA5), bromate, and chlorite

The rule also includes monitoring, reporting, and public notification requirements for the listed compounds. EPA estimates that the rule will provide public health protection for an additional 20 million households not previously covered by drinking water rules for DBPs (65 FR 19046 April 2000).

1.2.5 Long Term 1 Enhanced Surface Water Treatment Rule

The Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) (67 FR 1812 January 2002), finalized in January 2002, extends the requirements of the IESWTR to surface water and GWUDI systems serving fewer than 10,000 people.

1.2.6 Filter Backwash Recycling Rule

The Filter Backwash Recycling Rule (FBRR) (66 FR 31086 June 2001) regulates systems in which filter backwash is returned to the treatment process. The rule, promulgated in June 2001, applies to surface water and GWUDI systems that use direct or conventional filtration and recycle spent filter backwash water, sludge thickener supernatant, or liquids from dewatering processes. The rule requires that these recycled liquids be returned to a location such that all steps of a system's conventional or direct filtration process are employed. The rule also requires systems to notify the state that they practice recycling. Finally, systems must collect and maintain information for review by the state.

1.3 Public Health Concerns

1.3.1 Pathogenic Microorganisms

In 1990, EPA's SAB, an independent panel of experts established by Congress, cited drinking water contamination as one of the most important environmental risks and indicated that disease-causing microbial contaminants (e.g., bacteria, protozoa, and viruses) are probably the greatest remaining health risk management challenge for drinking water suppliers (EPA/SAB 1990). Information on the number of waterborne disease outbreaks from the U.S. Centers for Disease Control and Prevention (CDC) underscores this concern. CDC indicates that, between 1991 and 2000, 145 drinking water-related disease outbreaks were reported, with more than 431,000 associated cases of disease (This includes outbreaks in individual water systems, which are not PWSs. About 400,000 cases of illness were from one outbreak.) During this period, a number of agents were implicated as the cause, including protozoa, viruses, and bacteria.

Waterborne diseases are usually acute (i.e., sudden onset and typically lasting a short time in healthy people), and most waterborne pathogens cause gastrointestinal illness, with diarrhea, abdominal discomfort, nausea, vomiting, and/or other symptoms. Some waterborne pathogens cause, or are associated with, more serious disorders such as hepatitis, gastric cancer, peptic ulcers, myocarditis, swollen lymph glands, meningitis, encephalitis, and other diseases.

Cryptosporidium, a protozoan parasite, is of particular concern as a waterborne pathogen because it is highly resistant to inactivation by chlorine and chloramines. In addition, no therapeutic treatment currently exists for cryptosporidiosis, the infection caused by *Cryptosporidium.* Cryptosporidiosis usually causes 7-14 days of diarrhea, sometimes accompanied by a low-grade fever, nausea, or abdominal cramps in healthy individuals (Juranek 1995). It may, however, cause the death of individuals with compromised immune systems. In 1993, *Cryptosporidium* caused more than 400,000 people in Milwaukee to experience intestinal illness. More than 4,000 were hospitalized, and at least 50 deaths were attributed to the cryptosporidiosis outbreak. Nevada, Oregon, and Georgia have also experienced cryptosporidiosis outbreaks over the past several years.

Despite filtration and disinfection, *Cryptosporidium* oocysts have been found in filtered drinking water (LeChevallier et al. 1991, Aboytes et al. 2004), and many of the individuals affected by waterborne disease outbreaks caused by *Cryptosporidium* were served by filtered surface water supplies (Solo-Gabriele and Neumeister 1996). Surface water systems that filter and disinfect may still be vulnerable to *Cryptosporidium*, depending on the source water quality and treatment effectiveness.

1.3.2 Disinfectants/Disinfection Byproducts

While the use of chemical disinfectants is highly effective in reducing the risk of waterborne disease, disinfectants are known to react with NOM to form byproducts that may pose a public health risk. In addition, the disinfectants themselves may pose a public health risk at high concentrations.

The assessment of public health risks from chlorination of drinking water currently relies on inherently difficult and incomplete empirical analysis. Nevertheless, while recognizing these uncertainties and taking into account the large number of people exposed to DBPs and the different potential health risks that may result from exposure to DBPs (e.g., cancer and adverse reproductive and developmental effects), EPA believes that the weight of evidence represented by the available epidemiology and toxicology studies support a hazard concern and a protective public health approach to regulation.

1.4 Regulations

1.4.1 Long Term 2 Enhanced Surface Water Treatment Rule

In September 2000, an Agreement in Principle was reached by EPA and members of the Stage 2 Microbial-Disinfection Byproduct (M-DBP) Federal Advisory Committee Act (FACA) Committee regarding the requirements of the LT2ESWTR (65 FR 83015 December 2000). Under the agreement, the LT2ESWTR will require all surface water systems, including GWUDI, that serve at least 10,000 people to conduct two years of source water monitoring for *Cryptosporidium*. Conventional systems whose annual average *Cryptosporidium* concentrations are at least 0.075, 1.0, or 3.0 oocysts per liter would be required to achieve an additional 1, 2, or 2.5 logs, respectively, of *Cryptosporidium* removal or inactivation beyond conventional treatment. Systems could meet these additional treatment requirements through the use of various options including: enhanced filtration performance, watershed control, alternative disinfectants, membranes, various types of filters, and demonstrations of performance. Systems required to provide 2 or more log inactivation must achieve at least 1-log of the required treatment using ozone, chlorine dioxide, UV, membranes, bag filtration, cartridge filtration, or bank filtration.

1.4.2 Stage 2 Disinfectants/Disinfection Byproducts Rule

The Stage 2 DBPR, which was proposed along with the LT2ESWTR, will apply to all CWSs and NTNCWSs that add a disinfectant other than ultraviolet (UV) light or deliver disinfected water. Under the Stage 2 M-DBP Agreement in Principle (65 FR 83015 December 2000), the Stage 2 DBPR will retain the MCLs of 80 µg/L for TTHM and 60 µg/L for HAA5 established by the Stage 1 DBPR. However, the Stage 2 DBPR will change the way compliance with these MCLs is determined. Under Stage 1, compliance with the TTHM and HAA5 MCLs is based on a running annual average of all monitoring points within a distribution system. Under the Stage 2 DBPR, compliance would be based on a locational running annual average, which means that the running annual average at each monitoring point within a distribution system would have to be less than the MCL. The Stage 2 DBPR would also require systems to conduct an initial distribution system evaluation which would identify the areas with the highest concentrations of TTHM and HAA5; compliance monitoring will be conducted at those locations.

1.5 Technologies Evaluated for the Control of Pathogens and Disinfection Byproducts

Systems required to provide additional treatment for *Cryptosporidium* under the LT2ESWTR can use two basic mechanisms: inactivation and physical removal. While chlorine and chloramines are not effective against *Cryptosporidium* at doses used in drinking water treatment, chlorine dioxide, ozone, and UV light have been demonstrated to inactivate this pathogen. Chlorine dioxide and ozone generally require higher doses to inactivate *Cryptosporidium* than those necessary for *Giardia* and viruses; the use of these disinfectants is limited by the formation of regulated byproducts like chlorite and bromate. UV has been shown to achieve high levels of *Cryptosporidium* inactivation at relatively low doses but is currently not widely used in the United States for drinking water treatment. Nevertheless, EPA believes that ozone, chlorine dioxide, and UV are available to PWSs to inactivate *Cryptosporidium.* Consequently, EPA has evaluated these technologies in this document.

PWSs can increase the physical removal of *Cryptosporidium* in their treatment plants by using additional physical barriers like microfiltration (MF), bag filtration, and cartridge filtration. These technologies have been shown to achieve high log reductions of *Cryptosporidium* when properly designed and operated. This document addresses *Cryptosporidium* removal achieved by MF, bag filtration, and cartridge filtration.

Utilities can also take steps to reduce the concentration of *Cryptosporidium* entering the treatment plant through strategies such as watershed control, pre-sedimentation basins, and bank filtration. Costs for these technologies were obtained from design experts from the Technical Work Group (TWG) are provided in Chapter 4. However, these costs were too uncertain to use in the EA for the LT2ESWTR.

Systems required to reduce the formation of TTHM and HAA5 for compliance with the Stage 2 DBPR can use two approaches. One approach is to reduce the use of free chlorine by switching to disinfectants that do not form, or form only low concentrations of, TTHM and HAA5. Such disinfectants include: chloramines, ozone, chlorine dioxide, and UV. Systems may also reduce free chlorine doses by using physical barriers like microfiltration; microfiltration removes more microorganisms so that less disinfection is needed. This document evaluates chloramines, ozone, chlorine dioxide, UV, and MF as alternative disinfection strategies for reducing TTHM and HAA5 formation. (Note that several of these disinfection strategies were also evaluated for *Cryptosporidium* treatment as described above.)

The second approach for systems to reduce TTHM and HAA5 formation is to increase the removal of DBP precursors (i.e., NOM) prior to disinfection. Systems can remove precursors by increasing coagulation dosages in a process termed enhanced coagulation, or softening, or by installing granular activated carbon (GAC) or nanofiltration (NF). For the purposes of this document, it was assumed that utilities will have already optimized coagulation or softening practices to meet the requirements of the Stage 1 DBPR. As a result, this document evaluates only GAC and NF as precursor removal strategies.

In summary, this document provides an analysis of the following technologies:

<u>Alternative disinfection strategies</u>

- Chloramination
- Chlorine dioxide
- Ultraviolet (UV) light
- Ozone
- Microfiltration and ultrafiltration
- Bag and cartridge filters
- Bank filtration
- Second stage filtration
- Pre-sedimentation basins
- Watershed control
- Combined Filter Performance

<u>Alternative DBP precursor removal strategies</u>

- Granular activated carbon adsorption
- Nanofiltration

1.6 Document Organization

This remainder of this document contains the following sections:

Chapter 2 - Technologies for DBP and Microbial Contaminant Control: Presents comprehensive discussions of all disinfection, *Cryptosporidium* removal, and DBP precursor removal strategies considered in this document. Includes technology descriptions, effectiveness of technologies for DBP precursor and/or microbial control, and factors affecting the performance of each technology.

Chapter 3 - Technology Design Criteria: Discusses the rationale behind development of the design criteria for which costs are presented in Chapter 4. Includes design approach, assumptions and additional factors (e.g., residuals handling) which may impact design.

Chapter 4 - Technology Costs: Presents capital, operations and maintenance, and total annualized costs for each disinfection strategy and DBP precursor removal technology considered. Also includes discussion of estimation methods (e.g., cost models and vendor information).

Chapter 5 - References: Provides a comprehensive bibliography of all literature used in the compilation of this document.

Appendices: Contain capital cost breakdown summaries for technologies for which cost models were used.

2. Technologies for DBP and Microbial Contaminant Control

2.1 Introduction

Public water systems may employ various treatment strategies to reduce chlorinated DBPs and to provide better physical removal or inactivation of *Cryptosporidium* for compliance with the Stage 2 DBPR and LT2ESWTR. EPA considers the following treatment strategies as being available for compliance with these two regulations[1]:

<u>Alternative disinfection strategies</u>

- Chloramination (section 2.2.1)
- Chlorine dioxide (section 2.2.2)
- Ultraviolet light (section 2.2.3)
- Ozone (section 2.2.4)
- Microfiltration and ultrafiltration (section 2.2.5)
- Bag and cartridge filtration (section 2.2.6)
- Bank filtration (section 2.2.7)
- Second stage filtration (section 2.2.8)
- Pre-sedimentation (section 2.2.9)
- Watershed control (section 2.2.10)
- Combined filter performance (section 2.2.11)

<u>DBP precursor removal strategies</u>

- Granular activated carbon adsorption (section 2.3.1)
- Nanofiltration (section 2.3.2)

2.2 Alternative Disinfection Strategies

The following section discusses the alternative disinfection strategies available, their efficacy against pathogens, and factors affecting performance. DBP formation is also discussed for the chemical disinfectants and UV. It is not discussed for the other technologies, as they do not produce DBPs and generally do not remove DBP precursors to a significant extent.

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[1]Treatment strategies are classified based on their primary removal ability and their proposed use for the Stage 2 DBPR and LT2ESWTR.

2.2.1 Chloramination

Chloramines are formed by reactions of ammonia with aqueous chlorine. These reactions may result in the formation of monochloramine (NH_2Cl), dichloramine ($NHCl_2$) and trichloramine (NCl_3). The relative concentrations of these species depend upon the pH of the water and the relative proportion of chlorine and ammonia. At chlorine-to-ammonia mass ratios of 3:1 to 5:1 (Cl_2:NH_3-N) and neutral pHs, conditions common to drinking water treatment, the principal chloramine species formed is monochloramine (USEPA 1999b).

One of the least expensive methods for controlling DBP formation is the use of monochloramine, instead of free chlorine, to maintain a distribution system residual. After the appropriate free chlorine contact time, ammonia is added to quench the residual free chlorine and to retard DBP formation. This reduces the free chlorine contact time and, thus, DBP formation, without compromising microbial protection. The initial free chlorine contact time and chloramine together provide sufficient disinfection. A survey conducted by the American Water Works Association Research Foundation (AWWARF) has shown that most of the utilities that changed disinfection practices to lower distribution system THM levels have done so by switching to chloramine as the secondary disinfectant (McGuire 1989).

Systems that do not use free chlorine for primary disinfection (e.g., that use ozone or UV light) must add chlorine prior to ammonia addition. For most systems, the free chlorine residual needs to be increased prior to the point of ammonia addition to maintain the desired chloramine residual in the distribution system. This can be accomplished by: 1) simultaneous addition of chlorine and ammonia (after primary disinfection with free chlorine or ozone) or 2) the addition of ammonia after chlorine addition.

Further information, including case studies of systems converting from free chlorine to chloramine, is summarized in *Optimizing Chloramine Treatment* (Kirmeyer et al. 1993). This reference supplies additional information on the reason(s) for switching to chloramine and contains information on chloramination changeover and start-up procedures, nitrification, and impact on taste and odor.

2.2.1.1 Efficacy Against Pathogens

Chloramine is less effective than free chlorine for the disinfection of most pathogenic microorganisms. At pH 7 and below, monochloramine is approximately 200 times less effective than free chlorine for coliform inactivation under the same contact time, temperature, and pH conditions. For viruses and cysts, the combined chlorine forms (e.g., monochloramine and dichloramine) are considerably less effective than free chlorine (USEPA 1999b). Historical studies have found time factors (monochloramine contact time:free chlorine contact time) from 20:1 to 80:1 for the same bacterial inactivation efficiency. For the same conditions of contact time, temperature, and pH, combined chlorine (monochloramine) doses are approximately 25 times higher than free chlorine for the same bacterial inactivation efficiency (White 1999). There is evidence that dichloramine may be twice as effective as monochloramine; however, dichloramine is generally avoided because it contributes to taste and odor problems.

The *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (SWTR Guidance Manual–USEPA 1990) presents CT (contact time multiplied by residual disinfectant concentration) values for multiple disinfectants, pathogens, pH and temperature ranges. Exhibit 2.1 compares CT requirements for chloramine with those of free chlorine over a range of temperature and pH values.

Exhibit 2.1: Comparison of CT Values for Free Chlorine and Chloramine

Log Removal	*Giardia*						Viruses					
	<1° C		10° C		20° C		<1° C		10° C		20° C	
	Cl	NH_2Cl	Cl	NH_2Cl	Cl	NH_2Cl	Cl	NH_2Cl	Cl	NH_2Cl	Cl	NH_2Cl
0.5	40	635	21	310	10	185	--	--	--	--	--	--
1	79	1270	42	615	21	370	--	--	--	--	--	--
2	158	2535	83	1230	41	735	6	1243	3	643	1	321
3	237	3800	125	1850	62	1100	9	2063	4	1067	2	534

Note: -- Data not available.
Source: USEPA 1990.

Exhibit 2.1 demonstrates that chloramine is relatively ineffective compared to free chlorine for *Giardia* and virus inactivation. In addition, chloramine is ineffective for inactivation of *Cryptosporidium* (Peeters et al. 1989, Korich et al. 1990). Several studies have evaluated whether disinfection with ozone followed by chloramination (Liyanage et al. 1997a, Driedger et al. 1999) has a synergistic effect on *Cryptosporidium* inactivation (i.e., the inactivation achieved using both disinfectants combined is greater than what is expected for each of the disinfectants separately). Although the results of these studies are inconclusive, they do indicate that some synergism may exist for ozone/chloramine applications.

2.2.1.2 DBP Formation

The byproducts formed by chloramination, for the most part, are identical to those produced during chlorination and include THMs, HAAs, haloacetonitriles, and cyanogen chloride. With the possible exception of cyanogen chloride, chloramination does not preferentially form any of the halogenated DBPs compared to free chlorine. In fact, studies have demonstrated that chloramines produce much lower levels of DBPs than free chlorine (Kirmeyer et al. 1993, Symons et al. 1996). This is the primary reason water systems implement chloramines for secondary disinfection rather than free chlorine.

The formation of DBPs resulting from chloramination is influenced by the following treatment variables (Kirmeyer et al. 1993, Carlson and Hardy 1998):

- Contact time and chloramine dosage
- Point of ammonia application
- pH and temperature
- Total organic carbon
- Chlorine-to-ammonia ratio
- Mixing and reaction time for chloramine formation

The point of ammonia application after chlorine addition generally impacts the length of time free chlorine reacts with NOM. For most plants using chlorine as a primary disinfectant, the point of ammonia application depends on disinfection requirements and goals. Once ammonia is added, the rate of DBP formation is significantly reduced (Kirmeyer et al. 1993).

Within the range of chloramine residuals commonly used in the water industry (1 to 5 milligrams per liter (mg/L)), chloramine dose does not appear to be a significant factor in DBP formation; the chlorine-to-ammonia ratio appears to be more significant. TTHM concentrations remain quite low at chlorine-to-ammonia weight ratios less than 5:1, then increase dramatically above the 5:1 ratio (Kirmeyer et al. 1993). Most utilities use chlorine-to-ammonia ratios of 3:1 to 5:1 because dichloramine and trichloramine form at higher ratios. These species are unstable and cause taste and odor problems.

2.2.1.3 Factors Affecting Performance

When chlorine and ammonia are added simultaneously, good mixing can reduce the time free chlorine has to react with NOM. With complete mixing at neutral pHs (7 to 9) and temperatures of 20 to 25 degrees Celsius (˚C), the reaction of ammonia and chlorine to form monochloramine takes less than 3 seconds. This eliminates the free chlorine almost immediately and reduces the potential for DBP formation (Kirmeyer et al. 1993). At lower temperatures, the reaction can take longer and mixing becomes more important. Efficient mixing and dispersion of chemicals (chlorine and ammonia) at the point of addition determines the extent of free chlorine contact and, thus, substantially impacts the formation of DBPs.

As noted above, pH is important for rapid formation of chloramine. Symons et al. (1996) showed that DBP formation decreased with increasing pH. Exceptions to the trend are noted in some instances at pH 8, where Symons et al. noted that the complexity of chloramine chemistry may cause water-specific responses.

Carlson and Hardy (1998) evaluated the effects of various water quality variables, such as pH, temperature, chlorine dosage, and total organic carbon on THM and HAA formation for waters from five utilities. Of the variables studied, the free chlorine contact time was found to be the most important in forming chlorinated DBPs. Chlorine contact time must be balanced to provide disinfection and to control byproduct formation. The type of DBP precursor was also found to be important. Based on this study, the authors proposed the concept of two sets of precursors: those that form DBPs quickly and those that form DBPs slowly. The precursor material that rapidly reacts with chlorine to form DBPs (i.e., the quick formers) are of greater importance when chloramine is used to maintain a residual. These quick formers are less affected by reaction conditions than are the slow formers. Relatively consistent THM and HAA concentrations formed quickly after the addition of chlorine. Temperature, chlorine dosage, and pH had a greater effect on precursor materials that formed DBPs slowly.

White (1999) summarizes the effect of contact time and dose on the disinfection properties of chloramines. Generally, chloramines require much longer contact times than other chemical disinfectants (e.g., free chlorine and ozone). This is one reason they are more suitable for secondary disinfection in the distribution system, where residence times can be several days. Chloramines are a less powerful oxidant than many other chemical disinfectants and can require substantially higher doses to achieve the same level of disinfection (White 1999). Because longer contact times and higher doses are required for effective chloramine disinfection, residual stability is of major importance. Monochloramine, the preferred chloramine form, is the dominant species at pH levels greater than 5.5 and is essentially the only species present at pH levels around 7.5 (Kirmeyer et al. 1993). Systems using chloramines for secondary disinfection should try to maintain a distribution system pH between 7.5 and 9.0.

A primary concern for systems using chloramines is nitrification in the distribution system. Nitrification is a microbiological process by which free ammonia is converted to nitrite and nitrate. *Nitrosomonas* and *nitrobacter*, which are naturally present in distribution system biofilms and may infiltrate leaking or corroding pipes, convert free ammonia to nitrite and (in the presence of sufficient dissolved oxygen) nitrate, respectively. Among the effects of nitrification are a depletion of the chloramine residual and an increase in heterotrophic plate counts (HPC) (Kirmeyer et al. 1995). To prevent nitrification, it is important to optimize the chlorine:ammonia ratio and minimize free ammonia in the distribution system. Nitrification is most likely to occur in distribution system dead ends, areas of low demand, and storage tanks. As a result, the potential for nitrification can also be minimized by improving distribution system piping configurations (e.g., looping to eliminate dead ends and increasing flow in low demand areas) and by increasing storage tank turnover.

2.2.2 Chlorine Dioxide

Chlorine dioxide has been used for drinking water treatment in the United States for more than 50 years, primarily to control taste and odor problems. However, chlorine dioxide has received attention lately because of its potential application for *Cryptosporidium* inactivation (Finch et al.1995, Li et al. 1998) and for reduced formation of THMs or HAAs during disinfection (White 1999). However, chlorine dioxide degrades to form chlorite and chlorate. Chlorite is considered to have public health implications and is a regulated DBP.

Chlorine dioxide cannot be transported because of its instability and explosiveness. Therefore, it is generated on-site. The five common methods for producing chlorine dioxide are as follows: 1) sodium chlorite reaction with acid, 2) chorine solution reaction with chlorite solution, 3) chlorine gas reaction with chlorite solution, 4) reduction of sodium chlorate using hydrogen peroxide and concentrated sulfuric acid, and 5) chlorine gas reaction with solid chlorite (White 1999). The yield, purity, and production capacities of chlorine dioxide vary for the five types of methods. The most common chlorine dioxide generation technique is chlorine solution reaction with chlorite solution. Chlorine dioxide dosages that can be used in drinking water treatment are constrained by regulatory limits on the production of chlorite and chlorine dioxide residual.

2.2.2.1 Efficacy Against Pathogens

The SWTR Guidance Manual presents CT values for inactivation of *Giardia* and viruses for both free chlorine and chlorine dioxide. The values indicate that chlorine dioxide is approximately four times more effective that chlorine for the inactivation of *Giardia* at most conditions. Chlorine, however, is more effective for the inactivation of viruses. Exhibit 2.2 summarizes CT values contained in the guidance manual.

Exhibit 2.2: Comparison of CT Values for Free Chlorine and Chlorine Dioxide

Log Removal	*Giardia*						Viruses					
	<1° C		10° C		20° C		<1° C		10° C		20° C	
	Cl	ClO_2	Cl	ClO_2	Cl	ClO_2	Cl	ClO_2	Cl	ClO_2	Cl	ClO_2
0.5	40	10	21	4	10	2.5	--	--	--	--	--	--
1	79	21	42	7.7	21	5	--	--	--	--	--	--
2	158	42	83	15	41	10	6	8.4	3	4.2	1	2.1
3	237	63	125	23	62	15	9	25.6	4	12.8	2	6.4

Note: -- Data not available.
Source: USEPA 1990.

Chlorine dioxide has been compared to other oxidants for inactivating *Cryptosporidium* (Korich et al. 1990); chlorine dioxide and ozone are found to be more effective in inactivating *Cryptosporidium* compared to chlorine and monochloramine. However, unlike ozone, the degradation byproducts of chlorine dioxide do not contribute to the inactivation of *Cryptosporidium* (Liyanage et al. 1997b).

The American Water Works Service Company (AWWSC) evaluated the effectiveness of chlorine dioxide for the inactivation of *Cryptosporidium* (AWWSC 1998). AWWSC found that chlorine dioxide is effective for warm, high pH waters (pH of approximately 8 and temperature around 20 degrees Celsius). Finch et al. (1995) summarized the chlorine dioxide research regarding the inactivation of *Cryptosporidium*. Chlorine dioxide has also been proven effective for the inactivation of selected bacteria over a pH range of 3.0 to 8.0 (Junli et al. 1997, White 1999) and is a stronger disinfectant than chlorine for bacteria, requiring lower CT values. Some of the bacteria evaluated in Junli et al. (1997) are *E. coli* (A and B), *Staphylococcus aureus*, *Sarcina*, *Chloropseudomonas*, *Bacillus subtilis*, and *Shigella dysenteriae*.

In 2003, EPA developed CT values for *Cryptosporidium* inactivation by chlorine dioxide, which are presented in Exhibit 2.3 below.

Exhibit 2.3: Summary of Chlorine Dioxide CT Values for *Cryptosporidium* Inactivation

	Chlorine Dioxide at Temperature (° C)		
Log Inactivation	**1 °**	**15 °**	**20 °**
0.5	305	89	58
1.0	610	179	116
1.5	915	268	174
2.0	1220	357	232
2.5	1525	447	289
3.0	1830	536	347

Note: Stage 2 and LT2ESWTR only use the 0.5 log inactivation as a possible treatment option.

2.2.2.2 DBP Formation

Studies have demonstrated that chlorine dioxide does not produce THMs (White 1999); under proper generation conditions (i.e., no excess chlorine), halogen-substituted DBPs are not formed. The application of chlorine dioxide produces only a small amount of total organic halide (TOX) (Werdehoff and Singer, 1987). The use of chlorine dioxide aids in reducing the formation of TTHMs and HAAs by oxidizing precursors. By moving the point of chlorination downstream in the plant after coagulation, sedimentation, and filtration, the quantity of NOM is reduced. This results in a lower chlorine dosage during post-chlorination of the water which, in turn, results in fewer THMs.

In normal pH ranges (6 to 9), chlorine dioxide undergoes a variety of oxidation reactions with NOM to form oxidized organic species, such as chlorinated, brominated, or polysubstituted organic byproducts and chlorite (ClO_2^-). Chlorite concentrations can account for up to 70 percent of the chlorine dioxide consumed (American Water Works Association (AWWA) 1999; Werdehoff and Singer 1987). Chlorite, and chlorate (ClO_3^-) are formed when chlorine dioxide is added to water. All three oxidized chlorine species (chlorine dioxide, chlorite, and chlorate) are considered to have adverse health effects and are of concern in finished water (AWWA 1999).

Chlorine dioxide may also facilitate a number of chlorine substitution reactions. Studies evaluating drinking water and NOM have shown that TOX concentration increases upon application of chlorine dioxide at normal treatment dosages (AWWA 1999).

2.2.2.3 Factors Affecting Performance

Temperature dramatically affects *Cryptosporidium* inactivation by chlorine dioxide (Li et al. 1998). At 1 ºC, a 0.5 log inactivation is observed at a CT of 150 milligrams * minutes / liter (mg-min/L), compared to a 2.0 log inactivation for the same CT at 22°C. Chlorine dioxide can effectively inactivate bacteria over a pH range of 3.0 to 8.0. Because it is a more effective disinfectant for bacteria than free chlorine, lower CT values are required. Caution must be taken, however, when selecting the appropriate dose, as excessive dosages can lead to chlorite formation above permissible levels. Purity and generator yields are two of the most critical factors that effect chlorine dioxide use. Chlorine and the oxychlorine species (i.e., chlorite and chlorate) are typically present in the impurities of chlorine dioxide (White 1999). Therefore, the purity of the chlorine dioxide generated should be considered to avoid a violation of the chlorite maximum contaminant level (MCL).

2.2.3 Ultraviolet Light

The use of UV light for disinfection of drinking water has recently received much attention because of new developments regarding *Cryptosporidium* inactivation at low UV light doses (Bukhari et al. 1999) and because it creates very few known DBPs. Disinfection is accomplished by irradiating water with UV light, which alters the structure of the deoxyribonucleic acid (DNA) of the microorganisms in the treated water and thereby prevents the proper replication of the DNA strands. However, because microbes exposed to UV light still retain metabolic functions, some microbes are able to repair the damage done by the UV light and regain infectivity.

UV light is electromagnetic radiation between wavelengths of 100 and 400 nanometers (nm). The specific range of UV wavelengths and the level of irradiance depend on the type of UV lamp system used. The effective germicidal wavelength range for most microorganisms is generally considered to be between 200 and 300 nm (Malley 1998).

UV systems consist of UV reactors with an associated control panel. Commercial UV reactors used for drinking water applications are closed reactors containing UV lamps, quartz sleeves, UV intensity sensors, quartz sleeve wipers, and temperature sensors. UV lamps are housed within the quartz sleeves, which protect and insulate the lamps. Some reactors include automatic cleaning mechanisms to keep the quartz sleeves free of deposits that may form due to contact with the water. UV intensity sensors, flow meters, and in some cases, UV transmittance monitors are used to monitor dose delivery by the reactor.

UV lamps can be divided into two categories: continuous wave and pulsed wave. Currently, continuous wave UV lamps are most widely used for drinking water treatment. The types of continuous wave lamps are low pressure mercury vapor (LP), low pressure high output (LPHO), and medium pressure mercury vapor (MP). "Pressure" refers to the pressure of mercury vapor within the lamp casing. A comparison of the LP, LPHO, and MP lamps is shown in Exhibit 2.4.

Exhibit 2.4: Comparison of UV Lamps

Parameter	LP	LPHO	MP
Germicidal UV light	Monochromatic at 254 nm	Monochromatic at 254 nm	Polychromatic, including germicidal range (200 - 300nm)
Mercury Vapor Pressure (torr)	Optimal at 0.007	Optimal at 0.007	100 - 10,000
Operating Temperature (°C)	Optimal at 40	130 - 200	600 - 900
Electrical Input (W/centimeter (cm))	0.5	1.5 - 10	50 - 150
Germicidal UV Output (W/cm)	0.2	0.5 - 3.5	5 - 30
Electrical to Germicidal UV Conversion Efficiency (%)	35 - 38	30 - 40	10 - 20
Arc Length (cm)	10 - 150	10 - 150	5 - 75
Relative Number of Lamps Required for a Given Dose	High	Intermediate	Low
Lifetime (hours(hrs))	8,000 - 10,000	8,000 - 12,000	3,000 - 5,000

Source: EPA UV Disinfection Guidance Manual (USEPA 2003).

The light emitted by LP and LPHO lamps is essentially monochromatic at 253.7 nm, which is in the range of the most germicidal wavelengths for microorganisms. MP lamps emit at a higher intensity than LP lamps but at a wide range of wavelengths. Therefore, LP and LPHO lamps convert power to germicidal light more efficiently than MP lamps. Theoretically, LPHO lamps have the same efficiency as LP lamps because they operate at similar vapor pressures. However in practice, LPHO lamp efficiency can be significantly lower when operating at different power settings. The main differences between LP and MP lamps, as shown in Exhibit 2.4, are the vapor pressure, operating temperatures, electrical input, and germicidal UV output.

Pulsed ultraviolet (PUV) systems irradiate a high intensity UV light in flashes at approximately 50 flashes per second. PUV systems have limited operating experience on the full-scale and are not costed in this document.

The UV lamp ballast controls the amount of electricity supplied to the lamp and should ensure a consistent and constant power delivery. Power supplies and ballasts can be supplied in many different configurations and are tailored to a unique lamp type and application. UV systems may use electronic ballasts, magnetic ballasts, or transformers.

UV intensity sensors are photosensitive detectors that measure the UV intensity at a point within the UV reactor. This intensity information is used to indicate dose delivery. Intensity sensors can be classified as wet or dry. Dry sensors monitor UV light through a monitoring window whereas wet UV intensity sensors are in direct contact with the water flowing through the reactor. Monitoring windows and the wetted ends of the wet sensors can become fouled over time and require cleaning, similar to quartz sleeves.

The lamp cleaning mechanism used for a UV system depends on the lamp type, system size, and fouling potential of the water. Both manual and automatic cleaning regimes have been developed. Manual cleaning is primarily used for smaller systems with relatively few sleeves and lower fouling potential. Automatic cleaning approaches may be classified as flush and rinse systems, mechanical wipers, or physical-chemical wipers. LPHO systems typically use flush and rinse systems, and MP systems typically use wipers because the higher lamp temperatures accelerate fouling under certain water qualities. The cleaning frequency of the lamps is a function of the lamp temperature and the concentration of dissolved organic and inorganic species that can cause lamp fouling.

2.2.3.1 Efficacy Against Pathogens

When UV light is applied to a microorganism, the genetic material of a cell absorbs the light energy and its structure is altered, thereby interfering with replication of the microbe. The UV dose necessary for inactivation of microorganisms varies from species to species and across microorganism classifications. Inactivation of microorganisms increases with increasing UV dose, although it does not always follow the typical log-linear relationship.

Of the pathogens of interest in drinking water, viruses are most resistant to UV disinfection, followed by bacteria and protozoa. Exhibit 2.5 presents UV dose requirements for inactivation of *Cryptosporidium*, *Giardia*, and viruses (as derived in the USEPA UV Disinfection Guidance Manual, Appendix B). The UV dose requirements presented in Exhibit 2.5 are the minimum required; operational UV doses will likely be two to four times higher after application of a safety factor.

Exhibit 2.5: UV Dose Requirements for Inactivation of *Cryptosporidium*, *Giardia*, and Viruses During Validation Testing

	Log Inactivation							
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	11.7	-	-
Giardia	1.5	2.1	3.0	5.2	7.7	10.8	-	-
Virus	39.4	58.1	79.1	100.1	120.7	142.6	163.1	186.0

Note: All values presented in mJ / cm^2
Source: USEPA UV Disinfection Guidance Manual, Appendix B.

Based on the analysis presented in Appendix B of the EPA UV Disinfection Guidance Manual, the sensitivities of *Giardia* and *Cryptosporidium* to UV disinfection are very similar; viruses, however, are more difficult to inactivate. Battigelli et al. (1993) performed bench scale UV collimated beam experiments to determine the relationship between UV dose and inactivation of Hepatitis-A virus (strain HM-175), coxsackievirus type B-5, rotavirus strain SA-11, and bacteriophages MS-2 and fX174. MS-2 bacteriophage required the highest dose of 25 milliJoules per square centimeter (mJ/cm^2) for less than 1 log inactivation. With the other viruses, 4 log inactivation is achieved at doses ranging between 16 and 42 mJ/cm^2. The most UV-resistant viruses of concern in drinking water are adenovirus Type 40 and Type 41. Meng and Gerba (1996) report a dose of 23.6 to 30 mJ/cm^2 for a 1 log inactivation in adenovirus and a dose of 111.8 to 124 mJ/cm^2 for 4 log inactivation.

Because microbes that have been exposed to UV light still retain metabolic functions, some are able to repair the damage done by UV light and regain infectivity. Repair of UV light-induced DNA damage includes photoreactivation and dark repair (Knudson 1985). Photoreactivation (or photorepair) is an enzymatic DNA repair mechanism wherein the DNA damage is repaired when exposed to light between 310 and 490 nm. Dark repair is an enzymatic repair mechanism that does not require light. Not all microorganisms contain the necessary cellular mechanisms to repair UV-damaged DNA. One study has shown that *Cryptosporidium* contains the capability to undergo some DNA repair. However, even though the DNA was repaired, infectivity was not restored (Oguma et al. 2001). Another study, by Shin et al. (2001), did not observe photorepair with *Cryptosporidium parvum*. Linden et al. (2002a) did not observe photoreactivation or dark repair of *Giardia* at UV doses typical for UV disinfection applications (16 and 40 mJ/cm^2). However, unpublished data from the same study showed *Giardia* reactivation in light and dark conditions at very low UV doses (0.5 mJ/cm^2; Linden 2002a). Shaban et al. (1997) found that viruses also lack the repair enzymes necessary for photoreactivation. However, photorepair of viral DNA can occur using the enzyme systems of their host cells. Knudson (1985) found that bacteria were able to repair in light and dark conditions after exposure to a dose of 2.4mJ/cm^2 for up to 30 seconds, suggesting that bacteria may have the enzymes necessary for photorepair and dark repair. As such, photoreactivation is generally limited to bacteria.

E. coli and HPC inactivation by UV light are well documented, particularly with respect to wastewater disinfection (Chang et al.1985, Wilson et al. 1992). Photoreactivation of bacteria has been documented with *E. coli*, *S. aureus*, and coliphage, while dark repair has been documented with *S. aureus* and coliphage (Shaban et al. 1997). One study (Knudson, 1985) examined two different strains of *E. coli*: one that had the enzymes necessary for repair (B/R strain) and one that lacked the necessary repair enzymes ($recA^-$ uvr^- strain). The difference in UV dose needed for 1-log inactivation of the strain capable of repair was over two orders of magnitude higher than the dose needed for 1-log inactivation of the repair deficient strain, indicating that dark repair impacts the UV dose-response of microorganisms. Unlike bacteria, viruses do not have the enzymes necessary for dark repair. However, viruses can repair in the host cell using the host cells' enzymes (Rauth 1965).

2.2.3.2 DBP Formation

Several studies have been conducted to determine if DBPs are formed as a result of UV light irradiation. Zheng et al. (1999) found that TTHM and HAA9 formation did not increase when UV light was applied to chlorinated water at a dose of 100 mJ/cm^2. Linden et al. (1998) investigated DBP formation in wastewater secondary effluent that is irradiated with LP and MP UV lamps and found no evidence of photochemical reactions or DBP formation. Malley et al. (1996) examined the effects of post-UV disinfection (chlorination and chloramination) on DBP formation and found no significant impact by UV on DBP levels formed by chemical disinfection. Malley et al. (1995) also observed no significant change in THM, HAA, bromate, or other halogenated DBP concentrations following disinfection with UV light. A study performed with filtered drinking water indicated no significant change in aldehydes, carboxylic acids, or TOX (Kashinkunti et al., 2003). However, a low conversion rate (about one percent) of nitrate to nitrite by UV light has been observed (von Sonntag and Schuchman, 1992). Conversion of nitrate to nitrite is lower with LP lamps than with MP lamps because the UV absorbance of nitrate is higher below 240 nm than it is at 254 nm. Due to the low conversion rate of nitrate to nitrite by UV light, it is of minimal concern in drinking water applications. Several studies have shown low-level formation of non-regulated DBPs (e.g., aldehydes) as a result of applying UV light to wastewater and raw drinking water sources. The difference in results can be attributed to the difference in water quality, most notably the higher concentration of organic material in raw waters and wastewaters.

2.2.3.3 Factors Affecting Performance

Particle content can impact UV disinfection performance. Particles may absorb and scatter light, thereby reducing the UV intensity delivered to the microorganisms. Particle-associated microbes also may be shielded from UV light, effectively reducing disinfection performance. Particles in source waters are diverse in composition and size and include large molecules, microbes, clay particles, algae, and flocs.

Recent research by Linden et al. (2002b) indicates that the UV dose-response of microorganisms added to filtered drinking waters was not altered by variation in turbidity that met regulatory requirements. For unfiltered raw waters, Passantino and Malley (2001) found that source water turbidity up to 10 nephelometric turbidity units (NTU) did not impact the UV dose-response of separately added (seeded) organisms. In these experiments, however, organisms were added to waters containing various levels of treated or natural turbidity. Therefore, it was not possible to examine microbes associated with particles in their natural or treated states. Consequently, these drinking water studies can only suggest the impact of turbidity on dose-response as it relates to the impact of UV light scattering by particles. The studies cannot predict the effect on UV disinfection of microbes attaching to particles.

UV absorbance, often exerted by dissolved organic matter in drinking water applications, affects the design of the UV system. Water that absorbs a significant amount of UV light (i.e., high UV absorbance and low transmittance) will need a higher UV irradiance or longer exposure to achieve the same level of inactivation as water with lower UV absorbance. As UV absorbance increases, the intensity throughout the reactor decreases for a given lamp configuration. This results in a reduction in delivered dose and measured UV intensity for a given lamp output. In a situation with a fixed UV output, lower UV absorbance values result in more UV energy being available in the water column, causing a higher log-inactivation of microorganisms than a water with a higher UV absorbance. For systems with high levels of dissolved organic matter (high UV absorbance), it is more efficient to apply UV light after unit processes that remove organic matter.

Several chemicals used in water treatment processes can increase the UV absorbance of water (e.g., Iron (Fe^{+3})). However, some oxidants (including ozone) can reduce the UV absorbance (APHA et al. 1998). Water treatment processes upstream of the UV reactors can be operated to control and reduce UV absorbance, thereby optimizing the design and costs of the UV system.

Depending on the water quality (e.g., dissolved ions, hardness, alkalinity, and pH levels) and lamp temperature, scale can form on the UV lamps. MP lamps tend to scale more easily than LP and LPHO lamps because the operating temperature of MP lamps is considerably higher. Scale can reduce the UV energy being transmitted through the lamp sleeve into the water and potentially compromise disinfection. Lamp cleaning is an important consideration for the design of UV systems to control lamp scaling and to ensure consistent disinfection performance. Water pH may also affect lamp scale formation, but inactivation of microorganisms with UV light is not pH dependent (Malley 1998).

UV inactivation of microorganisms is not directly affected by water temperature. However, the performance of UV lamps is dependent on the lamp temperature. Most UV lamps have sleeves (usually made of quartz) that insulate the lamps, maintain optimal temperature, and provide maximum irradiance. If the lamp temperature deviates from optimal, the lamp irradiance will be reduced. This is especially true with LP UV lamps in cold waters (Mackey et al. 2000). Therefore, the water temperature variation should be considered when designing a low pressure system. However, MP lamps have a significantly higher operating temperature compared to the water temperature. Thus, as long as an insulating quartz sleeve is in place, the water temperature has little effect on the operating temperature of the MP lamp and MP lamp performance.

Hydraulics are an important part of the UV equipment. Ideally, the UV reactor should exhibit plug-flow characteristics. In plug flow, water that enters the reactor is completely mixed axially and moves through the reactor as a single plug with no dispersion in the direction of flow. However, "real world" hydraulics in a full-scale reactor are never plug flow. UV reactors are typically equipped with baffles to reduce the amount of short-circuiting through the reactor and to encourage plug flow, although these baffles can increase head loss through the reactor. Staggered lamp arrays also promote mixing within the reactor and minimize short-circuiting of flow. Alternatively, vortex mixers can be used to increase lamp spacing, thereby reducing head loss through the reactor.

Inlet and outlet conditions can have a significant impact on reactor hydrodynamics. Straight inlet conditions with gradual changes in cross sectional area can be used to develop flow for optimal dose delivery. Straight inlets with no sharp bends or sudden changes in cross sectional area optimize dose deliveries.

It may be necessary to characterize the reactor flow regime in order to determine the level of disinfection provided. Tracer tests are typically not feasible because the hydraulic residence time in the reactor is too short (i.e., on the order of seconds or fractions of a second). However, hydraulic models, such as computational fluid dynamics and light intensity distribution, are available to understand the behavior of the UV reactor.

For more details on factors affecting the efficacy of UV disinfection, see the *UV Disinfection Guidance Manual* (USEPA 2005).

2.2.4 Ozone

In recent years, the use of ozone technology in water treatment has dramatically increased. In 1991, approximately 40 water treatment plants in the United States, each serving more than 10,000 people, utilized ozone (Langlais et al. 1991). As of April 1998, this number had grown to 264 operating plants (Rice et al. 1999). The main reasons for the escalating use of ozonation are the strong oxidizing properties of ozone and the absence of the formation of chlorinated DBPs during disinfection (however, bromated DPBs are formed).

In water, ozone reacts with hydroxide ions (OH^-) to form hydroxyl free radicals ($HO^\bullet$). Because the decay of the hydroxyl radicals is pH dependent, pH is a very important parameter in determining the concentration of ozone and hydroxyl radicals in solution and therefore the oxidation rates. Oxidation with ozone is also influenced by other water quality characteristics, such as temperature, alkalinity, and the concentration of reduced chemical species (i.e., iron and manganese). Other important considerations include ozone dose and contact time.

Ozone is commonly added to raw water (pre-ozonation) or settled water. To take advantage of ozone's ability to improve flocculation and NOM removal, ozone may be applied to raw water.

Application of ozone to raw or settled water is considered to be equally effective for primary disinfection. However, larger doses may be necessary for raw water application due to the higher NOM and particulate matter concentrations.

There are two basic types of ozone generation equipment: liquid oxygen-based systems and air-based systems. Liquid oxygen feed systems are relatively simple (e.g., there is no air pretreatment equipment), less capital intensive, and yield a higher ozone concentration than air-based systems. The liquid oxygen feed system components include a storage tank, an evaporator to convert the liquid to a gas, filters to remove impurities, and pressure regulators to limit the gas pressure to the ozone generators.

Air-fed systems require air pretreatment equipment to prevent damage to the ozone generator. Air needs to be dry, free of contaminants, and with a dew point between -50° and -60°C. Air pretreatment equipment consists of compressors, after coolers (optional), refrigerant dryers, desiccant dryers, air filters, and pressure regulators. Power consumption is higher for air feed systems (8-12 kWh/lb O_3) than for oxygen feed systems (4-8 kWh/lb O_3). Exhibit 2.6 presents a comparison of the advantages and disadvantages of the two types of ozonation systems (USEPA 1999b).

Exhibit 2.6: Comparison of Air and Liquid Oxygen Systems

System	Advantages	Disadvantages
Air	• Commonly used equipment • Proven technology • Suitable for small and large systems	• More energy consumed per ozone volume produced • Extensive gas handling equipment required • Maximum ozone concentration of 1-5 % • Higher power consumption • Fairly complicated technology
Liquid Oxygen	• Less equipment required • Simple to operate and maintain • Suitable for small and large systems • Can store excess oxygen to meet peak demands • Higher ozone concentration (14-18%) • Approximately doubles ozone production for same generator • Lower power consumption	• Variable liquid oxygen costs • Storage of oxygen onsite (i.e., safety concerns) • Loss of liquid oxygen in storage when not in use • Oxygen-resistant materials required

Ozone is usually applied in one of three flow configurations: 1) co-current (ozone and water flowing in the same direction), 2) counter-current (ozone and water flowing in the opposite direction), or 3) alternating co-current/counter-current. Ozone application systems include fine bubble diffusers, injectors/static mixers, and turbine mixers (Langlais et al. 1991). The fine bubble diffuser system is the most common and offers high ozone transfer rates, process flexibility, operational simplicity, and no moving parts. The injector/static mixer system applies ozone in an in-line or a sidestream configuration. Ozone is injected under negative pressure, created by a venturi section, and then mixed to enhance dispersion of ozone in the water stream. The turbine mixer systems feed ozone in the contactor and mix ozone with the water in the contactor. The turbine mixer can either project outside of the ozone contactor or be submerged.

Hoigne and Bader (1976) described ozone decomposition in water. Once ozone enters solution, it follows one of two reaction pathways: 1) direct oxidation, which is slow and selective in its oxidation of organic compounds, and 2) autodecomposition to the hydroxyl free radical ($HO^{\bullet}$), which is extremely fast and nonselective. The hydroxyl free radical is scavenged by carbonate and bicarbonate ions, commonly measured as alkalinity, to form carbonate and bicarbonate free radicals. These radicals do not affect the organic reactions. The hydroxyl radicals produced by the autodecomposition react with organics and other radicals to reform hydroxyl radical in an autocatalytic process.

The stability of dissolved ozone is affected by pH, ultraviolet light, ozone concentration, and the concentration of radical scavengers (Langlais et al. 1991). Conditions of low pH favor the direct oxidation pathway, and high pH conditions favor the autodecomposition pathway described earlier. At pH levels between 3 and 6, the ozone is present primarily in its molecular form (O_3), and direct oxidation dominates. However, as the pH rises, the autodecomposition of ozone to produce the hydroxyl free radical ($HO^{\bullet}$) becomes increasingly rapid. At pH levels greater than 10, the conversion of molecular O_3 to $HO^{\bullet}$ is virtually instantaneous. In general, better disinfection would be expected at lower pHs, since free hydroxyl radicals are short-lived compared to molecular ozone. Studies have shown that increasing the temperature from 0° to 30° C reduces the solubility of ozone and increases its decomposition rate (Kinman 1975).

2.2.4.1 Efficacy Against Pathogens

Ozone is one of the most potent biocides used in water treatment. It is effective against a wide range of pathogenic microorganisms including bacteria, viruses, and protozoa. Ozone shows greater efficiency inactivating most types of pathogenic microorganisms than chlorine, chloramine, and chlorine dioxide (Clark et al. 1994). This is demonstrated by the CT values found in the SWTR Guidance Manual presented in Exhibit 2.7. The resistance of pathogenic microorganisms to ozone increases in the following order: bacteria, viruses, protozoa (Camel and Bermond 1999).

Exhibit 2.7: Comparison of CT Values for Free Chlorine and Ozone

Log Removal	*Giardia*						Viruses					
	<1° C		10° C		20° C		<1° C		10° C		20° C	
	Cl	O_3	Cl	O_3	Cl	O_3	Cl	O_3	Cl	O_3	Cl	O_3
0.5	40	0.48	21	0.23	10	0.12	--	--	--	--	--	--
1	79	0.97	42	0.48	21	0.24	--	--	--	--	--	--
2	158	1.9	83	0.95	41	0.48	6	0.9	3	0.5	1	0.25
3	237	2.9	125	1.43	62	0.72	9	1.4	4	0.8	2	0.4

Note: -- Data not available
Source: USEPA (1990)

Small concentrations of ozone are usually effective against bacteria. *E. Coli* levels were reduced by 4 log (99.99 percent removal) in less than one minute at an initial ozone concentration of 9 micrograms per liter (µg/L) (Wuhrmann and Meyrath 1955). *Legionella pneumophila* levels were reduced by 2 log (99 percent removal) in less than five minutes at an initial ozone concentration of 0.21 milligrams per liter (mg/L) (Domingue et al. 1988).

Typically, viruses are more resistant to ozone than bacteria, although ozone is still effective against viruses. Ozone dosages of 0.2 to 1.5 mg/L consistently achieved 2 log inactivation of poliomyelitis viruses with a contact time of 40 seconds (Katzenelson et al. 1974). Katzenelson et al.

(1974) also observed that poliomyelitis inactivation increased to nearly 5 log at a dose of 1.5 mg/L and a contact time of approximately 100 seconds. Coxsackie virus inactivation is more than 5 log with an initial ozone dosage of 1.45 mg/L (Keller et al. 1974). The sensitivity of human rotavirus to ozone was found to be similar to that of coxsackie virus (Vaughn et al. 1987).

Protozoan cysts are more resistant to ozone than bacteria and viruses. Data available for inactivation of *Cryptosporidium* oocysts suggest that, among protozoans, this pathogen is the most resistant to ozone (Peeters et al. 1989; Langlais et al. 1990).

Ozone inactivation kinetics of *Cryptosporidium* are evaluated by Gyurek et al. (1999). The observed inactivation behavior of *Cryptosporidium* by ozone is characterized by a "tailing-off" effect. At 22°C and a 5 minute contact time, an initial ozone residual of 1.2 mg/L was required to provide 2 log inactivation. For contact times less than 5 minutes, a relatively small increase in the applied contact time significantly decreases the required initial ozone residual; however, for contact times greater that 10 minutes an increase in the applied contact time provides a negligible decrease in the required initial ozone residual. Hence, the influence of contact time on the inactivation kinetics decreases as *Cryptosporidium* is progressively exposed to ozone.

Initial studies have demonstrated that CT values may be as much as 25 times higher than those required for *Giardia* (Rennecker et al. 1999). These preliminary studies also demonstrate that CT requirements for *Cryptosporidium* inactivation increase by an average factor of approximately three for every 10° C decrease in temperature. A summary of reported ozonation requirements for 2 log inactivation of *Cryptosporidium* oocysts is presented in Exhibit 2.8.

Exhibit 2.8: Reported Ozonation Requirements for 2 log Inactivation of *Cryptosporidium* Oocysts

Experimental Protocol	Initial Ozone Residual (mg/L)	Temperature (°C)	Contact Time (min)	CT (mg-min/L)	Reference
Batch liquid, batch ozone	0.77 0.51	Ambient	6 8	4.6 4.0	Peeters et al. 1989
Batch liquid, continuous gas	1.0	25	5-10	5-10	Korich et al. 1990
Batch liquid, batch ozone	0.50 0.50	7 22	18 7.8	9.0 3.9	Finch et al. 1993
Flow through contactor, continuous gas		22-25	7.4	5.5	Owens et al. 1994
Batch liquid, batch ozone	1.0	22	3.2	3.2	Gyurek et al. 1999

Note: Owens et al. do not report residual dose.

2.2.4.2 DBP Formation

Ozone does not produce chlorinated DBPs. Through the oxidation of natural organic precursor materials, however, ozone can alter the reactions between chlorine and NOM and affect the formation of chlorinated DBPs when chlorine is added downstream. Additionally, if bromide is present in the water supply, ozonation will create bromate, which is regulated chemical. Ozonation of natural waters produces aldehydes, haloketones, ketoacids, carboxylic acids, and other types of biodegradable organic material which must be adequately controlled (often with a granular media biofilter).

Ozonation often increases the biodegradability of NOM in the treated water. Increasing biodegradability could be beneficial if a biological filtration process follows the ozonation step. A biological filtration step can remove the biodegradable fraction of NOM, increasing organic precursor removal. Biological filters remove NOM by using it as a substrate. Biological filtration can be employed on adsorptive media, such as GAC, and/or non-adsorptive media, such as sand and anthracite. Conversely, if the biodegradable fraction is not removed, it can increase the regrowth of microorganisms in the distribution system.

Haag and Hoigne (1983) have shown that ozone oxidizes bromide to form hypobromous acid and hypobromite (HOBr and OBr^-) under water treatment conditions. Hypobromite was found to be further oxidized to bromate or to a species that regenerates bromide, whereas HOBr reacts with NOM to form brominated organic byproducts in waters containing bromide.

Changes in pH can have a dramatic effect on the concentrations of HOBr and OBr^- and, therefore, the species of byproducts formed. An increase in pH increases the relative concentration of Br^-, which, in turn, leads to increased bromate formation. Reduced pH levels are often accompanied by a reduction in bromate concentrations; the lower pH enhances formation of bromoform and other organic brominated DBPs.

Krasner et al. (1989) found that an ozone residual is necessary to produce detectable levels of bromate. Siddiqui and Amy (1993) found that the bromoform concentration first increased then diminished at higher dosages. Song et al. (1995) demonstrated that lower ozone dosage and longer contact time should produce less bromate than higher dosages and shorter contact times.

Halogenated organic compounds are formed when NOM reacts with free chlorine or free bromine. Free bromine can be formed in ozone disinfection whenever bromide is present in the raw water source. The level of brominated byproducts formed during oxidation is dependent on the concentration of bromide in the raw water source and/or the relative amount of bromide present compared to organic precursors.

Ozonation followed by chlorination has been observed to produce higher levels of haloketones than chlorination alone (Jacangelo et al. 1989b). Chloral hydrate occurs primarily as a result of chlorination, although ozonation followed by chlorination has been observed to increase levels beyond those observed with chlorination only. Ozonation followed by chlorination or chloramination can increase chloropicrin levels above those observed with chlorination or chloramination alone. Ozonation followed by chloramination has been observed to increase cyanogen chloride levels beyond those observed with chloramination only. Cyanogen bromide, the brominated analog of cyanogen chloride, has been detected after ozonation of water containing high bromide levels (McGuire et al. 1990).

Much less is known about non-halogenated disinfection byproducts than the halogenated organic compounds. Among the major ozonation byproducts, aldehydes and carboxylic acids have the highest concentrations (Glaze et al. 1993). Ozonation followed by chlorination has been found to yield the highest levels of acetaldehyde and formaldehyde. In addition, ozonation prior to chloramination is shown to produce more of these aldehydes than chloramination alone. Najm and Krasner (1995) report that the formation of ketoacids is proportional to the amount of dissolved organic carbon (DOC) in the water. Ketoacid concentrations are largely unaffected by bromide concentration.

Ammonia addition has been used to limit the formation of some ozonation byproducts. In one study (Siddiqui and Amy 1993), bromoform concentrations decrease by approximately 30 percent when ammonia is added at a NH_3-to-ozone ratio of 0.25 mg/mg. The reason for this reduction is because HOBr reacts with ammonia to form bromamines, presumably making HOBr unavailable for reaction with NOM.

Conflicting results of ammonia addition on bromate formation have been observed (Glaze et al. 1993, Krasner et al. 1993). Siddiqui et al. (1995) explained the percentage of bromate reduction upon adding ammonia is more dependent upon pH and bromide concentration than on ammonia concentration (Siddiqui et al. 1995). High bromide levels trap more oxidizing equivalents to give higher bromine yields and scavenge more radicals, thus reducing the radical processes that may cause bromate formation. Siddiqui et al. (1995) demonstrated that (at similar ammonia concentrations) bromate formation decreased by more than 80 percent upon increasing the bromide concentration from 0.1 to 1.0 mg/L.

2.2.4.3 Factors Affecting Performance

Ozone decays rapidly at high pH and warm temperatures. Krasner et al. (1993) noted that as the ozonation pH decreases, the required dose to meet inactivation requirements of the IESWTR drops and less bromate is formed. For one of the waters evaluated during bromide spiking experiments, bromate concentrations ranged from 24 to 68 µg/L at pH 8. For the same water, bromate concentrations ranged from less than 5 to 7 µg/L when the pH was decreased to 6. Better disinfection is expected at pH levels between 6 and 8 where molecular ozone dominates.

Temperature and alkalinity also affect formation of byproducts during ozonation. Increased temperature will increase the levels of bromate, bromoform, and total organic bromide. It also increases the decomposition of ozone. Conversely, increasing alkalinity has been shown to reduce the formation of bromoform and total organic bromide and increase the formation of bromate. Bicarbonate scavenges OH radicals, suggesting that the OH radical may play a role in the formation of brominated species by affecting the level of HOBr, which is presumed to be an active species for total organic bromide formation (Glaze et al. 1993).

Total organic carbon (TOC) concentration can have significant impacts on *Cryptosporidium* CT requirements. It has been demonstrated that ozone-to-TOC ratios greater than 1 are required for *Cryptosporidium* inactivation; whereas ozone-to-TOC ratios are typically less than 0.5 for *Giardia* inactivation. As previously discussed, temperature can also drastically affect the solubility, decomposition rate and biocidal effectiveness of ozone. Exhibit 2.9 presents CT requirements for *Cryptosporidium* inactivation at multiple temperatures and for inactivation ranging from 0.5 to 3 log. Exhibit 2.9 also compares the *Cryptosporidium* CT requirements with those of *Giardia* and presents the ratio of the *Cryptosporidium* requirement to the *Giardia* requirement.

Exhibit 2.9: CT Considerations for *Cryptosporidium* Inactivation

Log Inactivation	*Crypto* CT at Temperature (C)[1]			*Giardia* CT at Temperature (C)[2]			Multiplier at Temperature (C)[3]		
	1°	13°	22°	1°	13°	22°	1°	13°	22°
0.5	12	3.1	2.0	0.48	0.19	0.10	25.0	16.3	20.0
1.0	24	6.2	3.9	0.97	0.38	0.21	24.7	16.3	18.6
1.5	36	9.3	5.9	1.50	0.58	0.31	24	16.0	19.0
2.0	48	12	7.8	1.90	0.76	0.42	25.3	15.8	18.6
2.5	60	16	9.8	2.40	0.95	0.52	25.0	16.8	18.8
3.0	72	19	12	2.90	1.14	0.62	24.8	16.7	19.4

[1] Values reported to be acceptable for a pH range of 6 to 9, and are based CT on values developed by EPA in 2003.
[2] *Giardia* CT required numbers are based upon the CT table included in the SWTR Guidance Manual.
[3] Multiplier = *Crypto* CT at a given temperature / *Giardia* CT at the same temperature.

2.2.5 Microfiltration and Ultrafiltration

Membranes act as selective barriers, allowing some constituents to pass through while blocking the passage of others. The movement of these constituents across a membrane requires a driving force (i.e., to overcome the potential difference across the membrane). Only pressure-driven processes are discussed in this document due to their feasibility for DBP precursor and microbial control and their popularity in the drinking water field.

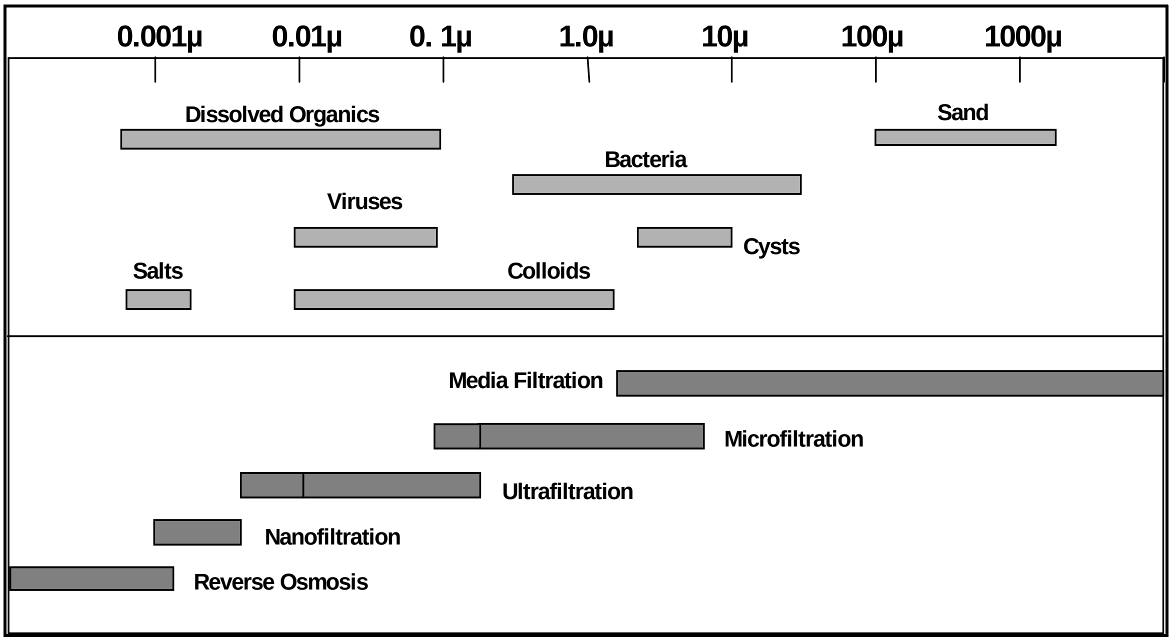
There are four categories of pressure-driven membrane processes: microfiltration, ultrafiltration (UF), nanofiltration, and reverse osmosis (RO). Low-pressure membrane processes, MF and UF, are typically applied for the removal of particulate and microbial contaminants and can be operated under positive or negative (i.e., vacuum) pressure. Positive pressure systems typically operate between 3 and 40 pounds per square inch (psi), whereas vacuum systems operate between -3 and -12 psi. RO and NF are typically applied for the removal of dissolved contaminants, including both inorganic and organic compounds. These processes operate at pressures significantly greater than the applied pressure in MF and UF processes, between 100 and 150 psi. Desalination applications can operate at pressures as high as 1,200 to 1,500 psi.

The ability of a membrane to remove a particular contaminant is influenced by its molecular weight cut-off (MWCO) or pore size. MWCO is a manufacturer specification that refers to the molecular mass of a macrosolute (e.g., glycol or protein) for which a membrane has a retention capacity greater than 90 percent. The pore size refers to the diameter of the micropores on the membrane surface. The true pore size is difficult to measure, and, as a result, membrane manufacturers typically use some measure of performance to categorize the pore size of a membrane. The nominal pore size is typically based upon a given percent removal of a marker (e.g., microsphere) of a known diameter. The absolute pore size is typically characterized as the minimum diameter above which 100 percent of a marker of a specific size is removed by the membrane. Exhibit 2.10 presents the MWCO/pore size ranges for membrane processes, as well as the relative size of common drinking water contaminants.

MF and UF are primarily used for particle and microbial removal, either following granular media filtration or as a replacement for media filters. Chemical disinfection may be required, depending upon the approach of the State regulatory agency and the class of membrane used (i.e., MF or UF). MF pore sizes are generally too large for virus removal and many States require a minimum 0.5 log chemical inactivation as part of a multiple barrier approach to disinfection.

The major components of a typical MF or UF membrane system include cartridge filters, low pressure feed pumps, membrane modules, high-pressure backwash pumps, a chemical cleaning system, a chlorination feed system, and a concentrate handling and disposal system.

Exhibit 2.10: Pressure-Driven Membrane Separation Spectrum



Note: µ = Microns.

2.2.5.1 Efficacy Against Pathogens

MF and UF have shown excellent capabilities in turbidity, particulate matter, and microbial removal. MF and UF processes remove contaminants through physical straining of the feed water as it passes through the membrane. In this respect, microbial contaminants that are larger than a given membrane pore will be retained and prevented from entering the treated water. Since the size and shape of microorganisms varies among species and since the size and shape of membrane pores varies among membrane types, the removal of a particular microorganism by MF and UF may vary. Many States have adopted disinfection log removal credits for MF and UF processes. States grant removal credits on a case-by-case basis for up to 3 log *Giardia* removal and 4 log virus removal. However, virus removal credits are typically 0.5 log or less due to the smaller size of viruses relative to MF/UF pores.

MF and UF offer disinfection capabilities that are much improved over conventional media filtration. Exhibits 2.11 through 2.14 summarize observed removals of bacteria, *Giardia*, *Cryptosporidium*, and viruses, respectively.

Exhibit 2.11: MF and UF Studies Documenting Bacteria Removal

Reference	Process	Membrane Pore Size	Bacteria Type	Log Removal
Hofmann et al. (1998)	MF	150,000 to 200,000 Daltons	HPC, coliforms, thermotolerant coliforms, SSRC	2.5 to 3.5
Jacangelo et al. (1997)	MF	100,000 Daltons	P. Aeruginosa	>8.7*
Jacangelo et al. (1997)	MF	0.2 µm	P. Aeruginosa	>8.2*
Jacangelo et al. (1997)	MF	0.2 µm	Coliforms	>1.8*
Jacangelo et al. (1997)	MF	0.2 µm	E. Coli	>7.8*
Jacangelo et al. (1997)	MF	0.2 µm	HPC	>1.8*
Clair et al. (1997)	MF	0.2 µm	HPC	2.4
Clair et al. (1997)	MF	0.2 µm	Total Coliforms	>3
Glucina et al. (1997)	MF	0.2 µm	HPC and total Coliforms	>3
Glucina et al. (1997)	UF	100,000 Daltons	Total Coliforms	>3
Jacangelo et al. (1997)	UF	100,000 Daltons	Coliforms	>2.1*
Jacangelo et al. (1997)	UF	100,000 Daltons	E. Coli	>7.8*
Luitweiler (1991)	MF	--	HPC	1.7
Jacangelo et al. (1991)	UF	--	Total Coliforms	>3
Heneghan and Clark (1991)	UF	--	HPC	>3.4
Jacangelo et al. (1989a)	UF	--	HPC	2.8

Note: *Indicates removal to detection limit.
-- Data not available.

Exhibit 2.12: MF and UF Studies Documenting *Giardia* Removal

Reference	Process	Membrane Pore Size	Log Removal
Scheider et al. (1999)	MF	0.2 µm	>4.8
Scheider et al. (1999)	MF	0.1 µm	>4.8*
Scheider et al. (1999)	MF	0.1 µm	>4.8*
Trussel et al. (1998)	MF	0.2 µm	>5.1*
Jacangelo et al. (1997)	MF	0.2 µm	>5.2*
Jacangelo et al. (1997)	MF	0.2 µm	>6.8*
Hagen (1998)	UF	100,000 Daltons	>8*
Trussel et al. (1998)	UF	100,000 Daltons	>5.1*
Jacangelo et al. (1997)	UF	100,000 Daltons	>5.2*
Jacangelo et al. (1997)	UF	100,000 Daltons	>6.8*
Jacangelo et al. (1991)	UF	–	>4*
Jacangelo et al. (1989a)	UF	100,000 Daltons	>5*

Note: *Indicates removal to detection limit.
--Data not available.

Exhibit 2.13: MF and UF Studies Documenting *Cryptosporidium* Removal

Reference	Process	Membrane Pore Size	Log Removal
Scheider et al. (1999)	MF	0.2 µm	4.2
Scheider et al. (1999)	MF	0.1 µm	>4.2
Scheider et al. (1999)	MF	0.1 µm	>4.2
Trussel et al. (1998)	MF	0.2 µm	>4.7*
Jacangelo et al. (1997)	MF	0.2 µm	>4.9*
Jacangelo et al. (1997)	MF	0.2 µm	>6.4*
Trussel et al. (1998)	UF	100,000 Daltons	>5.1*
Hagen (1998)	UF	100,000 Daltons	>8*
Jacangelo et al. (1997)	UF	100,000 Daltons	>4.9*
Jacangelo et al. (1997)	UF	100,000 Daltons	>6.4*
Jacangelo et al. (1989a)	UF	100,000 Daltons	>5*
Jacangelo et al. (1997)	UF	100,000 Daltons	>6.4*
Jacangelo et al. (1997)	UF	100,000 Daltons	>6.4*

Note: *Indicates removal to detection limit.

Exhibit 2.14: MF and UF Studies Documenting Virus Removal

Reference	Process	Membrane Pore Size	Log Removal
Scheider et al. (1999)	MF	0.2 µm	0.5
Scheider et al. (1999)	MF	0.1 µm	1.1
Scheider et al. (1999)	MF	0.1 µm	2.3
Trussel et al. (1998)	MF	0.2 µm	0.4 to 3.1
Jacangelo et al. (1997)	MF	0.2 µm	>1
Jacangelo et al. (1997)	MF	0.2 µm	>1.5
Kruithof et al. (1997)	MF	--	0.7 to 2.3
Trussel et al. (1998)	UF	100,000 Daltons	>6.9*
Jacangelo et al. (1997)	UF	100,000 Daltons	>6
Kruithof et al. (1997)	UF	--	>5.4
Jacangelo et al. (1989a)	UF	100,000 Daltons	>8*
Jacangelo et al. (1989a)	UF	--	>6

Note: *Indicates removal to detection limit.
-- Data not available.

As shown in Exhibits 2.11 through 2.14, both MF and UF systems are capable of significant log removal of bacteria, *Giardia cysts*, and *Cryptosporidium* oocysts. The data presented indicate that MF/UF are capable of bacteria removals of nearly 9 log and *Giardia* and *Cryptosporidium* removals in excess of 8 log. In fact, in nearly all cases, the log removal demonstrated is simply a function of the influent microbe concentration, since bacteria and cysts are typically removed to detection limits. As shown in Exhibit 2.14, however, MF and UF are differentiated by virus removal. The maximum virus removal reported for MF membranes is approximately 3 log, but the average reported removal is nearer to 1 log. UF membranes typically remove viruses to detection limits.

Note that the studies summarized in Exhibits 2.11 through 2.14 are conducted with intact membranes (i.e., the membranes are not compromised). Had a fiber from one of these membranes been broken, either deliberately or accidentally, the results could be significantly different, since the potential would exist for microorganisms to pass into the treated water. For this reason, it is important to include membrane integrity testing when assessing the ability of a membrane to act as a barrier against microorganisms. Many types of membrane integrity tests exist. These tests fall into two categories: 1) direct methods and 2) indirect methods. Indirect methods include monitoring the treated water for parameters such as particle counts or turbidity. Direct methods include tests, such as air pressure decay and diffusive airflow, that directly assess the integrity of the membrane itself. Integrity testing represents an important aspect of a membrane system from a regulatory perspective, as it is the only way to prove the membrane is intact and functioning as designed. Commercial manufacturers have recognized this, and most systems are now provided with automatic integrity testing that can be conducted frequently (e.g., hourly).

2.2.5.2 Factors Affecting Performance

Membrane pore size greatly affects microorganism removal. To illustrate this, Exhibit 2.10 shows the size of several microbes of concern against different membrane filtration options. As shown in

Exhibit 2.10, cysts (including *Giardia* and *Cryptosporidium*) are larger than essentially all MF and UF pore sizes. Consequently, these processes are capable of large log removal of cysts. On the other hand, as shown in Exhibit 2.10, viruses are larger than most UF pore sizes, but smaller than most MF pore sizes. For this reason, UF is capable of removing viruses while MF typically is not.

Membrane pores are typically a distribution of sizes (Mallevialle et al. 1996), only as accurate as the manufacturing process allows. At the present time, no precise techniques for membrane pore size determination are available. For these reasons, a membrane of a given MWCO may have pores that are larger and smaller than the given MWCO. Imperfections in the membrane module or membrane system may result in passage of microorganisms into the treated water.

Imperfections can arise through manufacturing imprecision, allowing microbes to penetrate o-rings, end seals, or spacers. Conversely, microbial contaminant removal may be increased by the cake layer, which forms on the membrane surface during a filtration cycle. This cake layer consists of contaminants rejected by the membrane, including particles, organic matter, and microorganisms. As this layer builds, it can aid filtration of suspended particulates, such as microorganisms, as water passes across the membrane. In this way, microorganisms that might normally pass through a membrane pore can be filtered from the feed water stream.

One of the critical design parameters for a membrane process is flux, which is typically expressed in gallons of filtrate per day per square foot of membrane area (gfd). The design flux determines the membrane area required for a specific plant capacity. Thus, flux has a significant impact on capital cost and results in a competitive motivation for design engineers to use a higher membrane flux, thereby reducing the area requirements. Although increasing the membrane flux can reduce the capital cost, it will increase operational costs due to higher operating pressure, more frequent chemical cleaning, and a potential increase in membrane replacement costs.

Another important design parameter is recovery, the ratio of feed water to product water. Recovery for MF and UF systems is typically 85 to 97 percent, and a function of the backwash method and frequency. Recovery can play a significant role in the design of membrane facilities, particularly in water-scarce regions.

Feed water quality can also have a significant impact on membrane system design, operation, and performance. Suspended solids and other contaminants (e.g., iron, calcium, barium, or silica) can result in more rapid fouling of the membrane, decreases in flux, and increases in transmembrane pressure (TMP). TMP is the pressure applied to drive water through the membrane. As a result, most membrane systems include some level of pretreatment to reduce the concentration of these foulants, with the level of pretreatment dependent upon raw water quality.

2.2.6 Bag and Cartridge Filtration

Like MF and UF, bag and cartridge filters act as selective barriers and are used to remove particles, including pathogens, in water treatment. As water passes through the bag or porous cartridge, particulate matter and organisms whose size exceeds the largest pore size are retained on the filter. The nature of the filter material and the direction of flow are two features that differentiate bag from cartridge filtration (AWWA 1999).

Bag filters can be either woven or felt and made of materials such as polypropylene, polyester, nylon, or teflon. Typically, only felt filters will display nominal pore size ratings as low as 0.5 to 1 μm, which are values likely to be associated with high removal of pathogens. Bag filters can also comprise a sealing system on their open end in order to ensure flow integrity between the water inlet and the bag filter.

The bag is housed in a pressure vessel and supported by a mesh basket. The pressure vessel is made of carbon steel or stainless steel. The water flow is from inside the bag filter to outside. As filtered material (i.e., suspended solids) accumulates on the filter surface, head loss increases, and a pressure differential develops between both sides of the filter.

A number of bag filter configurations are commercially available. Pressure vessels exist in single, duplex or four-plex, series or parallel modules, or as multi-filter vessels. Manufacturers claim that a single vessel can filter flow rates from 10 to approximately 2,000 gallons per minute (gpm), depending on its configuration. The standard pressure-rating for vessels has been observed to be 150 psi.

Cartridge filters are typically composed either of fiberglass or ceramic membranes supported by a rigid core or are made from strings of polypropylene, acrylics, nylon, or cotton wrapped around a filter element. Nominal pore size ratings generally range from 0.3 to 200 microns. With regard to membranes, the number of pleats in a cartridge filter is typically larger relative to a bag filter, thus providing greater surface area. The cartridge is housed in a pressure vessel made of carbon steel or stainless steel, similar to the bag filter, but the direction of the flow is from the outside to the inside of the cartridge. Accumulation of particulate matter on the surface and in the depth of the cartridge element leads to increased pressure loss across the cartridge. Operation of the cartridge filter beyond the recommended maximum pressure drop would result in the structural failure of the cartridge and potential damage to the cartridge filter vessel.

Commercially available cartridge filter single vessels allow for housing of 1 to approximately 200 cartridges. It is possible to connect these vessels in series (for multiple-stage filtration) or parallel (for treatment capacity increase and/or continuous operation). Because of the large number of units required to achieve high flows, bag and cartridge filtration is best suited for smaller systems.

2.2.6.1 Efficacy Against Pathogens

Because their mode of operation is based on a size-exclusion mechanism, bag and cartridge filters with the proper pore size rating can remove *Cryptosporidium*, *Giardia*, and other pathogens, depending on their size. Available studies assessing the efficacy of bag and cartridge filters against pathogens have frequently utilized polystyrene beads as surrogates for the *Cryptosporidium* oocysts and *Giardia* cysts (Li et al. 1997, Goodrich et al. 1995, Long 1983). Cysts and oocysts are suspected to fold and deform, eventually passing through filtration pores that are smaller than their nominal diameter. In an effort to account for this flexibility, investigators have used polystyrene beads smaller than the pathogens they represent.

In a study by Li et al. (1997), log removals of *Cryptosporidium* oocysts and 4-6 µm polystyrene microspheres by bag filters were determined and compared. The investigators concluded a linear correlation: 1 log removal of 4-6 µm polystyrene microspheres is equivalent to 1.040 log removal of *Cryptosporidium*. This is attributed to similar size distributions between the microspheres and the *Cryptosporidium* oocysts.

The EPA Risk Reduction Engineering Laboratory assessed the ability of bag filtration to remove *Cryptosporidium* and surrogates under various flow (12.5 and 25 gpm) and pressure drop (0, 7, 15, and 25 psi) conditions (Li et al. 1997). The study evaluated three polypropylene bag filters. The surrogates tested were turbidity, 1-25 µm particle counts, 4-6 µm particle counts, and 4-6 µm polystyrene microspheres. The study found the polystyrene microspheres to be "accurate and precise" indicators of filter performance with respect to *Cryptosporidium*. The results of this study are summarized in Exhibit 2.15.

Exhibit 2.15: Summary of Bag Filter Performance

Filter Type	Nominal Pore Size	Contaminant	Log Removal (Average)
Multi-layer polypropylene	1-µm	4.5-µm microspheres	1.14 - 1.88 (1.39)
		Cryptosporidium	1.35 - 1.48 (1.41)
Single-layer polypropylene	1-µm	4.5-µm microspheres	0.14 - 0.72 (0.46)
		Cryptosporidium	0.26 - 0.64 (0.42)
Multi-layer polypropylene	99% removal of 2.5 µm particles, 95% removal of 1.5 µm particles	4.5-µm microspheres	0.93 - 3.42 (2.08)
		Cryptosporidium	3.00 - 3.63 (3.29)

Source: Li et al. (1997).

The results presented in Exhibit 2.15 may indicate a benefit in removal efficiency associated with multi-layering of the filter fabric. Based on this study, a multi-layer fabric bag filter can achieve 1 to 2 log *Cryptosporidium* removal under proper operation conditions. One interesting result of these tests is that experimental controls performed with *Cryptosporidium* showed that 0.1 to 0.2 log removal can be attributed to the pressure vessels alone without bag filters. This is assumed to reflect the ability of *Cryptosporidium* oocysts to adhere to the surface walls of the vessel.

Another study by the Risk Reduction Engineering Laboratory (Goodrich et al. 1995) evaluated cartridge filters for the removal of 4-6 µm polystyrene spheres. The results of this study indicate that a single cartridge filter, with a 2 µm rating, achieved an average microsphere removal of 3.6 log.

A study conducted by Long (1983) evaluated the log removal of 17 different cartridge filters for *Giardia* surrogates. These cartridge filters were tested using the same pressure vessel at a pressure of 45 psi and a flow rate of 0.5 gpm. The microspheres used as surrogates for *Giardia* cysts had an average diameter of 5.7 µm, with a standard deviation of 1.5 µm. The filters were made of a variety of materials (cotton, cellulose, glass fiber, polypropylene, polyester) and configurations (majority pleated or spirally wound). The pore ratings ranged from 0.2 to 10.0 µm.

According to a scanning electron microscopy analysis that allowed visual counting of the microspheres passing through the filter, ten cartridge filters out of seventeen had a microsphere removal of 99.99 percent (4 log reduction). The lower performances seemed to be associated with the absence of end seals on the cartridges and the use of cotton or polyester as the main filtering material (Long 1983). Note that the tests were conducted at a flow rate of 0.5 gpm, which is significantly lower than the expected operation flow rate (typically 20 gpm per unit). The impact of this reduced flow rate on removal performance is unclear.

2.2.6.2 Factors Affecting Performance

Feed water quality is the primary factor affecting the performance of both bag and cartridge filters. Although these filters can operate at turbidity levels from 0.1 to 10 NTU, it is recommended that turbidity be minimized to extend the filter lifetime. If turbidity of the feed water is above 1 NTU, bag filters may operate properly for only a few hours (USEPA 1998). Thus, use as a secondary barrier following conventional treatment is a preferred mode of operation. Granular media filters can reduce feed water turbidity to less than 0.1 NTU and provide a feed water stream of appropriate quality for bag and cartridge filters.

Feed water should also contain very low levels of sand, silt, or algae to prevent clogging of the filters. If raw water quality is such that the concentrations of these parameters are high, pretreatment, such as sand, multimedia filters, or preliminary bag or cartridge filters with larger pore size (e.g., 10 μm), is encouraged.

The appropriate choice of the pore size rating is an important issue. *Giardia* cysts and *Cryptosporidium* oocysts are suspected to deform and fold, enabling them to pass through pores that are nominally smaller than the pathogen. The selected pore size should be sufficient to achieve significant removal of microorganisms while maximizing the expected filter lifetime, based upon raw water quality and filter loading. Likewise, the quality of the system's seals will greatly impact the level of performance. The most critical seals appear to be between the filter and the pressure vessel and within the structure of the filter itself. A faulty seal is a way for pathogens to partially or completely bypass filtration.

Pilot testing (i.e., challenge studies) is frequently recommended to assess the performance of bag and cartridge filters. However, the costs associated with pilot testing, particularly for small systems, can represent a significant portion of the installation costs. As a result, pilot testing may not be affordable for small systems and may limit the use of these technologies where pilot testing is necessary. Some States (e.g., Oregon) accept manufacturer data regarding removal efficiency and permit systems to operate in a demonstration mode, with additional monitoring requirements.

The skill level required to operate bag or cartridge filters is typically described as basic (AWWA 1999, Campbell et al. 1995a). Turbidity, head loss, and total number of gallons filtered should be monitored daily to evaluate the need to replace the bag or cartridge (AWWA 1999). For example, cartridges are generally replaced when the pressure differential reaches 35 psi, after one to six months of operation (Malcolm Pirnie 1993). The maximum allowable pressure differential is typically recommended by the manufacturer.

Cartridges and bags are easily damaged at the time of installation. Bags should be replaced with caution to prevent tearing of the material. Likewise, the operator should carefully install new cartridges, as the filter seal can be damaged and induce leakage.

Because of their rigid structure and multi-layer design, cartridge filters are generally more sturdy and offer more operational flexibility than bag filters. However, this higher performance is typically associated with higher cost. As mentioned previously, cysts and oocysts can adhere to and accumulate on the surface walls of the system. As a consequence, the inward flow of water in the cartridge filter requires that the housing be cleaned entirely when replacing the cartridge, which is not the case with bag filters.

2.2.7 Bank Filtration

Bank filtration is a water treatment process that uses a river bed or the bank of a river or lake as a natural filter. Water from a river or stream flows through the bank and draws from one or more wells. Microorganisms and other particles are removed by contact with the aquifer materials as the water travels through the subsurface, either horizontally or vertically. High removal occurs when ground water velocity is slow and the aquifer consists of granular materials with open pore space, allowing water flow around the grains. In these granular porous aquifers, the flow path is very tortuous, thereby providing ample opportunity for the microorganism to contact and attach to a grain surface. Although detachment from the grains can occur, it typically occurs at a very slow rate. When ground water velocity is exceptionally slow, or when little or no detachment occurs, most microorganisms become inactivated before they can enter a well. Thus, bank filtration provides physical removal and, in some cases, inactivation to protect wells from pathogen contamination.

2.2.7.1 Efficacy Against Pathogens

Due to the low recovery rate of *Cryptosporidium* oocysts in influent and effluent samples, full scale treatment data are of limited utility for assessing removal of *Cryptosporidium* via bank filtration. However, measurement of other parameters indicate the potential for pathogen removal. Exhibit 2.16 summarizes bank filtration studies that measured coliform and spore removal. *Cryptosporidium* removal is site-specific and highly dependent on the aquifer characteristics; therefore, these data are only an indication of contaminant removal that can be achieved by bank filtration.

Exhibit 2.16: Bank Filtration Studies Measuring Coliform and Spore Removal

			Log Removal		
Reference	**Travel Distance (m)**	**Travel Time (days)**	**Total Coliform**	**Thermotolerant Coliform**	**Spores[1]**
Havelaar et al. (1995)	30	15	≥ 5.0	≥ 4.1	≥ 3.1
Havelaar et al. (1995)	25	63	≥ 5.0	≥ 4.1	≥ 3.6
Medema et al. (2000)	13	7	N/A	4.1	3.3
	25	18	N/A	4.5	3.9
	150	43	N/A	6.2	5.0
Wang et al. (2000)	0.6	N/A	N/A	N/A	2.0
	1.6				2.0
	3.0				2.0
	16				3.0

[1] Spore data are sulphite-reducing clostridium for all references except Wang et al. (2000), where spore data are aerobic endospores.

2.2.7.2 Factors Affecting Performance

The main factor affecting the performance of bank filtration is the type of aquifer material through which the water is filtered. Granular media is the most effective, while fractured rock or gravel with large pore sizes may be the least effective and allow *Cryptosporidium* to pass through without contacting a grain surface. The flow rate is also an important factor in determining performance. Too high a flow rate can cause oocysts to detach from the aquifer material. Low flow rates, however, may make it difficult to meet volume demands.

2.2.8 Second Stage Filtration

Second stage, or secondary, filtration requires the use of rapid sand, dual media, GAC, or other fine grain media in a separate stage following rapid sand or dual media filtration. A cap, such as GAC, on a single stage of filtration is not considered second stage filtration.

Filtration processes are standard in the water treatment process, and much design and operational information is available. However, the use of a second filtration stage is not as common, and little information is available.

2.2.8.1 Efficacy Against Pathogens

There is relatively little published data on the removal of *Cryptosporidium* by second stage filtration. Results based on a number of single stage filtration studies demonstrate that rapid sand filtration, when preceded by coagulation, can achieve significant removal of *Cryptosporidium*. While these studies evaluated only a single stage of filtration, the same mechanisms of removal would occur with a second filtration stage. Studies have also shown that *Cryptosporidium* breakthrough occurs after the first stage of filtration (Hall and Croll 1996, Emelko et. Al 2000); therefore, a second stage of filtration is likely to provide a barrier to these oocysts.

Many studies (Dugan et al. 2001 and Emelko et al. 1999) have demonstrated that aerobic spores are a conservative indicator of *Cryptosporidium* removal by granular media filtration when preceded by coagulation. Consequently, EPA believes that data on spore removal by a second stage filtration process are indicative of the capacity of this process to remove *Cryptosporidium*.

Between 1999 and 2000, the Cincinnati Water Works collected spore and turbidity removal data from their GAC system. The specifics of their system are provided below.

- 11-foot deep GAC filter following dual media filter
- Loading Rate = 3.4 - 3.9 gpm/ft^2 (average); 7.1 gpm/ft^2 (design)
- 12*40 mesh
- d_{10} = 0.5 - 0.75 millimeters (mm); d10 is the diameter through which 10 percent of the media will pass
- Uniformity Coefficient (UC) ≤ 2; UC is the uniformity coefficient of the media
- Media age -- new to 7 years old; carbon reactivation two times per year

- Empty Bed Contact Time (EBCT) = 22 minutes at 120 million gallons per day (mgd) (average flow); 12 minutes at 220 mgd (design flow)

A median incremental spore removal of 0.92 log was observed in their GAC filter. Additionally, the secondary GAC filters were observed to dampen or eliminate turbidity spikes from preceding dual media filters that occurred during ripening, breakthrough, etc. These data indicate that 0.5 log or greater removal of *Cryptosporidium* can be achieved by a secondary filtration process like GAC contactors.

Based on information presented by Hall et al. (1994), up to a 50 percent improvement in turbidity removal was observed when using a second stage filter. However, no improvement in *Cryptosporidium* removal was observed due to the second stage filter. This information was collected after spiking 500 oocysts/L into the raw water of a conventional filter followed by a secondary filter consisting of GAC.

2.2.8.2 Factors Affecting Performance

Filter Type

There are several types of filters. Fine sand filters, dual media filters, and multimedia filters are the main types of filters used in conventional filtration plants. In order to encourage penetration of solids into the depth of the bed, the dual media filter, consisting of a layer of coarser anthracite coal on top of a layer of finer silica sand, was developed. Studies conducted by many researchers (Conley and Pitman 1960a, Conley 1961, Tuepker and Buescher 1968) showed the benefits of dual media filters in reducing the rate of head loss development, which lengthened the filter run. Although dual media is presumed to improve the quality of the filtrate, this benefit has not been well demonstrated (AWWA1999). Research conducted by Robeck, Dostal, and Woodward (1964) demonstrated that the head losses in dual media filters were lower than the head losses in traditional fine sand filters. When a typical dual media filter and a fine sand filter are operated at the same filtration rate on the same influent water, the head loss development rate for the typical dual media filter should be about half the rate of the fine sand filter (AWWA 1999). Multimedia filters add a layer of garnet to the media which allows for a finer layer of media at the bottom of the filter.

Filter Media

As with all filters (first or second stage), various properties of a filter medium, such as size, shape, density, and hardness, affect filtration performance. Filter media are defined by their uniformity coefficient (UC) and effective size (ES). The porosity of the filter bed formed by the grains is also important (AWWA1999). Filter media should be coarse enough to retain large quantities of floc, yet fine enough to prevent passage of suspended solids. The filter bed should also be deep enough to allow long filter runs and graded to permit backwash cleaning. In order to obtain high rates of filtration, coarse sands and dual media beds of anthracite overlying sand have been used in the recent past (Viessman et al. 1993).

The bed porosity and the ratio of the bed depth to media grain diameter affect the filter efficiency. The larger the depth of the filter bed (L), the more opportunities exist for particle capture; the larger the average diameter of the media (d), the more of the media is available to capture particles over the depth of the filter bed. The ratio of L/d is often used as a design parameter, balancing filter size and cost with removal efficiency. The two most commonly used methods in selecting the optimal filter bed depth and media size are pilot plant studies and existing data from filtration facilities treating similar waters.

Filter Hydraulics

Hydraulic surges occur when the flow through a filter changes rapidly (e.g., during either filter backwashing or servicing of valves). Hydraulic shifts can lead to significant particle detachment, above normal detachment rates. To ensure that the second stage filtration unit is unaffected by any hydraulic surges caused by the backwashing of the first stage filtration unit, the first stage filters should be hydraulically isolated during backwashing and servicing.

2.2.9 Pre-Sedimentation

Pre-sedimentation is a preliminary treatment process used to remove particulate material from the source water before the water enters the main treatment plant. Because pre-sedimentation reduces particle concentrations, it is also expected to reduce *Cryptosporidium* levels. In addition, by reducing variability in water quality of the source water, pre-sedimentation may improve the performance of subsequent processes in the treatment plant. To remove pathogens through floculation and sedimentation, it is necessary to add coagulant.

Sedimentation processes are standard in the water treatment process, and much design and operational information is available. However, the use of a pre-sedimentation basin is not as common, and little information is available.

2.2.9.1 Efficacy Against Pathogens

There is relatively little published data on the removal of *Cryptosporidium* by pre-sedimentation. Consequently, EPA analyzed studies that investigated *Cryptosporidium* removal by conventional sedimentation basins. The removal efficiency in conventional sedimentation basins may be greater than in pre-sedimentation due to differences in surface loading rates, coagulant doses, and other factors. To supplement these studies, EPA reviewed data provided by utilities on removal of other types of particles, primarily aerobic spores, in the pre-sedimentation processes of full-scale plants. Studies have shown that, in the presence of a coagulant, spore removal is a conservative indicator of *Cryptosporidium* removal (Dugan et al. 2001).

The literature studies reviewed by EPA show *Cryptosporidium* log removals of 0.6 to 3.8 (Dugan et al. 2001, Payment and Franco 1993) and mean *Bacillus subtilis* and total aerobic spores log removals of 0.6 to 1.1 (data collected independently by the Cincinnati, OH, and St. Louis, MO, water utilities) by sedimentation processes. The removal of aerobic spores through sedimentation basins in full-scale plants demonstrate that pre-sedimentation is likely to achieve mean reductions of greater than 0.5 log *Cryptosporidium* removal under routine operating conditions and over an extended time period.

2.2.9.2 Factors Affecting Performance

Short Circuiting

Short circuiting in the sedimentation tank occurs when a portion of the influent flow reaches the outlet of the sedimentation basin much faster than the designed detention time of the basin. Short circuiting increases the operational surface loading rate since the true settling area available for a portion of the flow is reduced. If short circuiting causes the basin to operate at an effective loading rate greater than 1.6 gpm/ft^2, the basin would not receive *Cryptosporidium* removal credit. High wind velocities and density and temperature differentials between the influent water and the water in the sedimentation basin cause short circuiting. Additionally, the design or configuration of both the inlet and outlet are important factors that can affect short-circuiting and turbulence. Systems can minimize short circuiting by adding baffles or making other modifications to the flow pattern.

Coagulant Dose

The principle goal of coagulation is to destabilize the particles so that they can be more easily aggregated into flocs. The commonly used coagulants are alum, ferric chloride, polyaluminum chloride (PACl), activated charcoal, and activated silica. The coagulant dose required to treat an influent stream depends on the chemical composition of the influent, the characteristics of the colloids and suspended matter in the influent, the water temperature, and mixing conditions. The use of a coagulant improves the pathogen removal capabilities of the pre-sedimentation process, although some pathogen removal is expected without coagulant addition. Optimizing a coagulation scheme for a two-stage sedimentation process is site-specific and not simple. It is therefore not possible to prescribe the type of coagulant and appropriate dose for an aggregate of source waters. To account for an additional sedimentation process, the standard jar test can be modified to a two-stage process reflecting the two stages of sedimentation.

2.2.10 Watershed Control

A well-designed watershed control program can reduce overall microbial risk. The risk reduction would be associated with the implementation of practices that reduce *Cryptosporidium,* as well as other pathogens. Knowledge of the watershed and factors affecting microbial risk, including sources of pathogens, fate and transport of pathogens, and hydrology can also help a system reduce microbial risk.

2.2.10.1 Efficacy Against Pathogens

No data are available on the ability of watershed control programs to reduce *Cryptosporidium* loading to surface water. This is partly because, until recently, most watershed programs have focused on improving water quality for recreational and ecological uses rather than for drinking water protection. Thus, studies of the success of such programs frequently monitor parameters such as phosphorus and sediment levels. Watershed programs that do have drinking water protection as a goal frequently track fecal coliform bacteria levels but do not regularly monitor *Cryptosporidium*. Fecal coliform concentrations do not always correlate with *Cryptosporidium*, but better indicator data are not usually available. *E. coli* may be a better indicator of fecal contamination than fecal coliform bacteria, but monitoring for *E. coli* is not common practice.

Most water systems that do monitor *Cryptosporidium* have been doing so for only a few years and would not have enough data to show a change in water quality resulting from watershed management. In addition, because *Cryptosporidium* occurs in such low concentrations and is often undetected, reductions in microbiological contamination are difficult to demonstrate.

Regardless of the constituents monitored, it is difficult to show that a watershed control program in its entirety has improved water quality. Often, reductions in contamination from one source can be overshadowed by increases from other sources, especially in urban areas. However, various components of a watershed control program have been shown to have a positive effect on microbiological water quality at a local level, at least for fecal coliform. Combined, these components should theoretically contribute to an overall decrease in microbiological contamination.

For instance, Thurston et al. (2001) showed that a constructed wetland could reduce fecal coliform levels in wastewater treatment plant effluent by 98 percent (where effluent had previously received secondary treatment). *Cryptosporidium* reductions of 64 percent were also achieved through this study. A similar pilot-scale study with untreated wastewater indicated an overall removal of microorganisms of 90 percent by constructed wetlands (Quinonez-Diaz et al. 2001). Preliminary results of a watershed restoration program in Vermont showed that streambank stabilization, fencing of riparian zones to prevent grazing, and protected stream crossings reduced bacterial levels (Meals 2001). A fencing program in Virginia suggested some reduction in fecal coliform levels, and the proportion of fecal streptococci strains traced to livestock was reduced (Hagedorn et al. 1999).

Another way to reduce microbiological contamination of an urban watershed is to upgrade wastewater collection systems. The Fairfax County, Virginia, Wastewater Collection Division decreased inflow and infiltration into its sewers and increased the sewers' capacity through a rehabilitation and maintenance program. Between 1995 and 2001, the utility reduced the number of sanitary sewer overflows throughout the county by 67 percent and reduced the peak flow to one of its wastewater treatment plants by 35 mgd (USEPA 2001). Similar programs throughout the United States are contributing to reduced effluent volumes from sanitary sewer overflows and combined sewer overflows.

2.2.10.2 Factors Affecting Performance

A combination of interventions such as those described above is expected to result in an overall decrease of *Cryptosporidium* in source water. However, many factors can negatively affect the success of a watershed control program. The interventions a system implements depend on the types of contamination sources in the watershed. Control of point source discharge (e.g., waste water treatment plants and industrial discharges) can be straightforward. Agricultural and urban nonpoint sources are the most difficult to control. Reduction of *Cryptosporidium* from these sources generally depends on the voluntary cooperation of urban residents and farmers.

Urban watersheds are subject to increasing development, which increases surface imperviousness and the amount of runoff entering surface waters, along with the pollutant load. Acquisition of undeveloped land, particularly that closest to the source water and its tributaries, is one of the best ways to prevent degradation of the water quality, but it may not be feasible in some watersheds. Other restrictions on development, such as zoning requirements, can also control urban runoff to some extent, but, again, these may not be feasible or may not have the support of the public or other government agencies.

Another problem facing PWSs is that the watershed may extend beyond the municipal boundaries into other jurisdictions. A higher authority (e.g., State or county government) may be needed to regulate activities outside a PWS's jurisdiction that could affect water quality.

2.2.11 Combined Filter Performance

Combined filter performance reduces *Cryptosporidium* levels by enhancing filter performance to produce very low turbidity water. It is defined specifically as producing 0.15 NTU turbidity water in the combined filter effluent (CFE) 95 percent of the time. Methods that systems may use to improve filter performance and lower turbidity include adding polymer, optimizing the filtration process by adding media or installing filter-to-waste capabilities, and improving staff ability to optimize the process by additional training, hiring new operators, and buying new laboratory equipment.

Systems likely to use this technology are those which operate conventional filtration or softening plants and which are already operating well below the current turbidity limits of 0.3 NTU. These systems more than likely target their effluent under 0.15 NTU already but are not currently hitting that target more than 95 percent of the time. These plants are assumed to be able to reach the target 95 percent of the time with relatively minor adjustments to their process. Because several of the components recommended for combine filter performance are also applicable to individual filter performance, EPA has not provided a separate analysis for individual filter performance.

2.2.11.1 Efficacy Against Pathogens

There have been a number of studies examining the removal of pathogens by conventional filtration. Several of these studies have examined the relationship between finished water turbidity and protozoa removal. Studies by Dugan et al. (2001) and Patania et al. (1995) showed that turbidity is an adequate indicator of pathogen removal. Although the correlation between turbidity removal and pathogen removal is not one to one, removal of turbidity is a conservative indicator of pathogen removal.

Under the IESWTR and LT1ESWTR, conventional and direct filtration plants may claim 2.0 log *Cryptosporidium* removal credit if their CFE turbidity never exceeds 1 NTU and is less than or equal to 0.3 NTU in 95 percent of samples taken. Under the LT2ESWTR, systems using conventional filtration treatment or direct filtration treatment may claim an additional 0.5 log *Cryptosporidium* removal credit for any month that a plant demonstrates CFE turbidity levels less than or equal to 0.15 NTU in at least 95 percent of the measurements taken each month, based on sample measurements collected under §§141.73,141.173(a) and 141.551.

EPA expects plants that rely on complying with a 0.15 NTU standard to consistently operate below 0.1 NTU. Results from studies conducted by Patania et al. (1995), Emelko et al. (1999), and Dugan et al. (2001) show that plants consistently operating below 0.1 NTU can achieve at least an additional 0.5 log of *Cryptosporidium* than when operating between 0.1 and 0.2 NTU.

2.2.11.2 Factors Affecting Performance

Many factors can affect removal of pathogens through sedimentation and filtration and hinder a plant's ability to achieve 0.15 NTU in its CFE. In order to achieve 0.15 NTU 95 percent of the time, plants will need to have tight control of their process. The areas which require specific attention include: control of coagulant dosing and mixing, control of dosing of other chemical additions, filter hydraulics and media, and backwashing procedures.

Coagulant Dose

Insufficient coagulant can lead to colloidal particles remaining in suspension, while too much coagulant can lead to inefficient settling. Therefore, coagulation must be optimized for the entire plant. It must also be adjusted as influent water quality varies or if there are other major changes in plant operation.

Filter Ripening

During the period immediately after a backwash, the lack of particles on the filter media can make capture of the particles by the media more difficult and lead to breakthrough of particles and turbidity. Hall and Croll (1996) studied *Cryptosporidium* removal in a pilot plant and saw peaks in both turbidity and oocysts in the filtered water for an hour after backwashing. West et al. (1994) found that *Cryptosporidium* removal increased from 2 log to 3 log once the filters had ripened, and the turbidity had dropped from an initial value of 0.2 NTU to a value less than 0.1 NTU.

Filter Breakthrough

During filter runs, particles can collect in the filter and, if not backwashed, will reach the point where an increased amount of particles pass through (referred to as breakthrough). Emelko et al. (2000) studied the performance of filters throughout a typical run cycle. They found that *Cryptosporidium* and microsphere removal was 5.5 log when the filters were operating at 0.04 NTU. When the turbidity began to climb, removal dropped to 2.1 log even while turbidities were still less than 0.1 NTU. By the time turbidity had reached 0.3 NTU, the removal had dropped to 1.4 log.

Filtration Rate

If the filtration rate is too high, filtration effluent water quality can suffer. McTigue et al. (1998) found that particle removal dropped by 2 log when the filtration rate was doubled. West et al. (1994), however found no difference in *Cryptosporidium* removal between filtration rates of 6 and 14 gpm/ft^2.

Backwashing

The flow rate used for backwashing is important in maintaining effluent quality. Too low a rate can leave the media dirty and lead to mudballs and eventual particle breakthrough. Too high a rate can cause loss of filter media and also lengthen filter ripening times. Various means have been developed for improving backwashing. These include surface washes and collapse pulsing with air scour during backwashing.

2.3 DBP Precursor Removal Strategies

2.3.1 Granular Activated Carbon Adsorption

Removal of undesired compounds, such as DBP precursors, from water supplies can be achieved through adsorption onto solids. GAC is used in water treatment to adsorb a variety of organic and inorganic compounds. Important properties of GAC that determine its effectiveness include particle size, specific surface area, pore size distribution, and chemical nature of the surface. GAC adsorption, as practiced in water treatment, is a non-steady state process, with the effluent concentration of the contaminant increasing with time. Once the effluent concentration meets the maximum allowable concentration for a contaminant, the GAC column must be taken off-line, and the GAC must be replaced with reactivated or fresh GAC. The operation time to reach this maximum allowable concentration is termed the reactivation or replacement interval.

The Empty Bed Contact Time (EBCT) is defined as the volume of media divided by the flow rate, and is an important design parameter. GAC contactors should be used when longer EBCTs are required, while sand filters with a GAC cap, where the top portion of the sand is replaced by GAC, can be used when shorter EBCTs are feasible. These GAC-capped filters are often called filter-adsorbers. Filter-adsorbers can also be filtration units which contain GAC alone. Because of their shorter EBCTs, filter-adsorbers meet desired water quality goals for a much shorter period of time than GAC contactors. For the purpose of treating short term changes in water quality, filter-adsorbers may have an economic advantage over post-filter GAC contactors. One disadvantage of filter-adsorbers is that GAC losses are high during backwashing, and reactivation and equipment separating GAC from sand may be required before reactivation.

GAC contactors operate in either downflow or upflow configurations. Downflow fixed-bed contactors offer the simplest and most common contactor configuration for drinking water treatment. Upflow beds are typically used in situations where very long contact times (greater than 120 minutes) are required and/or where the level of suspended solids is high. Flow through GAC contactors can be either gravity or pressure driven.

The hydraulic constraints of a given system govern the selection between pressure or gravity contactors. Pressure contactors may be more applicable for ground water systems, since these systems already are pumping their water. Gravity contactors are generally found in surface water systems, if sufficient head is available. Downflow contactors are typically placed downstream of the plant filters to minimize the solids loading to the contactor.

The GAC in a contactor is usually replaced when the effluent concentrations exceed the treatment objective. At this point, however, only a portion of the GAC is fully utilized, and replacement of the media will result in unnecessarily high carbon usage rates. Operating multiple GAC contactors in either series or parallel configurations are the two common methods to reduce GAC usage rates.

For contactors configured in series, the GAC in the first contactor is reactivated when the effluent from it no longer meets the treatment objective. Once the first contactor is reactivated, the position of the two contactors is reversed, with what was originally the second contactor becoming the first contactor and vice versa. To achieve efficient operation each contactor should be capable of achieving the necessary removal by itself. While this is often accomplished with reasonable bed length for microcontaminants, it can lead to unwieldy bed lengths for TOC. The use of two contactors in series does not result in significantly longer run times over single contactor operation (USEPA 1999a).

For contactors configured in parallel, multiple GAC beds are operated with a staggered reactivation pattern. The effluent from individual contactors may contain contaminants at concentrations higher than the treatment objective, since they may be blended with effluent from other contactors with little or no breakthrough. The combined effluent concentration, from all the GAC beds, can thus be maintained below the specified treatment objective, further reducing carbon usage rates. For DBP precursor removal, contactor effluents should be blended prior to disinfection.

The choice between a single contactor and contactors in series or parallel is site specific and depends on the type and concentration of the contaminant to be removed and its rate of adsorption. This choice also depends on the type, concentration, and adsorption rate of competing contaminants.

2.3.1.1 Pathogen Removal

GAC if used as a filter cap is not likely to result in additional removal over what would be expected from conventional treatment. If it is used as a secondary filter in series with conventional filtration, additional removal can be obtained. The efficacy of secondary filters in removing pathogens is discussed in full in Section 2.2.8.1.

2.3.1.2 DBP Precursor Removal

In many circumstances, GAC is an effective process for the removal of NOM from drinking water sources. The removal will depend on a number of factors which are more fully discussed in the following section.

It is important to note that, GAC will reduce TOC levels but may not significantly lower bromide. This can cause the bromide-to-TOC ratio to increase and can cause a net shift in speciation of DBPs to the more brominated compounds. The bromide-to-TOC ratio will continually change through the adsorption process, so the concentration of brominated DBPs may spike and then fall.

2.3.1.3 Factors Affecting Performance

The removal of NOM by GAC adsorption depends on a large number of factors including the following:

- Molecular size, polarity, and concentration of NOM entering the GAC process
- Water quality characteristics such as pH and ionic strength
- GAC characteristics such as pore size distribution and surface chemistry
- Operational characteristics such as EBCT and GAC usage rate
- Treatment processes used prior to the GAC process
- Configuration of GAC contactors

This section briefly describes the impacts of these factors as seen in several GAC studies.

Constituents of NOM are adsorbed within the GAC bed in a manner proportional to their adsorption potential. Weakly adsorbing components of NOM may irreversibly preload the GAC at the downstream end of the bed and may, therefore, reduce the capacity of the bed for stronger adsorbing components at the end of the bed.

The impacts of pH on adsorption of NOM and humic extracts have been well documented in equilibrium studies using powdered activated carbon (Weber et al. 1983, Randtke and Jepsen 1982, McCreary and Snoeyink 1980, Summers 1986). All of these studies showed increased removal of TOC with decreased pH levels. Unfortunately, some of the work has been done with different initial TOC concentrations, and the increased performance attributed to low pH may be because of the lower initial TOC. A relationship between the relative adsorption capacity for TOC at the same initial TOC and pH has been established for 13 different source waters and a bituminous coal-based GAC (Hooper et al. 1996b). Within the pH range of 5 to 10, a decrease in the pH of one unit yielded a six percent increase in adsorption capacity. However, the number of continuous flow evaluations of pH impacts is limited. The improved effiiciency is probably due to an increased positive charge on the GAC at lower pH, leading to a higher absorption of negatively charged organic species.

The relationship between GAC pore size distribution and NOM molecular size distribution has been shown to be important (Summers and Roberts 1988, Lee et al. 1983, Semmens and Staples 1986, El-Rehaili and Weber 1987, Chadik and Amy 1987). In general, investigators have found the GAC process to favor removal of NOM molecules of low to moderate size even though the adsorption process was expected to favor removal of large molecules. This phenomenon occurs because small GAC pores physically exclude large NOM molecules from adsorbing. Thus, GAC with a greater quantity of large pores can be expected to remove more NOM than GAC with a smaller quantity of large pores.

The impacts of EBCT on GAC usage rate for NOM removal have been studied in numerous continuous flow evaluations. The trend observed in all studies is that increasing EBCT can reduce the carbon usage rate. One study (Miller and Hartman 1982) saw significant reduction in usage rates as the EBCT is increased from 2.8 to 15.2 minutes. Summers et al. (1997) evaluated EBCTs of 10 and 20 minutes for a number of water sources and concluded that EBCT had a definite effect in prolonging the bed life of a GAC contactor. However, the carbon usage rate is relatively unaffected by EBCTs at the ranges evaluated. They also noted that the balance between EBCT and the frequency of GAC replacement or reactivation is primarily a choice between larger capital investment (i.e., longer EBCTs) and greater operational complexities (i.e., more frequent reactivation). Another study indicated that GAC usage rate decreased with an increase in EBCT from 7.5 to 30 minutes. However, a further increase in EBCT from 30 to 60 minutes did not influence the GAC usage rate (McGuire et al. 1989).

GAC systems may require some kind of pretreatment to prevent build-up of solids in the GAC bed, to minimize the organic loading on the GAC, and to improve cost effectiveness. Build-up of solids, which can cause poor filter performance, could be caused by suspended solids in the raw water or by precipitation of calcium carbonate, iron, and manganese on the GAC. Suspended solids typically cause problems in surface water systems, while carbonate scaling, iron, and manganese precipitation may occur in both surface and ground waters. When the GAC bed life is long, clogging may also be caused by biological growths. Pretreatment methods include coagulation, filtration, or softening ahead of the GAC system. Conventional coagulation, clarification, and filtration processes may be optimized for the removal of organic material to reduce natural organic loading to the GAC bed.

The impacts of coagulation on NOM adsorption have also been well documented in batch experiments studying adsorption equilibria (Weber et al. 1983, Randtke and Jepsen 1981, Lee et al. 1981, El-Rehaili and Weber 1987, Harrington and DiGiano 1989). Coagulation processes, as a pretreatment to GAC, can both reduce influent TOC concentration and decrease the influent pH to the adsorber, thus leading to improved GAC performance.

Several investigators have reported better GAC performance for TOC control after coagulation or after increasing the coagulant dose (i.e., enhanced coagulation). Hooper et al. (1996a, 1996b, 1996c) have shown that the increase in GAC run time after enhanced coagulation can be attributed to the lower pH and lower initial TOC concentration associated with the enhanced coagulated water. This improvement is most often attributed to a decrease in solubility of NOM at lower pH (Symons et al. 1998).

In most GAC applications of any significant size, multiple contactors are operated in a parallel configuration. Parallel GAC contactors are operated in a staggered mode wherein each contactor has been in operation for different lengths of time. In this mode of operation, one contactor at a time is taken off-line when the blended effluent exceeds the target effluent concentration, and a column with fresh or reactivated GAC is then placed on-line. The effluent from the contactor in operation the longest can be higher than the target breakthrough concentration, as it is blended with water from the contactors that have effluent concentrations much lower than the target concentrations. Consequently, the effluent of parallel contactors are blended prior to disinfection. Thus, parallel operation in a multiple contactor configuration will result in longer GAC bed-life and the time between reactivation will be longer. Under ideal conditions, staged blending with multiple parallel contactors leads to near steady-state effluent concentration (Roberts and Summers 1982).

Experimental and modeling methods for predicting the blended effluent concentration from GAC contactors were developed by Summers et al. (1997). The authors observed during this study that the time to GAC performance goals can be significantly extended by blending the effluent from multiple contactors. For the three waters examined, blending increased the run time by an average of 150 percent for both TOC and TTHM.

The research described above demonstrates how the performance of GAC systems can be influenced by many process variables. In general, the process can be modified to provide the same level of NOM removal at lower GAC usage rates by the following:

- Maintaining low pH conditions through the process

- Increasing NOM removal in processes that precede GAC adsorption

- Using an EBCT greater than or equal to 10 minutes

Ozonation prior to GAC does not guarantee improved NOM removals because it can either decrease or increase the ability to adsorb and increase the biodegradability of NOM. The overall impact of preozonation on NOM removal in GAC contactors depends on the efficiency of biotreatment to remove the weakly adsorbing hydrophilic fraction.

2.3.2 Nanofiltration

Nanofiltration is a high-pressure membrane process that has been traditionally used as a softening process to remove hardness ions. Generally, NF membranes reject divalent ions (e.g., Mg^{2+}, Ca^{2+}), but pass monovalent ions (e.g., Na^{+}, Cl^{-}). Recently, NF has been used more extensively for removal of DBP precursors and color, particularly in brackish waters, as well as other surface waters. Although NF processes remove nearly all turbidity in feed water, they cannot be used for turbidity removal in the same manner as MF and UF due to smaller pore sizes (Mallevialle et al. 1996). Smaller pore size makes NF membranes more prone to fouling. The application of NF for surface waters is generally not accomplished without extensive pretreatment for particle removal and possibly pretreatment for dissolved constituents.

The percentage of treated water that can be produced from the feed water is known as the recovery. Recovery is an important factor for cost of membrane processes and is one measure of the efficiency of a system. Recovery for NF systems is typically 75 to 90 percent and is impacted by feed water characteristics, membrane properties, and operating conditions, such as TMP. Since treatment and disposal of the reject stream (i.e., waste stream) can be a significant portion of the overall cost of a system, recovery can greatly affect cost efficiency.

2.3.2.1 Efficacy Against Pathogens

As would be expected based on MF and UF microbial removal efficiencies, NF processes are capable of excellent disinfection by removing nearly all microbial contaminants in feed water, including *Giardia*, *Cryptosporidium*, and viruses. Historically, NF processes have not been used as a primary means of disinfection, since, in large part, they have been used to treat ground water or have been coupled with pretreatment processes such as MF or UF. When only disinfection is required, MF and UF processes are typically used instead of NF, since they are less costly and can achieve the required level of pathogenic rejection (Mallevialle et al. 1996). Because of this, relatively few studies documenting microbial removal with NF membranes have been conducted in comparison to MF and UF processes. Because NF and RO processes represent systems that are very similar in terms of disinfection capabilities, available studies documenting microbial removal with RO as well as NF membranes are presented in Exhibit 2.17.

Exhibit 2.17: NF Studies Documenting Microbial Removal

Reference	Process	Membrane	Giardia Log Removal	Crypto Log Removal	MS2 Virus Log Removal
Gagliardo et al. (1999)	RO	HR	--	--	3.0
Gagliardo et al. (1999)	RO	DOW	--	--	5.4
Gagliardo et al. (1999)	RO	ESPA	--	--	4.7
Gagliardo et al. (1998)	RO	ULP	--	--	3.4
Seyde et al. (1999)	NF (Pilot)	Acumem-4040	>5[1]	>6[1]	4.2 to 5.0
Colvin et al. (1999)	RO (bench)	FilmTec BW30	--	--	>4[2]
Colvin et al. (1999)	RO (bench)	FilmTec BW30	--	--	>7[1]
Trussel et al. (1998)	RO (MF pretreat)	FilmTec BW30	--	--	4.1 to 5.9
Trussel et al. (1998)	RO (MF pretreat)	Hydranautics 4040 UHA	–	--	3.7 to 5.7
Trussel et al. (1998)	RO (MF pretreat)	Fluid Systems TFLC/M48 20HR	--	--	2.1 to 3.3
Trussel et al. (1998)	RO (MF pretreat)	Fluid Systems TFCL/ULP	–	--	2.9 to 4.3
Gagliardo et al. (1997)	RO (pilot)	TFC	>5.7	>5.7	3.0 to 4.0
Gagliardo et al. (1997)	RO (pilot)	CA	>5.7	>5.7	3.3 to 5.1

Note: –Data not available
[1] Indicates removal to detection limit.
[2] 0.02 μm Fluospheres

As shown in Exhibit 2.17, NF and RO processes are capable of significant removal of cysts and viruses. However, the data in Exhibit 2.17 show that NF and RO systems are not an absolute barrier; they can allow microorganisms to pass through the membrane into the treated water. For this reason, it is important to consider membrane integrity testing when assessing the ability of a membrane to act as a barrier to microorganisms. Although no standard NF integrity testing method exists, some tests that have been proposed include vacuum testing and monitoring effluent water quality parameters such as chloride, UV-254 absorbance, microorganisms, and particle counts (Spangenberg et al. 1999). Vacuum testing entails taking the membrane off-line. This has the disadvantage of being unable to provide on-line integrity monitoring. Should a system become compromised, it would not be realized until the module is taken off-line and tested. Effluent water quality monitoring does provide real-time results. However, the parameters being monitored must be sensitive enough to provide an alert if the system is compromised. Sensitivity of various parameters will depend on the influent level of that particular parameter along with the amount of removal accomplished by the membrane. The parameter acting as a surrogate for membrane integrity must be removed to a significant degree such that a noticeable increase in effluent concentration would be seen if the membrane system were compromised.

NF processes are also capable of reducing biodegradable organic carbon (BDOC) (Escobar and Randall 1999). Since BDOC serves as substrate for microorganisms in the distribution system, reducing BDOC can reduce the potential for regrowth in a distribution system, disinfectant doses, and DBPs. A recent full-scale study was performed to document the microbiological and disinfection benefits derived from implementing NF where conventional treatment had previously been practiced (Laurent et al. 1999). The results of this study showed significant decreases in chlorine residual fluctuations, microbiological counts, DOC, and BDOC in treated water and in the distribution system. In effect, this created greater water quality stability in all areas of the distribution system, particularly in areas with high residence times. In addition, the finished water chlorine dose required was lowered from about 1 mg/L to 0.2 mg/L by the use of NF.

2.3.2.2 DBP Precursor Removal

Membrane processes can remove DBP precursors through filtration and adsorption of organics. Membranes remove NOM through filtration (i.e., sieving) when NOM molecules are larger than a given membrane pore size, causing them to be rejected. Size, however, is only one factor that influences NOM rejection. Shape of the NOM molecules and membrane pores, along with chemical characteristics of the NOM molecules and membrane also play important roles in the permeation of NOM across a membrane (Mallevialle et al. 1996). Membranes may also remove NOM through adsorption of organics directly on the membrane surface. The level of adsorption to the membrane surface depends on the chemical characteristics, particularly charge and hydrophobicity, of both the membrane material and the NOM. Unfortunately, organic adsorption is generally undesirable since it has proven to be a primary cause of irreversible fouling of membranes, thereby shortening membrane life.

Without pretreatment, NF processes remove NOM to varying degrees. NOM removals for NF and RO processes are typically on the order of 50 to 99 percent. NOM removal depends on many factors, including membrane MWCO and hydrophobicity, characteristics of the NOM, and membrane system operating parameters such as recovery and operating pressure. Results from several studies on NOM removal by NF processes are provided in Exhibit 2.18.

Exhibit 2.18: NOM Removal Through NF Processes

Reference	Design Criteria	Conclusions of Study
Taylor et al. (1987 and 1989)	Operating pressure: 98-141 psi Flux: 8.9-16.4 gpd/sf Recovery: 50-79%	• MWCO of 100 to 500 are needed for DOC removal up to 90%. • MWCOs of 1000 to 3000 may achieve 50% DOC removal. • Trihalomethane formation potential (THMFP) and total organic halide formation potential (TOXFP) reductions up to 95% could be achieved with 300 MWCO. • Operating pressure had a negligible impact on NOM removal. • TDS[1] and hardness rejection are increased by increased operating pressure.
Conlon and McClellan (1989)	Operating pressure: 90-100 psi Recovery: 75%	• NOM removal greater than 90% for 200 MWCO.
Allgeier and Summers (1995)	Operating pressure: 95 psi Flux: 15-24 gpd/sf Recovery: 30-87%	• 66-94% TOC removal for 200 MWCO. • TOC removal decreased by up to 15% as recovery approached 90%.
Lozier et al. (1997)	Operating pressure: 70 psi Flux: 10 gpd/sf Recovery: 85%	• 69-98% TOC removal using MF pre-treated water.
Chellam et al. (1997)	Operating pressure: 70 psi Flux: 10 gpd/sf Recovery: 85%	• 90-95% TOC removal with 200 MWCO on MF and UF pretreated water. • 95-99% SDS THM precursor removal. • 96-99% SDS HAA6 precursor removal.
Mulford et al. (1999)	Operating pressure: 100 psi Flux: 15 gpd/sf Recovery: 82%	• 96% DOC removal with 200 MWCO.
Fu et al. (1995)	Operating pressure: 80 psi Flux: 15-20 gpd/sf Recovery: 75-90%	• 85-97% TOC removal with 100 to 500 MWCO.
Yoon et al. (1999)	Not reported	• 60-90% TOC removal with 200 to 8,000 MWCO. • Slightly higher NOM removal is achieved at pilot-scale than at bench-scale.
Legube et al. (1995)	Not reported	• 79-91% DOC removal. • 91-95% TOXFP reduction. • 93-94% THMFP reduction.

[1]TDS = total dissolved solids

In addition to NOM removal, NF processes are capable of some DBP and DBP precursor removal, although little work has been performed in the area. Bromide is a precursor for brominated DBPs, so its removal can be beneficial. NF membranes are capable of significant bromide removal. Several studies documenting the use of NF processes for bromide removal are summarized in Exhibit 2.19.

Exhibit 2.19: Bromide Removal Through NF Processes

Reference	Conclusions of Study
Amy and Siddiqui (1999)	38-41% bromide removal with 150 to 300 MWCO.
Mulford et al. (1999)	50-63% bromide removal with 200 MWCO.
Allgeier and Summers (1995)	40-61% bromide removal with 200 MWCO.
Fu et al. (1995)	24-38% bromide removal with 100 to 500 MWCO.
Prados-Ramirez et al. (1993)	63% bromide removal.
Conlon and McClellan; Taylor et al. (1989)	60-70% chloride removal, with bromide removal expected to be nearly identical.

As shown by the data in Exhibit 2.19, NF is capable of high percentage bromide removal. Overall, however, bromide removal using NF would probably not be cost effective if used only for that purpose. If the process were incorporated into a treatment train and used for other contaminant removal, membrane removal of bromide may become cost effective (Amy and Siddiqui 1999). It is important to note that, if bromide is not removed sufficiently but TOC levels are reduced, the bromide-to-TOC ratio will increase considerably and will cause a net shift in speciation of DBPs to the more brominated compounds. In the worst case, such a scenario could cause a net increase in the absolute level of brominated DBPs (i.e., bromoform) after chlorination (Amy and Siddiqui 1999).

2.3.2.3 Factors Affecting Performance

NF is gaining popularity as a DBP precursor removal process, since production costs are comparable with competing processes (Mallevialle et al.1996). Due to the small pore size associated with NF, other feed water constituents will also be removed. For example, divalent salts, some metals, and some synthetic organic chemicals (SOCs) may be rejected by these membranes and, therefore, be concentrated in the waste stream. This may increase the cost associated with disposing of the waste stream compared to disposal costs associated with MF, UF, and conventional treatment processes. If regulatory limits prohibit sending the waste stream to a receiving body, costs for waste handling and disposal can be a substantial portion of the overall treatment cost.

MWCO is a key characteristic affecting membrane performance. Membranes with MWCOs in the 100 to 500 range appear to be very effective as a means of DBP precursor removal. TOC, THMFP, and TOXFP reductions of 70 to 95 percent are commonly achieved in systems using such membranes. These processes can effectively remove bromide as well, with reductions up to 95 percent. Larger MWCO membranes (i.e., MWCO near and above 10,000), however, will not be as effective for NOM reduction.

Commercial NF (as well as MF and UF) membranes are available in many types of material (e.g., cellulose acetate and polysulphone) and in various configurations (e.g., spiral wound and hollow fiber). The chemistry of the membrane material, particularly surface charge and hydrophobicity, can play an important role in rejection properties, since membranes can remove contaminants through adsorption on the membrane surface as well as through sieving across the membrane pores. These factors must be taken into consideration to accommodate source water characteristics and removal requirements.

Source water quality can also dictate pretreatment requirements. The small pore size of NF and RO membranes makes them more prone to fouling than UF or MF membranes, necessitating higher quality feed water. The application of NF and RO for surface water treatment is generally not accomplished without extensive pretreatment for particle removal and possibly pretreatment for dissolved constituents. For example, the rejection of scale-forming ions, such as calcium and silica, can lead to precipitation on the membrane surface since these ions are concentrated on the feed side of NF and RO membranes. Organic constituents and metal compounds, such as iron and manganese, can promote fouling through precipitation and adsorption as well. Precipitation and adsorption can result in irreversible fouling and must be avoided through appropriate pretreatment, including anti-scaling chemical and/or acid pretreatment and possibly pretreatment for organics removal.

In terms of contaminant removal, membrane performance can also be influenced by the operating pressure and percent recovery, depending on the mechanism of rejection. (This is true for NF and RO systems, but generally not true for MF and UF systems.) Contaminant rejection by NF and RO systems generally increases with decreasing operating pressure and with decreasing recovery. Thus, rejection can be enhanced by changing operating parameters, but not without corresponding increases in operating costs. To increase recovery, membranes are often staged (i.e., the concentrate of one stage of membranes is treated by another stage of membranes). Two to three stages are common for NF and RO systems. (Staging, however, is generally not used for MF and UF.) Staging is also used to keep the fluid velocity across the membranes at a specified rate. The maximum attainable percent recovery is usually governed by the degree to which the water can be concentrated without the occurrence of precipitation for NF and RO.

3. Technology Design and Criteria

3.1 Introduction

This Chapter provides assumptions related to the overall design for each technology addressed in this document. Section 3.2 describes the assumed base treatment plant used for all technology modifications. Sections 3.3 and 3.4 describe the design approach for alternative disinfectant and DBP precursor removal technologies, respectively. These sections include the following types of information for each technology:

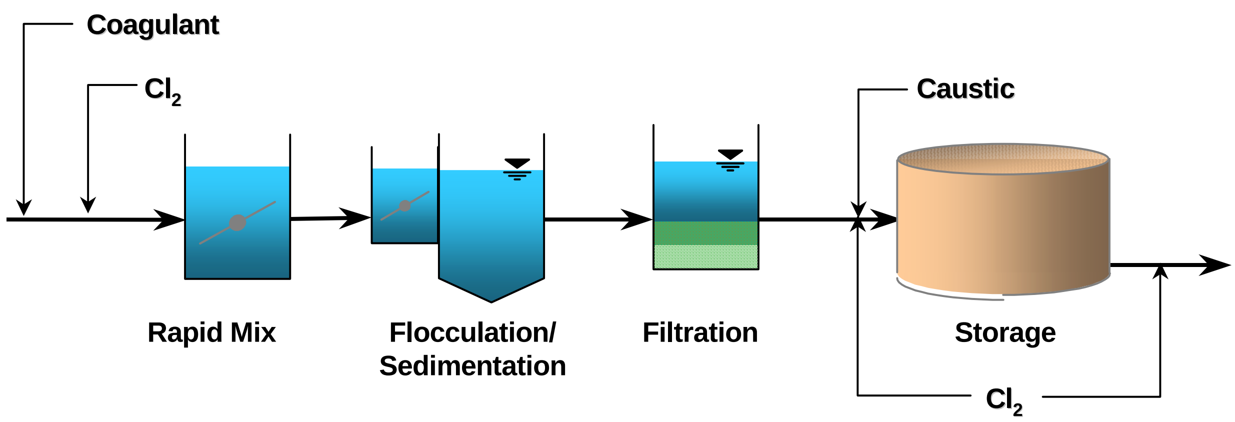
- Assumed water quality conditions (e.g., median filter water quality assumptions for UV design)
- Chemical doses (e.g., ozone dose for *Cryptosporidium* inactivation)
- Equipment type (e.g., types of UV lamps for various system sizes)
- Plant layout

Chapter 4 builds on this Chapter by providing more detailed design assumptions for technology components and presents the costs for each technology.

3.2 Base Treatment Plant

The base treatment plant is assumed to represent the existing treatment configuration. All modifications with alternative disinfection strategies and removal of DBP precursors are assumed to be retrofitted from this base treatment plant. The base plant is represented by a conventional treatment plant, employing the basic processes of coagulant addition and mixing, flocculation, clarification, granular media filtration, and chlorination for both primary disinfection and maintenance of a distribution system residual. EPA realizes that the base treatment plant does not and cannot represent every treatment plant. Instead the base plant is intended to represent a national average plant for the purposes of determining what equipment is available and what will need to be added. Even though they are not exactly the same, many smaller package plants are very similar to the base plant. In addition, many of the technologies in this document are modular in nature and can be added to other treatment schemes just as easily as to the base plant. In cases where such a base plant is absolutely necessary to install the technology, that technology is not considered for small systems. A schematic of the base plant is shown in Exhibit 3.1.

Exhibit 3.1: Base Plant



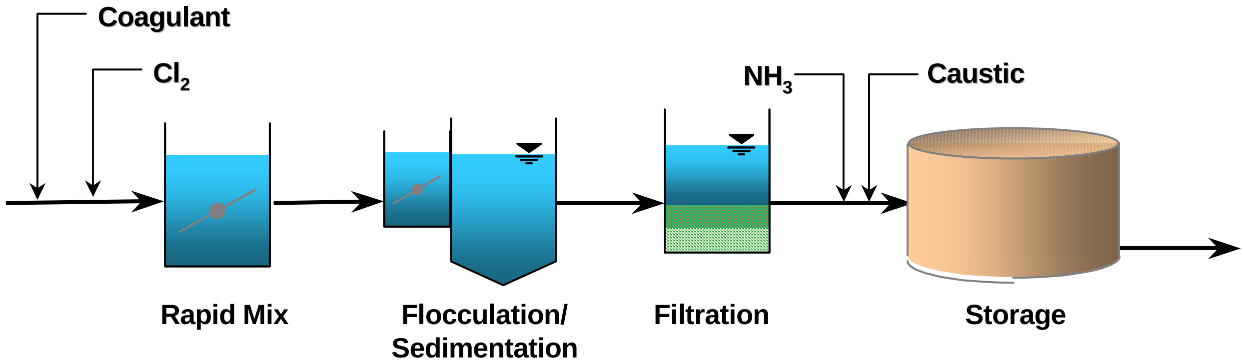
3.3 Alternative Disinfection Strategies

Pertinent to compliance with the Stage 2 DBPR and the LT2ESWTR, alternative disinfection strategies may be selected to provide additional treatment for *Cryptosporidium* and/or to limit the formation of DBPs. This section describes the overall design approach used for costing a number of alternative disinfection strategies capable of achieving these goals.

3.3.1 Chloramination

Chloramines can be used for secondary disinfection to limit DBP formation in the distribution system. Chloramines are less effective for microbial inactivation than chlorine and are typically ineffective as a primary disinfectant; however, they may be used in combination with other technologies discussed in this section (e.g., ozone for primary disinfection) to reduce DBP formation in the distribution system. Typically, ammonia is added after filtration (or possibly after storage) to quench the chlorine residual and form chloramines. A schematic of a chloramine system is shown in Exhibit 3.2

Exhibit 3.2: Plant Schematic for Chloramines for Secondary Disinfection



Description of Process: Pre-chlorination for primary disinfection; add ammonia after filtration at a residual chlorine to ammonia ratio of 4:1.

A range of finished water chlorine residuals were derived using the ICR database. The 10th and 90th percentile finished water chlorine residuals from the ICR database are approximately 0.6 and 2.2 mg/L, respectively. From these residuals, the ammonia dosages of 0.15 and 0.55 mg/L were derived assuming a 4:1 chlorine to ammonia ratio (typical chlorine to ammonia ratios are between 3:1 and 5:1 to ensure monochloramine formation). Upgrade costs were generated only for ammonia storage and feed systems (the base plant is assumed to provide the necessary chlorine). It is assumed that all chloramination can be accomplished at the plant and that no distribution system booster stations are required.

Aqueous ammonia is assumed for small systems (<1 mgd), and anhydrous ammonia is assumed for large systems (>1 mgd). Anhydrous ammonia is generally more cost effective for larger utilities; however, safety and handling issues with anhydrous ammonia also need to be considered. The aqueous ammonia system consists of a chemical storage container, metering pumps, an on-line process analyzer, piping, and valves. The anhydrous ammonia system consists of bulk storage pressure vessels, a vacuum feed system, an on-line process analyzer, piping, and valves: The larger systems may also include a vaporizer and an emergency scrubber system.

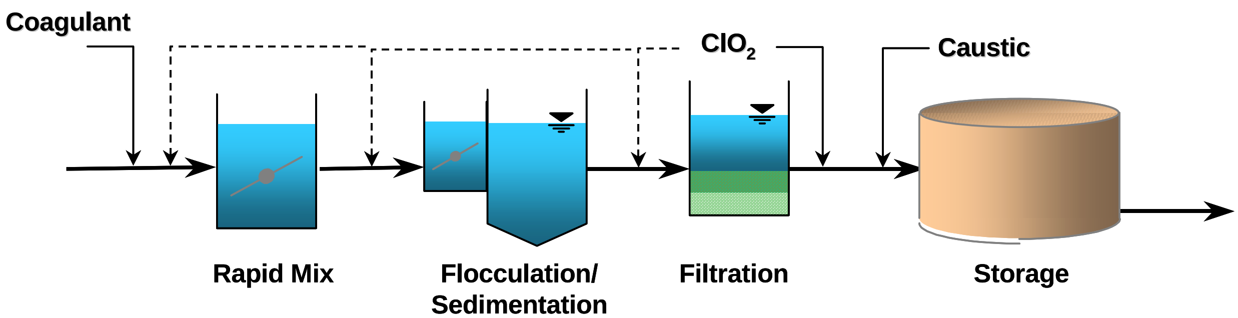
3.3.2 Chlorine Dioxide

Chlorine dioxide is an effective oxidant/disinfectant that is frequently used to control THM formation. It has also been shown to inactivate *Cryptosporidium*, as described in Chapter 2. Thus, chlorine dioxide can replace chlorine (or other oxidants) as the primary disinfectant and potentially achieve a greater level of pathogen inactivation while decreasing THM and HAA formation. However, controlling the formation of chlorite ions can be a considerable challenge in chlorine dioxide treatment implementation.

Because of the significant operator attention required to monitor and control chlorite formation as well as to address safety concerns, it is assumed that systems serving fewer than 500 people will not have the expertise necessary to use this technology. Therefore, costs are only developed for systems with a design flow of 0.091 mgd or greater.

Many plants add chlorine dioxide as a pre-oxidant, but it can also be added after filtration. For the analysis presented here, it is assumed that chlorine dioxide can be added at any point in the process train. (A schematic of the chlorine dioxide system is shown in Exhibit 3.3.) Chlorine dioxide costs do not include construction of a basin for additional chlorine dioxide contact time. It is assumed that plants can achieve adequate contact time with their existing configuration.

Exhibit 3.3: Plant Schematic for Disinfection with Chlorine Dioxide



Description of Process: Replace chlorination with chlorine dioxide addition.
Point of addition may be
1) prior to rapid mix, or
2) prior to flocculation, or
3) prior to filtration, or
4) post filtration

All chlorine dioxide cost analyses presented in this document are based on an applied dose of 1.25 mg/L. This is close to the maximum dosage of chlorine dioxide that can be added while remaining in compliance with a 1.0 mg/L MCL for chlorite, conservatively assuming a 70 percent conversion of chlorine dioxide to chlorite and a safety factor to account for impurities, such as unreacted chlorine, in the chlorine dioxide feed. This analysis evaluated chlorine dioxide costs at the maximum dosage because chlorine dioxide is being considered here for inactivation of *Giardia* and *Cryptosporidium*. Protozoa inactivation by chlorine dioxide typically requires high CT values as described in Chapter 2. Additionally, evaluating the maximum chlorine dioxide dose provides a degree of conservatism to these cost estimates. The level of *Cryptosporidium* inactivation that would be achieved by this dose depends on water quality and contact time and is not assessed in this cost analysis. Higher doses would necessitate the removal of chlorite and are not evaluated at this time due to uncertainty about the applicability and efficacy of chlorite removal processes.

For all systems, the use of an automatic generator is assumed. Key design assumptions for large systems are presented below.

- Chlorine dioxide generation is accomplished through addition of sodium chlorite to a chlorine solution created by dissolution of chlorine gas in water.
- A sodium chlorite metering and mixing system is provided.
- A chlorine dioxide generator (detention time = 0.2 minutes) is provided.
- A polyethylene day tank and mixer are provided to store chlorine dioxide prior to its addition to the process.
- A dual head metering pump is provided to add chlorine dioxide to the process.

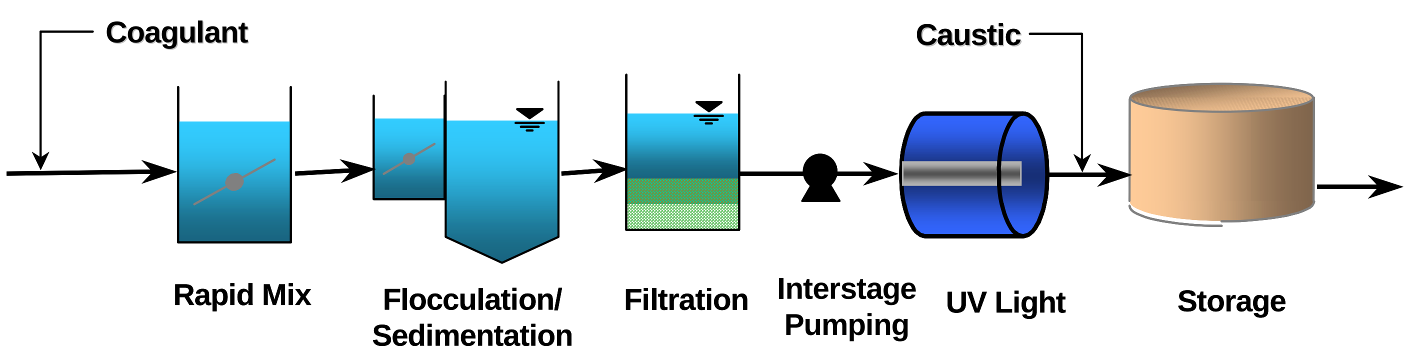
- A 1:1 mass ratio of chlorine gas to sodium chlorite is assumed to ensure that the sodium chlorite is completely utilized. (The additional chlorine serves to lower the pH for reaction through creation of hypochlorous acid.)

It is assumed that small systems (<2 mgd) will rent the ClO_2 generation equipment and only incur capital costs for instrumentation and piping and valves.

3.3.3 Ultraviolet Light

UV light is an effective disinfectant for bacteria, viruses, *Giardia*, and *Cryptosporidium* and does not form THMs or HAAs (see Chapter 2). For cost estimates in this document, a conceptual design for retrofitting the base plant with a UV disinfection system was developed based on plant flow (i.e., system size category) and water quality. Because particulate matter may affect the performance of UV systems, the cost estimates assume that the UV system is installed downstream from the filter. Exhibit 3.4 presents a schematic of a conventional water treatment plant (WTP) with UV disinfection. As shown in the schematic, interstage pumping is assumed because many utilities will not have sufficient hydraulic head to support the addition of UV disinfection facilities without significantly affecting plant operation.

Exhibit 3.4: Plant Schematic for UV Disinfection



Description of Process: Replace chlorination with UV light for disinfection.

The filtered water quality conditions assumed for all UV costs are based on median values reported in the ICR, as indicated in Exhibit 3.5.

Exhibit 3.5: Water Quality Assumptions for UV Disinfection

Parameter	Value
UV 254 absorbance[1] (cm^{-1})	0.051
UVT (%)[1]	89
Turbidity (NTU)	0.1
Alkalinity (mg/L as $CaCO_3$)[2]	60
Hardness (mg/L as $CaCO_3$)[2]	100

[1] Median of maximum filtered water UVT (minimum UV absorbance) from the ICR data
[2] Median of all ICR filtered water data
Source: ICR Data

Cost estimates for UV are provided for two UV doses: 40 and 200 mJ/cm^2.[1] As discussed in Chapter 2, a UV dose of 40 mJ/cm^2 has been shown to be sufficient for 3 log inactivation of *Cryptosporidium* and *Giardia* and 1 to 2 log inactivation of viruses. Studies have shown that a UV dose of 200 mJ/cm^2 is adequate for 4 log inactivation of viruses. It is, however, not possible to validate a UV reactor for 4 log virus inactivation. Therefore, it was assumed that two 200 mJ/cm^2 reactors would be used in series.

Low pressure UV lamp based systems have been used for small treatment plants but are not typically installed at larger facilities due to the high number of lamps that would be required. Medium pressure lamp systems are not typically used for smaller utilities due to higher capital costs in comparison to LP systems at low flow rates. Therefore, UV reactors utilizing LP lamps are assumed for the small system (<1 mgd) designs. Depending upon the manufacturer, LPHO and/or MP reactors are provided in the large system (>1 mgd) cost estimates.

All UV systems are designed with an equipment redundancy of one extra UV reactor (n+1) or 15 percent capacity above design flow, whichever is greater. The number of reactors costed for each system size is shown in Exhibit 3.6 below. The number of reactors for each design flow is based on currently available UV reactor sizes and flows.

Exhibit 3.6 Number of Assumed UV Reactors

Design Flow (mgd)	Duty UV Reactors	Standby UV Reactors	Total Number of UV Reactors
0.022 - 3.5	1	1	2
17	2	1	3
76	4	1	5
210	11	2	13
430	22	4	26

UV disinfection systems are sensitive to power interruptions and fluctuations. When a UV reactor goes down, it can take from four to ten minutes for the UV lamps to regain full power. A utility with poor power quality might have problems with their UV systems going down too frequently. One way to prevent this problem is to install a uninterruptible power supply (UPS), which is essentially a battery that smooths out the power interruptions and fluctuations. Because some systems may need UPS systems, cost estimates in Chapter 4 are completed at UV doses of 40 and 200 mJ/cm^2, with and without UPS systems.

3.3.4 Ozone

Ozone can be used to replace chlorine for primary disinfection and can provide a higher level of inactivation of certain pathogens, such as *Cryptosporidium*, while reducing formation of THMs and HAAs. Ozone is one of the most powerful oxidants available for water treatment (second only to the hydroxyl free radical). Disinfection with ozone is influenced by water quality characteristics such as pH, temperature, alkalinity, TOC, and certain inorganic compounds like iron and manganese. The use of

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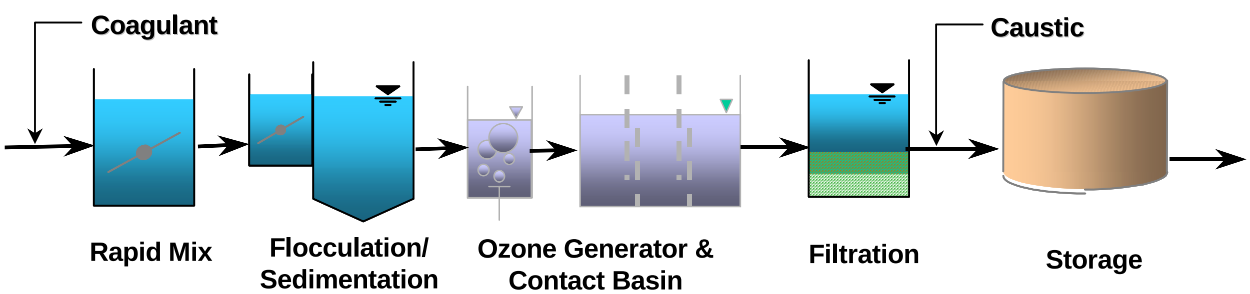
[1] EPA updated the 40 mJ/cm2 UV unit costs based on data obtained for recent installations of this technology. Similar data for 200 mJ/cm2 UV systems were not available within the time frame required to include in this analysis.

ozone can be limited by raw water bromide levels and consequent bromate formation. These factors, in conjunction with the CT necessary for the desired level of pathogen inactivation, impact the design and operation of the ozone system.

A schematic of the ozone configuration is shown in Exhibit 3.7. The costing process allows for ozone application to either raw or settled water (settled water application is depicted in Exhibit 3.7). To control bromate formation during ozonation, it may be necessary to lower the pH in certain waters. Separate costs are estimated for pH adjustment so that this cost may be added to the costs of ozonation, where appropriate. The pH adjustment costs include addition of a chemical feed system. To reduce the pH, sulfuric acid is used and caustic (after ozonation) is used to raise pH.

Exhibit 3.7: Plant Schematic for Ozone Disinfection



Description of Process: Replace chlorination with ozonation.

Costs for ozone treatment systems are directly related to the dose applied. For the purposes of the LT2ESWTR and the Stage 2 DBPR, three ozone doses are costed based on the three levels of *Cryptosporidium* inactivation: 0.5, 1.0, and 2.0 log. The Surface Water Analytical Tool (SWAT) model is used to calculate the ozone dose required for each inactivation level, based on CT tables in Chapter 2 (Exhibit 2.13) and assuming an ozone CT of 12 minutes. For each plant in the ICR survey, and for each month with data, the SWAT model was used for raw water characteristics and existing plant configurations to determine the dose required to achieve the desired *Cryptosporidium* inactivation. Mean and maximum doses were then determined for each ICR plant.

For costing purposes, two doses were established for each of the three *Cryptosporidium* inactivation levels (0.5, 1.0, and 2.0 logs). The median of all plant-mean ozone doses (1.78, 2.75, and 3.91 mg/L, respectively) were used to calculate operation and maintenance costs. This is the dose which will be the most common for all plants achieving the given inactivation and the dose most representative of daily plant flows. To determine capital costs, the median of the plant-maximum doses (3.19, 5.0, and 7.0 mg/L, respectively) are used, as systems will be designed to meet the maximum dose that could be required under typical conditions.

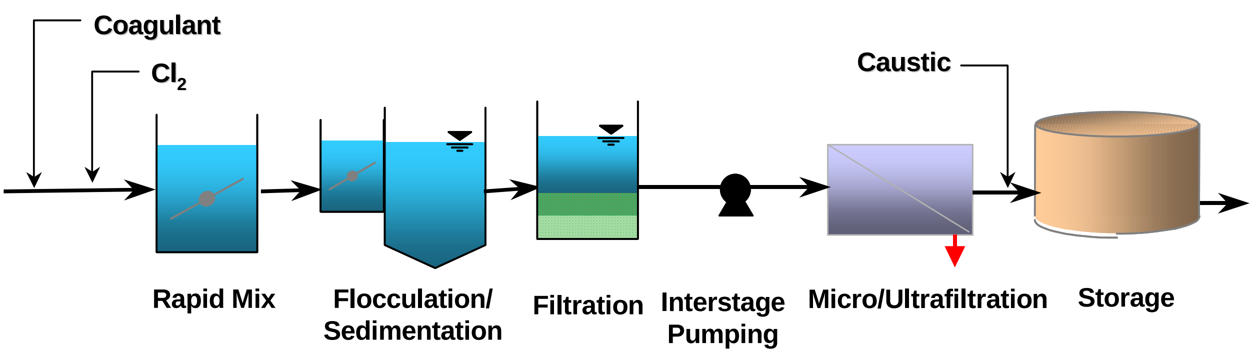
The primary components of the ozone process include in-plant pumping, ozone generation system, ozone contactor, off-gas destruction facilities, effluent ozone quench, stainless steel piping (including valves and ductwork), electrical and instrumentation (E&I), and chemical storage facilities. Components not related directly to the process (e.g., for which indirect costs are calculated) include piloting, permitting, land, operator training, and housing.

3.3.5 Microfiltration and Ultrafiltration

Microfiltration or ultrafiltration can be added to the base plant process train to enhance particle and microbial removal, including removal of *Cryptosporidium*. MF/UF may also allow treatment plants to reduce DBP formation by decreasing the disinfectant dose required to meet plant CT requirements. MF/UF can be added to the treatment process following conventional media filtration, or, in some cases, may be added as a replacement for media filtration. In certain applications (e.g., low total suspended solids (TSS) surface waters or groundwaters), MF/UF can replace the entire conventional treatment process. However, the design assumptions and costs presented in this document assume addition of MF/UF to an existing conventional treatment plant for enhanced removal of *Cryptosporidium* and/or DBP control. Consequently, the costs presented in Chapter 4 do not include all of the components that would be required to replace a conventional treatment train. A schematic of the MF/UF treatment process is shown in Exhibit 3.8

As discussed in section 2.2.5, flux is a critical design parameter for membrane applications and is often used in membrane procurements as a specification. However, the configuration of one membrane is often very dissimilar to that of another. Membrane fiber diameter, pore size, flow configuration (i.e., cross-flow vs. dead-end, pressure vessels vs. submersible membranes), and other membrane-specific factors can impact flux and other design and operating parameters. As a result, membrane feed water quality is used as the basis of design for the membrane portion of the costs presented.

Exhibit 3.8: Plant Schematic for Microfiltration and Ultrafiltration



Description of Process: Addition of microfiltration or ultrafiltration following granular media filtration. It may be necessary to move the point of chlorination to after MF/UF, as some membranes can be damaged by chlorine.

Cost estimates are based upon a design feed water temperature of 10°C. As previously discussed, temperature can have a significant impact on membrane system design. As the water temperature decreases, water viscosity increases. This, coupled with temperature effects on the membranes themselves, can result in the need for increased membrane area and/or increased operating pressures to maintain the desired level of production. It is important to note that this effect can vary from membrane to membrane, and many manufacturers have developed membrane-specific correction factors.

Membrane system costs were approximated using estimates provided by four manufacturers (all pressure vessel systems). The only criteria given to the manufacturers was the feed water temperature of 10°C. Since the design assumes a post-filtration retrofit, the effect of solids loading on the membrane is considered minimal and was not specified for manufacturer estimates. Each manufacturer then used its own flux specifications and temperature correction factor to provide cost estimates for design flows ranging from 0.01 to 430 mgd. Estimates for design flows of 0.007 and 520 mgd were extrapolated from these estimates.

The membrane costs from the manufacturers include skid-mounted membrane modules with associated piping, feed pumps, backwash and recirculation pumps (where appropriate), chemical cleaning feed tanks and pumps, and instrumentation and control for proper operation. Additional instrumentation and control and pipes and valves were included in process costs for interconnection with existing plant control systems and processes. Interstage pumping was also added based on the assumption that the existing plant may not have sufficient hydraulic head to accommodate the membrane process. O&M costs include replacement membranes (membrane life is 5 years), process power, chemicals for cleaning, and labor.

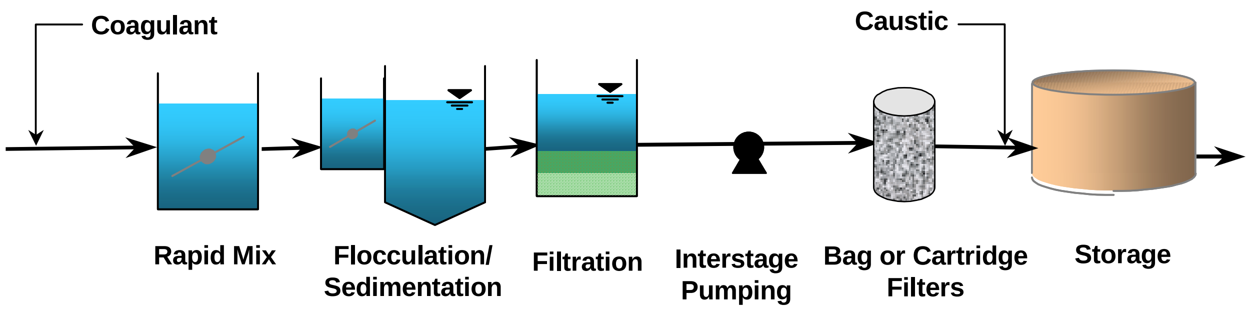
For the purposes of design, it was assumed backwash and reject water could be discharged to a sanitary sewer for treatment at a publicly owned treatment works (POTW). This assumes the sanitary sewer has sufficient capacity to accommodate the increase in flow, and the POTW is able to handle the increase in daily flow. However, in many cases, the reject and backwash water can be recycled to the head of the treatment plant. In some instances, recycle may be a lower cost option than discharge to a POTW. In other cases, recycle may require additional pumping and site piping, modification or addition of chemical feed systems, installation of equalization basins, or expansion of other process components. Therefore, the costs associated with POTW discharge represent a conservative estimate in some cases (i.e., where recycle requires few process improvements) and may underestimate costs in others (i.e., where extensive improvements are necessary). However, for the purposes of approximating treatment costs, POTW discharge represents an approximate average cost per utility.

3.3.6 Bag and Cartridge Filtration

Bag and cartridge filters may be an attractive, low cost option for small systems to improve microbial removal. Filter bags and cartridges are available in a number of different materials and a wide range of pore sizes. The removal efficiency can be affected by the filter material, pore size distribution, and filter durability. Filter durability affects how a filter stands up to routine cleaning and affects replacement frequency.

It is assumed, for the purposes of this document, that bag or cartridge filters are installed downstream of existing granular media filters. Exhibit 3.9 presents a schematic of bag and cartridge filtration.

Exhibit 3.9: Plant Schematic for Bag and Cartridge Filtration



Description of Process: Addition of bag filters OR cartridge filters following granular media filtration.

Costs for different bag and cartridge filter construction materials were used to develop a range of costs. The frequency of replacement depends upon the durability of construction and water quality and can vary from a few weeks to as long as a year. This can have a significant impact on O&M costs. Filter housings are available in carbon steel for approximately half the cost of a stainless steel unit. However, for drinking water application, stainless steel is more likely to be the material of choice. As a result, only stainless steel housing was considered in development of costs.

3.3.7 Bank Filtration

Bank filtration may be advantageous for systems that currently have surface intake from a stream which is underlain by a granular media. Such a system would essentially drill a well below the water table created by the surface water source. The well would replace the existing surface water intake. Particles and other contaminants would be trapped in the pores of the river bed material or adsorb onto the river bed material. The river bed material thus acts as a pre-filtration step for the treatment process.

3.3.8 Second Stage Filtration

Second stage filtration may be a desirable option for systems with frequent fluctuations in hydraulics and turbidity. Second stage filtration, like single stage filtration, operates by depth removal. Depth filtration is when the solids are removed within the granular media. The surface area of the media provides attachment sites for the particles suspended in the influent water.

To meet EPA's proposed 0.5 log credit for *Cryptosporidium* removal, second stage filtration must have the following characteristics:

- First stage of filtration must be preceded by a coagulation step.
- Both filtration stages must treat 100 percent of plant flow.

Other design characteristics would be similar to those of primary filtration.

3.3.9 Pre-Sedimentation

Pre-sedimentation basins will be useful for systems with high influent turbidities and high particle counts. EPA is proposing to give pre-sedimentation basins with coagulant addition 0.5 log credit if the following criteria are met:

- All flow must pass through basin.
- Continuous flow through basin and coagulant addition near the influent of the pre-sedimentation basin while plant is in operation.
- Maximum day settling surface loading rate of 1.6 gpm/ft^2.
- Annual mean influent turbidity $\geq$ 10 NTU or maximum daily influent turbidity $\geq$ 100 NTU.

Systems with existing pre-sedimentation basins may monitor after the pre-sedimentation basin and prior to the main treatment plant for the purpose of determining LT2ESWTR bin assignment. Costs in Chapter 4 were determined assuming that the basin met all the above specifications.

3.3.10 Watershed Control

Each PWS's watershed control program plan is expected to be site-specific and will depend on the hydrology and land use in the watershed, the location and type of *Cryptosporidium* sources in the watershed, the population served, size of the watershed, funding, and other issues. Watershed programs may include the following:

- Monitoring for *Cryptosporidium* or indicator organisms throughout the watershed
- Fencing or otherwise restricting access to the source water
- Land acquisition
- Managing land owned by the PWS
- Working with sewer or stormwater utilities to develop plans to upgrade treatment or otherwise reduce pollutant loads
- Working with municipal governments to regulate land use and development,
- Conducting outreach to other stakeholders

To receive credit for removal of *Cryptosporidium,* a watershed control program must have the following elements:

- It must be reviewed and approved by the primacy agency.
- It must include an analysis of the system's source water vulnerability to the different sources of *Cryptosporidium* identified in the watershed. The vulnerability assessment must include a characterization of the watershed hydrology and identification of an "area of influence on source water quality" (i.e., the area to be considered in future watershed surveys). The assessment must also address sources of *Cryptosporidium*, seasonal variability, and the

relative impact of the sources of *Cryptosporidium* on the system's source water quality. It is likely that water systems will obtain much of the information to be provided in the vulnerability assessment from the source water assessment performed as part of the State source water assessment program.

- It must present an analysis of sustainable interventions and an evaluation of their relative effectiveness in reducing *Cryptosporidium* in source water. Interventions may include anything from outreach to point source elimination.

- It must address goals and define and prioritize specific actions to reduce source water *Cryptosporidium* levels. The plan must 1) explain how actions are expected to contribute to specified goals, 2) identify partners and their roles, resource requirements and commitments, and 3) include a schedule for plan implementation.

- It must include submission of an annual report performance of a watershed survey, and submission of a request for review and reapproval.

A watershed control program could include interventions such as 1) the elimination, reduction, or treatment of discharges of contaminated wastewater or storm water, 2) treatment of *Cryptosporidium* contamination at the site of generation or storage, and 3) prevention of *Cryptosporidium* migration from the source (e.g., farms or wastewater treatment plants). The feasibility and sustainability of various interventions may depend on the cooperation of other stakeholders in the watershed. Stakeholders that have some level of control over activities that could contribute to *Cryptosporidium* contamination include municipal government, private operators of wastewater treatment plants, livestock farmers, and other government and commercial organizations.

The LT2ESWTR does not specifically mandate any interventions that must be included in a watershed control program plan. The only required elements are those submitted with an application for approval of the watershed control program plan. These are the delineation of an "area of influence on water quality" and a vulnerability assessment. Watershed delineation and susceptibility analyses are already required under the Source Water Assessment Program; data gathered under this program can, in many cases, be used in preparing information required for the application.

3.3.11 Combined Filter Performance

Combined filter performance is not a single technology but many different activities that can improve existing filtration processes to enhance performance. Plants, which can operate their filters in such a way to produce 0.15 NTU or lower turbidity water 95 percent of the time, will receive a 0.5 log *Cryptosporidium* reduction credit under the LT2ESWTR. Because several of the components recommended for combine filter performance are also applicable to individual filter performance, EPA has not provided a separate analysis for individual filter performance.

The Regulatory Impact Analyses (RIAs) for the IESWTR and LT1SWTR identified 35 actions that facilities could take to lower the finished water turbidity from the SWTR standard of 0.5 NTU to the IESWTR standard of 0.3 NTU. These tasks were examined and professional judgement was applied to determine which of these actions would be helpful in further lowering turbidity from 0.3 to 0.15 NTU.

In determining processes that could further reduce filtered water turbidity, systems that would select this *Cryptosporidium* removal option were assumed to be conventional filtration or softening plants which were already operating well within the 0.3 NTU standard currently. These plants would likely have to make only minor modifications to the treatment process to meet the 0.15 NTU standard. These plants were also assumed to be operating under 0.15 NTU less than 95 percent of the time or to be capable of achieving 0.15 NTU.

Based on these assumptions, the filter improvements listed in the IESWTR were reviewed for applicability to this treatment option. The following were considered as possible actions that systems may take to implement this option:

- Installing backwash polymer feed capability
- Installing coagulant feed points
- Adding filter media
- Adding filter to waste capabilities
- Replacing the filter rate-of-flow controller
- Increasing plant staffing
- Increasing staff qualifications
- Purchasing or replacing bench-top turbidimeters
- Purchasing or replacing jar test apparatus
- Purchasing or replacing a particle counter or streaming potential meter
- Staff training

It is not assumed that each system using this technology will use all eleven tasks. Instead, it is assumed that each system would have to use at least one of these tasks and, most likely, two or more to meet the turbidity target of 0.15 NTU 95 percent of the time. To develop costs for this technology, the percentage of the plants choosing each action was determined. The percentage of systems choosing a particular task was then multiplied by the unit cost for that task to arrive at an average unit cost for all plants. Further details of the percentages and costs are given in Chapter 4 of this document.

The assumptions for each filter improvement action is discussed below.

Installing Backwash Water Polymer/Coagulant Feed Capability

Adding coagulant to backwash water aids in filter ripening and helps to reduce post backwash turbidity spikes. Systems choosing backwash polymer to lower turbidity were assumed to not have this capability currently. Costs were for a dry polymer feed system that can be loaded with a seven-day polymer supply.

Installing Additional Coagulant Feed Points

Installing additional coagulant feed points can help to improve coagulation of particles and their removal by settling. Capital costs were based on feeding an additional 5 parts per million (ppm) dose of primary coagulant. The primary coagulant is assumed to be ferric chloride, ferric sulfate, or alum. Thirty days of bulk storage are assumed for ferric chloride or ferric sulfate (equivalent to approximately fifteen days of storage for alum).

Adding Filter Media

Often during routine operation of filters, media is lost either through attrition and passage out the underdrains or through the backwash. If too much media is lost, filter performance will suffer. Therefore, adding additional media on a regular basis can often improve turbidity in the effluent.

Adding Filter to Waste Capabilities

Filter turbidity often spikes immediately after backwashing. Installing filter to waste capabilities allows water to be wasted after a backwash instead of sending the high turbidity water to the CFE. Costs included piping, valves, and fittings.

Installing or Replacing Filter Rate-of-Flow Controllers

Flow surges can cause spikes in filter turbidity. Installing a rate-of-flow controller or replacing a faulty one can improve performance. Costs were for replacing a unit and were based on assumed 24-hour operation.

Increasing Plant Staffing

Systems which only have part time staff or are understaffed may have trouble controlling filter conditions closely enough to meet the 0.15 NTU turbidity target. Hiring additional staff or extending current staff's hours may help systems to more finely control filter operations.

Increasing Staff Qualifications

Better trained staff may be able to recognize conditions which lead to filter turbidity breakthrough and to prevent it. Costs for this option were based on the cost of sending an operator to a training class. Costs include class registration fees to attend an operator certification class.

Purchasing or Replacing Bench-Top Turbidimeters

Typically, every plant has at least one bench-top or on-line turbidimeter. However, some of these units may be obsolete to meet the monitoring requirements of the LT2ESWTR for combined and individual filter effluents. Bench-top turbidimeters do not appear to be suited to fulfill these monitoring tasks. Therefore the purchase of up-to-date on-line turbidimeters with electronic data acquisition interface was costed.

Purchasing or Replacing Jar Testing Apparatus

A jar testing apparatus is necessary for optimizing coagulant and polymer dosing. Old units will need to be replaced, and new units purchased if a facility does not have one. Systems serving greater than 100,000 people were assumed to buy two units, and those serving more than 1,000,000 people were assumed to purchase three units.

Purchasing or Replacing a Particle Counter

Instruments such as particle counters, zetameters, and streaming current monitors can be used to optimize filter processes. The cost for this option assumes the purchase of one of these instruments for use in troubleshooting and optimizing individual filters. The cost of a particle monitor was used as a surrogate for any one of these three instruments.

Staff Training

Better trained staff will be better able to spot and fix problems in filter performance. The costs for this option were based on hiring a consultant to provide on-the-job training for 10 to 140 hours.

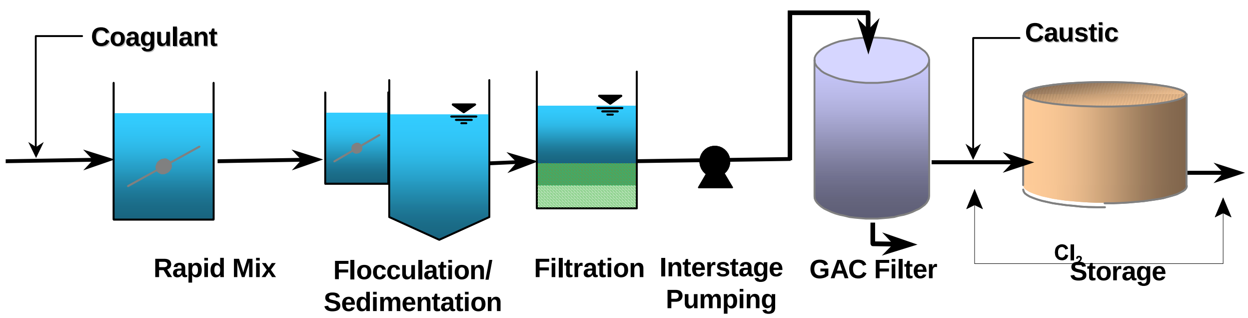
3.4 DBP Precursor Removal Technologies

A strategy for reducing DBP formation is removal of DBP precursors (e.g., natural organic matter). The technologies discussed in this section may not be applicable for all systems. Each technology section presents the approach and assumptions used to develop the costs presented in Chapter 4.

3.4.1 Granular Activated Carbon Adsorption

GAC filters reduce DBP formation by removing organic carbon. For the purposes of this document, installation was assumed after the existing filters. A schematic of the GAC process is shown in Exhibit 3.10.

Exhibit 3.10: Plant Schematic for GAC Filtration



Description of Process: Install GAC filter following granular media filter.

The application of GAC adsorption involves the following process design considerations:

- Empty bed contact time, volume of empty contactor divided by flow rate
- Reactivation interval or frequency, which affects the GAC usage rate (pounds of GAC used per gallon of water treated)
- Pre-treatment
- Contactor configuration (e.g., downflow versus upflow, pressure versus gravity, single-stage versus multi-stage or parallel, filter adsorber versus post-filter GAC contactor)
- Method of GAC reactivation (e.g., on-site versus off-site)
- Interstage pumping

- Performance monitoring (for TOC)

EBCTs of ten and twenty minutes were chosen for the cost evaluation based upon an analysis of EBCTs and NOM removal. This analysis indicated that EBCTs lower than 10 minutes do not remove sufficient NOM to warrant installation as a control for DBP precursors. Similarly, EBCTs in excess of 20 minutes do not provide significant improvements in NOM removal. Accordingly, 10 minutes and 20 minutes were selected to represent the upper and lower bounds of appropriate EBCTs for NOM removal.

Reactivation/replacement frequencies vary based on water quality and the number of contactors in parallel. For the purposes of this document frequencies of 90, 240, and 360 days were evaluated. Ninety days was selected as a minimum value based upon best professional judgement that reactivating at intervals lower than 90 days is impractical from an operational standpoint. Three hundred and sixty days was selected as the maximum reactivation frequency since the cost of GAC technology increases insignificantly for reactivation frequencies of greater than 1 year. High operating costs were captured by considering 90-day regeneration frequency for the GAC facility with EBCT of 20 minutes. Low operating costs were captured by considering 360-day regeneration frequency for the GAC facility with EBCT of 10 minutes. An intermediate operating cost was also captured by considering 240-day regeneration frequency for the GAC facility with EBCT of 20 minutes.

Based upon best professional judgement, it was decided that small systems are unlikely to regenerate on-site, since it requires more substantial capital investment and operator attention. As a result, small systems (less than 1 mgd) were assumed to operate on a replacement basis (i.e., when the carbon is spent, it is discarded and replaced with new carbon). While regional regeneration facilities do exist, many plants are not located near one of these facilities, so replacement is assumed. Large systems (greater than 1 mgd) were assumed to regenerate on-site using multiple hearth furnaces.

Very small system GAC installations (< 0.1 mgd) include: pressure GAC contactors, virgin GAC, pressure booster pumps, pipes and valves, and instrumentation and controls. O&M is a function of regeneration frequency.

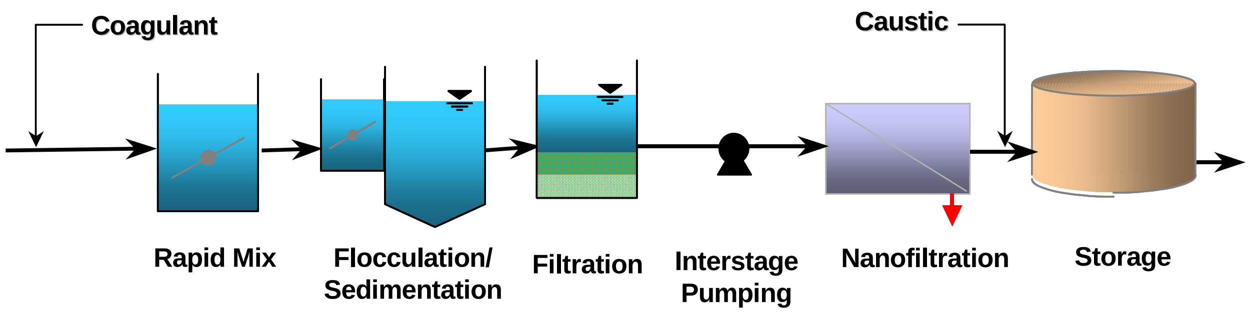
Small system GAC installations (>0.1 mgd and <1 mgd) include: pressure vessels designed for working pressure of 50 psi; factory assembled units mounted on steel skid 12 feet high and varying diameter depending on the EBCT; access for filling and removing carbon; pressure booster pump, valves, piping and pressure gauges, initial charge of activated carbon, supply and backwash pump, and electrical control panels.

Large system GAC installations (> 10 mgd) include: concrete gravity contactors 8.3 feet high; loading rate 5 gpm/ft^2; troughs and pipes for carbon removal as a slurry; other pipe gallery; pressure booster pump; flow measurement and instrumentation; master operations control panel; building; initial virgin carbon; single multiple-hearth furnace for carbon regeneration-loading rate of 50 pounds per square foot per day; and two TOC analyzers.

3.4.2 Nanofiltration

Nanofilters remove NOM, thereby reducing DBP formation. NF is an advanced treatment process which typically requires higher levels of pre- and post-treatment than traditional water treatment processes. For this cost analysis, nanofilters were assumed to be located downstream of existing filters. A schematic of the NF technology is shown in Exhibit 3.12.

Exhibit 3.11: Plant Schematic for Nanofiltration



Description of Process: Addition of nanofiltration following granular media filtration, OR replacement of granular media filters with nanofiltration

Typically, NF requires both physical and chemical pre-treatment. Pre-treatment is usually required for NF treatment of all surface waters and some ground waters. Physical pre-treatment often includes a component to remove particles, typically multi-media filtration, microfiltration, or cartridge filtration. Chemical pre-treatment often includes acid or anti-scalant addition to reduce the fouling potential of the feed water. Particle removal and softening with chemical addition are also used as pre-treatments. Attention should be paid to the compatibility of coagulant and the membrane for such situations.

Post-treatment may also be required, depending on the characteristics of the product water. NF product waters usually have low pH and total dissolved solids levels. This creates the potential for an unstable and corrosive finished water. Chemical post-treatment may be required to create a more stable and non-corrosive water. Commonly used post-treatments include addition of caustic (to raise the pH), soda ash (to raise pH and alkalinity), and poly/ortho phosphates for stabilizing the water. Blending a portion of raw water with finished water can also be used to stabilize the finished water.

The design criteria in this document assume that the NF system is an "add-on" process to an existing treatment plant which is generating a water that can be fed directly to the NF process without further pre-treatment. It is assumed that 100 percent of the design flow is passing through the NF membranes and that no raw water blending is done. Recoveries of 85 percent and operating pressures of 90-110 psi were assumed. Costs were developed assuming a design feed water temperature of 10 degrees Celsius. Like MF, the cost of a NF system can vary significantly with temperature because the membrane productivity, or flux (gallons/ft^2-day), is strongly dependent on feed water temperature. Empirical relations are available to estimate the flux at a design temperature using the flux at a reference temperature (i.e., 10 degrees Celsius). These relations are available both in published literature and with membrane manufacturers.

NF system cost quotations were obtained from manufacturers for all NF equipment items, including membrane elements, online instruments, booster pumps, clean-in-place systems and acid/anti-scalant addition systems. Unlike other treatment processes, membrane systems are typically supplied by the equipment vendor as package, skid-mounted units; therefore, smaller multipliers are assumed. Capital cost multipliers of 1.67 and 2.0 were used respectively for small and large systems to estimate total capital cost. It was assumed that a unit NF skid can produce up to 2 mgd of product water. NF systems smaller than 2 mgd were assumed to have fewer membrane modules and membranes.

The O&M costs include chemical usage, membrane replacement (assumed membrane life of five years), process/building power, additional labor hours, and process monitoring. Efforts were made to capture the drop in prices of the membranes, modules, and associated equipment over the past few years due to increasing use of the NF systems. Where necessary, the costs for retrofitting and operating an NF plant were verified with data from various surveys, including Florida's softening plants (Bergman 1996) and the Bureau of Reclamations (BOR 1997) surveys. The cost curves presented in Chapter 4 were verified with real-plant data for different flow levels.

NF design criteria developed here include handling of the brine stream generated by the NF process. This handling assumes direct discharge of the brine to a receiving body, ocean outfall, sanitary sewer, storm drain, or a salinity interceptor. The costs presented in Chapter 4 pertain only to plants located in areas where brine can readily be discharged to either a receiving water body, a sewer/storm drain, or a salinity interceptor. Plants located in areas where this is not an option will have significantly higher waste stream treatment and handling costs.

4. Technology Costs

4.1 Introduction

This chapter presents the estimated capital and O&M costs for the alternative disinfection strategies and DBP precursor removal technologies identified as potential compliance options for the LT2ESWTR and the Stage 2 DBPR. Previous technology cost estimates were primarily developed using three models: the *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie 1993), hereafter referred to as the VSS model; the Water Model (Culp/Wesner/Culp 1984); and the Water and Wastewater (W/W) Cost Model (Culp/Wesner/Culp 2000). The estimates provided in this document, however, were developed largely using information from manufacturers and other sources that are believed to be more accurate and more reflective of current practices than the models. For example, the use of manufacturer information is believed to be more appropriate for technologies where costs of process components have decreased since the models were developed (e.g., microfiltration/ultrafiltration, nanofiltration, chloramines, and chlorine dioxide). Manufacturer information was also necessary for processes that are not included in the models (i.e., UV disinfection and bag and cartridge filters).

Exhibit 4.1 shows technologies for which costs were developed and summarizes the methodology used to develop costs (i.e. cost model, cost build-up, lump sum estimate, or a combination). Sections 4.2 and 4.3 describe these methodologies and explain the assumptions used for all cost estimates. Subsequent sections (as indicated in Exhibit 4.1) describe the detailed assumptions used for each technology and present cost estimates in tabular format.

Exhibit 4.1: Technologies Costed and Methodology Used

Technology (Section in which technology is costed)	Costing Methodology Used
Alternative Disinfection Strategies	
Chloramination (section 4.4.1)	W/W model for P&V[1], I&C[2], cost build-up for all other process and O&M costs
Chlorine dioxide (section 4.4.2)	W/W model for all costs except CLO_2 generation equipment leasing costs
UV disinfection (section 4.4.3)	Cost build-up approach
Ozone (section 4.4.4)	Cost build-up approach
Microfiltration and ultrafiltration (section 4.4.5)	Water and W/W cost model for some O&M parameters, cost build-up for all other costs
Bag and cartridge filtration (section 4.4.6)	Cost build-up approach
Bank filtration (section 4.4.7)	Lump sum estimate using best professional judgement
Second stage filtration (section 4.4.8)	Lump sum estimate using best professional judgement
Pre-sedimentation (section 4.4.9)	Lump sum estimate using best professional judgement
Watershed control (section 4.4.10)	Lump sum estimate using best professional judgement
Combined filter performance (section 4.4.11)	Cost build-up approach
DBP Precursor Removal Technologies	
GAC adsorption (section 4.5.1)	Water model costs for systems > 0.1 mgd, VSS model for systems < 0.1 mgd, TOC analyzers by vendor quotes.
Nanofiltration (section 4.5.2)	Cost build-up approach

[1] P&V = Pipes and valves.
[2] I&C = Instrumentation and controls.

Notes:
VSS is the *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie 1993)
Water Model (Culp/Wesner/Culp 1984)
W/W Model (Culp/Wesner/Culp 2000)

4.2 Approach for Cost Estimates

Following the reauthorization of the Safe Drinking Water Act in 1996, EPA critically evaluated its tools for estimating the costs and benefits of drinking water regulations. As part of this evaluation, EPA solicited input from national drinking water experts at the Denver Technology Workshop, which was sponsored by EPA and held November 6 and 7, 1997, to improve the quality of its compliance cost estimating process for various drinking water treatment technologies. The Technology Design Panel (TDP), formed at the workshop for this purpose, recommended several modifications to existing cost models to improve the accuracy of EPA's compliance cost estimates (USEPA 1998a).

In 2001, the NDWAC convened the Arsenic Cost Working Group to review the cost methodologies, assumptions, and information underlying the system-size cost estimates presented in the December 2000 technologies and costs document, as well as the aggregated national cost estimate, for the Arsenic Rule. As part of the review, NDWAC made several recommendations that have since been incorporated into the cost approach applied for the Arsenic Rule. This document incorporates both the TDP and NDWAC recommendations, as appropriate. For each technology, costs were developed for a range of design criteria corresponding to different implementation scenarios and treatment goals and for design flows generally ranging from 0.007 to 520 mgd.

4.2.1 Cost Components and Capital Cost Multipliers

Capital Costs

For the purposes of this document, capital costs are divided into three main components:

- **Process costs**, which include manufactured equipment, concrete, steel, E&I (sometimes referred to as instrumentation and controls [I&C]), and pipes and valves (P&V).

- **Construction and engineering costs**. Construction costs include installation, sitework and excavation, subsurface considerations, standby power, contingencies, and interest during construction. Engineering costs include general contractor overhead and profit, engineering fees, and legal, fiscal, and administrative fees.

- **Indirect costs**, which include housing, permitting, land, operator training, piloting, and public education (these are not needed for all technology types).

The sum of process and construction and engineering costs is often referred to as "direct" capital costs. The TDP recommended that total capital cost estimates be based on process costs, which are then multiplied by a specific cost factor to estimate direct capital costs. The NDWAC recommendations were similar; however, the factors recommended by the two groups varied to some degree. This document primarily utilizes cost factors recommended by NDWAC, slightly modified as follows:

- A cost factor of 2.5 is used for systems less than 1.0 mgd

- A cost factor of 2.0 is applied for systems greater than 1.0 mgd

The cost factor for systems greater than 1.0 mgd is different from the 1.8 value recommended by NDWAC in order to account for installation. For some small package technologies (e.g., GAC or MF/UF), a revised multiplier of 1.67 or 1.2 is used instead of 2.5. The basis for the revised multipliers is that the 2.5 multiplier is applicable to relatively inexpensive technologies that require proportionally greater engineering and design effort than small package systems. In addition, many of the package technologies considered in this document are significantly more expensive than conventional technologies, yet installation is typically much less complicated than traditional non-packaged technologies. These alternate cost multipliers were developed using vendor quotes and experience with similar systems. Exhibit 4.2 summarizes the components of each of the capital cost multipliers used in this document.

Exhibit 4.2: Summary of Capital Cost Multiplier Components

Component	1.20	1.67	1.76	2.0	2.5[1]
Site work	--	10%	15%	15%	25%
Contractor OH&P*	--	10%	12%	10%	20%
Contingencies	--	15%	10%	20%	30%
Engineering and design	--	10%	20%	15%	25%
Mobilization and bonding	--	5%	--	3%	5%
Legal and administrative	--	–	11%	10%	15%
Interest during construction	--	7%	--	7%	10%
Installation	20%	10%	--	20%	20%
Permitting	--	--	3%	--	--
Standby Power	--	--	5%	--	--

*OH&P = overhead and profit

Source: 2.5 factor based on NDWAC recommendations. Other factors adjusted based on best professional judgement.

Note: A capital cost factor of 1.36 is used for large UV systems for surface water. This value is based on empirical data and cannot be broken out as in the above table.

Indirect capital costs are added to direct capital costs to produce total capital costs. The following equation indicates how total capital costs are calculated.

Total Capital Costs = Direct Costs + Indirect Costs

Where:

Direct Costs = Process Costs * Capital Cost Multiplier

Indirect Costs = Additional items developed by the cost build-up approach that are not multiplied by the capital cost multiplier, such as land, housing, operator training, and piloting.

O&M Costs

O&M costs represent the annual costs required to operate the technology. O&M costs include items such as labor, chemicals, power, and replacement parts. Each item is added (without multipliers) to produce total O&M costs.

4.2.2 Cost Indices and Unit Cost Inputs

To compare the estimated national costs to monetized benefits (for EPA proposed drinking water rules), it is necessary to use a consistent time value of money for all cost estimates. All capital and O&M costs are presented in year 2003 dollars. In order to adjust all costs to the same year, cost indices are used. Several different indices are used in the cost models and are listed in Exhibit 4.3. For all costs not developed using the models, the Engineering News Record (ENR) Building Cost Index (BCI) is used (BCI for year 2000 is also shown in Exhibit 4.3). The BCI is developed to reflect the cost of building across the country. It represents costs of labor, steel, concrete, and wood averaged across 20 different cities. To use it to adjust costs, the cost is multiplied by the ratio of the index in the year desired to the year in which the cost was developed. For example if a cost was developed using year 2001 vendor quotes it would be multiplied by the BCI index for year 2003 (3,693) and divided by the index for year 2001 (3,574). Thus if the cost were $2,500 dollars in year 2001 it would be $2,500*(3,693/3,574) = $2,583.24 in year 2003 dollars.

Exhibit 4.3: Costs Indices Used in the Water and W/W Cost Models

Description	Index Reference	Numerical Value[1]
Concrete Ingredients and Related Products	BLS 132	474.6
Electrical Machinery and Products	BLS 117	351.1
General Purpose Machinery and Equipment	BLS 114	455.8
Metals and Metal Products (Steel)	BLS 1017	375.2
Miscellaneous General Purpose Equipment (Pipes &Valves)	BLS 1149	504.1
Chemicals and Allied Products	BLS 06	457.8
Producer Price Index (PPI) Finished Goods Index	BLS 3000	392.0
ENR Building Cost Index[2]		3539

[1] BLS numerical values were re-based to 1967 base year.
[2] ENR BCI value for other years are available at www.enr.com

Energy and labor are required to operate most technologies. Exhibit 4.4 displays costs used for energy and labor in this document. Chemicals are also required for some technologies. Exhibit 4.5 displays costs for chemicals required to operate the technologies costed in this document.

Exhibit 4.4: Unit and General Cost Assumptions

Unit	Cost*
Electricity[1,2]	$0.076/kWh
Diesel Fuel[1]	$1.48/gallon
Natural Gas[1]	$0.009/scf
Building Energy Use	102.6 kWh/ft^2/yr

Note - variable labor rates are used, based on the system size
[1] Energy Information Administration, 2003. EPA is aware that DOE has updated its 2003 average national cost of electricity per kilowatt hour per year from $0.076kWhr/yr to $0.074kWhr/yr. However, EPA continues to use the $0.076kWhr/yr value in order to maintain consistency with Stage 2 DBPR and LT2ESWTR analyses.
[2] Includes public street and highway lighting, other sales to public authorities, sales to railroads and railways, sales for irrigation, and interdepartmental sales.
* Where kWh = kilowatt hour; scf = standard cubic feet; hr = hour; ft = feet; and yr = year.

Exhibit 4.5: Chemical Costs

Chemical	Cost	Units
Alum, Dry Stock	$300	per ton
Alum, Liquid Stock	$230	per ton
Carbon Dioxide, Liquid	$340	per ton
Chlorine, 1 ton cylinder	$280	per ton
Chlorine, 150-pound cylinder	$600	per ton
Chlorine, bulk	$280	per ton
Ferric Chloride	$400	per ton
Hexametaphosphate	$1300	per ton
Lime, Hydrated	$110	per ton
Lime, Quick Lime	$100	per ton
Phosphoric Acid	$650	per ton
Polymer	$1.00	per lb
Potassium Permanganate	$2900	per ton
Sodium Hydroxide, 50%	$350	per ton
Sodium Hypochlorite, 12%	$1100	per ton
Sodium Chlorite	$325	per ton
Sodium Chloride	$100	per ton
Sulfuric Acid	$100	per ton
Surfactant, 5%	$0.15	per gal

Source: Vendor quotes, 2000
Note: Ammonia costs vary depending on plant size and are not shown. See Section 4.4.1.2 for details

4.2.3 Cost Build-up Approach

To estimate capital costs for those technologies where cost model estimates were found to be inaccurate based on professional engineering judgement or when modeled costs were not available, a cost build-up approach was used. Process components were identified and sized using engineering design principles and were costed using estimates from manufacturers, vendors, and field engineers. Several vendor quotes were used when possible, and regressions were developed to identify the best fit curves from these quotes in many cases when they reflect different design flows. In some cases (e.g., NF) manufacturer's estimates were checked against real-world installations to verify cost reasonableness. Vendor quotes were discounted from the year in which they were obtained back to year 2003 dollars, using the methodology described in section 4.2.2.

For other process cost items (e.g., E&I, P&V) engineering principles were used in conjunction with engineering cost estimating guides such as RS Means. Such guides contain nationwide averages for costs of common items such as housing, pumps, and tanks. For some items, vendor quotes or cost estimating guides were not useful in determining costs. In these cases professional engineering judgement was used. Costs for which best professional judgement was used are generally a small portion of the total overall cost of a technology.

4.2.4 Lump Sum Estimates

For some relatively new or untraditional technologies a large data set of cost data is not available. Using a cost build-up approach for these technologies was not possible. A single lump sum figure representing all process costs was estimated for these technologies which include, bank filtration, secondary filtration, presedimentation, and watershed control.

4.2.5 Cost Modeling Approach

When one or more of the cost models was used to estimate costs, process costs were determined based upon the breakdown of capital costs provided in the original model documentation. Process costs were then multiplied by the appropriate cost multipliers (as discussed in section 4.2.1) to estimate total direct costs. Capital cost breakdowns for all technologies costed using the VSS model are presented in Appendix A. The reports *Estimation of Small System Water Treatment Costs* (Culp/Wesner/ Culp 1984) and *Estimating Treatment Costs, Volume 2: Cost Curves Applicable to 1 to 200 mgd Treatment Plants* (Culp/Wesner/Culp 1979) were used to develop capital cost breakdown summaries for the Water and W/W Cost models. These summaries are presented in Appendix B and C, respectively.

Sections 4.2.5.1, 4.2.5.2, and 4.2.5.3 briefly demonstrate how the capital cost breakdowns are applied and how total direct capital cost estimates are generated.

4.2.5.1 VSS Model

The VSS model presents capital and O&M costs as functions of design and average flow, respectively. Accordingly, the capital cost equation for a package GAC plant is:

$$CAP = 1.7[EBCT]^{0.54}\ [DES]^{0.54}$$

Where:		
	CAP	= Total Capital Cost, $1,000s
	EBCT	= Empty Bed Contact Time, minutes
	DES	= Design Treated Flow, kgpd (thousand gallons per day)

Thus, for a 0.037 mgd (37 kgpd) plant with an EBCT of 10 minutes, the capital cost is:

$$CAP = 1.7[10]^{0.54}\ [37]^{0.54}$$
$$CAP = 41.4 \text{ or } \$41,400$$

The VSS model equations produce estimates in year 1993 dollars. To escalate to year 2003 dollars, the equation-generated capital cost is multiplied by the ratio of the ENR BCI for year 2003 to the 1993 index value.

$$\$41,400 \times (3693/3009) = \$50,800$$

The escalated capital cost for a 0.037 mgd package GAC plant is $50,800.

Using the capital cost breakdown in Appendix A, the total process cost is:

$$\$50,800 \times 0.5478 = \$27,800$$

The total direct capital cost can then be calculated using the capital cost multiplier presented in Exhibit 4.2 (1.67 in this case).

$$\$27,800 \times 1.67 = \$46,400$$

4.2.5.2 Water Model

The Water model output for a 0.27 mgd (270,000 gpd) GAC plant with an EBCT of 10 minutes is $267,000 (escalated to year 2003 dollars). To make costs equivalent to the cost buildup approach, the following method was used. The costs for process equipment, pipes and valves and electrical are broken out using the capital cost breakdown shown in Appendix B:

$267,000 × (0.3331 + 0.052)	= $102,800	*(equipment)*
$267,000 × (0.0324)	= $8,650	*(pipes and valves)*
$267,000 × (0.1034)	= $27,600	*(electrical)*

The total process cost is $139,100.

This approach must be applied to each unit process (e.g., interstage pumping) separately, then totaled for the entire treatment process to estimate the total process cost. Pipes and valves and electrical equipment from various processes are totaled and included as a single line item in estimates presented in this document.

The total direct capital cost can then be calculated by multiplying the process cost by the appropriate capital cost factor (1.67 in this case).

$139,100 × 1.67 = $232,300

4.2.5.3 W/W Cost Model

The W/W Cost model output for a 10 mgd gravity carbon contactor (EBCT = 10 minutes) is $2,293,600 (year 2003 dollars). Using the capital cost breakdown shown in Appendix C, the process costs associated with process equipment, pipes and valves, and electrical are:

$2,293,600 × (0.1463 + 0.0595 + 0.0455)	= $576,400	*(equipment)*
$2,293,600 × (0.2353)	= $539,700	*(pipes and valves)*
$2,293,600 × (0.0612)	= $140,400	*(electrical)*

The total process cost is $1,256,500.

This approach must be applied to each unit process (e.g., interstage pumping) separately, then totaled for the entire treatment process to estimate the total process cost. Pipes and valves and electrical equipment from various processes are totaled and included as a single line item in estimates presented in this document.

The total direct capital cost is then calculated by multiplying the process cost by the capital cost factor (2.0 in this case).

$1,256,500 × 2.0 = $2,513,000.

4.2.6 Indirect Capital Costs

At the recommendation of the TDP and NDWAC cost working groups, total capital cost estimates include not only direct costs (process, construction, and engineering), but also the costs associated with permitting, piloting, land, housing, operator training, and public education, when applicable.

Permitting

Permitting costs can be highly variable. Some permits can require extensive studies, (e.g., Environmental Assessments (EAs) or Environmental Impact Statements (EIs)). Others may require extensive legal assistance. Costs also are affected by whether a utility has the in-house expertise to develop and submit the necessary permits or if additional consulting is required. Permitting cost estimates in this chapter are assumed to be three percent of the total process cost. The minimum cost assigned for permitting is $2,500, and costs do not exceed $500,000 for any system for which permitting costs are included. Permitting costs are assumed to be included as a part of the engineering fees (included in the capital cost factor) for those processes requiring minor process modifications (e.g., chloramination).

Piloting

NDWAC recommended that the costs of pilot tests be included for all technologies. For the purposes of this document, it is assumed that piloting would not be necessary for technologies requiring relatively minor process modifications (e.g., chloramination). For these technologies, in-house DBP formation potential tests would be sufficient. Piloting costs are also not included for technologies where manufacturer studies (e.g., the National Science Foundation (NSF) Environmental Technology Verification reports) may satisfy regulatory agency technology verification requirements (e.g., bag and cartridge filters). All other technologies include the costs associated with bench- or pilot-scale tests. For systems less than 1 mgd, bench-scale tests are assumed. Pilot-scale tests are assumed for all systems larger than 1 mgd. Costs are based on best professional judgement and experience with similar systems. Exhibit 4.6 summarizes the piloting cost assumptions used in this document.

Exhibit 4.6: Summary of Piloting Cost Assumptions

Technology	Design Flow (mgd)		
	<0.1	0.1 to <1	≥ 1
Chlorine Dioxide	$5,000	$10,000*	$50,000
Ozone	$5,000	$10,000	$65,000
Microfiltration and Ultrafiltration	$1,000	$10,000	$60,000
Granular Activated Carbon	$5,000	$10,000	$50,000
Nanofiltration	$1,000	$10,000	$60,000

Note: Piloting costs for chloramination, and bag and cartridge filtration were assumed to be $0 for all design flows evaluated. Piloting costs for UV are broken out differently from the presentation in Exhibit 4.6, and therefore are presented in section 4.4.3.1.
* piloting cost of $10,000 applies to design flows of 0.1 - 1 mgd.

Land

The majority of the technologies discussed in this document will likely fit in existing plant footprints, and additional land will not be required. However, several of the processes (i.e., ozone, MF/UF, GAC, and NF) will not likely fit in existing footprints and may require utilities to purchase additional land.

Exhibit 4.7 summarizes the land cost assumptions used in this document. The NDWAC cost working group recommended that land costs be included at two to five percent of total capital costs. This recommendation is based on new treatment plant construction and is determined to be excessive for the purposes of this document. As a result, land costs are included at percentages ranging from 0.5 to 2 percent, depending on the technology. The percentage varies from technology to technology because of the relative capital cost of each technology. For example, the total capital cost for a 210 mgd GAC plant with an EBCT 10 mins is approximately $38 million, whereas the capital cost for a 210 mgd MF/UF plant is $153 million. Using identical percentages, the land costs for the MF/UF plant would be significantly higher than those for a GAC plant; however, the footprint associated with a GAC facility is larger than that of a MF/UF system. Land cost percentages were adjusted to account for this discrepancy. Percentages were also adjusted based on the estimated footprint of the technology. That is, if the land cost per acre were considered unreasonable, the percentage was adjusted accordingly. For example, assuming two percent of the capital cost, the land cost per acre for a 520 mgd MF/UF system is nearly $500,000, which is unreasonable based on best professional judgment, and the land cost percentage is, therefore, adjusted.

Exhibit 4.7: Summary of Land Cost Assumptions (as a percentage of Capital Cost)

Technology	System Size (mgd)		
	< 1	1 - 10	> 10
Ozone	0.8%	1%	1%
Microfiltration and Ultrafiltration	1%	1%	0.5%
Granular Activated Carbon	2%	2%	2%
Nanofiltration	2%	1%	0.5%

Source: Best professional judgement

Housing

In many instances, additional building space will be constructed at the treatment plant to house a new technology. For the purposes of this document, all housing costs were calculated by multiplying the estimated technology footprint size (ft^2) by a unit housing cost ($\$/ft^2$). The footprint size for each technology was derived from the cost models or was based on best professional judgement and experience with similar systems. The unit housing cost is taken from the year 2000 RS Means building construction data, for the construction of a "factory" type building. The median value of $\$48.95/ft^2$ is assumed for all technologies[1], which includes site work, plumbing, HVAC, and electrical.

Operator Training

A system that adds a significantly different technology will have to train its operators in the use of the new technology. Costs for this largely represent the operator's time, as most manufacturers will provide free training with their products. The amount of time will vary depending on the complexity of the technology installed. Some technologies (e.g., chloramines) may require no additional training because they are very similar to existing systems. Large systems also often have regularly scheduled training sessions and will be able to include training for new technologies into these sessions. For this reason, no additional cost is included for large systems for some technologies that work on similar principles to existing technologies. Costs assumed in this document for operator training range from $0 to $25,000.

Public Education

If adding a technology will significantly affect the properties of the water delivered to customers, systems will need to spend money to notify their customers of the changes. In the case of chloramines, the chloramine residual can have an adverse effect on dialysis patients and owners of aquariums. Therefore costs are included to notify the public of the change. Costs include preparing material such as bill inserts and employee time to either call or visit specifically affected customers.

[1]For surface water UV systems a value of $150 per square foot is used. The value was based directly on data for UV installations and represents some of the special requirements of UV installations.

4.3 Estimation of Annualized Costs

The models and other cost estimation methods are used to develop total capital costs and annual O&M costs. Capital costs can be annualized and converted into cents per thousand gallons (¢/kgal) treated using the following formula:

$$\text{Annualized Capital Cost} = \frac{\text{Capital Cost (\$)} \times \text{Amortization Factor} \times 100\ ¢/\$}{\text{Average Daily Flow (mgd)} \times \text{(1000 kgal/mgal)} \times \text{365 days/year}}$$

Where: kgal = thousand gallons
mgal = million gallons

Factors that correspond to discount rates of 3, and 7, and 10 percent over 20 years are shown in Exhibit 4.8. Alternative capital recovery factors can be calculated using the formula presented below.

$$\text{Amortization Factor} = \frac{i(1 + i)^N}{(1 + i)^N - 1}$$

Where: i = discount rate
N = number of years

Exhibit 4.8: Determining an Amortization Factor based on Discount Rates over 20 years

Discount Rate (%)	Period (years)	Amortization Factor
A	B	$C = \frac{a(1+a)^b}{(1+a)^b-1}$
3	20	0.0672157
7	20	0.0943929
10	20	0.1174596

Annual O&M costs include the costs for materials, chemicals, power, and labor. The annual O&M costs can be converted into cents per thousand gallons treated using the following formula:

$$\text{O\&M Cost (¢/kgal)} = \frac{\text{Annual O\&M (\$)} * \text{100 (¢/\$)}}{\text{Average Daily Flow (mgd)}*\text{1000 kgal/mgal}*\text{365 days/year}}$$

Total annualized costs for the treatment process can then be determined by:

Total annualized cost (¢/kgal) = Annualized Capital Costs (¢/kgal) + O&M (¢/kgal)

4.4 Alternative Disinfection Strategies

This section presents capital and O&M cost estimates for a number of alternative disinfection strategies capable of removing/inactivating *Cryptosporidium* and/or reducing DBP formation. Each technology section presents costs in tabular format, and provides a detailed discussion of how costs were developed for that technology.

4.4.1 Chloramination

As explained in Chapter 3, the 10^{th} and 90^{th} percentile finished water chlorine residuals from the ICR database (0.6 and 2.2 mg/L, respectively) were used to establish two ammonia dosages of 0.15 and 0.55 mg/l NH_3-N based on a 4:1 chlorine-to-ammonia ratio. The base plant is assumed to provide the necessary chlorine.

Aqueous ammonia is assumed for small systems (<1 mgd), and anhydrous ammonia is assumed for large systems (>1 mgd). Capital and O & M costs are based primarily on discussion with vendors and typical industry equipment and chemical unit costs. Some capital process costs (P&V; E&I, and controls) are generated from the W/W model.

4.4.1.1 Summary of Chloramine Capital Cost Assumptions

Process Costs

Capital cost estimates for conversion to chloramines are presented in Exhibits 4.9 and 4.10 for ammonia doses of 0.15 and 0.55 mg/L, respectively. Estimates were based on June 2001 dollars and were adjusted to 2003 dollars using the ENR BCI. Assumptions for ammonia systems are as follows:

- Chemical metering pumps for aqueous ammonia: tube pumps for very small systems (< 0.1 mgd), diaphragm pumps for small systems (0.1 - 1 mgd). Redundant pumps were assumed.

- Vacuum feed systems for anhydrous ammonia: the system included redundant vacuum regulators, a flow-proportioning dosing system, a water softening system and an ejector. Costs for feed systems with different feed capacities are used (0 to 100 lb/day, and 0 to 1,000 b/day), as determined by the system size and dose. A vaporizer is also included for large systems using more than 1,000 lb/day of ammonia.

- Storage tanks for aqueous ammonia: due to the small storage volumes, tank costs were not included. Aqueous ammonia are assumed to be pumped directly from the portable drum container provided by the chemical supplier. A minimum 30-day storage capacity was assumed.

- Storage tanks for anhydrous ammonia: based on discussions with anhydrous ammonia suppliers, it is common for water treatment plants to lease the anhydrous ammonia pressure vessels from the chemical supplier. Hence, capital costs are not included for storage tanks (they are accounted for as a tank lease cost in the O&M costs). A minimum 30-day storage capacity was assumed.

- Emergency scrubber system: the cost of an emergency scrubber system was included for large systems (>1 mgd) storing more than 10,000 pounds of anhydrous ammonia, as would be required by a Process Safety Management Plan.

- Analyzers: On-line total chlorine analyzer for small systems and on-line chloramine analyzer for large systems. Hand-held analyzer for small systems for ammonia and nitrate analysis of distribution system samples. Desktop analyzer for large systems for ammonia and nitrate analysis of distribution system samples.

Additional process costs were based on percentage of equipment costs.

- P&V costs were estimated to represent 18 percent of the sum of the previous process costs, based on capital cost breakdowns used in the W/W cost model.

- E&I and control costs were estimated at 20 percent of the sum of all previous costs (including pipes and valves), based on capital cost breakdowns used in the W/W cost model.

Capital Cost Multipliers

Total direct capital costs were obtained by applying capital cost multipliers to the sum of all process costs. For large systems, a factor of 2.0 was used. For small systems, NDWAC recommended a factor of 2.5. This factor is applicable to conventional treatment processes that involve significant engineering, design and installation efforts. It was for this document the ammonia storage and feed systems for very small and small systems were assumed to be relatively less complex, require minimal design effort, and comparably easier to install. As a result, the 2.5 multiplier was considered excessive for conversion to chloramines, and a 1.67 multiplier was used instead.

Indirect Capital Costs

Indirect capital costs include the following:

- Public education costs of $500 to $50,000, based on system size and budget figures obtained from systems that implemented chloramine conversion. The estimated costs include the creation of informative brochures, visits to customers most affected by a conversion to chloramines (i.e., pet stores, hospitals), as well as ad publication in the local newspapers.

- Housing costs were included for large systems storing more than 10,000 pounds of anhydrous ammonia, as would be required by a Process Safety Management Plan. The housing costs were calculated by multiplying the assumed footprint for the anhydrous ammonia storage building by a unit cost of $48.95/ft^2 based on RS Means data (see section 4.2 for more details on this unit cost). Building area ranged from 300 to 1200 square feet.

- Piloting and permitting costs were not explicitly costed; these costs were assumed to be negligible and were included in the engineering cost (capital cost factor).

4.4.1.2 Summary of Chloramine O&M Cost Assumptions

Exhibits 4.9 and 4.10 summarize O&M costs for ammonia doses of 0.15 and 0.55 mg/L, respectively. The following assumptions were used to estimate O&M costs associated with ammonia storage and feed systems:

- Chemical costs were developed based on vendors' quotations.

- Aqueous ammonia: \$1,069/ton as NH_3 in 15-gal drum
  \$1,027/ton as NH_3 in 55-gal drum
  \$646/ton as NH_3 in 300-gal drum

- Anhydrous ammonia: \$840/ton as NH_3 for first large system category (1.2 mgd design flow)
  \$400/ton as NH_3 for large system storing >10,000 lb
  Costs are interpolated between these systems based on flow.

- Tank lease cost was included only for large systems (anhydrous ammonia). Based on chemical suppliers' information and assuming that plant operators perform maintenance of the tanks, the annual tank lease costs varied from \$500 per 1,000-gal tank to \$800 per 4,000-gal tank.

- Part replacement costs were estimated based on vendors' quotations for parts anticipated to fail or be consumed (i.e., tube or diaphragm for chemical metering pumps, reagents for on-line chloramine analyzer).

- Electricity costs were estimated based on metering pump power requirements for small systems and on vacuum feed system and vaporizer power requirements for large systems. Due to high energy consumption from heating, vaporizers represent a significant increase in electricity cost for systems using >1,000 lb ammonia/day. The electricity unit cost is \$0.076/kWh (from Exhibit 4.4).

- Labor costs were estimated as the sum of maintenance labor cost and monitoring labor cost. Total labor costs vary from 58 to 1,472 hours per year. The distribution system was assumed to monitor for nitrate and free ammonia, with an average sampling and analytical time of 0.25 hours per analyte; the number of sampling locations ranges from one location each month for very small systems to 72 sampling locations each month for the largest systems. Labor rates used varied based on system size.

Exhibit 4.9: Costs of Chloramines as Secondary Disinfectant Cost Summary - Ammonia Dose = 0.15 mg/L

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary									
Total Capital Cost	29,104	29,104	29,104	29,104	30,604	37,939	38,858	42,127	53,396
Subtotal Indirect Capital Costs	500	500	500	500	2,000	2,000	2,000	2,000	10,000
Public education	500	500	500	500	2,000	2,000	2,000	2,000	10,000
Housing	-	-	-	-	-	-	-	-	-
Direct Capital Cost[1]	28,604	28,604	28,604	28,604	28,604	35,939	36,858	40,127	43,396
Subtotal Process Cost	17,128	17,128	17,128	17,128	17,128	21,520	22,071	24,028	25,985
Chemical Feed System	7,857	7,857	7,857	7,857	7,857	10,959	11,348	12,730	14,112
Scrubber	-	-	-	-	-	-	-	-	-
Analyzer	4,239	4,239	4,239	4,239	4,239	4,239	4,239	4,239	4,239
Pipes and Valves	2,177	2,177	2,177	2,177	2,177	2,736	2,806	3,054	3,303
E&I and controls	2,855	2,855	2,855	2,855	2,855	3,587	3,678	4,005	4,331
Annual O&M Summary									
Total Annual O&M Cost	1,361	1,362	1,363	1,463	1,472	2,949	2,956	2,966	4,274
Chemicals	0	2	3	7	16	24	31	41	62
Tank Lease	-	-	-	-	-	-	-	-	-
Part Replacement	50	50	50	50	50	80	80	80	80
Electricity	67	67	67	67	67	124	124	124	124
Labor$	1,244	1,244	1,244	1,339	1,339	2,721	2,721	2,721	4,008

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.1

Exhibit 4.9 (continued): Costs of Chloramines as Secondary Disinfectant Cost Summary - Ammonia Dose = 0.15 mg/L

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430	520
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270	350
Capital Cost Summary										
Total Capital Cost	83,772	83,772	83,772	83,772	98,772	98,772	98,772	158,907	428,047	428,047
Subtotal Indirect Capital Costs	10,000	10,000	10,000	10,000	25,000	25,000	25,000	50,000	70,265	70,265
Public education	10,000	10,000	10,000	10,000	25,000	25,000	25,000	50,000	50,000	50,000
Housing	-	-	-	-	-	-	-	-	20,265	20,265
Direct Capital Cost[1]	73,772	73,772	73,772	73,772	73,772	73,772	73,772	108,907	357,782	357,782
Subtotal Process Cost	36,886	36,886	36,886	36,886	36,886	36,886	36,886	54,454	178,891	178,891
Chemical Feed System	14,474	14,474	14,474	14,474	14,474	14,474	14,474	26,881	26,881	26,881
Scrubber	-	-	-	-	-	-	-	-	87,879	87,879
Analyzer	11,575	11,575	11,575	11,575	11,575	11,575	11,575	11,575	11,575	11,575
Pipes and Valves	4,689	4,689	4,689	4,689	4,689	4,689	4,689	6,922	22,740	22,740
E&I and controls	6,148	6,148	6,148	6,148	6,148	6,148	6,148	9,076	29,815	29,815
Annual O&M Summary										
Total Annual O&M Cost	5,743	6,266	7,231	8,688	11,333	12,887	23,579	46,355	73,620	87,174
Chemicals	94	177	321	686	1,761	2,468	7,950	20,583	29,604	38,376
Tank Lease	-	-	-	-	500	500	500	1,000	1,200	1,200
Part Replacement	1,284	1,284	1,284	1,284	1,284	1,284	1,284	1,284	1,284	1,284
Electricity	200	200	200	200	200	200	200	300	300	300
Labor$	4,165	4,604	5,425	6,518	7,587	8,435	13,645	23,188	41,232	46,015

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.1

Exhibit 4.10: Costs of Chloramines as Secondary Disinfectant Cost Summary - Ammonia Dose = 0.55 mg/L

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary									
Total Capital Cost	29,104	29,104	29,104	29,104	30,604	37,939	38,858	42,127	53,396
Subtotal Indirect Capital Costs	500	500	500	500	2,000	2,000	2,000	2,000	10,000
Public education	500	500	500	500	2,000	2,000	2,000	2,000	10,000
Housing	-	-	-	-	-	-	-	-	-
Direct Capital Cost	28,604	28,604	28,604	28,604	28,604	35,939	36,858	40,127	43,396
Subtotal Process Cost	17,128	17,128	17,128	17,128	17,128	21,520	22,071	24,028	25,985
Chemical Feed System	7,857	7,857	7,857	7,857	7,857	10,959	11,348	12,730	14,112
Scrubber	-	-	-	-	-	-	-	-	-
Analyzer	4,239	4,239	4,239	4,239	4,239	4,239	4,239	4,239	4,239
Pipes and Valves	2,177	2,177	2,177	2,177	2,177	2,736	2,806	3,054	3,303
E&I and controls	2,855	2,855	2,855	2,855	2,855	3,587	3,678	4,005	4,331
Annual O&M Summary									
Total Annual O&M Cost	1,362	1,366	1,370	1,483	1,515	3,014	3,041	3,077	4,443
Chemicals	2	6	10	27	59	88	115	152	231
Tank Lease	-	-	-	-	-	-	-	-	-
Part Replacement	50	50	50	50	50	80	80	80	80
Electricity	67	67	67	67	67	124	124	124	124
Labor$	1,244	1,244	1,244	1,339	1,339	2,721	2,721	2,721	4,008

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.1

Exhibit 4.10 (continued): Costs of Chloramines as Secondary Disinfectant Cost Summary - Ammonia Dose = 0.55 mg/L

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430	520
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270	350
Capital Cost Summary										
Total Capital Cost	83,772	83,772	83,772	83,772	98,772	133,907	397,173	492,039	590,780	736,773
Subtotal Indirect Capital Costs	10,000	10,000	10,000	10,000	25,000	25,000	39,391	75,699	98,314	109,621
Public education	10,000	10,000	10,000	10,000	25,000	25,000	25,000	50,000	50,000	50,000
Housing	-	-	-	-	-	-	14,391	25,699	48,314	59,621
Direct Capital Cost	73,772	73,772	73,772	73,772	73,772	108,907	357,782	416,340	492,467	627,151
Subtotal Process Cost	36,886	36,886	36,886	36,886	36,886	54,454	178,891	208,170	246,233	313,576
Chemical Feed System	14,474	14,474	14,474	14,474	14,474	26,881	26,881	47,558	74,439	121,997
Scrubber	-	-	-	-	-	-	87,879	87,879	87,879	87,879
Analyzer	11,575	11,575	11,575	11,575	11,575	11,575	11,575	11,575	11,575	11,575
Pipes and Valves	4,689	4,689	4,689	4,689	4,689	6,922	22,740	26,462	31,301	39,861
E&I and controls	6,148	6,148	6,148	6,148	6,148	9,076	29,815	34,695	41,039	52,263
Annual O&M Summary										
Total Annual O&M Cost	6,000	6,747	8,102	10,536	15,491	18,954	31,538	80,340	161,502	204,728
Chemicals	351	659	1,193	2,534	6,420	8,936	15,509	48,975	110,193	142,843
Tank Lease	-	-	-	-	-	-	800	1,600	3,200	4,000
Part Replacement	1,284	1,284	1,284	1,284	1,284	1,284	1,284	1,284	1,284	1,284
Electricity	200	200	200	200	200	300	300	5,293	5,593	10,586
Labor$	4,165	4,604	5,425	6,518	7,587	8,435	13,645	23,188	41,232	46,015

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.1

4.4.2 Chlorine Dioxide

Chlorine dioxide costs were evaluated at an applied dose of 1.25 mg/L. As explained in Chapter 3, this is a conservative maximum dose for compliance with the chlorite MCL of 1 mg/L, assuming 70 percent conversion of chlorine dioxide to chlorite and allowing for impurities in chlorine dioxide generation. This cost analysis did not assess the level of *Cryptosporidium* inactivation that would be achieved by this dose, which would depend on water quality and contact time. The chlorine dioxide costs presented assume the existing plant has sufficient contact time (i.e., basin volume) to provide the required CT. All costs are for automatic generation systems. Because of the level of operator attention and knowledge required to ensure compliance with the chlorite MCL and the safety concerns surrounding chlorine dioxide generation, this technology was assumed to be inappropriate for systems serving fewer than 500 people. Therefore no costs were developed for flows less than 0.091 mgd.

For systems treating less than 2 mgd, vendor quotations for rental of chlorine generation equipment were used (these are shown as an O&M item). The remainder of the capital cost line items for small systems were estimated using the W/W Cost model. Capital costs for the systems treating at least 2 mgd were also generated using the W/W Cost model. In addition, O&M costs for all systems were estimated using the W/W Cost model.

Costs for chlorine dioxide addition are presented in Exhibit 4.12. Detailed summaries of the capital and O&M costs assumptions are presented below.

4.4.2.1 Summary of Chlorine Dioxide Capital Cost Assumptions

Process Costs

Capital costs were estimated based on cost estimating models and vendor information. Vendor quotes were obtained in June 2001 and adjusted to year 2003 dollars using the ENR BCI. This section presents line item costs for the various components that contribute to the total capital costs.

<u>Feed Equipment</u>

Feed equipment costs for systems with design capacities above 2 mgd were estimated using the W/W Cost model. Assumptions for feed equipment in the model include a sodium chlorite mixing and metering system, a chlorine dioxide generator (0.2 minute detention time), a polyethylene day tank and mixer, and a dual head metering pump.

For design capacities less than 2 mgd, utilities can lease the equipment for less money than they would spend constructing their own systems. As a result, vendor quotations for equipment leasing were used instead of capital equipment costs for these plants. These leasing costs were included in annual O&M estimates rather than capital costs. Note that, although feed equipment is leased for systems treating less than 2 mgd, they still incur capital costs for instrumentation and controls.

<u>Instrumentation & Controls, and Pipe & Valves</u>

The W/W Cost model was used to estimate these line item capital costs for all plant design capacities. The calculation method for these capital cost line items is not explicitly stated in the W/W Cost model documentation; however, the costs developed in the model were based on quantity takeoffs from actual and conceptual designs and information from actual plant construction projects as well as equipment supplier quotations.

Capital Cost Multipliers

The feed equipment, I&C, and P&V capital cost items were added to obtain a subtotal representing process costs. The process cost subtotal was multiplied by the capital cost factor (2.5 for small systems <1 mgd or 2.0 for large systems $\geq$1 mgd) to produce total direct capital costs. A complete discussion of capital cost factors, including the components that make up the costs, is presented in section 4.2.1.

Indirect Capital Costs

Permitting

Significant process improvements will likely require coordination with the appropriate regulatory agency. As such, permitting costs were included at three percent of the process cost. A minimum of $2,500 for permitting costs was assumed.

Pilot/Bench Testing

The necessity for pilot- or bench-scale testing was assumed to ensure that chlorine dioxide use would be compatible with the current treatment process at a given plant. The level of testing required was estimated based on system size. For systems less than 0.1 mgd, a lump sum of $5,000 was assumed for testing. For systems from 0.1 to 1 mgd, a lump sum of $10,000 was assumed for testing. For systems greater than 1 mgd, a lump sum $50,000 was assumed for testing.

Chlorine Dioxide System Housing

Housing costs for a chlorine dioxide system include the cost for a building to house the equipment and associated appurtenances (i.e., heating, ventilation and air conditioning (HVAC), etc.). The footprint (area) required to house the equipment for each size system is calculated in the W/W Cost model. The areas, calculated in square feet, were then priced using the RS Means median price of $48.95/ft^2 for a factory building.

4.4.2.2 Summary of Chlorine Dioxide O&M Cost Assumptions

Chlorine dioxide operations and maintenance costs were estimated using the W/W Cost model. Cost factors for chemicals ($/ton), electricity ($/kWh), and labor ($/hour), as shown in Exhibit 4.4, were used to calculate line item O&M costs. The sections below address specifics of the line O&M costs.

Feed Equipment (systems smaller than 2.0 mgd)

As previously mentioned, it is more cost effective for systems with design capacities less than 2 mgd to lease rather than purchase chlorine dioxide feed equipment. An equipment lease fee of $6.50 per day was included for systems less than 2 mgd based on vendor quotes. This estimate was based on information provided by chlorine dioxide equipment manufacturers that lease feed equipment. Feed equipment costs for systems larger than 2 mgd were included as capital cost items.

Chemical Usage

Chlorine dioxide costs were evaluated at an applied dose of 1.25 mg/L. Chemical usage was calculated within the W/W Cost model assuming a 1:1 mass ratio of sodium chlorite to chlorine. The theoretical ratio of sodium chlorite to chlorine is 2.68:1. However, chlorine is normally overdosed to ensure complete conversion of sodium chlorite; the remaining chlorine, when in solution, is converted to hypochlorous acid and lowers the pH, which improves the chlorine dioxide production efficiency.

Materials, Electricity, and Labor

The materials costs, kilowatt hours (kWh) of electricity, and labor hours were calculated within the W/W Cost model. Material costs include all supplies necessary for routine maintenance on the system, such as gaskets, oil for pumps, spare fittings, etc. Exhibit 4.11 presents the values calculated by the model.

Exhibit 4.11: W/W Cost Model Electricity Usage and Required Labor for Chlorine Dioxide

Average Flow (MGD)	Materials Costs ($/year)	Electricity Usage/Year (kWh)	O&M Labor/Year (hours)	O&M Labor/Day (hours)
0.025	1,708	3,437	421	1.1
0.054	2,026	3,437	454	1.2
0.084	2,239	3,437	475	1.3
0.11	2,320	3,437	482	1.3
0.23	2,542	3,437	500	1.3
0.35	2,748	3,437	517	1.4
0.41	2,866	3,443	526	1.4
0.77	3,499	3,457	577	1.6
1.4	3,952	3,504	619	1.7
3.0	4,315	3,638	667	1.8
7.8	5,444	3,917	816	2.2
11.0	5,954	4,163	897	2.5
38.0	7,463	7,241	1,356	3.7
120.0	11,157	15,165	2,548	7.0
270.0	13,957	24,749	3,835	11
350.0	15,451	29,766	4,521	12

Source: W/W model

Exhibit 4.12: Chlorine Dioxide Cost Summary

Design Flow (mgd)	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary						
Total Capital Cost	32,427	38,370	39,172	40,066	43,005	40,035
Subtotal Indirect Capital Costs	12,827	17,827	17,827	17,827	17,827	17,827
Piloting	5,000	10,000	10,000	10,000	10,000	10,000
Permitting	2,500	2,500	2,500	2,500	2,500	2,500
Land	-	-	-	-	-	-
Operator Training	-	-	-	-	-	-
Housing	5,327	5,327	5,327	5,327	5,327	5,327
Other Indirect Costs	-	-	-	-	-	-
Direct Capital Cost[1]	19,600	20,543	21,344	22,239	25,177	22,208
Subtotal Process Cost	7,840	8,217	8,538	8,895	10,071	11,104
Pipes and Valves	1,701	1,900	2,073	2,265	2,898	3,454
Instrumentation and controls	6,139	6,317	6,465	6,630	7,173	7,650
Pumping	-	-	-	-	-	-
Chlorine Dioxide Generator	-	-	-	-	-	-
Storage Tanks	-	-	-	-	-	-
Process Monitoring Equipment	-	-	-	-	-	-
Feed Equipment	-	-	-	-	-	-
Annual O&M Summary						
Total Annual O&M Cost	14,093	15,204	16,721	16,999	17,812	18,571
Feed Equipment	2,373	2,373	2,373	2,373	2,373	2,373
Chemicals	30	61	97	121	266	399
Part Replacement	-	-	-	-	-	-
Performance monitoring	-	-	-	-	-	-
Materials	1,708	2,026	2,239	2,320	2,542	2,748
Electricity	261	261	261	261	261	261
Labor $	9,721	10,483	11,752	11,925	12,370	12,791

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Based on ClO_2 dose = 1.25 mg/L
Source: Section 4.4.2

Exhibit 4.12 (continued): Chlorine Dioxide Cost Summary

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430	520
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270	350
Capital Cost Summary										
Total Capital Cost	80,585	82,054	191,088	211,473	268,223	296,568	603,425	897,449	1,245,987	1,368,982
Subtotal Indirect Capital Costs	58,098	58,821	60,177	63,520	70,424	73,503	106,839	168,220	262,882	299,288
Piloting	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
Permitting	2,500	2,500	2,500	2,500	2,967	3,346	7,449	10,938	14,747	16,045
Land	-	-	-	-	-	-	-	-	-	-
Operator Training	-	-	-	-	-	-	-	-	-	-
Housing	5,598	6,321	7,677	11,020	17,457	20,157	49,390	107,281	198,135	233,243
Other Indirect Costs	-	-	-	-	-	-	-	-	-	-
Direct Capital Cost[1]	22,487	23,233	130,911	147,954	197,799	223,065	496,587	729,229	983,105	1,069,694
Subtotal Process Cost	11,243	11,617	65,456	73,977	98,899	111,532	248,293	364,614	491,553	534,847
Pipes and Valves	3,462	3,484	3,526	3,627	4,968	5,824	15,084	22,541	30,324	32,976
Instrumentation and controls	7,781	8,132	8,790	10,413	14,743	16,868	39,866	59,146	79,948	87,050
Pumping	-	-	-	-	-	-	-	-	-	-
Chlorine Dioxide Generator	-	-	-	-	-	-	-	-	-	-
Storage Tanks	-	-	-	-	-	-	-	-	-	-
Process Monitoring Equipment	-	-	-	-	-	-	-	-	-	-
Feed Equipment	-	-	53,140	59,937	79,189	88,841	193,343	282,928	381,281	414,820
Annual O&M Summary										
Total Annual O&M Cost	18,984	21,638	22,001	25,392	35,939	42,336	87,061	216,813	446,533	561,934
Feed Equipment	2,373	2,373	-	-	-	-	-	-	-	-
Chemicals	471	883	1,658	3,425	8,941	12,699	43,724	138,128	310,813	402,894
Part Replacement	-	-	-	-	-	-	-	-	-	-
Performance monitoring	-	-	-	-	-	-	-	-	-	-
Materials	2,866	3,499	3,952	4,315	5,444	5,954	7,463	11,157	13,957	15,451
Electricity	262	263	266	276	298	316	550	1,153	1,881	2,262
Labor $	13,013	14,621	16,125	17,375	21,257	23,367	35,324	66,375	119,882	141,326

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Based on ClO_2 dose = 1.25 mg/L
Source: Section 4.4.2

4.4.3 Ultraviolet Light

UV disinfection is a potential alternative to chemical disinfection. Costs were estimated for median post-filter water quality based on data collected during the ICR. See Chapter 3 for the water quality conditions assumed for all UV costs.

LP UV lamp-based systems were assumed for all systems treating <1 mgd. For systems treating >1 mgd, cost estimates reflect either LPHO or medium pressure lamp systems. Manufacturer/vendor supplied information was used to determine equipment costs, replacement parts costs, and estimates of labor and power requirements[2]. Best professional judgement and engineering estimates were used to assess other associated costs. Costs for UV disinfection are summarized in Exhibits 4.13 through 4.16.

4.4.3.1 Summary of UV Disinfection Capital Cost Assumptions

Capital costs were developed from manufacturer/vendor supplied information and best professional judgment. Equipment costs were obtained from vendors in February 2002 and adjusted to year 2003 dollars using the ENR BCI. For large systems (serving >1 mgd), UV equipment costs represent only a portion of the total process costs. Additional process costs were estimated for instrumentation and controls, interstage pumping, piping and valves, and housing. For small systems (flows <1.0 mgd), additional process costs were assumed to be captured in the capital cost multiplier. Indirect capital costs (for both large and small systems) include pilot testing, training, and spare parts. Pilot testing cost assumptions for UV are presented below.

For design flows:

- <0.1 - 1.2 mgd $1,000
- 2 - <17 mgd $5,000
- 17 - <76 mgd $10,000
- >76 mgd $200,000

Process Costs

Manufacturers were asked to provide UV equipment cost estimates based on the anticipated UV system layout (based on the specified number of reactors as show in Exhibit 3.6, building size, piping, etc.) and a given water quality (see Exhibit 3.5). In addition, actual construction and design costs for 18 facilities were submitted to EPA during the proposal comment period. The actual costs were used to check and in some cases revise the vendor quotes. System validation costs were included in the UV equipment cost line item in Exhibits 4.13 through 4.16.

EPA updated the 40 mJ/cm^2 UV unit costs based on data obtained for recent installations of this technology. Similar data for 200 mJ/cm2 UV systems were not available within the time frame required to include in this analysis. For large systems, UV process costs include estimates for interstage pumping of filter effluent to UV facilities prior to storage because some plants will not be able to retrofit the UV system into the existing hydraulic gradeline. It was assumed that 35 percent of systems would need to install additional pumping, based on an AWWARF survey of "average" facilities. Costs for the pump

[2]Two manufacturers' estimated costs for LP lamp systems. These quotes were averaged to estimate the equipment and components of the O&M costs. Four manufacturers' quotes were averaged to estimate the equipment and O&M costs for large systems (>1 mgd).

equipment were supplied by pump vendors. Instrumentation and controls (including HVAC and electrical) were assumed to be $20,000 per reactor for larger systems, based on the data from actual facilities. Pipes and valving were calculated from vendor quotes.

Costs were developed with and without a UPS that could be used to prevent UV system shut downs. To determine the costs of the UPS system, three manufacturers were contacted. Their costs were based on the power supply (i.e., 3 phase 240 volt), total kilowatts (kW) necessary, and the minutes of backup necessary if a total power outage occurred. The power supply and the total kW needed were determined based on manufacturer information and an assumed battery backup time of five minutes.

Capital Cost Multipliers

Capital cost multipliers used for UV disinfection differ from those recommended by NDWAC. For flows less than 1 mgd, the capital cost multiplier is 1.2. For flows greater than or equal to 1 mgd, the capital cost multiplier is 1.36 for systems using a dose of 40 mJ/cm^2, and 1.76 for a dose of 200 mJ/cm^2. Systems less than 1 mgd require a smaller capital cost multiplier than other treatment technologies because small UV systems do not need significant area (i.e., new building not needed), equipment installation is not complex, and plant modifications are minor compared to other technologies. The capital cost multiplier of 1.36 used for 40 mJ/cm^2 systems is a revised multiplier based on actual data from facilities. The lower cost multiplier was used because lower installation costs and less site work are necessary compared to other treatment technologies.

Indirect Capital Costs

For systems using a dose of 40 mJ/cm^2, pilot testing, operator training, housing, and a spare parts inventory are included as indirect capital costs. Pilot testing was assumed to be $1,000 for systems with a design flow of less than 2 mgd, $5,000 from 2 to 10 mgd, $10,000 for 10 to 25 mgd, and $200,000 for systems with a design flow greater than 25 mgd. See section 4.3 for a more detailed discussion of piloting assumptions. Operator training was assumed to be $1,000 for small systems and ranges from $3,000 to $25,000 for larger systems. Housing costs were based on the estimated UV system footprint size multiplied by a median housing unit costs of $150/ft^2 based on actual UV costs (see Section 4.3 for details). Footprint sizes ranged from 335 square feet to 22,000 square feet. Also, based on data reported from 18 actual UV facilities, it was assumed that 39 percent of facilities would not require an additional building, therefore the housing costs were reduced by this percentage to reflect a national average cost. The spare parts inventory costs were based on a ten percent back-up of system equipment including lamps, sleeves, and sensors, with the exception of ballasts and ultraviolet transmittance (UVT) monitors that were based on a five percent and one unit back-up of system equipment, respectively.

4.4.3.2 Summary of UV Disinfection O&M Cost Assumptions

The O&M costs reflect labor hours, replacement parts, and lamp operating information provided by the manufacturer. The number of lamps, sensors, and ballasts are different, depending on the different manufacturer. Costs for replacement parts for each manufacturer were based on the following replacement intervals:

- LP lamps replaced annually.
- MP lamps replaced every six months.
- Sleeves replaced every eight years.

- Intensity sensors and reference sensors replaced every five years.

- Ballasts and UVT monitors replaced every ten years.

The calculated costs for each for each manufacturer were averaged to estimate the average UV replacement parts costs.

For systems treating less than 2 mgd, one hour of labor per month plus an additional two hours per lamp replacement was assumed. For systems treating more than 2 mgd, labor hours were estimated by manufacturers for the following tasks: daily operation, lamp replacement (annually for low pressure lamps and every 6 months for medium pressure lamps), quarterly sensor calibration, and cleaning once per month for UV systems that do not use automatic cleaning. Labor costs were derived from the labor hours estimate and assumed labor rate. (See section 4.2 for a discussion of the operator labor rate used in this document.)

Power requirements were estimated from manufacturer-supplied information regarding the number of lamps in a given system, the kilowatt draw of each lamp, the warranty power setting, and the average number of UV reactors needed. The total kilowatt draw from each manufacturer was then determined, and the average power consumption (kW) was calculated. The average power consumption was used to calculate the total power costs by multiplying the total power requirements by the assumed power rate of 0.076$/kWh (see Exhibit 4.4).

For the cost estimates that included a UPS system, the power efficiency of the UPS was assumed to be 90 percent and was factored into the power costs. In addition, UPS systems need to replace the batteries and electronics; the battery and electronics life expectancy varied depending on the manufacturer and were between 4 and 15 years. The replacement costs were determined for each manufacturer, and then the three manufacturers' replacement costs were averaged and added to the cost estimates.

EPA updated the 40 mJ/cm2 UV unit costs based on data obtained for recent installations of this technology. However, similar data for 200 mJ/cm2 UV systems were not available within the time frame required to include in this analysis. For the 2, 200 mJ/cm^2 reactors in series, costs for a single reactor were obtained from vendors and then multiplied by two to account for the second reactor. Some costs were not doubled as they would not likely be directly proportional to the number of reactors because of economies of scale. Training and pilot testing were not increased at all. Pumping, housing, and labor were increased by 50 percent and instrumentation was increased by 80 percent.

Exhibit 4.13: UV Disinfection Cost Summary (40 mJ/cm^2 Without UPS)

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary									
Total Capital Cost	10,195	13,034	15,834	25,596	40,597	54,386	66,790	99,661	310,154
Indirect Capital Costs	3,686	3,704	3,722	3,794	3,934	4,102	4,296	5,200	6,206
Training	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Treatability Testing	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Spare Parts	1,686	1,704	1,722	1,794	1,934	2,102	2,296	3,200	4,206
Direct Capital Cost[1]	6,509	9,330	12,112	21,802	36,662	50,284	62,493	94,461	303,947
Subtotal Process Cost	5,424	7,775	10,094	18,168	30,552	41,903	52,078	78,717	223,491
I&C (incl.HVAC)	-	-	-	-	-	-	-	-	40,000
Pipes and Valves	-	-	-	-	-	-	-	-	17,717
Adjusted Pumping	-	-	-	-	-	-	-	-	1,564
Adjusted Housing	-	-	-	-	-	-	-	-	20,210
UV reactors	5,424	7,775	10,094	18,168	30,552	41,903	52,078	78,717	128,000
Electrical	-	-	-	-	-	-	-	-	16,000
Annual O&M Cost Summary									
Total O&M Cost	3,350	3,380	3,769	4,549	4,736	6,115	6,493	8,152	9,016
Replacement Parts	3,000	3,000	3,377	4,000	4,000	5,200	5,400	6,400	6,800
Power/Electricity	50	80	91	180	320	420	524	960	1,400
Labor $	300	300	300	369	416	495	569	792	816

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.3

Exhibit 4.13 (continued): UV Disinfection Cost Summary (40 mJ/cm^2 Without UPS)

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430	520
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270	350
Capital Cost Summary										
Total Capital Cost	313,662	333,331	362,965	544,728	1,342,022	1,933,041	3,367,751	8,074,450	15,798,603	18,601,681
Indirect Capital Costs	7,161	16,980	24,141	24,449	37,823	38,510	235,927	269,332	299,549	311,910
Training	1,000	3,000	3,000	3,000	10,000	10,000	10,000	25,000	25,000	25,000
Treatability Testing	1,000	5,000	5,000	5,000	10,000	10,000	200,000	200,000	200,000	200,000
Spare Parts	5,161	8,980	16,141	16,449	17,823	18,510	25,927	44,332	74,549	86,910
Direct Capital Cost[1]	306,501	316,351	338,824	520,279	1,304,199	1,894,532	3,131,825	7,805,118	15,499,054	18,289,771
Subtotal Process Cost	225,368	232,611	249,135	382,558	958,970	1,393,038	2,302,812	5,739,058	11,396,363	13,448,361
I&C (incl.HVAC)	40,000	40,000	40,000	60,000	60,000	80,000	100,000	260,000	520,000	600,000
Pipes and Valves	19,442	25,898	41,127	86,822	187,514	230,497	694,725	1,846,699	3,738,000	4,511,714
Adjusted Pumping	1,716	2,502	3,798	7,526	15,174	18,403	55,075	160,326	377,179	481,673
Adjusted Housing	20,210	20,210	20,210	20,210	107,282	126,124	255,472	576,446	1,103,419	1,318,998
UV reactors	128,000	128,000	128,000	192,000	573,000	764,000	955,000	2,483,000	4,966,000	5,730,000
Electrical	16,000	16,000	16,000	16,000	16,000	174,014	242,540	412,586	691,766	805,976
Annual O&M Cost Summary										
Total O&M Cost	9,450	11,512	13,979	16,183	22,908	27,531	66,755	188,219	422,455	551,123
Replacement Parts	7,100	8,200	9,689	10,166	11,605	13,704	31,629	80,143	174,324	246,358
Power/Electricity	1,509	2,400	3,300	4,975	10,000	12,331	32,000	100,000	230,000	283,182
Labor $	841	912	990	1,042	1,303	1,496	3,126	8,076	18,131	21,584

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.3

Exhibit 4.14: UV Disinfection Cost Summary (200 mJ/cm^2 Without UPS)

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1	1.2	2
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35	0.41	0.77
Capital Cost Summary											
Total Capital Cost	39,390	47,873	56,357	86,898	137,234	188,136	239,038	420,021	889,941	966,625	1,372,981
Indirect Capital Costs	3,045	3,555	4,066	5,903	8,932	11,994	15,056	25,945	28,099	28,313	148,311
Training	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	3,000
Treatability Testing	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	118,143
Spare Parts	1,045	1,555	2,066	3,903	6,932	9,994	13,056	23,945	26,099	26,313	27,168
Direct Capital Cost[1]	36,345	44,318	52,291	80,995	128,303	176,142	223,982	394,077	861,842	938,312	1,224,671
Subtotal Process Cost	30,287	36,932	43,576	67,496	106,919	146,785	186,651	328,397	489,683	533,132	695,836
I&C (incl.HVAC)	-	-	-	-	-	-	-	-	75,525	82,275	107,355
Pipes and Valves	-	-	-	-	-	-	-	-	19,952	23,215	31,162
Pumping	-	-	-	-	-	-	-	-	2,041	2,512	4,045
Housing	-	-	-	-	-	-	-	-	15,208	17,825	24,571
UV reactors	30,287	36,932	43,576	67,496	106,919	146,785	186,651	328,397	376,956	407,305	528,702
Annual O&M Cost Summary											
Total O&M Cost	7,595	7,864	8,999	11,583	14,000	17,316	18,019	20,936	22,359	24,308	30,142
Replacement Parts	6,509	6,649	7,647	9,938	10,905	13,228	13,420	14,019	14,360	15,620	18,040
Power/Electricity	410	540	677	813	2,160	2,976	3,318	5,135	6,162	6,795	10,049
Labor $	675	675	675	831	935	1,113	1,280	1,781	1,837	1,893	2,053

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)

Note: EPA updated the 40 mJ/cm2 UV unit costs based on data obtained for recent installations of this technology. Similar data for 200 mJ/cm2 UV systems were not available within the time frame required to include in this analysis.

Source: Section 4.4.3

Exhibit 4.15: UV Disinfection Cost Summary (40 mJ/cm^2 with UPS)

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary									
Total Capital Cost	10,566	13,453	16,304	26,268	41,668	55,949	68,929	104,547	317,091
Indirect Capital Costs	3,686	3,704	3,722	3,794	3,934	4,102	4,296	5,200	6,206
Training	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Treatability Testing	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Spare Parts	1,686	1,704	1,722	1,794	1,934	2,102	2,296	3,200	4,206
Direct Capital Cost[1]	6,880	9,749	12,582	22,473	37,734	51,846	64,632	99,347	310,884
Subtotal Process Cost	5,733	8,124	10,485	18,728	31,445	43,205	53,860	82,789	228,591
I&C (incl.HVAC)	-	-	-	-	-	-	-	-	40,000
Pipes and Valves	-	-	-	-	-	-	-	-	17,717
Adjusted Pumping	-	-	-	-	-	-	-	-	1,564
Adjusted Housing	-	-	-	-	-	-	-	-	20,210
UV reactors	5,424	7,775	10,094	18,168	30,552	41,903	52,078	78,717	128,000
Electrical	-	-	-	-	-	-	-	-	16,000
UPS	309	349	391	559	893	1,302	1,782	4,072	5,101
Annual O&M Cost Summary									
Total O&M Cost	3,350	3,380	3,769	4,549	4,736	6,115	6,493	8,152	9,016
Replacement Parts	3,000	3,000	3,377	4,000	4,000	5,200	5,400	6,400	6,800
Power/Electricity	50	80	91	180	320	420	524	960	1,400
Labor $	300	300	300	369	416	495	569	792	816

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.3

Exhibit 4.15 (continued): UV Disinfection Cost Summary (40 mJ/cm^2 with UPS)

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430	520
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270	350
Capital Cost Summary										
Total Capital Cost	321,473	344,641	380,834	577,903	1,418,926	2,019,884	3,569,168	8,617,465	17,079,543	20,247,943
Indirect Capital Costs	7,161	16,980	24,141	24,449	37,823	38,510	235,927	269,332	299,549	311,910
Training	1,000	3,000	3,000	3,000	10,000	10,000	10,000	25,000	25,000	25,000
Treatability Testing	1,000	5,000	5,000	5,000	10,000	10,000	200,000	200,000	200,000	200,000
Spare Parts	5,161	8,980	16,141	16,449	17,823	18,510	25,927	44,332	74,549	86,910
Direct Capital Cost[1]	314,312	327,661	356,693	553,454	1,381,104	1,981,375	3,333,242	8,348,133	16,779,995	19,936,033
Subtotal Process Cost	231,112	240,927	262,274	406,951	1,015,517	1,456,893	2,450,913	6,138,333	12,338,231	14,658,848
I&C (incl.HVAC)	40,000	40,000	40,000	60,000	60,000	80,000	100,000	260,000	520,000	600,000
Pipes and Valves	19,442	25,898	41,127	86,822	187,514	230,497	694,725	1,846,699	3,738,000	4,511,714
Adjusted Pumping	1,716	2,502	3,798	7,526	15,174	18,403	55,075	160,326	377,179	481,673
Adjusted Housing	20,210	20,210	20,210	20,210	107,282	126,124	255,472	576,446	1,103,419	1,318,998
UV reactors	128,000	128,000	128,000	192,000	573,000	764,000	955,000	2,483,000	4,966,000	5,730,000
Electrical	16,000	16,000	16,000	16,000	16,000	174,014	242,540	412,586	691,766	805,976
UPS	5,744	8,316	13,139	24,393	56,547	63,855	148,101	399,275	941,868	1,210,487
Annual O&M Cost Summary										
Total O&M Cost	9,450	11,512	13,979	16,183	22,908	27,531	66,755	188,219	422,455	551,123
Replacement Parts	7,100	8,200	9,689	10,166	11,605	13,704	31,629	80,143	174,324	246,358
Power/Electricity	1,509	2,400	3,300	4,975	10,000	12,331	32,000	100,000	230,000	283,182
Labor $	841	912	990	1,042	1,303	1,496	3,126	8,076	18,131	21,584

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.3

Exhibit 4.16: UV Disinfection Cost Summary (200 mJ/cm^2 with UPS)

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1	1.2	2
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35	0.41	0.77
Capital Cost Summary											
Total Capital Cost	61,339	70,807	79,593	111,222	163,352	216,068	268,783	456,216	952,484	1,035,080	1,465,082
Indirect Capital Costs	3,045	3,555	4,066	5,903	8,932	11,994	15,056	25,945	28,099	28,313	148,311
Training	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	3,000
Treatability Testing	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	118,143
Spare Parts	1,045	1,555	2,066	3,903	6,932	9,994	13,056	23,945	26,099	26,313	27,168
Direct Capital Cost[1]	58,294	67,252	75,527	105,319	154,421	204,074	253,727	430,271	924,385	1,006,767	1,316,771
Subtotal Process Cost	48,578	56,043	62,939	87,766	128,684	170,061	211,439	358,559	525,219	572,027	748,166
I&C (incl.HVAC)	-	-	-	-	-	-	-	-	75,525	82,275	107,355
Pipes and Valves	-	-	-	-	-	-	-	-	19,952	23,215	31,162
Pumping	-	-	-	-	-	-	-	-	2,041	2,512	4,045
Housing	-	-	-	-	-	-	-	-	15,208	17,825	24,571
UV reactors	30,287	36,932	43,576	67,496	106,919	146,785	186,651	328,397	376,956	407,305	528,702
UPS	18,291	19,111	19,363	20,270	21,765	23,276	24,788	30,162	35,536	38,895	52,330
Annual O&M Cost Summary											
Total O&M Cost	7,595	7,864	8,999	11,583	14,000	17,316	18,019	20,936	22,359	24,308	30,142
Replacement Parts	6,509	6,649	7,647	9,938	10,905	13,228	13,420	14,019	14,360	15,620	18,040
Power/Electricity	410	540	677	813	2,160	2,976	3,318	5,135	6,162	6,795	10,049
Labor $	675	675	675	831	935	1,113	1,280	1,781	1,837	1,893	2,053

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)

Note: EPA updated the 40 mJ/cm2 UV unit costs based on data obtained for recent installations of this technology. Similar data for 200 mJ/cm2 UV systems were not available within the time frame required to include in this analysis.

Source: Section 4.4.3

4.4.4 Ozone

Costs are estimated based on ozone dosages required to achieve 0.5, 1, and 2 log *Cryptosporidium* inactivation. Required doses to meet this inactivation level were based on ozone CT values presented in Chapter 2 (Exhibit 2.13) and SWAT model runs for all ICR plants. (See Chapter 3 for a more detailed description of SWAT runs used to develop ozone dose estimates.) The design dosages used to meet the inactivation requirements are 4.5 mg/L, 8.25 mg/L and 10.88 mg/L. These values were factored into capital costs and used to size facilities. Corresponding average values assumed for day-to-day operations are 2.43 mg/L, 4.22 mg/L, and 5.84 mg/L. These values were used to determine O&M costs.

To control bromate formation during ozonation, it may be necessary to lower the pH in certain waters. Separate costs were estimated for pH adjustment so that this cost could be added to the costs of ozonation, where appropriate. The pH adjustment costs include addition of a feed system and chemical costs to reduce the pH using sulfuric acid and to raise the pH using caustic (after ozonation). Costs for pH adjustment were included as an indirect capital cost and were not multiplied by a capital cost factor.

Ozone costs were based primarily on vendor quotes from ozone manufacturers. Exhibits 4.19 through 4.21 summarize the capital and O&M costs associated with ozone.

4.4.4.1 Summary of Ozonation Capital Cost Assumptions

Process Costs

Process costs for ozone include in-plant pumping, ozone generation system, ozone contactor, off-gas destruction facilities, effluent ozone quench, stainless steel piping (including valves and ductwork), electrical and instrumentation, and chemical storage. Process costs were mostly provided by equipment vendors in June 2001 and were adjusted to year 2003 dollars using the ENR BCI.

<u>In-plant Pumping</u>

The in-plant pumping costs in Exhibits 4.19 through 4.21 include costs for a concrete wet-well, vertical turbine constant-speed pumps, piping, valving, manifolding, and all E&I associated with the in-plant pumping only. No corrosion-resistant materials (e.g., stainless steel) are required for the pumps. The in-plant pumping was designed so that it can take place either near the ozone system or at some other location somewhat removed from the generator and/or contactor. Other details are provided below.

- A vertical turbine pump vendor was contacted and provided the range of flow rates and total dynamic head (TDH) requirement of 15 feet. They provided budgetary costs for a set of pumps (one duty, one standby) to meet the requirements. The costs quoted included bowls, column, shaft, pump discharge head, and motor.

- Wet-well tankage costs were estimated using the same unit cost curve (cost vs. volume of wet-well) developed for the ozone contactors (without concrete baffles). Details of this cost curve development are provided in the section labeled "Ozone Contactor Costs" below.

- Pipes, valves, and E&I were estimated as a percentage of the manufactured equipment (i.e., pump cost), based on the percentages provided in the W/W Cost model for in-plant pumping.

Ozone Generation System

Ozone generation costs include costs for the ozone generators, feed gas delivery system, ozone dissolution system, ambient air ozone monitors, and process monitoring equipment necessary to verify generation rates and dosing. These costs were developed through contacting suppliers of ozone generation equipment. The vendors were contacted and given the oxygen generation rates required (lbs/day); they responded with complete system costs for all components.

All ozone generation equipment costs include N+1 redundancy; thus, a minimum of two ozone generators would be provided. The type of feed gas delivery system is dependant on the size of the system and, more specifically, the amount of ozone required each day. For systems requiring less than 100 lbs/day of ozone, oxygen is generated onsite via pressure swing absorption (PSA). PSA requires feed gas equipment such as an air compressor, air chiller, and air dryer. For systems requiring more than 100 lbs/day of ozone, oxygen is provided via liquid oxygen stored in an onsite tank. (The liquid oxygen tank is included in the ozone generation equipment heading.)

The ozone dissolution system can consist of venturi-type injector devices or porous diffusers in the ozone contacting tank. Vendors providing cost estimates universally preferred venturi-type injectors and therefore the costs are based on that type of ozone dissolution. Ozone generation systems are sized based on a transfer efficiency of 90 percent. As an example for a design dose of 4.5 mg/L (to meet CT at 0.5 log removal), the actual ozone generation requirement is estimated as:

$$\text{Ozone generation requirement (lbs/day)} = (4.5\ \text{mg/L}) \times (\text{design flow}) \times (\text{conversion factor}) \times (1.1)$$

Ozone Contactor Costs

The ozone contactor is a concrete tank with a total hydraulic detention time of 12 minutes. N+1 redundancy also applies to the ozone contactor design. Baffles are included to segregate the reactor into five chambers flowing in an over/under configuration. The tank has a concrete top to ensure capture of any ozone that may off-gas from the reactor. Specific design criteria applied are as follows.
.

- Wall thickness = 18 inches, bottom slab and cover thickness = 12 inches
- Length-to-width ratio = 2.5
- Water depth inside the tank ranges from 5 to 20 feet.
- Design volume = 1.2 x required volume for freeboard and odor control connections
- Stainless steel baffles for contactors <10,000 gallons (<1 mgd design flow); concrete baffles for contactors >10,000 gallons (≥1 mgd)
- Concrete baffle thickness = 8 inches

Ozone contactor costs include all costs related to installing reinforced concrete tankage. These costs include excavation, formwork, rebar, concrete, backfill, tank coatings, and miscellaneous hardware relating directly to the tank (e.g., railings, hatches, pipe supports, and additions). The cost does not include costs for connecting process lines or ductwork to the exterior of the tank or connecting instrumentation cabling or required electrical cabling to the tank. (These costs are included in the piping and valves and E&I process line items.) With a given tank volume estimate (per design criteria above) unit costs measured in terms of $/cubic yard of concrete were applied. The unit costs used for concrete are as follows.

- $525/cubic yard for floors and slabs
- $675/cubic yard for walls and baffles
- $825/cubic yard for decks

These unit costs were based on best professional judgment where each of the above unit costs is 1.5 times a base cost for concrete work only (i.e., to perform only the concrete work with no excavation, backfill, miscellaneous fittings, coatings, etc.). Values of $350, $450, and $550 per cubic yard are commonly used as budgetary values for installation of floors, walls, and decks, respectively. The value of $525 used here for slabs results from (1.5) × ($350). The 1.5 multiplier represents approximately 25 percent for excavation and backfill costs and 25 percent for miscellaneous hardware related directly to the tank. Using these unit costs and the tankage design assumptions, cost vs. contactor volume relations were developed for both concrete baffled (> 1 mgd) and nonconcrete baffled tanks. This relation was then applied to the various flow categories, noting that contactor volume is a function of design flow, contact time, and tank geometry design assumptions.

<u>Off Gas Destruction</u>

Ozone contactors must be covered and have systems for the collection of the ozone off-gas because ozone is toxic and must be kept within Occupational Safety and Health Administration (OSHA) allowable limits. A negative pressure is maintained in the headspace of the contacting basin. Blowers are used to convey the gas to catalytic ozone off-gas destruction devices that destroy the remaining ozone and release the treated gas to the atmosphere. Off-gas facilities include a thermal-catalytic destruct unit, blowers, and ductwork necessary to convey off-gas to the destruct unit.

Ductwork for conveying the off-gas from the contactors to the unit and E&I for the unit were not included in this line item cost. (They are covered by the stainless steel piping and E&I line items.) Off-gas destruction facility costs were based on vendor estimates.

<u>Effluent Ozone Quench</u>

Ideally, the ozone dose provides the treatment necessary in the contactor and no ozone residual is left as the treated stream leaves the contactor. However, this situation is not always achieved, and some ozone residual usually leaves the reactor. To eliminate downstream reactions outside of the contactor, the residual ozone must be quenched (destroyed) prior to the next unit process. The ozone quenching was assumed to be conducted with hydrogen peroxide fed from a storage facility into the effluent stream by chemical feed pumps. The quench system includes peroxide storage, chemical feed pumps, and a liquid phase ozone analyzer. Design assumptions are outlined below.

- Peroxide is stored and used as 35 percent solution (by weight).
- Peroxide quenches ozone 1:1 by weight.
- Ten percent of design transferred dose remains as residual and requires peroxide quench.
- Peroxide storage facilities must allow for 30 days of storage without new deliveries.

Costs were based on calls to vendors; some package delivery systems were costed as well as the individual components to build a complete system. The following three quenching systems, based on dosing requirements, were costed.

- Very small quenching systems are those systems dosing less than 100 gallons per month. These systems were assumed to store peroxide in 55 gallon drums and dose directly from the drums with chemical feed pumps. The pump controls are skid- or frame-mounted near the drums and pumps. No capital cost for tankage is incurred; the drums were assumed to be changed by a chemical supplier (O&M cost only). Cost does not include piping or valving necessary to convey peroxide to the injection location or E&I beyond the purchase of the ozone analyzer. The system cost is the sum of the individual components as quoted by vendors.

- Small quenching systems are those required to dose between 100 and 1000 gallons of peroxide per month. These systems were assumed to maintain permanent stainless steel storage tanks on site in addition to the chemical feed pumps and analyzer. The system cost is the sum of the individual components as quoted by vendors.

- Large quench systems are associated with doses in excess of 1000 gallons of peroxide per month. The costs were based on package systems from a peroxide supply vendor. The cost includes a 9,600 gallon stainless steel storage tank, skid-mounted dosing pumps, some controls between the pumps and the tanks, and all suction piping between the tank and the chemical feed pump.

Chemical Storage

A concrete pad was assumed as a capital cost for the LOX tank and the peroxide tanks at the larger dose and quench requirements. The concrete was assumed to be 12-inch-thick reinforced concrete with an installed slab on grade cost of $350/cubic yard.

Stainless Steel Piping (Including Valves and Duct Work)

A cost addition of 25 percent of the sum of the costs for the ozone generation system, ozone contactor, off-gas destruction facilities, and effluent quench system was included as a process cost line item. This addition captures the material cost of all piping, valves, fittings, ductwork, and dampers to convey the liquid and air streams to or from one unit process to the next. New piping and appurtenances for the liquid stream can be expected before and after the in-plant pumping facilities, ozone generation system, ozone contactors, and effluent ozone quench system.

Budgetary cost estimates for these components in water and wastewater treatment facilities range widely with values from 10 to 35 percent of the process costs being commonly referenced. In the Water model documentation, pipes and valves range from 7 to 20 percent of the cost of the manufactured equipment, depending on the ozone feed rate (lb/day). A recent cost estimate for a full scale ozone retrofit in Southern California has piping (including valves and appurtenances) at 24 percent of total equipment cost and 27 percent of the ozone equipment cost. Ozone is very corrosive; therefore, all process piping that may come into contact with ozone must be made of a corrosion-resistant metal such as stainless steel. The value of 25 percent was selected to represent the premium paid for the corrosive resistant piping that will be required in much of the process.

Electrical and Instrumentation (E&I)

A cost addition of 20 percent of the sum of the costs for the ozone generation system, ozone contactors, off-gas destruction facilities, and effluent quench system was included as a process cost line item to capture the cost of electrical and instrumentation equipment (e.g., cabling, motor control centers, programmable logic controllers (PLCs), additional ozone analyzers, flow meters, communications cable, software, and standby power) beyond that provided with the ozone generation system or effluent quench system. This addition includes instrumentation to ensure the housing around the ozone generator is monitored for ambient ozone levels (alarm systems are typically part of a monitoring program).

Like stainless steel piping, budgetary numbers for E&I range widely depending on the process and the source. The Water model documentation suggests that E&I costs as a percentage of manufactured equipment range from 41 to 56 percent. When applied to the other components of the process not solely to the generation equipment the value of 20 percent was determined to be representative. The ozone generation system costs include much of the monitoring devices needed in and around the ozone generation systems.

pH Adjustment

To control bromate formation during ozonation, it may be necessary to lower the pH in certain waters. Separate costs were estimated for pH adjustment so that this cost could be added to the costs of ozonation, where appropriate. The pH adjustment costs include addition of a feed system and chemical costs to reduce the pH using sulfuric acid and to raise the pH using caustic (after ozonation). Capital costs for pH reduction were developed based on calls to vendors for significant components that make up an acid feed system. Since the acid feed may or may not be used depending on the system, percentages for pipes and valves, E&I, and capital cost multipliers were estimated separately and included as a line item under "indirect costs" in Exhibits 4.19 through 4.21.

Capital Cost Multipliers

Process costs were estimated and added, resulting in a total process cost at each flow rate. This value was then multiplied by the appropriate capital cost multiplier (either 2.0 for large systems treating >1 mgd or 2.5 for small systems treating <1 mgd), resulting in a value that represents constructed process facilities.

Indirect Capital Costs

Indirect costs assumed for the ozone system include housing, operator training, land, permitting, and piloting. Housing costs were based on the estimated footprint of the ozone generation equipment (minimum 100 ft^2), multiplied by an average housing cost of $48.95/$ft^2$ based on RS Means factory building estimates. Operator training was assumed as a capital cost for systems with flows less than 1 mgd. Forty hours were assumed for training; the technical labor rate used varied by system size.

Exhibit 4.17 shows the piloting assumptions for ozone.

Exhibit 4.17: Ozone Piloting Cost Assumptions

Flow range	Pilot Cost ($)
<0.1 mgd	5,000
0.1 to < 1.0 mgd	10,000
≥1.0 mgd	65,000

Source: Exhibit 4.6

The pilot costs for the smaller systems (<1.0 mgd) assume limited testing of the water in an off-site laboratory or possibly at the ozone generation system vendor's facility. The cost for larger systems was based on a detailed cost estimate of an existing pilot system. The piloting assumptions for the larger systems include equipment necessary to perform the testing (using a small clear polyvinyl chloride (PVC) contactor), enough labor to run the test four different times for a week each time (to capture seasonal variability), and labor to write up the findings in the report. No off-gas destruction or ozone quenching is provided. The objective of such a pilot test is to develop design criteria for ozone dose and reactor sizing. The costs above do not capture the effort required to understand how ozone treatment may impact other plant unit processes or the stability of the treated water in the distribution system. Such a piloting effort for a large treatment system would cost significantly more than the numbers shown in Exhibit 4.20.

4.4.4.2 Summary of Ozonation O&M Cost Assumptions

O&M costs include liquid oxygen (LOX) (when used), quenching agent, part replacement, performance monitoring, electricity, and labor. Exhibit 4.18 details the O&M assumptions. Exhibits 4.19 through 4.21 show the O&M costs.

Exhibit 4.18: Ozonation O&M Cost Assumptions

Cost Item	Basis
LOX (where used)	$80/ton for LOX
Quench (H_2O_2)	Chemical suppliers contacted for chemical costs.
Part Replacement	Vendor provided estimates as a percentage of ozone equipment costs.
Electricity	Pumps and ozone generation. $0.08/kWh, 11.3 kWh/lb ozone for smaller systems (<100 lbs/day), includes generator, destruct, and PSA. 5.2 kWh/lb ozone for LOX systems, includes generator and destruct.
Performance Monitoring	1 sample/week/reactor for biological dissolved organic carbon, $100/sample.
pH reduction (when used)	Assuming 50th percentile alkalinity (78 mg/L as CaCO3) and pH (7.7) from the ICR database, acid and caustic O&M costs were estimated. The unit costs for chemicals were based on bulk shipments from chemical suppliers.

Source: Section 4.4.3

The labor costs are a function of the cost category and the assumptions on the level of effort for each system. Assumptions for systems at the technical rate are as follows:

- 3 hr/week for monitoring plus 4 hr/month maintenance (<100 mgd design flow)
- 6 hr/week for monitoring plus 8 hr/month maintenance (>100 mgd design flow)

Assumptions for systems at the managerial rate are as follows:

- 1 hr/week (<100 mgd design flow)
- 4 hr/week (>100 mgd design flow)

Exhibit 4.19: Ozonation Cost Summary (0.5 log *Cryptosporidium* Inactivation)

Design Flow (mgd)	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.025	0.054	0.084	0.11	0.23	0.35
Unit Capital Cost Summary						
Total Unit Capital Cost (no pH adj.)	322,787	382,874	438,785	493,394	675,951	804,614
Indirect Capital Costs (no pH adj.)	17,416	23,496	24,657	25,727	29,307	88,293
Total Unit Capital Cost (with pH adj.)	345,519	425,999	483,484	539,668	727,824	862,086
Indirect Capital Costs (with pH adj.)	40,147	66,620	69,356	72,001	81,180	145,765
Piloting	5,000	10,000	10,000	10,000	10,000	65,000
Permitting	3,664	4,313	4,970	5,612	7,760	10,745
Land	2,443	2,875	3,313	3,741	5,173	7,163
Operator Training	924	924	990	990	990	-
Housing	5,385	5,385	5,385	5,385	5,385	5,385
pH adjustment (if used)	22,732	43,124	44,699	46,274	51,873	57,472
Direct Capital Cost[1]	305,371	359,379	414,128	467,667	646,644	716,322
Subtotal Process Cost	122,149	143,752	165,651	187,067	258,657	358,161
Stainless pipes, valves, ductwork	15,954	19,483	23,061	26,556	38,593	54,321
Ozone process E&I	12,763	15,586	18,449	21,245	30,875	43,457
Off-Gas Destruction	6,528	7,712	8,910	10,108	14,366	18,625
Effluent Ozone Quench	4,908	4,955	5,003	5,051	5,221	5,391
Ozone Contactor	8,164	13,027	17,982	22,603	37,476	67,114
Ozone Generation System	44,215	52,238	60,351	68,463	97,309	126,155
In-plant pumping	29,617	30,750	31,895	33,040	34,817	43,097
Chemical Storage	-	-	-	-	-	-
Annual O&M Summary						
Total Annual O&M Cost (no pH adj.)	55,520	55,884	59,391	59,737	61,152	62,566
Total Annual O&M Cost (with pH adj.)	56,513	58,029	62,728	64,107	70,289	76,470
Chemicals O2	-	-	-	-	-	-
Chemicals H2O2	36	79	123	161	336	511
Part Replacement	946	1,118	1,292	1,465	2,082	2,700
Performance monitoring	10,400	10,400	10,400	10,400	10,400	10,400
Electricity	306	456	611	746	1,368	1,990
Labor	43,832	43,832	46,966	46,966	46,966	46,966
pH adjustment (when used)	993	2,145	3,337	4,370	9,137	13,904

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Design Dose = 4.5 mg/L, Average Dose = 2.43 mg/L
Source: Section 4.4.4

Exhibit 4.19 (continued): Ozonation Cost Summary (0.5 log *Cryptosporidium* Inactivation)

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270
Unit Capital Cost Summary									
Total Unit Capital Cost (no pH adj.)	902,391	1,226,541	1,595,373	2,357,412	3,946,957	4,546,365	12,628,950	26,317,852	44,918,178
Indirect Capital Costs (no pH adj.)	90,677	104,174	121,302	158,864	270,284	317,434	865,894	1,947,368	3,430,304
Total Unit Capital Cost (with pH adj.)	963,363	1,301,510	1,696,587	2,519,866	4,284,381	4,971,274	13,998,697	30,032,197	52,481,863
Indirect Capital Costs (with pH adj.)	151,649	179,143	222,516	321,318	607,708	742,343	2,235,641	5,661,713	10,993,989
Piloting	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000
Permitting	12,176	16,836	22,111	32,978	55,150	63,434	176,446	365,557	500,000
Land	8,117	11,224	14,741	21,985	36,767	42,289	117,631	243,705	414,879
Operator Training	-	-	-	-	-	-	-	-	-
Housing	5,385	11,114	19,450	38,900	113,367	146,710	506,817	1,273,106	2,450,426
pH adjustment (if used)	60,971	74,969	101,215	162,454	337,424	424,909	1,369,747	3,714,345	7,563,685
Direct Capital Cost[1]	811,714	1,122,367	1,474,071	2,198,548	3,676,673	4,228,931	11,763,056	24,370,484	41,487,874
Subtotal Process Cost	405,857	561,184	737,035	1,099,274	1,838,337	2,114,466	5,881,528	12,185,242	20,743,937
Stainless pipes, valves, ductwork	61,756	85,853	111,868	167,219	280,370	322,289	811,823	1,542,432	2,433,201
Ozone process E&I	49,405	68,682	89,494	133,775	224,296	257,831	649,458	1,233,946	1,946,560
Off-Gas Destruction	21,287	29,525	36,307	52,132	82,171	91,729	251,298	425,249	594,031
Effluent Ozone Quench	5,497	5,922	6,719	8,578	13,889	16,545	72,638	121,238	201,029
Ozone Contactor	76,058	107,982	158,526	255,057	468,843	559,567	1,221,228	2,742,878	4,914,161
Ozone Generation System	144,184	199,982	245,920	353,108	556,575	621,315	1,702,128	2,880,363	4,023,582
In-plant pumping	47,671	63,238	86,184	126,461	206,601	238,274	1,151,745	3,182,452	6,516,449
Chemical Storage	-	-	2,018	2,944	5,592	6,915	21,211	56,684	114,924
Annual O&M Summary									
Total Annual O&M Cost (no pH adj.)	63,350	67,621	77,719	95,346	145,700	177,752	464,832	1,377,320	2,871,997
Total Annual O&M Cost (with pH adj.)	79,638	98,210	133,334	214,522	455,559	614,733	1,974,401	6,144,381	13,597,884
Chemicals O2	-	-	4,557	9,764	25,387	35,802	123,681	390,570	878,783
Chemicals H2O2	598	1,124	1,605	3,439	8,943	12,611	43,567	137,580	309,554
Part Replacement	3,086	4,280	5,263	7,557	11,911	13,296	36,426	61,640	86,105
Performance monitoring	10,400	10,400	10,400	10,400	10,400	10,400	15,600	31,200	52,000
Electricity	2,301	4,166	7,431	15,722	40,596	57,179	197,096	622,028	1,399,343
Labor	46,966	47,652	48,463	48,463	48,463	48,463	48,463	134,302	146,212
pH adjustment (when used)	16,287	30,589	55,616	119,177	309,859	436,981	1,509,569	4,767,061	10,725,886

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Design Dose = 4.5 mg/L, Average Dose = 2.43 mg/L
Source: Section 4.4.4

Exhibit 4.20: Ozonation Cost Summary (1.0 log *Cryptosporidium* Inactivation)

Design Flow (mgd)	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.025	0.054	0.084	0.11	0.23	0.35
Unit Capital Cost Summary						
Total Unit Capital Cost (no pH adj.)	351,943	440,546	525,292	608,737	893,979	1,043,133
Indirect Capital Costs (no pH adj.)	17,987	24,626	26,353	27,989	33,737	96,809
Total Unit Capital Cost (with pH adj.)	374,675	483,670	569,991	655,011	945,852	1,100,605
Indirect Capital Costs (with pH adj.)	40,719	67,751	71,052	74,263	85,610	154,281
Piloting	5,000	10,000	10,000	10,000	10,000	65,000
Permitting	4,007	4,991	5,987	6,969	10,323	14,195
Land	2,672	3,327	3,992	4,646	6,882	9,463
Operator Training	924	924	990	990	990	-
Housing	5,385	5,385	5,385	5,385	5,542	8,151
pH adjustment (if used)	22,732	43,124	44,699	46,274	51,873	57,472
Direct Capital Cost[1]	333,956	415,919	498,939	580,748	860,242	946,324
Subtotal Process Cost	133,582	166,368	199,576	232,299	344,097	473,162
Stainless pipes, valves, ductwork	17,925	23,382	28,910	34,355	53,324	74,149
Ozone process E&I	14,340	18,706	23,128	27,484	42,659	59,319
Off-Gas Destruction	7,537	9,709	11,904	14,100	21,908	28,771
Effluent Ozone Quench	4,948	5,035	5,122	5,210	5,522	5,833
Ozone Contactor	8,164	13,027	17,982	22,603	37,476	67,114
Ozone Generation System	51,051	65,759	80,633	95,506	148,390	194,878
In-plant pumping	29,617	30,750	31,895	33,040	34,817	43,097
Chemical Storage	-	-	-	-	-	-
Annual O&M Summary						
Total Annual O&M Cost (no pH adj.)	55,827	56,438	60,197	60,781	63,138	65,357
Total Annual O&M Cost (with pH adj.)	56,820	58,583	63,534	65,150	72,274	79,261
Chemicals O2	-	-	-	-	-	-
Chemicals H2O2	63	137	213	279	583	887
Part Replacement	1,092	1,407	1,726	2,044	3,176	4,170
Performance monitoring	10,400	10,400	10,400	10,400	10,400	10,400
Electricity	440	662	893	1,092	2,013	2,934
Labor	43,832	43,832	46,966	46,966	46,966	46,966
pH adjustment (when used)	993	2,145	3,337	4,370	9,137	13,904

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Design Dose = 8.25 mg/L, Average Dose = 4.22 mg/L
Source: Section 4.4.4

Exhibit 4.20 (continued): Ozonation Cost Summary (1.0 log *Cryptosporidium* Inactivation)

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270
Unit Capital Cost Summary									
Total Unit Capital Cost (no pH adj.)	1,119,608	1,416,784	1,922,483	2,912,264	4,697,222	5,517,296	15,011,417	30,378,296	55,716,052
Indirect Capital Costs (no pH adj.)	100,264	117,850	145,093	204,024	380,751	460,391	1,294,845	2,967,593	5,369,742
Total Unit Capital Cost (with pH adj.)	1,180,580	1,491,753	2,023,698	3,074,718	5,034,646	5,942,205	16,381,164	34,092,641	63,279,737
Indirect Capital Costs (with pH adj.)	161,236	192,819	246,308	366,478	718,175	885,300	2,664,592	6,681,938	12,933,427
Piloting	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000
Permitting	15,290	19,484	26,661	40,624	64,747	75,854	205,749	411,161	500,000
Land	10,193	12,989	17,774	27,082	43,165	50,569	137,166	274,107	503,463
Operator Training	-	-	-	-	-	-	-	-	-
Housing	9,781	20,376	35,659	71,318	207,840	268,969	886,930	2,217,326	4,301,279
pH adjustment (if used)	60,971	74,969	101,215	162,454	337,424	424,909	1,369,747	3,714,345	7,563,685
Direct Capital Cost[1]	1,019,344	1,298,934	1,777,390	2,708,240	4,316,471	5,056,904	13,716,572	27,410,702	50,346,310
Subtotal Process Cost	509,672	649,467	888,695	1,354,120	2,158,235	2,528,452	6,858,286	13,705,351	25,173,155
Stainless pipes, valves, ductwork	79,655	100,718	137,883	210,891	334,878	392,829	977,339	1,796,532	3,180,504
Ozone process E&I	63,724	80,575	110,306	168,713	267,902	314,263	781,871	1,437,226	2,544,403
Off-Gas Destruction	30,429	37,060	49,494	74,206	109,252	126,775	333,513	547,838	961,858
Effluent Ozone Quench	6,028	6,807	8,268	11,676	21,414	26,283	95,608	184,708	330,991
Ozone Contactor	76,058	107,982	158,526	255,057	468,843	559,567	1,221,228	2,742,878	4,914,161
Ozone Generation System	206,107	251,024	335,243	502,626	740,003	858,692	2,259,005	3,710,705	6,515,004
In-plant pumping	47,671	63,238	86,184	126,461	206,601	238,274	1,151,745	3,182,452	6,516,449
Chemical Storage	-	2,062	2,790	4,489	9,342	11,769	37,977	103,011	209,785
Annual O&M Summary									
Total Annual O&M Cost (no pH adj.)	66,210	75,885	87,731	115,823	194,432	245,991	694,758	2,083,382	4,473,882
Total Annual O&M Cost (with pH adj.)	82,498	106,474	143,347	234,999	504,291	682,971	2,204,327	6,850,443	15,199,769
Chemicals O2	-	4,352	7,913	16,957	44,088	62,175	214,787	678,274	1,526,117
Chemicals H2O2	1,039	1,951	2,787	5,973	15,530	21,901	75,659	238,924	537,580
Part Replacement	4,411	5,372	7,174	10,756	15,836	18,376	48,343	79,409	139,421
Performance monitoring	10,400	10,400	10,400	10,400	10,400	10,400	15,600	31,200	52,000
Electricity	3,395	6,158	10,993	23,274	60,115	84,675	291,906	921,272	2,072,552
Labor	46,966	47,652	48,463	48,463	48,463	48,463	48,463	134,302	146,212
pH adjustment (when used)	16,287	30,589	55,616	119,177	309,859	436,981	1,509,569	4,767,061	10,725,886

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Design Dose = 8.25 mg/L, Average Dose = 4.22 mg/L
Source: Section 4.4.4

Exhibit 4.21: Ozonation Cost Summary (2.0 log *Cryptosporidium* Inactivation)

Design Flow (mgd)	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.025	0.054	0.084	0.11	0.23	0.35
Unit Capital Cost Summary						
Total Unit Capital Cost (no pH adj.)	372,391	480,993	585,963	689,631	1,069,196	1,107,713
Indirect Capital Costs (no pH adj.)	18,388	25,420	27,543	29,575	38,905	100,919
Total Unit Capital Cost (with pH adj.)	395,123	524,117	630,662	735,905	1,121,069	1,165,185
Indirect Capital Costs (with pH adj.)	41,120	68,544	72,242	75,849	90,778	158,391
Piloting	5,000	10,000	10,000	10,000	10,000	65,000
Permitting	4,248	5,467	6,701	7,921	12,363	15,102
Land	2,832	3,645	4,467	5,280	8,242	10,068
Operator Training	924	924	990	990	990	-
Housing	5,385	5,385	5,385	5,385	7,309	10,749
pH adjustment (if used)	22,732	43,124	44,699	46,274	51,873	57,472
Direct Capital Cost[1]	354,003	455,573	558,420	660,056	1,030,292	1,006,794
Subtotal Process Cost	141,601	182,229	223,368	264,022	412,117	503,397
Stainless pipes, valves, ductwork	19,308	26,117	33,013	39,825	65,052	79,362
Ozone process E&I	15,446	20,894	26,410	31,860	52,041	63,490
Off-Gas Destruction	8,245	11,109	14,004	16,900	27,916	31,414
Effluent Ozone Quench	4,976	5,091	5,206	5,322	5,733	6,144
Ozone Contactor	8,164	13,027	17,982	22,603	37,476	67,114
Ozone Generation System	55,845	75,242	94,857	114,473	189,082	212,776
In-plant pumping	29,617	30,750	31,895	33,040	34,817	43,097
Chemical Storage	-	-	-	-	-	-
Annual O&M Summary						
Total Annual O&M Cost (no pH adjust.)	56,096	56,900	60,858	61,627	64,836	66,956
Total Annual O&M Cost (with pH adjust)	57,089	59,046	64,195	65,997	73,973	80,860
Chemicals O2	-	-	-	-	-	-
Chemicals H2O2	88	189	295	386	807	1,227
Part Replacement	1,195	1,610	2,030	2,450	4,046	4,553
Performance monitoring	10,400	10,400	10,400	10,400	10,400	10,400
Electricity	581	869	1,167	1,425	2,617	3,809
Labor	43,832	43,832	46,966	46,966	46,966	46,966
pH adjustment (when used)	993	2,145	3,337	4,370	9,137	13,904

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Design Dose = 10.88 mg/L, Average Dose = 5.84 mg/L
Source: Section 4.4.4

Exhibit 4.21 (continued): Ozonation Cost Summary (2.0 log *Cryptosporidium* Inactivation)

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270
Unit Capital Cost Summary									
Total Unit Capital Cost (no pH adj.)	1,200,916	1,547,877	2,151,897	3,124,381	5,223,408	6,291,141	16,720,757	34,225,903	63,362,091
Indirect Capital Costs (no pH adj.)	105,289	127,385	161,779	231,378	458,226	562,918	1,634,118	3,781,084	6,803,065
Total Unit Capital Cost (with pH adj.)	1,261,887	1,622,846	2,253,111	3,286,835	5,560,832	6,716,050	18,090,504	37,940,248	70,925,776
Indirect Capital Costs (with pH adj.)	166,261	202,354	262,994	393,832	795,650	987,827	3,003,865	7,495,429	14,366,750
Piloting	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000	65,000
Permitting	16,434	21,307	29,852	43,395	71,478	85,923	226,300	456,672	500,000
Land	10,956	14,205	19,901	28,930	47,652	57,282	150,866	304,448	565,590
Operator Training	-	-	-	-	-	-	-	-	-
Housing	12,899	26,872	47,026	94,053	274,096	354,713	1,191,953	2,954,963	5,672,474
pH adjustment (if used)	60,971	74,969	101,215	162,454	337,424	424,909	1,369,747	3,714,345	7,563,685
Direct Capital Cost[1]	1,095,627	1,420,493	1,990,118	2,893,004	4,765,182	5,728,222	15,086,639	30,444,819	56,559,026
Subtotal Process Cost	547,813	710,246	995,059	1,446,502	2,382,591	2,864,111	7,543,319	15,222,410	28,279,513
Stainless pipes, valves, ductwork	85,911	111,144	156,128	226,633	373,107	450,115	1,093,421	2,052,492	3,704,612
Ozone process E&I	68,729	88,915	124,903	181,306	298,485	360,092	874,736	1,641,994	2,963,690
Off-Gas Destruction	33,600	42,346	58,743	82,027	128,245	151,354	391,174	673,823	1,219,827
Effluent Ozone Quench	6,401	7,428	9,354	13,849	26,692	64,365	111,718	229,221	422,138
Ozone Contactor	76,058	107,982	158,526	255,057	468,843	559,567	1,221,228	2,742,878	4,914,161
Ozone Generation System	227,585	286,821	397,889	555,597	868,647	1,025,172	2,649,562	4,564,047	8,262,322
In-plant pumping	47,671	63,238	86,184	126,461	206,601	238,274	1,151,745	3,182,452	6,516,449
Chemical Storage	1,859	2,371	3,332	5,572	11,972	15,173	49,735	135,502	276,314
Annual O&M Summary									
Total Annual O&M Cost (no pH adjust.)	68,079	74,291	85,473	211,156	424,479	541,290	1,710,724	4,846,200	10,067,081
Total Annual O&M Cost (with pH adjust)	84,366	104,880	141,088	330,332	734,338	978,271	3,220,293	9,613,261	20,792,968
Chemicals O2	-	-	-	102,009	247,736	320,600	1,107,526	3,060,270	6,266,268
Chemicals H2O2	1,438	2,122	3,858	8,266	21,492	30,309	104,704	330,644	743,949
Part Replacement	4,870	6,138	8,515	11,890	18,589	21,939	56,701	97,671	176,814
Performance monitoring	10,400	10,400	10,400	10,400	10,400	10,400	15,600	31,200	52,000
Electricity	4,405	7,980	14,237	30,128	77,799	109,580	377,730	1,192,113	2,681,838
Labor	46,966	47,652	48,463	48,463	48,463	48,463	48,463	134,302	146,212
pH adjustment (when used)	16,287	30,589	55,616	119,177	309,859	436,981	1,509,569	4,767,061	10,725,886

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Design Dose = 10.88 mg/L, Average Dose = 5.84 mg/L
Source: Section 4.4.4

4.4.5 Microfiltration and Ultrafiltration

Microfiltration and ultrafiltration can be effective for the control of microbial contaminants, including *Cryptosporidium*. The costs presented in this section assume an MF/UF system is either an addition to an existing conventional treatment plant, or a replacement for granular media filters. In the latter case, it is assumed the settled water is of sufficient quality (i.e., low total suspended solids) that additional pretreatment is not required. Costs are provided for a design feed water temperature of 10°C. As discussed in Chapters 2 and 3, water temperature can impact system flux. The design feed water temperature was selected as an approximate average condition for systems that might consider MF/UF treatment. Systems with lower feed water temperatures may require additional membrane area or increased operating pressure to maintain the desired level of production. Systems with warmer feed water temperatures may require smaller membrane areas and lower operating pressures.

MF/UF processes will generate a liquid residual stream that must be disposed of or recycled. For the purposes of this document, it was assumed that backwash and reject water would be discharged to a sanitary sewer for treatment at a POTW. The costs presented assume an average system recovery of 93 percent (i.e., the residuals volume equals seven percent of the average daily plant flow).

4.4.5.1 Summary of MF/UF Capital Cost Assumptions

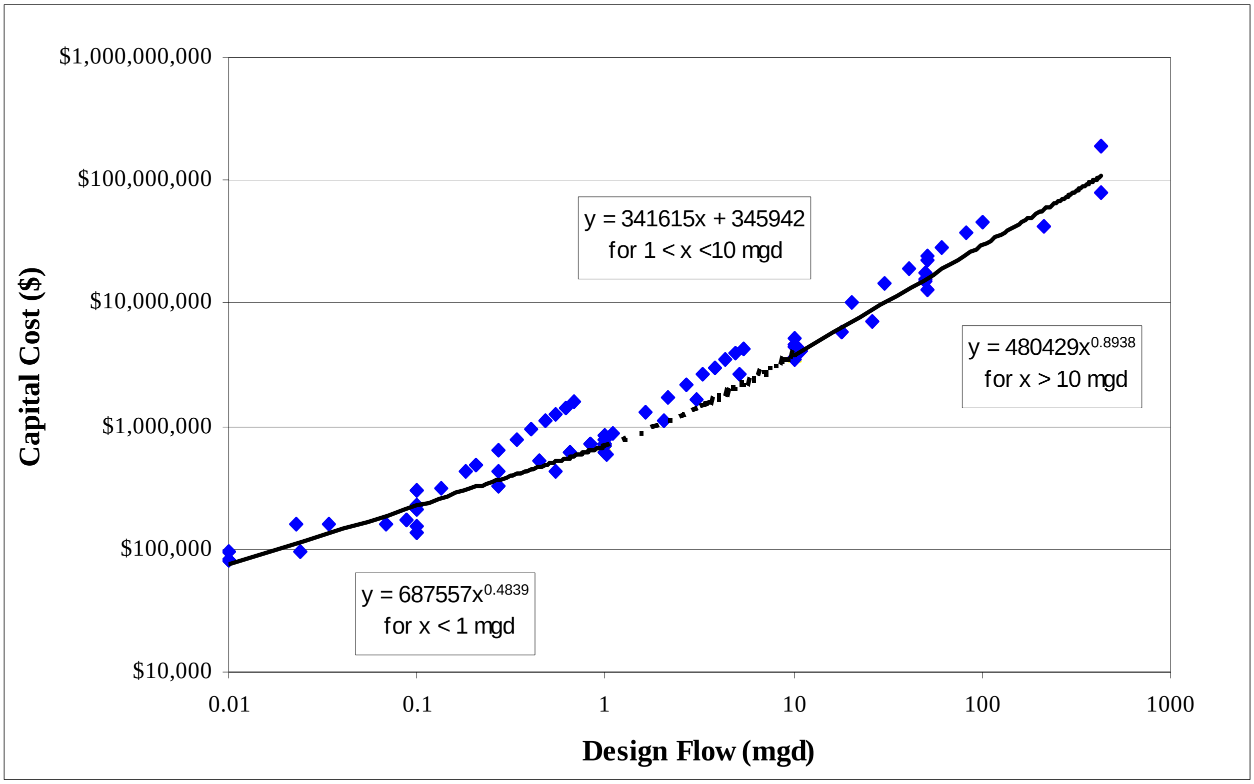
Process Costs

Capital costs were estimated based on vendor data, cost estimating guides (RS Means), and best professional judgment. Process costs were obtained in 2002 adjusted to year 2003 dollars using the ENR BCI. Exhibit 4.29 presents a summary of line item capital costs for MF/UF, based on a design flow of 10°C, and assuming discharge of backwash water to a sanitary sewer for treatment at a POTW. This section discusses the methodology used for estimating capital costs.

<u>Membrane System</u>

For a range of flows, vendors were asked to provide costs for skid-mounted membrane modules that included prefilters (about 200 micron), associated piping, feed pumps, backwash and recirculation pumps (where appropriate), chemical cleaning feed tanks and pumps, and direct integrity testing instrumentation. A maximum skid size of 2 mgd was required. Exhibit 4.22 plots the cost estimates received from the vendors for different design flows, as well as the resulting cost equations that are used to estimate membrane system costs.

Exhibit 4.22: Summary of MF/UF Vendor Estimates



Source: Vendor quotes

Interstage Piping and Pumping

The costs associated with interstage pumping are included as a process cost based on the assumption that some systems may not be able to incorporate MF/UF into the existing plant hydraulic profile. Depending on the system size, the additional total dynamic head requirements were assumed to vary because of the increased complexities of the larger systems (e.g., additional pipes, valves, and fittings, and more membrane skids). For the purposes of estimating a typical MF/UF system cost, total dynamic head (TDH) needs for systems were assumed to vary between 30 and 75 feet as shown in Exhibit 4.23. These assumptions are based on experience with similar systems.

Exhibit 4.23: Summary of MF/UF Interstage Pumping Assumptions

System Size (mgd)	Interstage Pumping Requirements (TDH)
< 1	30 feet
1 - 10	50 feet
> 10	75 feet

Costs for interstage piping and pumping were estimated based upon vendor data and RS Means (1999). Pump and piping costs were totaled and a regression line was fit through the data to estimate the costs for each of the required flow categories. The resulting equations are presented below.

For design flow <1 mgd:
$$\text{Interstage pumps and piping (\$)} = 28023 \times (\text{Design Flow})^{0.7265}$$

For design flow >1 mgd:
$$\text{Interstage pumps and piping (\$)} = 30918 \times (\text{Design Flow})^{0.8103}$$

An additional 20 percent was added for the cost of electrical and instrumentation associated with the interstage pumping.

Process Monitoring Equipment

Membrane skids are generally equipped to conduct periodic, direct integrity tests (e.g., pressure-hold test or bubble-point test). While these methods are the most sensitive to breaches in membrane integrity, they do not provide a real-time measure of membrane integrity (USEPA 2001). As a result, on-line integrity testing may be required for use of MF/UF to remove microbial contaminants. Accordingly, one turbidimeter ($2,500 each) was assumed per skid for systems less than 1 mgd, and one particle counter ($5,000 each) was assumed per skid for systems larger than 1 mgd. (A maximum skid size of 2 mgd was assumed for all system sizes.)

Membrane I&C

Costs for membrane system I&C were estimated based upon vendor data and input from industry experts. For systems less than 1 mgd, membrane I&C was included in the cost of the membrane system. For systems larger than 1 mgd, the cost of membrane I&C was assumed to be $102,000 for the first skid and $77,000 for each additional skid. These costs include interconnection between skids and tie-in to existing plant control (e.g., SCADA) systems.

Capital Cost Multipliers

The capital costs previously discussed (membrane system, interstage pumping and piping, membrane E&I, and process monitoring equipment) were totaled to arrive at a total process cost, and multiplied by a capital cost factor of 1.67 (for flow <2 mgd) or 2.0 (for flow >2 mgd). The result of this multiplication was then added to the indirect capital costs (discussed later in this section) to arrive at the total capital cost. The capital cost factors were intended to account for items not included in vendor estimates. A complete discussion of capital cost factors, including the components, is presented in section 4.2.1.

Indirect Capital Costs

The total permitting, piloting, membrane housing, land, operator training, and backwash pipeline costs are referred to as indirect capital costs for the purposes of this document.

Permitting

Significant process improvements will likely require coordination with the appropriate regulatory agency. As such, permitting costs were included at three percent of the process cost. A minimum permitting fee of $2,500 and a maximum of $500,000 was assumed.

Pilot Testing

It was assumed that pilot- or bench-scale tests would be necessary to ensure compatibility of membrane materials with process chemicals (e.g., coagulants or polymers), as well as to determine critical design parameters, such as design flux. Bench-scale flat sheet tests were assumed for systems less than 0.1 mgd, at a cost of $1,000. Single-element tests ($10,000) were assumed for systems between 0.1 and 1 mgd, and three-month pilot tests were assumed for systems 1 mgd and larger ($60,000).

Membrane Housing

Membrane housing costs include the cost for a building to house the membrane skids and any associated appurtenances (e.g., building electrical, HVAC, and lighting). For this document, size was based on an industry rule of thumb for MF/UF processes: 1,100 ft^2 per mgd for systems with design flows less than 10 mgd and 1,300 ft^2 per mgd for design flows greater than 10 mgd. A minimum size of 200 ft^2 was also assumed. The footprint was multiplied by a housing unit cost of $48.95, based on RS Means values for a factory type building.

Land

MF/UF requires significantly larger footprints than other technologies for which costs are provided. MF/UF is also likely to be able to be incorporated into existing process footprints. Land cost assumptions for MF/UF are listed in Exhibit 4.24.

Exhibit 4.24: MF/UF Land Cost Assumptions

Design Flow (mgd)	Land Cost (% of Capital)*
< 10	1%
> 10	0.5%

Note: * Capital = Total Process Cost × Capital Cost Multiplier
Source: Exhibit 4.7

As discussed in section 4.2.4, the NDWAC cost working group recommended a factor of two to five percent for land. Previous technology cost efforts (USEPA 2001) adopted land costs at factor of five percent for systems less than 1 mgd and 2 percent for systems greater than 1 mgd; however, previous cases assumed new plant construction, as opposed to a retrofit as was assumed in this document. To measure the appropriateness of the NDWAC recommendations, an analysis of the land cost (per acre) was conducted based upon the footprint of the MF/UF process. The land cost (as a percent of capital) was adjusted based upon this analysis and best professional judgment. A list of assumptions used in this analysis is listed below.

- Minimum land purchase - 0.5 acres
- Building area - 1300 ft^2 per mgd for systems < 10 mgd
- 1100 ft^2 per mgd for systems > 10 mgd
- Building is square
- 50-foot perimeter around building

The land area was compared to the land costs at various percentages, and a "reasonableness" valuation was made based on best professional judgment. Under the final scenario, estimates of land costs gradually increased from $2,200 per acre for the smallest system size to $92,500 per acre for the largest.

Operator Training

The NDWAC cost working group also recommended inclusion of operator training. Based upon system size, this training could last a few hours or a few days. Exhibit 4.25 summarizes the operator training cost assumptions used in this document. Costs are based on experience with similar systems and best professional judgement.

Exhibit 4.25: Summary of MF/UF Operator Training Cost Assumptions

Design Flow (mgd)	Training Cost ($)
< 0.3	included in membrane system price
0.3 - 1	$1,000
1 - 10	$3,000
10 - 100	$10,000
> 100	$25,000

Backwash Pipeline

Capital costs for a 500-foot pipeline to discharge backwash and reject water to a sanitary sewer were estimated based on cost equations presented in *Small Water System Byproducts Treatment and Disposal Cost Document* (DPRA 1993a) and *Water System Byproducts Treatment and Disposal Cost Document* (DPRA 1993b). These costs are shown as an indirect cost (after the application of the capital cost multiplier) because they already include factors for engineering, contractor overhead and profit, and installation.

Exhibit 4.26 summarizes the pipe diameter assumptions used in the DPRA documents. The equations used to estimate pipeline costs follow the exhibit.

Exhibit 4.26: Summary of Backwash Disposal Pipeline Assumptions

Backwash Volume (mgd)	Pipeline Diameter (inches)	Pipe Material
< 162,500	2	Sch-40 PVC
162,500 - 500,000	3	Sch-40 PVC
500,000 - 750,000	4	Sch-40 PVC
750,000 - 10,000,000	6	Sch-40 PVC
10,000,000 - 25,000,000	24	Reinforced concrete
> 25,000,000	36	Reinforced concrete

Source: DPRA (1993a and 1993b).

For systems < 1 mgd (DPRA 1993a)
Backwash volume <150,000 gpd:
Pipeline cost ($) = 3,500
Backwash volume > 150,000 gpd:
Pipeline cost ($) = 27,000 + (3.1 × (Backwash Volume)$^{0.5}$)

For systems > 1 mgd (DPRA 1993b)
Backwash volume < 150,000 gpd:
Pipeline cost ($) = 4,500
Backwash volume > 150,000 gpd:
Pipeline cost ($) = 4,600 + (0.0019 × Backwash Volume)

Costs in the DPRA documents are presented in year 1992 dollars. The ENR BCI (average 1992 value = 2,834) was used to escalate costs to year 2003 (index = 3,693). Consequently, the results of the previous equations were multiplied by a factor of 1.30 (3,693 ÷ 2,834) to obtain the final pipeline cost estimates.

4.4.5.2 Summary of MF/UF O&M Cost Assumptions

MF/UF operations and maintenance costs were based on vendor estimates, industry guidelines, and cost models. Exhibit 4.28 presents a summary of line item O&M costs. This section discusses the assumptions regarding O&M estimates presented in this document.

Membrane Replacement

Membrane replacement costs for all flows were derived from typical, or average, replacement cost estimates provided by manufacturers. The manufacturer estimates as shown in Exhibit 4.27 were plotted and liner regressions were used to develop the following best fit equation for the full range of design flows:

$$\text{Membrane replacement (\$/yr)} = (0.5647 \times \text{Design Flow}^2) + (13{,}152 \times \text{Design Flow}) + 304.49$$

Exhibit 4.27: Summary of Membrane Replacement Costs

Design Flow (mgd)	Average Membrane Replacement Cost ($/year)
0.01	$436
0.1	$1620
1	$13,457
10	$131,881
50	$659,316
430	$5,760,078

Source: Vendor estimates

Performance Monitoring

In addition to continuous turbidity or particle count monitoring (included in the process monitoring equipment line item), the costs for periodic HPC monitoring were included in the O&M estimates. HPC is monitored to detect biological activity on the finished water side of the membrane. HPC tests are available for approximately $1 per test, and require one hour of labor. One test per membrane skid per week was assumed.

Clean-in-Place Chemicals

MF/UF systems will require periodic (typically, quarterly or semi-annually) chemical cleaning to remove biological and colloidal foulants. This is referred to as a clean-in-place (CIP) operation. CIP practices can include the use of detergents, acids, bases, oxidizing agents (e.g., chlorine for removal of biofilm), chelating agents, or enzymatic cleaners. Because of the variability in CIP practices, a standard rule-of-thumb of $0.01 per 1000 gallons of water produced was applied to estimate CIP chemical costs. Thus, CIP chemical costs can be estimated as follows:

$$\text{CIP chemicals (\$/yr)} = 0.01 \times \text{Average Flow (mgd)} \times 1000 \times 365$$

Materials

Materials include replacement parts for interstage piping and pumping and were estimated based on output from the Water and W/W Cost models. The resulting material cost equations are presented below:

For average flow up to 0.35 mgd
$\text{Materials (\$/yr)} = (-283.6 \times \text{Average Flow}^2) + (283.77 \times \text{Average Flow}) + 107.62$

For average flow greater than 0.35 to 4.5 mgd
$\text{Materials (\$/yr)} = (547.62 \times \text{Average Flow}) - 24.122$

For average flow >4.5 mgd
$\text{Materials (\$/yr)} = (-0.3794 \times \text{Average Flow}^2) + (394.56 \times \text{Average Flow}) + 672.35$

Power

Power costs include electricity for interstage pumps, membrane skids, and instrumentation. Interstage pumping power costs were estimated based on annual kWh estimates provided by the Water and W/W Cost models and membrane skid power requirements provided by vendors. The equations used for annual power costs are provided below.

<u>For average flow < 0.36 mgd</u>:
Power ($/yr) = 16561 × (Average Flow)$^{1.0113}$

<u>For average flow 0.36 - 4.5 mgd</u>:
Power ($/yr) = (5096.5 × Average Flow) + 4058.8

<u>For average flow > 4.5 mgd</u>:
Power ($/yr) = (5356.9 × Average Flow) + 2666.3

Labor

Labor estimates include operation and maintenance of interstage pumping and membrane skids, as well as labor associated with repair of process equipment. Technical labor rates varied based on system size. Labor hours are based on vendor estimates and experience with similar systems. No additional managerial labor was assumed. A summary of labor hour assumptions is provided in Exhibit 4.28.

Exhibit 4.28: Summary of MF/UF Labor Assumptions

System Size (mgd)	Technical Labor (hrs/week)
< 0.1	4
0.1 - 1	12
1 - 5	24
5 - 10	40
10 - 100	80
> 100	160

POTW Surcharge

The reject and backwash volume is assumed to be at a volume of seven percent of the feed flow (i.e., 93 percent recovery). The discharge of reject and backwash water to a POTW assumed the following (DPRA 1993):

- POTW surcharge of $0.00183/1,000 gallons discharged
- Base charge of $375/year for small systems, $1,000/year for large systems

Exhibit 4.29: Microfiltration/Ultrafiltration Cost Summary

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary									
Total Unit Capital Cost	131,478	214,432	270,819	409,983	628,117	748,563	850,970	1,133,988	1,594,911
Indirect Capital Costs	18,759	20,553	22,087	25,873	92,942	96,219	99,977	107,676	172,007
Membrane housing	9,790	9,790	9,790	9,790	63,635	63,635	63,635	63,635	63,635
Bench/pilot-scale testing	1,000	1,000	1,000	1,000	10,000	10,000	10,000	10,000	60,000
Permitting	2,500	3,483	4,468	6,900	9,614	11,719	13,491	18,437	25,561
Land	1,127	1,939	2,487	3,841	5,352	6,523	7,510	10,263	14,229
Operator Training	-	-	-	-	-	-	1,000	1,000	3,000
500' backwash discharge pipeline	4,342	4,342	4,342	4,342	4,342	4,342	4,342	4,342	5,582
Direct Capital Cost[1]	112,719	193,878	248,732	384,110	535,174	652,345	750,992	1,026,312	1,422,904
Subtotal Process Cost	67,496	116,095	148,941	230,006	320,464	390,626	449,696	614,558	852,038
Interstage piping and pumping	783	1,798	2,623	5,044	8,280	11,116	13,700	21,747	31,752
Membrane equipment	63,990	111,370	143,226	221,385	307,960	374,719	430,688	585,894	706,103
Process monitoring equipment	2,567	2,567	2,567	2,567	2,567	2,567	2,567	2,567	5,135
Electrical	157	360	525	1,009	1,656	2,223	2,740	4,349	6,350
Instrumentation and controls	-	-	-	-	-	-	-	-	102,697
Annual O&M Summary									
Total Annual O&M Cost	6,230	6,686	7,156	9,329	22,042	26,348	29,272	41,522	69,214
Membrane Replacement	397	594	791	1,501	2,672	3,856	5,039	9,248	13,457
Performance monitoring	1,167	1,167	1,167	1,253	1,253	1,338	1,338	1,338	1,338
CIP Chemicals	5	20	35	91	197	307	402	840	1,278
Materials	108	109	110	115	122	129	135	158	172
Electricity	23	84	149	397	865	1,353	1,777	3,746	5,728
Technical labor	4,460	4,460	4,460	4,803	14,408	15,438	15,438	15,438	30,876
POTW surcharge	70	252	444	1,169	2,525	3,928	5,143	10,754	16,365

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Based on Temperature=10°C
Assume discharge to sanitary sewer
Source: Section 4.4.5

Exhibit 4.29 (continued): Microfiltration/Ultrafiltration Cost Summary

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430	520
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270	350
Capital Cost Summary										
Total Unit Capital Cost	1,738,505	2,720,593	4,142,559	7,382,351	15,991,348	20,058,196	61,150,358	153,184,031	293,759,889	349,252,221
Indirect Capital Costs	188,294	257,431	385,922	682,795	1,287,944	1,632,441	4,961,409	12,635,544	25,158,006	30,270,801
Membrane housing	76,362	127,270	222,723	445,445	915,365	1,184,590	4,092,220	11,307,450	23,153,350	27,999,400
Bench/pilot-scale testing	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000
Permitting	27,848	36,947	56,350	100,493	220,551	276,386	500,000	500,000	500,000	500,000
Land	15,502	24,632	37,566	66,996	73,517	92,129	280,945	702,742	1,343,009	1,594,907
Operator Training	3,000	3,000	3,000	3,000	10,000	10,000	10,000	25,000	25,000	25,000
500' backwash discharge pipeline	5,582	5,582	6,283	6,861	8,511	9,335	18,244	40,351	76,646	91,494
Direct Capital Cost[1]	1,550,211	2,463,162	3,756,637	6,699,556	14,703,405	18,425,756	56,188,949	140,548,488	268,601,883	318,981,420
Subtotal Process Cost	928,270	1,231,581	1,878,319	3,349,778	7,351,702	9,212,878	28,094,475	70,274,244	134,300,942	159,490,710
Interstage piping and pumping	36,807	55,680	87,625	153,658	315,358	388,630	1,061,193	2,418,050	4,321,858	5,041,369
Membrane equipment	776,269	1,056,933	1,583,178	2,811,083	6,208,177	7,817,110	23,673,367	58,720,324	111,425,078	132,054,324
Process monitoring equipment	5,135	5,135	10,270	20,539	46,214	56,484	195,125	539,162	1,103,997	1,335,067
Electrical	7,361	11,136	17,525	30,732	63,072	77,726	212,239	483,610	864,372	1,008,274
Instrumentation and controls	102,697	102,697	179,721	333,767	718,882	872,928	2,952,551	8,113,098	16,585,637	20,051,675
Annual O&M Summary										
Total Annual O&M Cost	75,317	106,798	164,173	324,393	786,427	1,034,793	3,301,730	9,888,387	21,519,157	27,300,426
Membrane Replacement	16,088	26,611	46,343	92,396	224,052	289,922	1,003,118	2,787,128	5,760,078	6,992,039
Performance monitoring	1,338	1,370	2,813	5,626	12,659	15,473	53,451	147,693	360,667	436,155
CIP Chemicals	1,497	2,811	5,110	10,950	28,470	40,150	138,700	438,000	985,500	1,277,500
Materials	200	398	743	1,619	3,727	4,967	15,118	42,556	79,545	92,292
Electricity	6,148	7,983	11,194	19,348	44,450	61,592	206,229	645,494	1,449,029	1,877,581
Technical labor	30,876	31,624	32,510	54,184	108,368	108,368	108,368	216,736	260,083	260,083
POTW surcharge	19,170	36,003	65,459	140,270	364,701	514,322	1,776,747	5,610,780	12,624,255	16,364,775

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Based on Temperature=10°C
Assume discharge to sanitary sewer
Source: Section 4.4.5

4.4.6 Bag and Cartridge Filtration

The costs presented in this section assume installation of bag or cartridge filters following conventional treatment (i.e., granular media filtration). This level of pre-treatment reduces the suspended solids concentration delivered to the filters, which in turn allows for longer run times and reduced maintenance demands. As a result, costs for installation of bag or cartridge filters as the sole treatment technology may be different than those presented here.

Costs for bag and cartridge filters were only estimated for systems with a design flow of 2 mgd or less. These technologies are not typically used in large systems due to poor economies of scale and difficulties with design for high flow rates.

4.4.6.1 Summary of Bag and Cartridge Filter Capital Cost Assumptions

Process Costs

Capital costs for bag and cartridge filters were estimated using vendor quotes and cost estimating guides (RS Means). Vendor quotes were received in July 2002 and adjusted to year 2003 dollars using the ENR BCI. Bag and cartridge filter vendors were screened based on anticipated *Cryptosporidium* removal credits granted under the LT2ESWTR and on demonstrated *Cryptosporidium* removal efficiency. Bag filters are eligible for up to l log removal credit and must have been capable of 1.5 log removal (includes 0.5-log safety factor). Cartridge filters are eligible for up to 2 log removal credit and must have been capable of 2.5 log removal (includes 0.5 log safety factor). Two bag filter and three cartridge filter vendors were identified that met these criteria. Exhibits 4.32 and 4.33 present line item summaries of capital costs for bag and cartridge filters. This section presents the methodology by which line item costs are estimated.

<u>Filter Housing</u>

Estimates for bag and cartridge filter housing were estimated based on quotes provided by vendors. Vendors provided estimates for stainless steel filter housing at each of the flows for which costs were provided. Vendor quotations were averaged at each flow to develop estimates for filter housing costs.

<u>Initial Bag and Cartridge Filters</u>

The initial cost of bag and cartridge filters was estimated using vendor quotes. As previously mentioned, vendors were pre-screened based on demonstrated *Cryptosporidium* removal efficiency. Vendors provided estimates for a variety of bag and cartridge types and sizes. Exhibit 4.30 is a summary of the design criteria provided by the vendors for bag and cartridge filtration.

Exhibit 4.30: Design Criteria for Bag and Cartridge Filters

Criteria	Bag Filters	Cartridge Filters
Nominal Pore Size	1 micron	1 micron
Material	polyester or polypropylene	pleated polyester, pleated polypropylene, spun bonded polypropylene, and absolute rated polypropylene
Dimensions	7 inches by 16 inches, and 7 inches by 32 inches	1 inch ID by 2.5 inches OD, lengths of 10, 20, and 30 inches
Housing Construction	304 Stainless Steel	304 Stainless Steel
Loading Rate	45 gpm per 16 inches equivalent length	10 gpm (pleated construction only), 5 gpm per 10 inches equivalent length

Source: Vendor quotes

Vendors provided estimates at each of the flows for which costs are provided. Vendor quotations were averaged at each flow to develop the estimates for initial bags or cartridges.

Interstage Pumping

Costs for centrifugal in-line vertical-mount single-stage pumps were estimated using RS Means (1999). A summary of the data used for estimating the line item cost for pumping is presented in Exhibit 4.31. The resulting equation is listed here.

$$\text{Interstage pumping (\$)} = ((-2{,}245.4 \times \text{Design Flow}^2) + (8{,}127.7 \times \text{Design Flow}) + 149.26)*1.03$$

Exhibit 4.31: Summary of Bag and Cartridge Filter Pump Cost Data

Design Flow (mgd)	Max Pumping Rate (gpm)	Pump Rating (Hp)	Pump Cost ($)
0.024	50	3	$445
0.087	75	5	$755
0.27	200	7.5	$2,125
0.65	750	25	$4,525
1.8	1500	50	$7,500

Source: RS means

Instrumentation and Controls, Pipes and Valves

Estimates for P&V and I&C, which primarily include tie-ins to existing electrical and pressure gauges, were based on vendor estimates. Vendors provided estimates for these items at each of the flows for which costs were provided. The quotations were averaged at each flow to estimate the costs presented in Exhibits 4.32 and 4.33.

Capital Cost Multipliers

Filter housing, initial filters, pumps, electrical, and P&V were totaled to arrive at the total process cost. For systems treating less than 2 mgd, the process cost was multiplied by a capital cost factor of 1.2, assuming that these are package systems which only require an installation cost. A capital cost factor of 1.67 was used for the 2 mgd systems.

Indirect Capital Costs

Indirect capital costs include permitting, operator training, and housing. Permitting fees were estimated at $2,500 for all system sizes. Operator training was assumed to be $500 for all system sizes.

Housing represents the cost associated with a building for the bag or cartridge filters. Many facilities may be able to incorporate these systems into the existing plant footprint. However, it was assumed that, in half or more cases, this would not be possible. In such cases, bag or cartridge filters would be installed near the plant high-service pump station, which may not have sufficient space available to accommodate these processes. Based on housing area requirements for membrane processes (e.g., 1,300 ft^2 per mgd for MF/UF less than 10 mgd), a housing area of 500 ft^2 per mgd was assumed. This was based on best professional judgment as to the relative size of bag and cartridge filter systems and membrane systems. A minimum housing area of 50 ft^2 was assumed. Housing costs were generated by multiplying the footprint area by an average housing cost of $48.95 per square foot (factory building in RS Means).

4.4.6.2 Summary of Bag and Cartridge Filter O&M Cost Assumptions

O&M costs for bag and cartridge filters were estimated using vendor data and cost estimating guides. Line item summaries of O&M costs are presented in Exhibits 4.32 and 4.33. This section discusses the assumption used to estimate the costs presented in the tables.

Bag and Cartridge Replacement

The average cost of a single bag or cartridge, as well as the average number of bags or cartridges, was determined based on vendor estimates. Cartridges are typically more durable than bags and require less frequent replacement. For the purposes of this document, it was assumed that cartridges would be replaced every six months and that bags would be replaced every three months.

Power

Power requirements were based solely on the additional power required for the interstage pumping. Costs were estimated based on pump horsepower ratings (see Exhibit 4.31) and a unit cost of $0.076 per kWh. A linear regression was completed to develop the following equation and estimate line item costs:

$$\text{Power (\$/yr)} = (-286.6 \times \text{Average Flow}^2) + (545.48 \times \text{Average Flow}) + 7.4011$$

Labor

Labor requirements are considered a function of the durability of the bag or cartridge filter and the size of the system. For systems less than 2 mgd, one hour of labor per month plus 15 minutes per bag or cartridge per replacement was assumed. For systems 2 mgd and larger, one hour of labor per week plus 15 minutes per bag or cartridge per replacement was assumed. Technical labor rates used to produce labor costs varied by system size.

Exhibit 4.32: Bag Filter Cost Summary

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1	1.2	2
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35	0.41	0.77
Total Unit Capital Cost	10,280	10,420	12,828	13,320	19,487	23,424	28,771	42,479	65,653	75,011	136,788
Indirect Capital Costs	5,448	5,448	5,448	5,448	7,406	9,608	11,811	19,643	27,475	32,370	51,950
Operator Training	500	500	500	500	500	500	500	500	500	500	500
Housing	2,448	2,448	2,448	2,448	4,406	6,608	8,811	16,643	24,475	29,370	48,950
Permitting	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500
Direct Capital Cost[1]	4,832	4,973	7,380	7,872	12,082	13,816	16,960	22,836	38,178	42,641	84,838
Subotal Process Cost	4,027	4,144	6,150	6,560	10,068	11,513	14,133	19,030	31,815	35,534	50,801
Pipes and Valves	969	969	969	969	969	969	969	969	1,938	1,938	2,907
I&C	969	969	969	969	969	969	969	969	1,938	1,938	2,907
Pumping	200	317	433	843	1,492	2,113	2,698	4,494	5,845	6,463	7,193
Bag Filters	48	48	97	97	145	194	291	485	775	969	1,454
Filter Housing	1,841	1,841	3,682	3,682	6,493	7,268	9,206	12,113	21,319	24,226	36,340
Annual O&M Summary											
Total Annual O&M Cost	479	481	701	732	962	1,223	1,673	2,602	3,956	4,851	8,151
Bag Replacement	192	192	388	388	580	776	1,164	1,940	3,100	3,876	5,816
Electricity	8	10	13	21	36	51	64	118	163	183	257
Labor	279	279	300	323	346	396	445	544	693	792	2,078

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.6

Exhibit 4.33: Cartridge Filter Cost Summary

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1	1.2	2
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35	0.41	0.77
Total Unit Capital Cost	10,465	10,605	13,196	17,256	24,024	31,479	43,699	73,535	111,151	136,393	265,089
Indirect Capital Cost	5,448	5,448	5,448	5,448	7,406	9,608	11,811	19,643	27,475	32,370	51,950
Operator Training	500	500	500	500	500	500	500	500	500	500	500
Housing	2,448	2,448	2,448	2,448	4,406	6,608	8,811	16,643	24,475	29,370	48,950
Permitting	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500
Direct Capital Cost[1]	5,017	5,158	7,748	11,808	16,619	21,871	31,888	53,892	83,676	104,023	213,139
Subtotal Process Cost	4,181	4,298	6,457	9,840	13,849	18,226	26,573	44,910	69,730	86,686	127,628
Pipes and Valves	969	969	969	969	969	969	969	969	1,938	1,938	2,907
I&C	969	969	969	969	969	969	969	969	1,938	1,938	2,907
Pumping	200	317	433	843	1,492	2,113	2,698	4,494	5,845	6,463	7,193
Cartridge Filters	202	202	404	566	1,213	2,062	2,556	4,561	6,711	8,513	12,870
Filter Housing	1,841	1,841	3,682	6,493	9,206	12,113	19,381	33,917	53,298	67,834	101,751
Annual O&M Summary											
Total Annual O&M Summary	680	682	1,099	1,465	2,808	4,596	5,621	9,821	14,315	18,075	28,189
Cartridge Replacement	404	404	808	1,132	2,426	4,124	5,112	9,122	13,422	17,026	25,740
Electricity	8	10	13	21	36	51	64	118	163	183	257
Labor	268	268	279	312	346	421	445	581	730	866	2,192

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.4.6

4.4.7 Bank Filtration

Because bank filtration has not been a widely used technology, little cost data are available to be able to give a detailed cost breakout. In 2000, design experts from the Technical Work Group (TWG) were asked to estimate a cost for three plant sizes: 0.6, 6.5, and 55 mgd. Costs for other plant sizes were derived from these estimates. Plants less than 0.6 mgd in design flow were assumed to incur the same costs as a 0.6 mgd plant. Costs for plants with greater than 0.6 mgd were calculated assuming a linear cost versus design flow function. The costs provided by the TWG are given in Exhibit 4.34.

Exhibit 4.34: Bank Filtration Cost Estimates for Three System Sizes

Design Flow (mgd)	Capital Cost ($)	O & M Cost ($)
0.6	150,000	0
6.5	1,625,000	0
55	13,750,000	0

Source: TWG

4.4.8 Second Stage Filtration

Chapter 3 provides design criteria for systems to receive 0.5 log credit for *Cryptosporidium* inactivation using second stage filtration. Because second stage filtration has not been a widely used technology, little cost data are available to provide a detailed cost breakout. Design experts from the TWG were asked to estimate a cost for three second stage filtration plant sizes that meet the criteria in Chapter 3: 0.6, 6.5, and 55 mgd. Costs for other size plants were derived from these estimates. Plants less than 0.6 mgd in design flow were assumed to incur the same costs as a 0.6 mgd plant. Costs for plants with greater than 0.6 mgd were calculated by assuming a linear cost versus design flow function. The costs provided by the TWG are given in Exhibit 4.35.

Exhibit 4.35: Second Stage Filtration Cost Estimates for Three System Sizes

Design Flow (mgd)	Capital Cost ($)	O & M Cost ($)
0.6	1,106,000	62,300
6.5	5,550,000	148,500
55	20,600,000	393,000

Source: TWG

4.4.9 Pre-Sedimentation

Chapter 3 provides design criteria for systems to receive 0.5 log credit for *Cryptosporidium* inactivation using pre-sedimentation basins. Because pre-sedimentation basins have not been a widely used technology, little cost data are available for this technology to provide a detailed cost breakout. Design experts from the TWG were asked to estimate a cost for three plant sizes, which met the design criteria in Chapter 3: 0.6, 6.5, and 55 mgd. Costs for other plant sizes were derived from these estimates.

Plants less than 0.6 mgd in design flow were assumed to incur the same costs as a 0.6 mgd plant. Costs for plants with greater than 0.6 mgd were calculated by assuming a linear cost versus design flow function. The costs provided by the TWG are given in Exhibit 4.36.

Exhibit 4.36: Pre-Sedimentation Cost Estimates for Three System Sizes

Design Flow (mgd)	Capital Cost ($)	O & M Cost ($)
0.6	1,200,000	37,000
6.5	3,700,000	119,000
55	25,500,000	560,000

Source: TWG

4.4.10 Watershed Control

Chapter 3 provides criteria for systems to receive *Cryptosporidium* inactivation credit for watershed control. Because each watershed control program will be site-specific, it is difficult to estimate detailed costs for such programs. However, the TWG provided EPA with rough estimates of capital and O&M costs, based on flow for a program that meets the criteria outlined in Chapter 3. Capital costs are assumed to include development of an oocyst loading model, as well as associated validation monitoring. These capital costs are $250,000 for small systems, $500,000 for medium systems, and $1,000,000 for large systems. O&M costs are divided into three categories: agreements and legal mechanisms to mitigate sources, staff and resources to mitigate sources in the watershed, and public health surveillance for *Cryptosporidium*. O&M costs for these categories and for three system sizes are shown in Exhibit 4.37.

Exhibit 4.37: Watershed Cost Categories for Three System Sizes

Watershed Program Component	O&M Cost ($)		
	Small (0.6 mgd)	Medium (6.5 mgd)	Large (55 mgd)
Agreements and Legal Mechanisms to Mitigate Sources	150,000	500,000	1,000,000
Demonstrated Staff/Resource Commitment to Mitigate Sources	100,000	250,000	1,000,000
Public Health Surveillance for *Cryptosporidium*	100,000	250,000	500,000

Source: TWG

4.4.11 Combined Filter Performance

Combined filter performance is not a single technology, but a variety of actions that a system can take to achieve 0.15 NTU combined filter effluent concentration 95 percent of the time. Chapter 3 provides a list of actions or steps that a plant could take to reduce effluent turbidity. The actions are:

- Chemical Addition
  - Installing backwash polymer feed capability
  - Coagulant improvement
  - Adding primary coagulant feed points
- Filter Improvements
  - Filter media addition
  - Post backwash filter-to-waste
  - Filter rate-of-flow controller
- Process Management Changes
  - Plant staffing increase
  - Staff qualifications
- Laboratory Modifications
  - Turbidimeter purchase
  - Jar test apparatus purchase
  - Purchase a particle counter or other alternative process control testing equipment

- Process Control Testing Modification
  - Staff Training

Each action was costed individually. Then the proportion of plants selecting each action was estimated. Percentages were multiplied by the individual unit costs to arrive at an average unit cost. Because several of the components recommended for combine filter performance are also applicable to individual filter performance, EPA has not provided a separate cost analysis for individual filter performance.

Similar assumptions were used for all of the steps involving filtration. The assumptions regarding filter size and flow were the same for filter media addition, filter-to-waste, and filter rate-of-flow controller replacement. Exhibit 4.38 summarizes the design assumptions used in estimating capital and O&M costs for filtration improvements. A conservative filter design loading rate (2.5 gpm/ft^2) was used to estimate the number of filters. The number of filters was based on a maximum filter area—125 ft^2, 250 ft^2, 700 ft^2, or 1,000 ft^2—determined by system size. The total number of filters was based on the number of filters required to produce the design flow at the design loading rate plus one (n+1). Filter piping diameters were determined using the criteria below (*Water Treatment Plant Design*, AWWA, 1969).

- Filter effluent piping velocity = 3-6 feet per second (fps)
- Filter to waste (FTW) piping velocity = 6-12 fps
- Drain piping velocity = 3-8 fps

Exhibit 4.38: Summary of Filtration Improvement Design Assumptions

Population	**500 - 1,000**	**1,001 - 3,300**	**3,301 - 10,000**	**10,001- 50,000**	**50,001- 100,000**	**100,001- 1,000,000**	**> 1,000,000**
Avg. Flow (mgd)	0.093	0.250	0.626	2.758	5.082	23.671	109.707
Design Flow (mgd)	0.245	0.633	1.511	6.277	11.040	48.429	205.503
Design Filter Loading Rate (gpm/sf)	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total Filter Area (sf)	68	176	420	1744	3067	13453	57084
Max filter area (sf)	125	125	250	700	700	700	1000
Number of Filters	2	3	3	4	6	21	59
Pipe Sizing Loading Rate (gpm/sf)	5	5	5	5	5	5	5
Flow per Filter (gpm)	340	440	1049	2906	3067	3363	4921
Effluent Piping Diameter (inches)	6	6	10	16	16	20	20
Filter Effluent Pipe Velocity (fps)	3.9	5.0	4.3	4.6	4.9	3.4	5.0
FTW Diameter (in)	4	6	8	12	12	14	16
FTW Pipe Velocity (fps)	8.7	5.0	6.7	8.2	8.7	7.0	7.9
Backwash Rate (gpm/sf)	20	20	20	20	20	20	20
Backwash Flow (gpm)	1,361	1,758	4,197	11,624	12,267	13,453	19,684
Drain Diameter (inches)	10	12	16	30	36	36	36
Drain Pipe Velocity (fps)	5.6	5.0	6.7	5.3	3.9	4.2	6.2

Source: Section 4.4.11

Because of the operator attention required to produce such low turbidity water and because few very small plants are conventional, it was assumed that systems serving fewer than 500 people would not use this technology. Also construction, engineering, and indirect costs, such as housing or permitting, are not typically included in the cost estimates. This is because most of these actions are either operational changes or involve very little capital modifications. Therefore, costs for items such as engineering and sitework are not appropriate.

The assumptions behind each filter improvement action are given in section 4.4.11.1 to 4.4.11.11. Unit capital and O&M costs for each action are summarized in Exhibits 4.40 and 4.41.

4.4.11.1 Installing Backwash Polymer Feed

Capital costs were based on feeding a 0.5 ppm dose of polymer from a 0.25 percent, by weight, solution. The backwash duration was assumed to be 15 minutes per filter at a backwash rate of 20 gpm/ft^2, with an average filter run of three days. Conceptual design assumed a dry polymer feed system that can be loaded with a seven-day polymer supply. Extra storage capacity for dry polymer bags was assumed within the plant. Equipment includes mixing tank, solution tank, secondary dilution mixer, and metering pumps.

Capital costs include equipment, installation (25 percent of equipment), electrical (10 percent of equipment), instrumentation and control (10 percent of equipment), contingencies (30 percent of equipment, installation, electrical, and instrumentation and control), contractor overhead and profit (15 percent of equipment, installation, electrical, and instrumentation and control), and engineering (20 percent of equipment, installation, electrical, and instrumentation and control).

O&M costs for the backwash water polymer feed system include polymer cost ($2.25 per pound), additional maintenance labor, and parts and materials (10 percent of equipment cost per year).

4.4.11.2 Installing Additional Coagulant Feed Points

Capital costs were based on an additional 5 ppm dose of primary coagulant. The primary coagulant was assumed to be ferric chloride, ferric sulfate, or alum. Thirty days of bulk storage were assumed for ferric chloride or ferric sulfate (equivalent to approximately 15 days of storage for alum). Equipment includes bulk storage tanks, day tanks, metering pumps, pipes, and valves.

Capital costs include equipment, installation (25 percent of equipment), electrical (10 percent of equipment), instrumentation and control (10 percent of equipment), contingencies (30 percent of equipment, installation, electrical, and instrumentation and control), contractor overhead and profit (15 percent of equipment, installation, electrical, and instrumentation and control), and engineering (20 percent of equipment, installation, electrical, and instrumentation and control).

O&M costs for expansion of the coagulant feed system include coagulant cost ($350 per ton), additional maintenance labor, and parts and materials (10 percent of equipment cost per year).

4.4.11.3 Filter Media Addition

Individual filter area and number of filters were based on a design filter loading rate of 2.5 gpm/sf as listed in Exhibit 4.38. It was assumed that only anthracite media needs to be replaced (i.e., no sand media losses in dual-media filters) and that only anthracite media is added to increase the total media depth. Topping off existing media was assumed to require 2 inches to 6 inches of anthracite and average 4 inches of anthracite per filter. It was also assumed that an additional 6 inches of anthracite media is added to each filter to increase the total media depth, giving a total required depth of 10 inches.

Capital costs were based on a total of 10 inches additional anthracite media annually. Costs include anthracite media, transportation ($2/mile—assumed 1,000 miles—plus $0.50/lb), installation (25 percent of media cost), contingencies (30 percent of media, transportation, and installation), contractor overhead and profit (15 percent of media, transportation, and installation), and engineering (20 percent of media, transportation, and installation). O&M costs for this task were assumed to be zero.

4.4.11.4 Filter to Waste

The number of filters was based on design filter loading rate of 2.5 gpm/ft^{2,} and pipe sizing was based on a filter loading rate of 5 gpm/ft^2, as listed in Exhibit 4.38. Filter effluent piping, filter-to-waste piping, and drain piping sizes are also listed in Exhibit 4.38. Installing filter-to-waste capability requires modification of existing filter effluent piping and connection of the new filter-to-waste piping to the filter drain piping. The extent of modifications required to complete these modifications can vary significantly depending on plant size and existing piping configuration. The cost estimates presented were based on the following assumptions:

- Cutting existing pipe
- Replacing 10 feet of filter effluent pipe per filter
- Replacing two filter effluent valves (control valve and isolation valve) per filter
- Installing one tee in filter effluent piping for FTW piping per filter
- Installing one filter-to-waste isolation valve per filter
- Installing 25 feet of filter-to-waste piping and four 90 degree elbows per filter
- Connecting FTW, including conical reducers and tees, into existing drain piping

Capital costs include equipment, installation (25 percent of equipment), electrical (10 percent of equipment), instrumentation and control (10 percent of equipment), contingencies (30 percent of equipment, installation, electrical, and instrumentation and control), contractor overhead and profit (15 percent of equipment, installation, electrical, and instrumentation and control), and engineering (20 percent of equipment, installation, electrical, and instrumentation and control).

O&M costs for addition of filter-to-waste capabilities include additional labor associated with longer backwash/filter-to-waste/return-to-service duration (15 minutes per filter per backwash), additional maintenance labor (1 hour per filter per month), and parts and materials (10 percent of equipment cost per year). Filter run time between backwashes was assumed to be 72 hours.

4.4.11.5 Filter Rate-of-Flow Controller Replacement

Number of filters was based on a design filter loading rate of 2.5 gpm/ft^2, and pipe sizing was based on a filter loading rate of 5 gpm/ft^2, as listed in Exhibit 4.38. Filter effluent piping sizes are also listed in Exhibit 4.38. Installing or replacing the filter rate-of-flow controller requires replacement of existing filter effluent piping and valves. The extent of modifications required to complete these modifications can vary significantly depending on plant size and existing piping configuration. The cost estimates presented were based on the following assumptions:

- Cutting existing pipe
- Replacing 10 feet of filter effluent pipe per filter
- Replacing two filter effluent valves (control valve and isolation valve) per filter
- Installing/Replacing a venturi meter

Capital costs include equipment, installation (25 percent of equipment), electrical (10 percent of equipment), instrumentation and control (10 percent of equipment), contingencies (30 percent of equipment, installation, electrical, and instrumentation and control), contractor overhead and profit (15 percent of equipment, installation, electrical, and instrumentation and control), and engineering (20 percent of equipment, installation, electrical, and instrumentation and control).

O&M costs for addition or replacement of filter rate-of-flow controllers include additional maintenance labor (1 hour per filter per month), electricity (based on valve actuator horsepower and a motor efficiency of 70 percent), and parts and materials (10 percent of equipment cost per year). Exhibit 4.39 shows the assumptions for valve actuator horsepower. Horsepowers are based on experience with similar systems and vender quotes.

Exhibit 4.39: Valve Actuator Horsepower Assumptions

Valve Diameter (in)	Actuator Horsepower (Hp)
<8	1/50
<14	1/6
<24	1/4
>24	1

4.4.11.6 Increase Plant Staffing

A capital cost of $6,000 per new staff or fraction thereof for office and field fixtures, computer hardware, and training was assumed. The O&M costs were developed assuming labor increases between 10 and 120 hours per week, depending on system size. Systems serving fewer than 3,300 people were assumed to increase labor by ten hours per week (0.25 operator). Systems serving between 3,300 and 49,999 people were assumed to hire one half-time operator. Systems serving between 50,000 and 99,999 people were assumed to hire one additional operator. Systems serving between 100,000 and 999,999 people were assumed to hire two additional operators. Systems serving 1,000,000 or more people were assumed to hire three operators.

4.4.11.7 Update Plant Staff Qualifications

No capital costs were associated with this estimate. The O&M costs were calculated including an annual allowance for training staff members. The best means of continuing the education of staff is through local or state operator certification training. Using March 2003 AWWA prices, class fees per operator were assumed to be $260 for systems serving fewer than 10,000 people and $400 for systems serving 10,000 or more people. Systems serving fewer than 10,000 people were assumed to send one operator. Systems serving between 10,000 and 99,999 people were assumed to send two operators. Systems serving between 100,000 and 999,999 people were assumed to send four operators. It was assumed that systems serving 1,000,000 or more people would send six operators to the training course.

4.4.11.8 Purchase Turbidimeter

This step involves replacing obsolete bench-top or on-line turbidimeters with new on-line units with electronic data acquisition interface. Based on vendor quotes, the cost for a conventional turbidimeter, including shipping and installation, was estimated to be $3,242, and the cost of a laser turbidimeter, including shipping and installation, was estimated to be $5,449.

For systems serving 10,000 or more people, it was assumed that laser turbidity meters will be purchased. For systems serving fewer than 10,000 people it was assumed that standard on-line turbidimeters will be purchased. It was assumed that systems serving 1,000,000 or more people would purchase six additional laser turbidimeters. Systems serving between 100,000 and 999,999 people were assumed to purchase four additional laser instruments. Systems serving between 50,000 and 99,999 people were assumed to purchase two additional laser instruments. Systems serving between 10,000 and 49,999 people were assumed to purchase one additional instrument (laser). Systems serving fewer than 10,000 people were assumed to purchase one additional standard on-line instrument.

The O&M costs were calculated considering annual maintenance material and labor required for general maintenance and monthly calibration of the equipment. For each additional instrument, twenty hours per year were assumed to be required for labor.

4.4.11.9 Purchase Jar Test Apparatus

Based on vendor quotes the cost of a six-paddled stirrer with two liter jars, including shipping, was estimated to be $2,722. Systems serving fewer than 100,000 people were assumed to purchase one apparatus. Systems serving between 100,000 and 999,999 people were assumed to purchase two apparatuses. It was assumed that systems serving 1,000,000 or more people would purchase three apparatuses.

More frequent jar testing may be required to optimize chemical addition during coagulation. It has been assumed that seven hours per week will be required to operate each jar testing apparatus.

4.4.11.10 Purchase Particle Counters

Based on vendor quotes, the cost of a particle counter with interface for data acquisition system was estimated to be $6,024. It was assumed that only systems serving 1,000 or more people would purchase the instrument. Systems serving between 1,000 and 99,999 people were assumed to purchase one instrument. Systems serving between 100,000 and 999,999 people were assumed to purchase two particle counters. Systems serving 1,000,000 or more people were assumed to purchase three particle counters. It was assumed that 20 hours per unit would be required for installation and initial calibration of each unit. It was assumed that 40 hours of labor per year would be required for the calibration and maintenance of each instrument.

4.4.11.11 Staff Training

No capital costs were associated with this estimate. The costs associated with this estimate were assumed to be an annual O&M commitment for training all staff members and were based on an average consultant hourly wage of $100/hour. The O&M costs were developed assuming between 14 and 140 hours of consultant time, depending on the size of the system. The hours budgeted for consultants include time spent on site conducting training and time for customizing the training.

Exhibit 4.40: Capital Unit Costs for Combined Filter Performance Components

System Population Size Categories	501-1,000	1,001-3,300	3,301-10,000	10,001 - 50,000	50,001 - 100,000	100,001 - 1,000,000	>1,000,000
Chemical Addition							
Install backwash water polymer feed capability	$113,000	$113,000	$118,300	$126,200	$126,200	$210,300	$323,300
Coagulant Improvements							
Primary coagulant feed points, control, measurement	$36,300	$37,400	$57,500	$116,000	$128,400	$207,900	$703,300
Filtration Improvements							
Filter media additions (10" typical)	$5,900	$9,500	$19,800	$67,800	$106,100	$401,600	$1,644,900
Post backwash filter-to-waste	$18,900	$38,100	$70,700	$243,900	$434,600	$1,906,300	$5,436,900
Filter rate-of-flow controller replacement	$21,360	$38,079	$94,418	$233,728	$479,684	$2,749,255	$9,801,092
Process Managament Changes							
Plant staffing increase	$1,500	$1,500	$3,000	$3,000	$6,000	$12,000	$18,000
Staff qualifications	$0	$0	$0	$0	$0	$0	$0
Laboratory Modifications							
Purchase on-line turbidimeter with data acquisition interface	$3,243	$3,243	$3,243	$5,449	$21,796	$87,184	$196,164
Jar test apparatus purchase	$2,722	$2,722	$2,722	$2,722	$2,722	$5,444	$8,166
Alternative process control testing equipment, particle counter	$0	$6,523	$6,523	$6,523	$6,523	$13,046	$19,570
Process Control Modifications							
Staff training (consultant as trainer)	$0	$0	$0	$0	$0	$0	$0

Source: Section 4.4.11

Exhibit 4.41: O&M Unit Costs for Combined Filter Performance Components

System Population Size Categories	501-1,000	1,001-3,300	3,301-10,000	10,001 - 50,000	50,001 - 100,000	100,001 - 1,000,000	>1,000,000
Chemical Addition							
Install backwash water polymer feed capability	$6,000	$6,100	$6,700	$8,000	$8,300	$16,300	$36,700
Coagulant Improvements							
Primary coagulant feed points, control, measurement	$2,000	$2,300	$3,200	$8,800	$14,100	$54,000	$199,800
Filtration Improvements							
Filter media additions (10" typical)	$0	$0	$0	$0	$0	$0	$0
Post backwash filter-to-waste	$2,300	$3,600	$3,900	$6,600	$10,500	$40,700	$116,200
Filter rate-of-flow controller replacement	$2,500	$3,800	$5,400	$8,700	$13,100	$47,800	$134,300
Process Managament Changes							
Plant staffing-increase	$12,979	$12,979	$25,958	$25,958	$51,917	$103,834	$155,750
Staff qualifications	$460	$460	$659	$1,199	$1,599	$3,197	$4,796
Laboratory Modifications							
Purchase on-line turbidimeter with data acquisition interface	$684	$684	$684	$724	$1,223	$2,447	$3,445
Jar test apparatus purchase	$9,085	$9,085	$9,085	$9,085	$9,085	$18,171	$27,256
Alternative process control testing equipment-Particle counter	$0	$1,239	$1,239	$1,239	$1,239	$2,238	$3,236
Process Control Modifications							
Staff training (consultant as trainer)	$1,400	$1,600	$2,800	$5,000	$7,000	$10,000	$14,000

Source: Section 4.4.11

4.4.11.12 Average Plant Cost

Percentages of plants using each of the filter performance options described in 4.4.11.1 through 4.4.11.11 were determined using best professional judgement. The percentages do not add to 100 as many systems will have to use more than one of the steps to achieve the desired reduction in CFE turbidity. Exhibit 4.42 shows the percentages used.

Exhibit 4.42: Percentages of Plants Using Each Filter Improvement Option

System Population Size Categories	501-1,000	1,001-3,300	3,301-10,000	10,001-50,000	50,001-100,000	100,001-1,000,000	>1,000,000
Chemical Addition							
Install backwash water polymer feed capability	10%	10%	10%	10%	10%	10%	10%
Coagulant Improvements							
Primary coagulant feed points, control, measurement	0%	5%	10%	10%	10%	10%	10%
Filtration Improvements							
Filter media additions (10" typical)	5%	10%	15%	20%	20%	20%	20%
Post backwash filter-to-waste	5%	5%	5%	5%	5%	5%	5%
Filter rate-of-flow controller replacement	15%	15%	15%	15%	15%	15%	15%
Process Managament Changes							
Plant staffing-increase	100%	100%	100%	100%	100%	100%	100%
Staff qualifications	100%	100%	100%	100%	100%	100%	100%
Laboratory Modifications							
Bench top turbidimeter purchase-replace obsolete units	10%	10%	10%	10%	10%	10%	10%
Jar test apparatus purchase	10%	10%	10%	10%	10%	10%	10%
Alternative process control testing equipment, particle counter	10%	10%	10%	20%	20%	20%	20%
Process Control Modifications							
Staff training (consultant as trainer)	80%	80%	80%	80%	80%	80%	80%

Source: Section 4.4.11

To compute an average capital and O&M cost for all plants using the combined filter performance toolbox option, the percentages were multiplied by the capital and O&M costs for each of the processes from Exhibits 4.40 and 4.41. Exhibits 4.43 and 4.44 show the final capital and O&M costs used for plants using combined filter performance to achieve LT2ESWTR compliance.

Exhibit 4.43: Capital Cost Estimates for the Combined Filter Performance

System Population Size Categories	501-1,000	1,001-3,300	3,301-10,000	10,001 - 50,000	50,001 - 100,000	100,001 - 1,000,000	>1,000,000
Chemical Addition							
Install backwash water polymer feed capability	$11,300	$11,300	$11,830	$12,620	$12,620	$21,030	$32,330
Coagulant Improvements							
Primary coagulant feed points, control, measurement	$0	$1,870	$5,750	$11,600	$12,840	$20,790	$70,330
Filtration Improvements							
Filter media additions (10" typical)	$295	$950	$2,970	$13,560	$21,220	$80,320	$328,980
Post backwash filter-to-waste	$945	$1,905	$3,535	$12,195	$21,730	$95,315	$271,845
Filter rate-of-flow controller replacement	$3,204	$5,712	$14,163	$35,059	$71,953	$412,388	$1,470,164
Process Managament Changes							
Plant staffing increase	$1,500	$1,500	$3,000	$3,000	$6,000	$12,000	$18,000
Staff qualifications	$0	$0	$0	$0	$0	$0	$0
Laboratory Modifications							
Purchase on-line turbidimeter with data acquisition interface	$324	$324	$324	$545	$2,180	$8,718	$19,616
Jar test apparatus purchase	$272	$272	$272	$272	$272	$544	$817
Alternative process control testing equipment, particle counter	$0	$652	$652	$1,305	$1,305	$2,609	$3,914
Process Control Modifications							
Staff training (consultant as trainer)	$0	$0	$0	$0	$0	$0	$0
Total	17,840	24,486	42,497	90,156	150,119	653,715	2,215,996

Source: Capital costs from Exhibit 4.40 multiplied by percentages in Exhibit 4.42. “Total” represents the average cost per plant.

Exhibit 4.44: O&M Costs for the Combined Filter Performance

System Population Size Categories	501-1,000	1,001-3,300	3,301-10,000	10,001 - 50,000	50,001 - 100,000	100,001 - 1,000,000	>1,000,000
Chemical Addition							
Install backwash water polymer feed capability	$600	$610	$670	$800	$830	$1,630	$3,670
Coagulant Improvements							
Primary coagulant feed points, control, measurement	$0	$115	$320	$880	$1,410	$5,400	$19,980
Filtration Improvements							
Filter media additions (10" typical)	$0	$0	$0	$0	$0	$0	$0
Post backwash filter-to-waste	$115	$180	$195	$330	$525	$2,035	$5,810
Filter rate-of-flow controller replacement	$375	$570	$810	$1,305	$1,965	$7,170	$20,145
Process Managament Changes							
Plant staffing-increase	$12,979	$12,979	$25,958	$25,958	$51,917	$103,834	$155,750
Staff qualifications	$460	$460	$659	$1,199	$1,599	$3,197	$4,796
Laboratory Modifications							
Purchase on-line turbidimeter with data acquisition interface	$68	$68	$68	$72	$122	$245	$345
Jar test apparatus purchase	$909	$909	$909	$909	$909	$1,817	$2,726
Alternative process control testing equipment- Particle counter	$0	$124	$124	$248	$248	$448	$647
Process Control Modifications							
Staff training (consultant as trainer)	$1,120	$1,280	$2,240	$4,000	$5,600	$8,000	$11,200
Total	16,626	17,295	31,954	35,702	65,124	133,775	225,069

Source: O&M costs from Exhibit 4.41 multiplied by the percentages in Exhibit 4.42. “Total” represents the average O&M cost per plant.

4.5 DBP Precursor and Microbial Removal Technologies

This section presents capital and O&M estimates for new or enhanced technologies employed for the removal of DBP precursors. It should be noted that all of the technologies discussed in this section may not be applicable for all systems.

4.5.1 Granular Activated Carbon Adsorption

Costs for GAC adsorption were estimated for two EBCTs: 10 minutes and 20 minutes. Installation of the GAC contactors was assumed to be after filtration. The number of contactors (*n*) varies by system size, with a minimum of two operating contactors to take advantage of blending. Exhibit 4.45 presents the number of contactors assumed for each system size for which costs are presented.

Exhibit 4.45: GAC Contactor Assumptions

Number of Contactors	Design Flow (mgd)															
	0.024	**0.087**	**0.1**	**0.27**	**0.45**	**0.65**	**0.83**	**1**	**10**	**11**	**18**	**26**	**51**	**210**	**430**	**520**
n	2	2	4	4	5	5	5	5	10	10	10	10	10	20	20	20
***n*+1**	3	3	5	5	6	6	6	6	11	11	11	11	11	21	21	21

Note: *n* = number of operating contactors
n+1 = number of contactors including redundant contactors, which are used for costing
Source: Calculated based on flow and reactor size.

Costs are also presented for a range of reactivation frequencies (90, 240, and 360 days) to account for variability in source water quality. For an EBCT of 10 minutes, costs are presented for reactivation frequency of 360 days. For an EBCT of 20 minutes, costs are presented for reactivation frequencies of 90 and 240 days. The reactivation frequency is a function of the number of contactors and system size. The reactivation frequency identified (e.g., 90 days) represents the reactivation frequency of the largest system for which costs are provided (430 mgd). The frequency for systems with fewer than 20 contactors (i.e., the number of operating contactors assumed for the largest system) is actually a fraction of the frequency identified. The correlation between *n* and blended run time is based upon results presented in *Analysis of GAC Effluent Blending During the ICR Treatment Studies* (USEPA 1999a), which includes an analysis of the incremental increase in blended run time attributable to the addition of a contactor in parallel. The true reactivation frequencies for each system size are presented in Exhibits 4.46 through 4.48.

4.5.1.1 Summary of GAC Capital Cost Assumptions

Costs were generally obtained from the Water model. Some cost components were based on vendor quotes; these were discounted to year 2003 dollars using the ENR BCI. The original regression equations provided costs in 2001 year dollars. The ENR BCI index was used to update these values to 2003 year dollars.

Process Costs

At least two contactors were assumed to be in service with one stand-by. Exhibit 4.45 summarizes the number of contactors or pressure vessels assumed for each flow category. Systems with design flows of less than 1 mgd were assumed to use package plants.

<u>GAC Contactor, Media, and Regeneration Furnace Costs (large systems)</u>

For large systems (>1 mgd design flow), the capital costs for GAC contactor, initial media, and regeneration furnace were obtained from the Water model. The model was used to calculate the capital costs, based on design flow, average operating flow, EBCT, and regeneration frequency. Capital costs include concrete gravity contactors operated at a loading rate 5 gpm/ft^2, troughs and pipes for carbon removal as a slurry, initial virgin carbon.

Large systems regenerate on-site utilizing a multiple-hearth furnace. The size of the furnace is affected by the carbon usage rate, which is affected by the reactivation frequency. A loading rate of 50 lb/ft^2 per day was assumed for all systems.

For EBCT 10 min and Reactivation Frequency = 360 days:
GAC Contactor and Regeneration Furnace ($) = $(194516 \times (\text{Design Flow})^{0.751})*1.033$

For EBCT 20 min and Reactivation Frequency = 240 days:
GAC Contactor and Regeneration Furnace($) = $(298015 \times (\text{Design Flow})^{0.7876})*1.033$

For EBCT 20 min and Reactivation Frequency = 90 days:
GAC Contactor and Regeneration Furnace ($) = $(370226 \times (\text{Design Flow})^{0.7562})*1.033$

Package GAC System Costs (Small Systems)

For small systems (0.1-1.0 mgd design flow), the capital costs for package units were estimated using the Water model. Capital costs include pressure vessels, factory-assembled contactors mounted on steel skid, initial charge of activated carbon, supply and backwash pump, valves, piping, and pressure gauges, and electrical control panels.

For very small systems (< 0.1 mgd design flow), the capital costs for GAC package units were estimated using the VSS Model. Capital costs include GAC pressure contactor vessels, virgin GAC, pipes and valves, and instrumentation and controls.

Because small and very small systems operate on a replacement basis, capital costs are unaffected by reactivation frequency or carbon usage rate. As a result, capital costs for small systems vary only by EBCT and design flow.

For EBCT 10 min and Reactivation Frequency = 360 days:
GAC Package Plant ($) = $(-33425 \times (\text{Design Flow})^2 + 332500 \times (\text{Design Flow}) + 17765)*1.033$

For EBCT 20 min and Reactivation Frequency = 240 days:
GAC Package Plant ($) = $(-129710 \times (\text{Design Flow})^2 + 640704 \times (\text{Design Flow}) + 10721)*1.033$

For EBCT 20 min and Reactivation Frequency = 90 days:
GAC Package Plant ($) = $(-129710 \times (\text{Design Flow})^2 + 640704 \times (\text{Design Flow}) + 10721)*1.033$

Piping and Valves Costs

For large systems, the capital costs for pipes and valves were obtained from the Water model. The costs include the pipes and valves associated with GAC contactors, regeneration furnace, and booster pumps.

For EBCT 10 min and Reactivation Frequency = 360 days:
Pipes and Valves ($) = $(81744 \times (\text{Design Flow})^{0.7327})*1.033$

For EBCT 20 min and Reactivation Frequency = 240 days:
Pipes and Valves ($) = $(104596 \times (\text{Design Flow})^{0.7701})*1.033$

For EBCT 20 min and Reactivation Frequency = 90 days:
Pipes and Valves ($) = $(106594 \times (\text{Design Flow})^{0.7674})*1.033$

For small and very small systems, the capital costs for pipes and valves were included in the GAC package costs.

Electrical Costs

For large systems, the electrical capital costs are obtained from the Water model. These costs included flow measurement and instrumentation, and master operations control panel.

For EBCT 10 min and Reactivation Frequency = 360 days:
$$\text{Electrical (\$)} = (25862 \times (\text{Design Flow})^{0.7329})*1.033$$

For EBCT 20 min and Reactivation Frequency = 240 days:
$$\text{Electrical (\$)} = (32569 \times (\text{Design Flow})^{0.7623})*1.033$$

For EBCT 20 min and Reactivation Frequency = 90 days:
$$\text{Electrical (\$)} = (34188 \times (\text{Design Flow})^{0.7554})*1.033$$

For small and very small systems, the capital costs for electrical control panels were included in the GAC package costs.

Process Monitoring Equipment Costs

The performance of GAC in removing DBP can be measured by monitoring the amount of TOC or DOC removed by the GAC column. Regular monitoring for TOC will also enable the detection of any unexpected breakthrough. For large systems, it was assumed that TOC monitoring will be conducted in-house; therefore, two TOC analyzers will be purchased. For small systems, it was assumed that samples will be sent to contracted laboratories for TOC measurement; therefore, TOC analyzers will not be purchased. Costs were obtained from vendor quotes.

Booster Pump Costs

A booster pump system is included to overcome additional head loss introduced by the GAC system. For design flows greater than 1 mgd, the capital costs for the booster pump system were obtained from the Water model. These costs were projected to 0.1 mgd using a straight line. The assumption in the model was a horizontal centrifugal pump capable of providing up to 100 feet of head. For design flows less than 0.1 mgd, estimates from vendors were used to determine capital costs for an in-line centrifugal pump.

For design flow >0.1 mgd:
$$\text{Booster Pump (\$)} = (20913 \times (\text{Design Flow})^{0.7543})*1.033$$

For design flow <0.1 mgd:
$$\text{Booster Pump (\$)} = (665970 \times (\text{Design Flow})^{2} - 13682 \times (\text{Design Flow}) + 829.1)*1.033$$

Capital Cost Multipliers

The total direct costs were estimated by multiplying the subtotal of process costs by 1.67 for small systems (design flow less than 1 mgd) and 2.0 for large systems (design flow greater than 1 mgd). The capital cost multiplier includes percentages for process installation, site work, contractor overhead and profit, contingencies, engineering and design, mobilization and bonding, legal and administrative, and interest during construction. See Exhibit 4.2 for the percentages of each that make up the multiplier.

Indirect Capital Costs

The indirect capital costs for all systems include housing, piloting, permitting, land, and operator training.

Housing Costs

For design flows greater than 1 mgd, a building cost was assumed to house the process equipment. The process costs estimated in the previous steps do not include the cost of the building. The building cost was assumed to be a function of the process area. The process area was obtained from the Water model.

For EBCT 10 min and Reactivation Frequency = 360 days:
Process Area (sq ft) = $(681.18 \times (\text{Design Flow})^{0.612})*1.033$

For EBCT 20 min and Reactivation Frequency = 240 days:
Process Area (sq ft) = $(925.83 \times (\text{Design Flow})^{0.6631})*1.033$

For EBCT 20 min and Reactivation Frequency = 90 days:
Process Area (sq ft) = $(1210.4 \times (\text{Design Flow})^{0.6297})*1.033$

Housing ($) = 48.95 × Process Area

Additional housing was not assumed to be needed for small systems.

Piloting Costs

It was assumed that pilot-scale or bench-scale tests would be necessary to determine the capacity of GAC to remove DBP precursors (TOC or DOC) for a particular type of water. Piloting costs were assumed to be $5,000 for design flow less than 0.1 mgd, $10,000 for design flow greater than 0.1 mgd but less than 1.0 mgd, and $50,000 for design flow greater than 1.0 mgd.

Permitting Costs

Permitting costs were assumed for all system sizes. Permitting was estimated at three percent of the total process cost (i.e., pre-capital cost multiplier). A minimum permitting cost of $2,500 and a maximum of $500,000 was also assumed. For further details about these costs, refer to section 4.2.

Land Costs

Land costs were assumed to be two percent of the total capital cost for all system sizes. For further details about these costs, refer to section 4.2.

Operator Training Costs

While the operators from large systems generally undergo regular training, the operators from small systems may require additional training. For design flow less than 1 mgd, it was assumed that one operator will be trained on GAC treatment process for three days at a cost of approximately $500 ($25 per hour).

4.5.1.2 Summary of GAC O&M Cost Assumptions

GAC Usage Rate and Replacement Costs

For design flows greater than 10 mgd and in the 0.1-1 mgd range, the annual GAC usage rate (lbs/year) was calculated from average flow, EBCT, and number of regenerations per year. The annual GAC replacement costs were based on a unit cost that declines with higher quantities of GAC. The unit cost ranged from $1.00 to $1.20 per pound. For design flows between 1 and 10 mgd, the annual GAC replacement costs were obtained by linear interpolation between the costs for 1 mgd and 10 mgd systems. For design flows less than 0.1 mgd, the annual GAC replacement costs were not listed separately but were included in the total O&M costs obtained from the VSS model.

<u>For design flow < 1 mgd</u>

For EBCT 10 min and Reactivation Frequency = 360 days:
GAC Replacement (lb/yr) = 33034 × (Average Flow) + 111.2

For EBCT 20 min and Reactivation Frequency = 240 days:
GAC Replacement (lb/yr) = 98716 × (Average Flow) + 344.55

For EBCT 20 min and Reactivation Frequency = 90 days:
GAC Replacement (lb/yr) = 260881 × (Average Flow) + 795.77

<u>For design flow >1 mgd and < 10 mgd</u>

For EBCT 10 min and Reactivation Frequency = 360 days:
GAC Replacement (lb/yr) = 926.57 × (Average Flow) + 11693

For EBCT 20 min and Reactivation Frequency = 240 days:
GAC Replacement (lb/yr)) = 2774.2 × (Average Flow) + 34957

For EBCT 20 min and Reactivation Frequency = 90 days:
GAC Replacement (lb/yr) = 7266.7 × (Average Flow) + 92267

<u>For design flow > 10 mgd</u>

For EBCT 10 min and Reactivation Frequency = 360 days:
GAC Replacement ($/yr) = 3146.3 × (Average Flow) + 4073.3

For EBCT 20 min and Reactivation Frequency = 240 days:
GAC Replacement (lb/yr) = 9440.3 × (Average Flow) + 11853

For EBCT 20 min and Reactivation Frequency = 90 days:
GAC Replacement (lb/yr) = 25190 × (Average Flow) + 27754

GAC Replacement ($/yr) = (-0.0541*LN(Usage Rate (lb/yr)) + 1.9172)*Usage Rate (lb/yr)

Labor Costs

For design flows greater than 10 mgd, the annual labor hours were obtained from the Water model. The labor hours include the requirements associated with operation of GAC contactors, media replacement, regeneration furnace, and booster pumps.

For design flows between 0.1-1 mgd, the annual labor hours were obtained from the Water model. For this model, the labor hours included requirements associated with operation of the GAC package unit, media replacement, and booster pumps. For design flows between 1 and 10 mgd, the annual labor hours were obtained by linear interpolation between the labor hours for 1 mgd and 10 mgd systems.

For the very small systems (design flows <0.1 mgd), labor requirements were assumed to be one hour per week plus an additional 8 hours per reactivation. However, the annual labor hours were not listed separately but were included in the total O&M costs obtained from the VSS model.

The annual labor costs for all flow rates were obtained by multiplying the labor hours by the labor costs per hour.

For design flow < 1 mgd

For EBCT 10 min and Reactivation Frequency = 360 days:
Labor ($/yr) = ((858.36 × Average Flow) + 402.56) × labor($/hr)

For EBCT 20 min and Reactivation Frequency = 240 days:
Labor ($/yr) = ((1503.2 × Average Flow) + 433.84) × labor($/hr)

For EBCT 20 min and Reactivation Frequency = 90 days:
Labor ($/yr) = ((1503.2 × Average Flow) + 433.84) × labor($/hr)

For design flow >1 mgd and < 10 mgd

For EBCT 10 min and Reactivation Frequency = 360 days:
Labor ($/yr) = ((551.97 × Average Flow) + 533.12) × labor($/hr)

For EBCT 20 min and Reactivation Frequency = 240 days:
Labor ($/yr) = ((683.86 × Average Flow) + 709.64) × labor($/hr)

For EBCT 20 min and Reactivation Frequency = 90 days:
Labor ($/yr) = ((810.91 × Average Flow) + 663.91) × labor($/hr)

For design flow > 10 mgd

For EBCT 10 min and Reactivation Frequency = 360 days:
Labor ($/yr) = (143.15 × Average Flow) + 2538.7) × labor($/hr)

For EBCT 20 min and Reactivation Frequency = 240 days:
Labor ($/yr) = ((-0.2147 × Average Flow^2) + (343.74 × Average Flow) + 2100) × labor($/hr)

For EBCT 20 min and Reactivation Frequency = 90 days:
Labor ($/yr) = (1297.2 × Average Flow$^{0.7536}$) × labor($/hr)

Power (Electricity) Costs

For design flows greater than 10 mgd, the annual power requirements (kWh/year) were obtained from the Water model. For this model, the power requirements included those associated with operation of GAC contactors, media replacement, regeneration furnace, and booster pumps.

For design flows between 0.1-1 mgd, the annual power requirements were obtained from the Water model. For this model, the power requirements included those associated with operation of GAC package unit and booster pumps.

For design flows between 1 and 10 mgd, the annual power requirements were obtained by linear interpolation between the power requirements for 1 mgd and 10 mgd systems.

For the very small systems (design flows < 0.1 mgd), the annual power costs were not listed separately but were included in the total O&M costs obtained from the VSS model.

The annual power costs were obtained by multiplying the energy requirements (kWh/year) by unit energy costs of $0.076 per kWh. Note, the unit energy cost value is rounded to $0.08 per kWh in the regression equations below.

For design flow <1 mgd

For EBCT 10 min and Reactivation Frequency = 360 days:
Power ($/yr)) = (240221 × Average Flow) + 71518) × 0.08

For EBCT 20 min and Reactivation Frequency = 240 days:
Power ($/yr) = (276311 × Average Flow$^{0.3872}$) × 0.08

For EBCT 20 min and Reactivation Frequency = 90 days:
Power ($/yr) = (276311 × Average Flow$^{0.3872}$) × 0.08

For design flow >1 mgd and < 10 mgd

For EBCT 10 min and Reactivation Frequency = 360 days:
Power ($/yr)) = ((74235 × Average Flow) + 127519) × 0.08

For EBCT 20 min and Reactivation Frequency = 240 days:
Power ($/yr) = ((99122 × Average Flow) + 149023) × 0.08

For EBCT 20 min and Reactivation Frequency = 90 days:
Power ($/yr) = ((127743 × Average Flow) + 138719) × 0.08

For design flow > 10 mgd

For EBCT 10 min and Reactivation Frequency = 360 days:
Power ($/yr) = ((73380 × Average Flow) + 215530) × 0.08

For EBCT 20 min and Reactivation Frequency = 240 days:
Power ($/yr) = ((75925 × Average Flow) + 329950) × 0.08

For EBCT 20 min and Reactivation Frequency = 90 days:
Power ($/yr) = ((79096 × Average Flow) + 410520) × 0.08

Natural Gas Costs

For design flows greater than 1 mgd, the natural gas requirements (cubic feet/year) associated with the regeneration furnace were obtained from the Water model. The annual costs for natural gas were obtained by multiplying the gas requirements (cubic feet/year) by unit gas costs of $0.006 per cubic feet.

For EBCT 10 min and Reactivation Frequency = 360 days:

$$\text{Natural Gas (\$/yr)} = (510552 \times \text{Average Flow}^{0.84}) \times 0.006$$

For EBCT 20 min and Reactivation Frequency = 240 days:

$$\text{Natural Gas (\$/yr)} = (1000000 \times \text{Average Flow}^{0.853}) \times 0.006$$

For EBCT 20 min and Reactivation Frequency = 90 days:

$$\text{Natural Gas (\$/yr)} = (3000000 \times \text{Average Flow}^{0.8702}) \times 0.006$$

Performance Monitoring Costs

For design flows less than 1 mgd, the number of TOC samples were based on analyzing one sample every two weeks per GAC pressure vessel. Performance monitoring costs were based on the assumption that the samples will be sent to contract laboratories and that the cost of TOC analyses are $65 per sample.

For design flows greater than 1 mgd, it was assumed that the TOC samples will be analyzed in-house using the automated TOC analyzers. Therefore, no additional performance monitoring costs were assumed for this system size.

Maintenance Materials Costs

For design flows greater than 10 mgd, the maintenance materials costs were obtained from the Water model. For this model, the maintenance materials included those associated with operation of GAC contactors, media replacement, regeneration furnace, and booster pumps.

For design flows between 0.1-1 mgd, the maintenance materials costs were obtained from the Water model. For this model, the maintenance materials requirements included those associated with operation of GAC package units and booster pumps.

For design flows between 1 and 10 mgd, the maintenance materials costs were obtained by linear interpolation between the power requirements for 1 mgd and 10 mgd systems. For the very small systems (design flows < 0.1 mgd), the maintenance materials costs were not listed separately but included in the total O&M costs obtained from the VSS model.

<u>*For design flow < 1 mgd*</u>

For EBCT 10 min and Reactivation Frequency = 360 days:

$$\text{Materials (\$/yr)} = (6702.4 \times \text{Average Flow}) + 626.84$$

For EBCT 20 min and Reactivation Frequency = 240 days:

$$\text{Materials (\$/yr)} = (12444 \times \text{Average Flow}) + 898.16$$

For EBCT 20 min and Reactivation Frequency = 90 days:

$$\text{Materials (\$/yr)} = (12444 \times \text{Average Flow}) + 898.16$$

For design flow >1 mgd and < 10 mgd

For EBCT 10 min and Reactivation Frequency = 360 days:

Materials (\$/yr) = 3458.7 × Average Flow$^{0.6551}$

For EBCT 20 min and Reactivation Frequency = 240 days:

Materials (\$/yr) = (2708.8 × Average Flow) + 4333.4

For EBCT 20 min and Reactivation Frequency = 90 days:

Materials (\$/yr) = (3529.2 × Average Flow) + 4038

For design flow > 10 mgd

For EBCT 10 min and Reactivation Frequency = 360 days:

Materials (\$/yr) = 3458.7 × Average Flow$^{0.6551}$

For EBCT 20 min and Reactivation Frequency = 240 days:

Materials (\$/yr) = 6202.7 × Average Flow$^{0.641}$

For EBCT 20 min and Reactivation Frequency = 90 days:

Materials (\$/yr) = 7750.8 × Average Flow$^{0.6105}$

VSS Model Costs

For the very small systems (design flows <0.1 mgd), the total O&M costs were obtained from the VSS model. These costs include operation of GAC pressure vessels and booster pumps, material replacement, labor, and power.

For EBCT 10 min and Reactivation Frequency = 360 days:

VSS Model (\$/yr) = 144625 × Average Flow$^{0.5907}$

For EBCT 20 min and Reactivation Frequency = 240 days:

VSS Model (\$/yr) = 231094 × Average Flow$^{0.6421}$

For EBCT 20 min and Reactivation Frequency = 90 days:

VSS Model (\$/yr) = 607295 × Average Flow$^{0.7075}$

Exhibit 4.46: Summary of GAC Costs (EBCT = 10 minutes, 360 day reactivation frequency)

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary									
Total Capital Cost	-	-	63,046	101,302	159,645	215,163	269,400	452,926	783,808
Indirect Capital Costs	-	-	9,079	10,062	17,602	20,246	22,829	31,568	85,419
Housing	-	-	-	-	-	-	-	-	-
Piloting	-	-	5,000	5,000	10,000	10,000	10,000	10,000	50,000
Permitting	-	-	2,500	2,737	4,261	5,848	7,397	12,641	20,952
Land	-	-	1,079	1,825	2,841	3,898	4,931	8,427	13,968
Operator Training	-	-	500	500	500	500	500	500	500
Direct Capital Cost[1]	-	-	53,966	91,240	142,043	194,917	246,572	421,358	698,388
Subtotal Process Cost	-	-	32,315	54,635	85,056	116,717	147,648	252,310	349,194
GAC Contactor, Media, & Regeneration Furnace	-	-	-	-	-	-	-	-	-
GAC Package Unit (for small systems)	-	-	31,039	49,363	79,125	108,664	137,643	236,147	327,573
Pipes and Valves	-	-	-	-	-	-	-	-	-
Electrical (Instrumentation & Controls)	-	-	-	-	-	-	-	-	-
Process Monitoring Equipment (TOC Analyzer)	-	-	-	-	-	-	-	-	-
Booster Pumps	-	-	1,276	5,272	5,931	8,053	10,005	16,164	21,621
Annual O&M Summary									
Total O&M Cost per Year	-	-	12,360	19,485	27,213	30,798	34,808	46,000	57,078
GAC Replacement ($/yr)	-	-	-	-	2,859	4,289	5,513	11,047	16,466
Labor ($/yr)	-	-	-	-	10,365	11,743	12,295	14,844	17,392
Power ($/yr)	-	-	-	-	6,759	7,336	7,835	10,142	12,448
Natural Gas ($/yr)	-	-	-	-	-	-	-	-	-
Performance Monitoring ($/yr)	-	-	3,120	3,120	6,240	6,240	7,800	7,800	7,800
Maintenance Materials ($/yr)	-	-	-	-	989	1,190	1,364	2,168	2,973
Total O&M costs (from VSS Model) - ($/yr)	-	-	9,240	16,365	-	-	-	-	-

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.5.1

Exhibit 4.46 (continued): Summary of GAC Costs (EBCT = 10 minutes, 360 day reactivation frequency)

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270
Capital Cost Summary									
Total Capital Cost	999,248	1,385,099	2,014,217	3,258,534	6,140,593	7,400,352	18,311,317	38,194,366	64,571,358
Indirect Capital Costs	130,707	162,111	211,893	307,265	519,857	610,583	1,361,145	2,150,334	3,142,215
Housing	37,280	50,962	71,777	109,702	188,821	221,094	472,142	879,453	1,363,632
Piloting	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
Permitting	26,056	36,690	54,070	88,538	168,622	203,693	500,000	500,000	500,000
Land	17,371	24,460	36,046	59,025	112,415	135,795	339,003	720,881	1,228,583
Operator Training	-	-	-	-	-	-	-	-	-
Direct Capital Cost[1]	868,541	1,222,988	1,802,324	2,951,268	5,620,735	6,789,769	16,950,172	36,044,032	61,429,143
Subtotal Process Cost	434,271	611,494	901,162	1,475,634	2,810,368	3,394,885	8,475,086	18,022,016	30,714,571
GAC Contactor, Media, & Regeneration Furnace	230,615	338,452	515,250	867,145	1,688,458	2,049,192	5,198,933	11,153,467	19,105,482
GAC Package Unit (for small systems)	-	-	-	-	-	-	-	-	-
Pipes and Valves	96,592	140,439	211,623	351,663	673,711	813,798	2,018,347	4,250,244	7,185,650
Electrical (Instrumentation & Controls)	30,561	44,438	66,970	111,302	213,268	257,627	639,114	1,346,122	2,276,140
Process Monitoring Equipment (TOC Analyzer)	51,694	51,694	51,694	51,694	51,694	51,694	51,694	51,694	51,694
Booster Pumps	24,809	36,471	55,626	93,830	183,236	222,574	566,998	1,220,490	2,095,605
Annual O&M Summary									
Total O&M Cost per Year	51,809	61,887	79,158	120,100	227,710	280,625	709,287	1,952,120	4,368,760
GAC Replacement ($/yr)	17,007	17,459	18,248	20,246	38,974	52,056	158,605	466,311	1,005,806
Labor ($/yr)	18,788	24,279	34,018	57,024	95,220	107,153	207,837	513,620	1,287,574
Power ($/yr)	12,636	14,774	18,516	28,018	63,032	81,817	240,318	721,690	1,602,250
Natural Gas ($/yr)	1,449	2,459	4,064	7,709	17,201	22,959	65,044	170,885	337,704
Performance Monitoring ($/yr)	-	-	-	-	-	-	-	-	-
Maintenance Materials ($/yr)	1,929	2,914	4,312	7,104	13,284	16,639	37,483	79,613	135,425
Total O&M costs (from VSS Model) - ($/yr)	-	-	-	-	-	-	-	-	-

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.5.1

Exhibit 4.47: Summary of GAC Costs (EBCT = 20 minutes, 90 day reactivation frequency)

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary									
Total Capital Cost	36,117	53,091	70,491	137,932	241,793	340,528	435,155	739,387	1,228,620
Indirect Capital Costs	8,551	8,884	9,225	11,806	21,514	26,216	30,722	45,209	106,601
Housing	-	-	-	-	-	-	-	-	-
Piloting	5,000	5,000	5,000	5,000	10,000	10,000	10,000	10,000	50,000
Permitting	2,500	2,500	2,500	3,784	6,608	9,429	12,133	20,825	33,661
Land	551	884	1,225	2,523	4,406	6,286	8,089	13,884	22,440
Operator Training	500	500	500	500	500	500	500	500	500
Direct Capital Cost[1]	27,566	44,207	61,266	126,126	220,279	314,313	404,433	694,178	1,122,019
Subtotal Process Cost	16,506	26,471	36,686	75,524	131,904	188,211	242,176	415,676	561,009
GAC Contactor, Media, & Regeneration Furnace	-	-	-	-	-	-	-	-	-
GAC Package Unit (for small systems)	15,714	25,592	35,410	70,253	125,973	180,158	232,171	399,512	539,388
Pipes and Valves	-	-	-	-	-	-	-	-	-
Electrical (Instrumentation & Controls)	-	-	-	-	-	-	-	-	-
Process Monitoring Equipment (TOC Analyzer)	-	-	-	-	-	-	-	-	-
Booster Pumps	792	879	1,276	5,272	5,931	8,053	10,005	16,164	21,621
Annual O&M Summary									
Total O&M Cost per Year	9,222	18,223	25,644	47,782	47,639	61,728	74,417	123,691	171,149
GAC Replacement ($/yr)	-	-	-	-	20,798	31,216	40,122	80,331	119,625
Labor ($/yr)	-	-	-	-	11,892	13,857	14,824	19,287	23,749
Power ($/yr)	-	-	-	-	7,140	8,472	9,404	12,513	14,721
Natural Gas ($/yr)	-	-	-	-	-	-	-	-	-
Performance Monitoring ($/yr)	3,120	3,120	3,120	3,120	6,240	6,240	7,800	7,800	7,800
Maintenance Materials ($/yr)	-	-	-	-	1,570	1,943	2,267	3,760	5,254
Total O&M Cost (from VSS or Water Model) - ($/yr)	6,102	15,103	22,524	44,662	-	-	-	-	-

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.5.1

Exhibit 4.47 (continued): Summary of GAC Costs (EBCT = 20 minutes, 90 day reactivation frequency)

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430	520
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270	350
Capital Cost Summary										
Total Capital Cost	1,551,122	2,203,728	3,275,153	5,411,638	10,411,502	12,611,714	31,503,622	67,096,117	114,813,572	132,437,789
Indirect Capital Costs	184,775	239,866	327,770	497,471	879,379	1,043,376	2,044,968	3,538,984	5,435,163	6,116,944
Housing	66,457	91,673	130,401	201,762	352,773	414,959	905,795	1,717,842	2,697,595	3,040,527
Piloting	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
Permitting	40,990	58,916	88,421	147,425	285,964	347,050	500,000	500,000	500,000	500,000
Land	27,327	39,277	58,948	98,283	190,642	231,367	589,173	1,271,143	2,187,568	2,526,417
Operator Training	-	-	-	-	-	-	-	-	-	-
Direct Capital Cost[1]	1,366,348	1,963,862	2,947,383	4,914,168	9,532,123	11,568,338	29,458,653	63,557,133	109,378,409	126,320,844
Subtotal Process Cost	683,174	981,931	1,473,691	2,457,084	4,766,062	5,784,169	14,729,327	31,778,567	54,689,205	63,160,422
GAC Contactor, Media, & Regeneration Furnace	439,351	646,508	987,095	1,667,239	3,261,371	3,963,463	10,120,594	21,827,148	37,528,708	43,328,784
GAC Package Unit (for small systems)	-	-	-	-	-	-	-	-	-	-
Pipes and Valves	126,755	187,591	288,216	490,601	969,275	1,181,342	3,058,701	6,672,241	11,564,432	13,380,169
Electrical (Instrumentation & Controls)	40,565	59,668	91,061	153,719	300,485	365,096	931,340	2,006,994	3,448,765	3,981,168
Process Monitoring Equipment (TOC Analyzer)	51,694	51,694	51,694	51,694	51,694	51,694	51,694	51,694	51,694	51,694
Booster Pumps	24,809	36,471	55,626	93,830	183,236	222,574	566,998	1,220,490	2,095,605	2,418,608
Annual O&M Summary										
Total O&M Cost per Year	177,242	199,489	237,836	330,703	656,235	863,063	2,448,311	6,727,479	14,362,281	18,123,898
GAC Replacement ($/yr)	123,533	126,783	132,460	146,831	280,444	376,193	1,153,011	3,384,412	7,278,711	9,302,877
Labor ($/yr)	24,651	32,646	46,869	80,667	158,890	205,877	524,010	1,246,481	2,755,952	3,351,240
Power ($/yr)	15,287	18,966	25,405	41,756	82,198	102,446	273,293	792,163	1,741,315	2,247,530
Natural Gas ($/yr)	8,285	14,338	24,123	46,823	107,541	145,042	426,580	1,160,315	2,349,878	2,945,239
Performance Monitoring ($/yr)	-	-	-	-	-	-	-	-	-	-
Maintenance Materials ($/yr)	5,485	6,755	8,979	14,626	27,163	33,506	71,417	144,108	236,425	277,013
Total O&M Cost (from VSS or Water Model) - ($/yr)	-	-	-	-	-	-	-	-	-	-

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.5.1

Exhibit 4.48: Summary of GAC Costs (EBCT = 20 minutes, 240 day reactivation frequency)

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary									
Total Capital Cost	36,117	53,091	70,491	137,932	241,793	340,528	435,155	739,387	1,228,620
Indirect Capital Costs	8,551	8,884	9,225	11,806	21,514	26,216	30,722	45,209	106,601
Housing	-	-	-	-	-	-	-	-	-
Piloting	5,000	5,000	5,000	5,000	10,000	10,000	10,000	10,000	50,000
Permitting	2,500	2,500	2,500	3,784	6,608	9,429	12,133	20,825	33,661
Land	551	884	1,225	2,523	4,406	6,286	8,089	13,884	22,440
Operator Training	500	500	500	500	500	500	500	500	500
Direct Capital Cost[1]	27,566	44,207	61,266	126,126	220,279	314,313	404,433	694,178	1,122,019
Subtotal Process Cost	16,506	26,471	36,686	75,524	131,904	188,211	242,176	415,676	561,009
GAC Contactor, Media, & Regeneration Furnace	-	-	-	-	-	-	-	-	-
GAC Package Unit (for small systems)	15,714	25,592	35,410	70,253	125,973	180,158	232,171	399,512	539,388
Pipes and Valves	-	-	-	-	-	-	-	-	-
Electrical (Instrumentation & Controls)	-	-	-	-	-	-	-	-	-
Process Monitoring Equipment (TOC Analyzer)	-	-	-	-	-	-	-	-	-
Booster Pumps	792	879	1,276	5,272	5,931	8,053	10,005	16,164	21,621
Annual O&M Summary									
Total O&M Cost per Year	6,673	11,206	14,742	24,752	35,068	42,835	50,123	75,023	98,679
GAC Replacement ($/yr)	-	-	-	-	8,227	12,323	15,828	31,664	47,154
Labor ($/yr)	-	-	-	-	11,892	13,857	14,824	19,287	23,749
Power ($/yr)	-	-	-	-	7,140	8,472	9,404	12,513	14,721
Natural Gas ($/yr)	-	-	-	-	-	-	-	-	-
Performance (TOC) Monitoring ($/yr)	3,120	3,120	3,120	3,120	6,240	6,240	7,800	7,800	7,800
Maintenance Materials ($/yr)	-	-	-	-	1,570	1,943	2,267	3,760	5,254
Total O&M costs (from VSS Model) - ($/yr)	3,553	8,086	11,622	21,632	-	-	-	-	-

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.5.1

Exhibit 4.48 (continued): Summary of GAC Costs (EBCT = 20 minutes, 240 day reactivation frequency)

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270
Capital Cost Summary									
Total Capital Cost	1,351,323	1,931,036	2,894,585	4,844,129	9,491,603	11,561,478	29,712,377	64,708,727	112,528,561
Indirect Capital Costs	160,676	207,918	284,509	435,140	782,092	933,328	1,906,778	3,348,109	5,222,719
Housing	51,143	71,762	104,005	164,690	296,616	351,920	800,666	1,570,896	2,526,602
Piloting	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
Permitting	35,719	51,694	78,302	132,270	261,285	318,845	500,000	500,000	500,000
Land	23,813	34,462	52,202	88,180	174,190	212,563	556,112	1,227,212	2,146,117
Operator Training	-	-	-	-	-	-	-	-	-
Direct Capital Cost[1]	1,190,648	1,723,117	2,610,076	4,408,989	8,709,512	10,628,150	27,805,599	61,360,618	107,305,842
Subtotal Process Cost	595,324	861,559	1,305,038	2,204,494	4,354,756	5,314,075	13,902,799	30,680,309	53,652,921
GAC Contactor, Media, & Regeneration Furnace	355,688	531,860	826,445	1,426,610	2,869,509	3,515,589	9,333,290	20,781,931	36,544,812
GAC Package Unit (for small systems)	-	-	-	-	-	-	-	-	-
Pipes and Valves	124,440	184,419	283,772	483,942	958,411	1,168,914	3,036,669	6,642,385	11,534,984
Electrical (Instrumentation & Controls)	38,693	57,115	87,501	148,419	291,906	355,305	914,148	1,983,810	3,425,826
Process Monitoring Equipment (TOC Analyzer)	51,694	51,694	51,694	51,694	51,694	51,694	51,694	51,694	51,694
Booster Pumps	24,809	36,471	55,626	93,830	183,236	222,574	566,998	1,220,490	2,095,605
Annual O&M Summary									
Total O&M Cost per Year	96,623	110,575	134,831	193,396	367,103	469,818	1,294,938	3,624,295	7,945,037
GAC Replacement ($/yr)	48,709	50,002	52,261	57,980	111,376	148,839	453,404	1,330,667	2,865,233
Labor ($/yr)	24,493	31,326	43,426	71,930	124,209	152,527	386,897	1,048,698	2,477,610
Power ($/yr)	15,173	18,028	23,024	35,711	73,773	93,210	257,208	755,276	1,666,376
Natural Gas ($/yr)	2,805	4,801	7,995	15,316	34,603	46,394	133,569	356,199	711,385
Performance (TOC) Monitoring ($/yr)	-	-	-	-	-	-	-	-	-
Maintenance Materials ($/yr)	5,444	6,419	8,126	12,460	23,143	28,848	63,859	133,455	224,432
Total O&M costs (from VSS Model) - ($/yr)	-	-	-	-	-	-	-	-	-

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Source: Section 4.5.1

4.5.2 Nanofiltration

Nanofiltration can be effective for the control of DBP precursors (i.e., NOM), as well as microbial contaminants. NF is an advanced treatment process that typically requires higher levels of pre- and post-treatment than traditional water treatment processes. The costs provided in this section assume that the NF system is an "add-on" polishing treatment process for an existing conventional treatment plant generating water of desired quality for NF. These costs do not include any additional post-treatments that may be necessary. Costs were developed assuming a feed water temperatures of 10°C. (Costs of a NF system can vary with temperature.)

The cost estimates assume that 100 percent of the flow will be treated by the NF membranes (i.e., no blending). Recovery was assumed to be 85 percent. In some regions, an additional cost for purchased water may be incurred as a result of the 15 percent water loss. The costs associated with these losses were not included in the estimates provided.

4.5.2.1 Summary of NF Capital Cost Assumptions

Process Costs

Capital costs were estimated based on vendor quotations, cost estimating guides, and best professional judgment and were adjusted to year 2003 dollars using the ENR BCI. Exhibit 4.54 presents a summary of line item capital costs for retrofitting NF into an existing treatment plant for design flows ranging from 0.007 mgd to 520 mgd. Costs were based on a feed water temperature of 10°C and a recovery of 85 percent. The spent brine was assumed to be directly discharged to a sewer, storm drain, ocean outfall, or a salinity interceptor. The methodology used for estimating capital costs is discussed in this section.

<u>Membrane System Costs</u>

Unlike other treatment processes, NF systems are typically supplied by equipment vendors as package skid-mounted units. Vendors, contacted to provide cost estimates, provided a single cost estimate that included the following items:

- Membrane skid with filter housings
- NF membrane elements (initial batch)
- Cartridge pre-filtration
- System feed pumps
- Acid and anti-scalant feed systems
- Clean-in-place system
- Instrumentation and controls
- Pipes and valves

The typical percent distribution of the above components in the NF equipment cost is shown in

Exhibit 4.49. The NF skids are equipped with all necessary instrumentation and controls and pipes and valves; therefore, these costs were included as part of the NF equipment cost.

Exhibit 4.49: Percent Distribution of NF Equipment Cost

Capital Cost Item	NF Equipment Cost (as %)
Membrane skid with filter housings	20%
NF membrane elements (initial batch)	20%
Cartridge pre-filtration	10%
System feed pumps	12%
Acid and anti-scalant feed systems	3%
Clean-in-place system	5%
Instrumentation and controls	20%
Pipes and valves	10%
Sub-Total NF Equipment Cost	**100%**

Source: Vendor quotes

Online Process Monitoring Equipment

Additional process monitoring for pH and turbidity was assumed for all NF systems. Process monitoring equipment includes an on-line conductivity/pH meter ($2,500 for meter and probe) and a turbidimeter ($2,500 for meter and probe). For systems smaller than 2 mgd capacity, one conductivity/pH meter and one turbidimeter were assumed. For systems larger than 2 mgd, the number of meters was based on one instrument per train/skid. Costs were obtained from vendor quotes and were adjusted to the year 2003 dollars using the ENR BCI.

Brine Discharge Pipeline

Costs for brine discharge include construction of a 500-foot pipeline from the NF process to an appropriate sanitary sewer connector. Pipe material was assumed to be PVC or reinforced concrete with diameters varying from 2 to 24 inches depending on the quantity of water to be discharged. Costs for the pipeline were obtained from *Small Water System Byproducts Treatment and Disposal Cost Document* (DPRA 1993a) and *Water System Byproducts Treatment and Disposal Cost Document* (DPRA 1993b). For more details on pipeline costs refer to section 4.4.5.

Capital Cost Multipliers

Total direct capital costs were obtained by applying a capital cost multiplier to the sum of all process costs. The capital cost multipliers of 1.67 and 2.0 were used respectively for small (<2 mgd) and large (≥2 mgd) systems. Unlike other treatment processes, membrane systems are typically supplied by the equipment vendor as package, skid-mounted units; therefore, smaller multipliers were used compared to those recommended by NDWAC. For more discussion on the multipliers refer to section 4.2.1.

Indirect Capital Costs

Costs for permitting, piloting, membrane housing, land, and operator training were totaled and are referred to as indirect capital costs for the purposes of this document. Indirect capital costs were added to the direct capital costs to obtain total capital costs.

Permitting

Incorporating NF treatment will likely require coordination with the appropriate regulatory agencies. To account for this, permitting costs were included at three percent of the process cost. A minimum permitting fee of $2,500 and a maximum of $500,000 was assumed.

Pilot Testing

It was assumed that pilot- or bench-scale tests would be necessary to ensure compatibility of membrane materials with process chemicals (e.g., coagulants or polymers), as well as to determine critical design parameters, such as design flux and cleaning frequency. Bench-scale flat sheet tests were assumed for systems less than 0.1 mgd, at a cost of $1,000. Single-element tests at a one-time cost of $10,000 was assumed for systems between 0.1 and 1 mgd. For systems 1 mgd and larger, three-month pilot tests at a cost of $60,000 were assumed.

Membrane Housing

Membrane housing costs include the cost for a building to house the membrane skids and any associated appurtenances (e.g., building electrical, HVAC, and lighting). Housing costs will vary depending on size of the system. Exhibit 4.50 summarizes the membrane housing cost assumptions used for NF costs. A range of housing areas from 900 to 1,100 ft^2 per mgd was assumed with a minimum of 100 ft^2. Housing areas are based on experience with similar systems. A unit cost of $48.95/$ft^2$ was taken from RS Means. The $48.95/$ft^2$ unit cost assumes a factory type building.

Exhibit 4.50: Summary of NF Housing Cost Assumptions

System Size (mgd)	Housing Area[1]
< 10 mgd	1,100 ft^2 per mgd
> 10 mgd	900 ft^2 per mgd

Note: [1]A minimum housing area of 100 ft^2 was also assumed for very small systems.

Land

Land cost assumptions for NF treatment are listed in Exhibit 4.51. The NDWAC cost working group recommended a factor of two to five percent of capital cost for land. Previous technology cost efforts (USEPA 2001) adopted land costs at a factor of five percent for systems less than 1 mgd and two percent for systems greater than 1 mgd; however, previous cases assumed new plant construction, instead of a retrofit which was assumed in this document. Using a two to five percent factor for land resulted in unrealistic costs for land acquisition ($/acre). Therefore, the land cost factors were adjusted, as discussed under MF cost assumptions, to obtain reasonable costs.

Exhibit 4.51: NF Land Cost Assumptions

System Design Flow (mgd)	Land Cost (% of Total Direct Cost)
< 1	2%
1 - 10	1%
> 10	0.5%

Source: Exhibit 4.7

<u>Operator Training</u>

The NDWAC cost working group also recommended inclusion of operator training. The operator training costs were based on the number of hours required per system size to train an operator. Training hours are based on experience with similar systems. Based upon system size, this training could last a few hours or a few days. Exhibit 4.52 summarizes the operator training cost assumptions used in this document.

Exhibit 4.52: NF Operator Training Cost Assumptions

System Design Flow (mgd)	Training Cost ($)
< 0.3	included in membrane system price
0.3 - < 1	$1,000
1 - 10	$3,000
10 - 50	$10,000
> 50	$25,000

4.5.2.2 Summary of NF O&M Cost Assumptions

NF O&M costs were estimated using current plant operational data and industry guidelines. Exhibit 4.54 presents a summary of line items of O&M costs. This section discusses the assumptions regarding O&M estimates presented in this document.

Clean-in-Place Chemicals

NF systems will require periodic (typically quarterly or semi-annually) chemical cleaning to remove biological/particulate foulants and scalants from the membrane surfaces. Membrane cleaning is performed using manufacturer-recommended cleaning agents, and costs can vary. Based on discussions with manufacturers and experience with similar systems, a typical costs of $0.01 per 1,000 gallons of water produced was assumed for all system sizes to account for cleaning chemical costs. Thus, cleaning chemical costs can be estimated by the following equation:

$$\text{Cleaning Chemicals (\$/yr)} = 0.01 \times \text{Average Flow (mgd)} \times 1{,}000 \times 365$$

A minimum cost of $50/year was assumed for cleaning chemicals; this accounts for the cost of purchasing a 15-gallon pail of cleaning chemical.

Acid/Anti-Scalant and Caustic Chemicals

Addition of acid and anti-scalant is necessary to reduce the fouling and scaling of NF membranes. Caustic may be necessary to raise pH and lower the corrosiveness of the product water. The dosages of acid, anti-scalant, and caustic are a function of the feed water quality. Based on conversations with manufacturers and experience with similar NF systems, a typical cost for all three chemicals is $0.04 per 1,000 gallons of water produced for average flows less than 0.35 mgd, and $0.03 per 1,000 gallons for average flows above 0.35 mgd. Therefore, acid, anti-scalant, and caustic chemical costs can be estimated by the following equations:

For average flows less than 0.35 mgd

$$\text{Acid, Anti-Scalant, and Caustic Chemicals (\$/yr)} = 0.04 \times \text{Average Flow (mgd)} \times 1{,}000 \times 365$$

For average flows greater than or equal to 0.35 mgd

$$\text{Acid, Anti-Scalant, and Caustic Chemicals (\$/yr)} = 0.03 \times \text{Average Flow (mgd)} \times 1{,}000 \times 365$$

A minimum cost of $50 was assumed for acid/anti-scalants and caustic to account for purchasing these chemicals in small quantities of five gallons.

NF Membrane Replacement

NF membranes were assumed to have a life of five years, which is typical for this type of membrane. Therefore, the annual cost for NF membrane replacement was assumed to be 20 percent of the NF membrane purchase cost.

$$\text{NF Membrane Replacement (\$/yr)} = 0.20 \times \text{NF Membrane Element Process Cost}$$

Cartridge Filter Replacement

Cartridge filters collect particles and keep them from depositing on to the NF membranes. These cartridge filters must be replaced more frequently for turbid waters. Cost for cartridge filter replacement was assumed to be $0.002 per 1,000 gallons of water produced for systems with average flows less than 0.35 mgd and $0.02 per 1,000 gallons produced for systems with flows above 0.35 mgd. Costs were obtained from a study of Florida NF plants (Bergman 1996).

For average flows less than 0.35 mgd

$$\text{Cartridge Filter Replacement Cost (\$/yr)} = 0.0002 \times \text{Average Flow (mgd)} \times 1{,}000 \times 365$$

For average flows greater than or equal to 0.35 mgd

$$\text{Cartridge Filter Replacement Cost (\$/yr)} = 0.02 \times \text{Average Flow (mgd)} \times 1{,}000 \times 365$$

Repair, Maintenance and Replacement

NF systems require periodic maintenance and repair. The O&M costs for repair, maintenance, and purchase of replacement parts is typically about $0.01 per 1,000 gallons produced (Bergman 1996) for existing systems. A minimum cost of $100 per year was assumed for repair and replacement for small systems. The cost equation for repair, maintenance, and replacement is:

Repair, Maintenance & Replacement Cost ($/yr) = 0.01 × Average Flow (mgd) × 1,000 × 365

Performance Monitoring

In addition to on-line conductivity, pH, and turbidity meters (included in capital cost estimates), periodic HPC tests are typically performed to monitor biological activity on the finished water side of the membrane. Field HPC tests cost approximately $1 per test and require one hour of labor. The frequency of HPC testing was assumed to be one test per membrane skid per week. As mentioned earlier, the NF skid size of 2 mgd was assumed for all system sizes.

Power

Power costs include power for NF feed pumps, instrumentation and controls, and building maintenance. The power requirements for process pumping and building maintenance were assumed to be 1.2 kWh/1,000 gallons and 0.6 kWh/1,000 gallons, respectively. Additional power for instruments and controls was assumed to be negligible. Unit power cost of $0.076 per kWh was used to estimate the power cost. The equation for power cost is given below.

Power Cost ($/yr) = 1.8 x 0.076 x Average Flow (mgd) x 1,000 x 365

Labor

Technical labor estimates for operation and maintenance of the membrane systems include periodic data logging, repair of process equipment, and sampling. Hours are based on experience with similar systems. Technical labor rates used varied with system size. No additional managerial labor was assumed. A summary of labor hour assumptions is provided in Exhibit 4.53.

Exhibit 4.53: Summary of NF Technical Labor Assumptions

System Size (mgd)	Technical Labor (hrs/week)
< 0.1	4
0.1 - < 1	12
1 - < 5	24
5 - < 10	40
10 - 100	80
> 100	160

POTW Surcharge

A fee of $0.00183 per 1,000 gallons discharged to the sanitary sewer was assumed. This rate was based upon data provided in the DPRA reports (1993a and 1993b). The discharge volume was based on an average system recovery of 85 percent; therefore, the waste volume is 0.15 × average daily flow. The surcharge for brine discharge can be calculated using the equation below.

$$\text{Surcharge for Brine Discharge (\$/yr)} = 1.83 \times 0.15 \times \text{Average Flow (mgd)} \times 1{,}000 \times 365$$

Costs for concentrate handling included the following components:

- Direct discharge of 15 percent of the feed flow to a sewer/storm/salinity interceptor or ocean outfall, located 500 feet or less from the NF plant (at 85 percent recovery, 15 percent would be the brine stream).

- No additional pumping is necessary, assuming that the brine stream is leaving the NF system at 30 psi residual pressure.

Exhibit 4.54: Nanofiltration Cost Summary

Design Flow (mgd)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow (mgd)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Capital Cost Summary									
Total Unit Capital Cost	51,894	69,241	86,588	156,079	222,829	315,937	357,087	663,375	912,423
Indirect Capital Costs	9,248	9,588	9,928	11,393	27,122	35,196	42,334	70,136	138,487
Piloting	1,000	1,000	1,000	1,000	10,000	10,000	10,000	10,000	60,000
Permitting	2,500	2,500	2,500	2,599	3,516	5,043	5,654	10,657	13,903
Land	853	1,193	1,533	2,894	3,914	5,615	6,295	11,865	7,739
Operator Training	-	-	-	-	-	-	1,000	1,000	3,000
Housing	4,895	4,895	4,895	4,900	9,692	14,538	19,384	36,615	53,845
Direct Capital Cost[1]	42,646	59,653	76,660	144,687	195,707	280,740	314,754	593,239	773,935
Subtotal Process Cost	25,537	35,720	45,904	86,639	117,190	168,108	188,475	355,233	463,434
Pipes and Valves	2,068	3,102	4,135	8,271	11,373	16,542	18,610	35,539	46,524
Instrumentation and Controls	4,135	6,203	8,271	16,542	22,745	33,084	37,219	71,079	93,049
Cartridge Prefiltration	1,654	2,481	3,308	6,617	9,098	13,234	14,888	28,432	37,219
Acid and Anti-Scalent Feed Systems	620	930	1,241	2,481	3,412	4,963	5,583	10,662	13,957
System Feed Pumps	2,585	3,877	5,169	10,339	14,216	20,677	23,262	44,424	58,155
Nanofilter Membrane Elements	4,135	6,203	8,271	16,542	22,745	33,084	37,219	71,079	93,049
Membrane Skid with Filter Housing	4,135	6,203	8,271	16,542	22,745	33,084	37,219	71,079	93,049
Clean-In-Place (CIP) System	1,034	1,551	2,068	4,135	5,686	8,271	9,305	17,770	23,262
Online Conductivity/pH and Turbidity Meters	5,169	5,169	5,169	5,169	5,169	5,169	5,169	5,169	5,169
Brine Discharge Pump (Not Included in Subtotal Process Cost)	258	388	517	1,034	1,422	2,068	2,326	4,442	5,816
Annual O&M Summary									
Total Annual O&M Cost	6,909	7,937	9,025	13,703	29,539	37,904	43,223	70,725	112,309
Acid, Anti-Scalant Caustic Chemicals	50	79	139	365	788	1,226	1,606	3,358	3,832
Clean-In-Place Chemicals	50	50	50	91	197	307	401	839	1,277
NF Membrane Replacement	827	1,241	1,654	3,308	4,549	6,617	7,444	14,216	18,610
Cartridge Filter Replacement	30	30	30	30	39	61	80	168	2,555
Repair, Maintenance and Replacement	100	100	100	100	197	307	401	839	1,277
Process monitoring (HPCs)	1,167	1,167	1,167	1,253	1,253	1,338	1,338	1,338	1,338
Power	75	270	474	1,248	2,696	4,194	5,493	11,484	17,476
Labor	4,460	4,460	4,460	4,803	14,408	15,438	15,438	15,438	30,876
Surcharge for Brine Discharge (Sewer/Storm Drain/Brine Interceptor)	150	541	952	2,505	5,410	8,416	11,021	23,044	35,067

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Assume temperature = 10°C, discharge to sewer
Source: Section 4.5.2

Exhibit 4.54 (continued): Nanofiltration Cost Summary

Design Flow (mgd)	1.2	2	3.5	7	17	22	76	210	430	520
Average Flow (mgd)	0.41	0.77	1.4	3	7.8	11	38	120	270	350
Capital Cost Summary										
Total Unit Capital Cost	1,080,532	2,018,579	3,404,129	6,745,258	15,456,118	19,862,964	57,558,238	129,659,099	265,356,059	318,914,577
Indirect Capital Costs	153,537	215,760	328,352	593,704	1,105,939	1,408,303	4,199,971	10,432,682	20,751,672	24,963,356
Piloting	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000
Permitting	16,653	27,042	46,137	92,273	215,253	276,820	500,000	500,000	500,000	500,000
Land	9,270	18,028	30,758	61,516	71,751	92,273	266,791	596,132	1,223,022	1,469,756
Operator Training	3,000	3,000	3,000	3,000	10,000	10,000	25,000	25,000	25,000	25,000
Housing	64,614	107,690	188,458	376,915	748,935	969,210	3,348,180	9,251,550	18,943,650	22,908,600
Direct Capital Cost[1]	926,996	1,802,819	3,075,777	6,151,554	14,350,179	18,454,661	53,358,267	119,226,417	244,604,387	293,951,221
Subtotal Process Cost	555,087	901,409	1,537,888	3,075,777	7,175,090	9,227,331	26,679,134	59,613,208	122,302,193	146,975,610
Pipes and Valves	55,829	90,464	155,081	310,162	723,712	930,487	2,688,074	5,996,473	12,303,108	14,784,406
Instrumentation and Controls	111,658	180,928	310,162	620,325	1,447,424	1,860,974	5,376,148	11,992,945	24,606,215	29,568,813
Cartridge Prefiltration	44,663	72,371	124,065	248,130	578,970	744,390	2,150,459	4,797,178	9,842,486	11,827,525
Acid and Anti-Scalent Feed Systems	16,749	27,139	46,524	93,049	217,114	279,146	806,422	1,798,942	3,690,932	4,435,322
System Feed Pumps	69,787	113,080	193,851	387,703	904,640	1,163,109	3,360,092	7,495,591	15,378,884	18,480,508
Nanofilter Membrane Elements	111,658	180,928	310,162	620,325	1,447,424	1,860,974	5,376,148	11,992,945	24,606,215	29,568,813
Membrane Skid with Filter Housing	111,658	180,928	310,162	620,325	1,447,424	1,860,974	5,376,148	11,992,945	24,606,215	29,568,813
Clean-In-Place (CIP) System	27,915	45,232	77,541	155,081	361,856	465,244	1,344,037	2,998,236	6,151,554	7,392,203
Online Conductivity/pH and Turbidity Meters	5,169	10,339	10,339	20,677	46,524	62,032	201,606	547,954	1,116,585	1,349,206
Brine Discharge Pump (Not Included in Subtotal Process Cost)	6,979	11,308	19,385	38,770	90,464	116,311	336,009	749,559	1,537,888	1,848,051
Annual O&M Summary										
Total Annual O&M Cost	126,572	205,817	343,298	710,894	1,780,761	2,429,844	7,914,024	23,845,168	52,975,344	68,097,181
Acid, Anti-Scalant Caustic Chemicals	4,489	8,431	15,329	32,848	85,405	120,442	416,073	1,313,916	2,956,311	3,832,255
Clean-In-Place Chemicals	1,496	2,810	5,110	10,949	28,468	40,147	138,691	437,972	985,437	1,277,418
NF Membrane Replacement	22,332	36,186	62,032	124,065	289,485	372,195	1,075,230	2,398,589	4,921,243	5,913,763
Cartridge Filter Replacement	2,993	5,621	10,219	21,899	56,936	80,295	277,382	875,944	1,970,874	2,554,836
Repair, Maintenance and Replacement	1,496	2,810	5,110	10,949	28,468	40,147	138,691	437,972	985,437	1,277,418
Process monitoring (HPCs)	1,338	2,739	2,813	5,626	12,659	16,879	54,857	149,100	362,344	437,833
Power	20,472	38,448	69,905	149,796	389,470	549,252	1,897,416	5,991,840	13,481,640	17,476,200
Labor	30,876	31,624	32,510	54,184	108,368	108,368	108,368	216,736	260,083	260,083
Surcharge for Brine Discharge (Sewer/Storm Drain/Brine Interceptor)	41,079	77,148	140,270	300,578	781,502	1,102,118	3,807,315	12,023,100	27,051,975	35,067,375

[1] Direct Capital Cost = (Capital Cost Multiplier * Subtotal Process Cost)
Note: Assume temperature = 10°C, discharge to sewer
Source: Section 4.5.1

4.6 Annualized Costs

To compare technologies' cost to one another, it is helpful to annualize the capital costs and add them to the O&M costs to obtain an average annual expenditure for each technology. The annualization is done according to the methodology described in section 4.3. Expressing the annualized costs in cents per thousand gallons allows costs to be expressed in similar units for all size plants so economies of scale and other factors can be seen. Exhibit 4.55 shows the annualized cost for each of the technologies discussed above for all size ranges. Costs are annualized using a three percent discount rate over a twenty year period, which is the assumed lifetime of the equipment.

Exhibit 4.55: Annualized Cost Summary

Design Flow	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1
Average Flow	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35
Bag Filters	213.7	59.9	45.1	17.8	11.5	9.1	9.0	6.5	6.6
Cartridge Filters (filter loading 30 pgm/filter)	252.7	70.8	57.3	28.8	22.4	21.9	21.3	17.6	17.1
Convert to Chloramines (NH4 dose = 0.55mg/l)	606.0	168.6	95.9	37.7	18.1	18.1	14.1	7.0	6.3
Convert to Chloramines (NH4 dose = 0.15mg/l)	605.8	168.3	95.7	37.5	17.9	17.9	13.9	6.9	6.2
GAC (EBCT = **10**, 360 day regeneration)	Data Not Used		478.7	288.2	192.5	147.6	131.8	91.1	85.9
GAC (EBCT = **20**, 90 day regeneration)	2,127.8	1,105.6	876.2	625.2	324.2	276.0	258.2	206.5	198.6
GAC (EBCT = **20**, 240 day regeneration)	1,662.2	749.6	561.8	372.9	260.4	214.4	197.7	148.6	141.9
Nanofiltration (100% flow treated, 10C)	1,899.0	638.8	428.1	265.1	225.9	192.9	167.4	137.4	135.9
Chlorine Dioxide (ClO2 dose = 1.25 mg/l, no additional contact time)	Data Not Used			178.3	90.2	63.1	49.0	24.7	16.6
Ozone (**0.5** log dose, 12 minute contact time)				846.2	414.1	289.9	231.4	127.0	91.3
Ozone (**1.0** log dose, 12 minute contact time)				871.1	436.6	311.5	253.3	146.8	106.0
Ozone (**2.0** log dose, 12 minute contact time)				889.1	452.7	327.0	268.9	162.8	110.7
UV (dose = **40** mJ/cm2, UV254 = 0.05, turbidity = 0.1 NTU, Alk = 60 mg/l, Hardness = 100 mg/l)	737.1	215.9	139.4	68.7	37.9	31.9	27.4	17.7	23.4
UV (dose = **200** mJ/cm2, UV254 = 0.05, turbidity = 0.1 NTU, Alk = 60 mg/l, Hardness = 100 mg/l)	1,870.7	562.2	368.8	190.9	117.8	97.7	84.9	58.6	64.3
UV with UPS (dose = **40** mJ/cm2, UV254 = 0.05, turbidity = 0.1 NTU, Alk = 60 mg/l, Hardness = 100 mg/l)	129.7	45.9	31.6	19.3	14.2	12.3	11.5	8.4	16.7
UV with UPS (dose = **200** mJ/cm2, UV254 = 0.05, turbidity = 0.1 NTU, Alk = 60 mg/l, Hardness = 100 mg/l)	2,140.2	640.5	413.8	208.9	126.7	103.8	89.9	61.5	67.6
Microfiltration/Ultrafiltration (T = 10C, sewer discharge)	2,752.0	1,070.5	731.3	404.2	326.0	250.0	215.4	140.3	138.1
Ozone w/ pH adj (**0.5** log dose, 12 minute contact time)	Data Not Used			873.8	439.7	310.6	250.0	142.0	105.2
Ozone w/ pH adj (**1.0** log dose, 12 minute contact time)				898.7	462.2	332.2	271.9	161.8	120.0
Ozone w/ pH adj (**2.0** log dose, 12 minute contact time)				916.7	478.3	347.6	287.6	177.9	124.6
Combined Filter Performance						58.1		22.6	
In Bank Filtration									
Secondary Filters									
Watershed Control									
Presedimentation Basins									

Source: Derived from sections 4.4 and 4.5

Exhibit 4.55 (continued): Annualized Cost Summary

Design Flow	1.2	2	3.5	7	17	22	76	210	430	520
Average Flow	0.41	0.77	1.4	3	7.8	11	38	120	270	350
Bag Filters	6.6	6.2	Data Not Used							
Cartridge Filters (filter loading 30 pgm/filter)	18.2	16.4								
Convert to Chloramines (NH4 dose = 0.55mg/l)	7.8	4.4	2.7	1.5	0.8	0.7	0.4	0.3	0.2	0.2
Convert to Chloramines (NH4 dose = 0.15mg/l)	7.6	4.2	2.5	1.3	0.6	0.5	0.2	0.1	0.1	0.1
GAC (EBCT = **10**, 360 day regeneration)	79.5	55.1	42.0	31.0	22.5	19.4	14.0	10.3	8.8	8.3
GAC (EBCT = **20**, 90 day regeneration)	188.1	123.7	89.6	63.4	47.6	42.6	32.9	25.7	22.4	21.2
GAC (EBCT = **20**, 240 day regeneration)	125.3	85.5	64.5	47.4	35.3	31.1	23.7	18.2	15.7	14.6
Nanofiltration (100% flow treated, 10C)	133.1	121.5	112.0	106.3	99.0	93.8	85.0	74.3	71.9	70.1
Chlorine Dioxide (ClO2 dose = 1.25 mg/l, no additional contact time)	16.3	9.7	6.8	3.6	1.9	1.6	0.9	0.6	0.5	0.5
Ozone (**0.5** log dose, 12 minute contact time)	82.9	53.4	36.2	23.2	14.4	12.0	9.5	7.2	6.0	5.7
Ozone (**1.0** log dose, 12 minute contact time)	94.5	60.9	42.5	28.5	17.9	15.4	12.3	9.4	8.3	8.0
Ozone (**2.0** log dose, 12 minute contact time)	99.4	63.5	45.0	38.5	27.2	24.0	20.4	16.3	14.5	13.7
UV (dose = **40** mJ/cm2, UV254 = 0.05, turbidity = 0.1 NTU, Alk = 60 mg/l, Hardness = 100 mg/l)	20.4	12.1	7.5	4.8	4.0	3.9	2.1	1.7	1.5	1.4
UV (dose = **200** mJ/cm2, UV254 = 0.05, turbidity = 0.1 NTU, Alk = 60 mg/l, Hardness = 100 mg/l)	59.7	43.6	Data Not Used							
UV with UPS (dose = **40** mJ/cm2, UV254 = 0.05, turbidity = 0.1 NTU, Alk = 60 mg/l, Hardness = 100 mg/l)	14.4	8.2	5.0	3.5	3.3	3.4	1.7	1.3	1.2	1.1
UV with UPS (dose = **200** mJ/cm2, UV254 = 0.05, turbidity = 0.1 NTU, Alk = 60 mg/l, Hardness = 100 mg/l)	62.7	45.8	Data Not Used							
Microfiltration/Ultrafiltration (T = 10C, sewer discharge)	128.4	103.1	86.6	74.9	65.4	59.4	53.4	46.1	41.9	39.7
Ozone w/ pH adj (**0.5** log dose, 12 minute contact time)	96.5	66.1	48.4	35.1	26.1	23.6	21.0	18.6	17.4	17.0
Ozone w/ pH adj (**1.0** log dose, 12 minute contact time)	108.2	73.6	54.7	40.3	29.6	27.0	23.8	20.9	19.7	19.3
Ozone w/ pH adj (**2.0** log dose, 12 minute contact time)	113.1	76.1	57.2	50.3	38.9	35.6	32.0	27.8	25.9	25.1
Combined Filter Performance		12.4		3.8	2.6		1.3			0.3
In Bank Filtration	4.6				4.6		4.6			
Secondary Filters	62.4				22.0		8.9			
Watershed Control	115.3				43.6		12.8			
Presedimentation Basins	49.6				15.5		11.3			

Source: Derived from sections 4.4 and 4.5

Note: Costs are in cents/1000 gallons and at 3% discount rate over 20-year period

5. References

Aboytes, Ramon; Di Giovanni, George D.; Abrams, Felicia A.; Rheinecker, Corey; McElroy, Wyndi;Shaw, Nancy; LeChevallier, Mark W. 2004. “Detection of Infectious *Cryptosporidium* in Filtered Drinking Water” *J. AWWA*, 95:9:88-98

Adham, Samer S., Snoeyink, V. J., Clark, M. M. and C. Anselme. 1993. “Predicting and Verifying Organics Removal by PAC in Pilot-scale UF Systems.” *J. AWWA*, 85:12:58.

Adham, Samer S., Snoeyink, V. J., Clark, M. M. and Bersillon, Jean-Luc. 1991. “Predicting and Verifying Organics Removal by PAC in an Ultrafiltration System.” *J. AWWA*, 83:12:81.

Allgeier, S.A. and R.S. Summers. 1995. "Evaluating Nanofiltration for DBP Control with the RBSMT," J. AWWA, 86:3:87-99.

Amy, G.L. and M.S. Siddiqui. 1999. Strategies to Control Bromate and Bromide. Report No. 90751, AWWARF, Denver, CO.

Anselme, C. and Charles, P. 1990. “The Use of Powdered Activated Carbon for the Removal of Specific Pollutants in Ultrafiltration processes.” Laboratoire Central, Lyonnaise des Eaux, Le Pecq, France.

APHA-AWWA-WEF. 1998. *Standard methods for the examination of water and wastewater*, 20th ed. Washington, DC.

Arora, H., M.W. LeChevallier, and K.L. Dixon. 1997. “DBP Occurrence Survey.” *J. AWWA*, 89:6:60-68.

AWWA. 1969. *Water Treatment Plant Design.* First Edition, American Water Works Association, Inc.

AWWA. 1999. *Water Quality and Treatment.* Fifth Edition, McGraw-Hill, New York, NY.

AWWA and ASCE. 1998. *Water Treatment Plant Design.* Third Edition, McGraw-Hill, New York, NY.

AWWSC. 1998. *Evaluation of Chlorine Dioxide for Inactivation of Cryptosporidium and Byproduct Control.* AWWSC, Voorhees, NJ.

Babcock, D. B. and Singer, P. C. 1979. “Chlorination and Coagulation of Humic and Fulvic Acids.” *J. AWWA*, 71:3:149.

Battigelli, D.A., M.D. Sobsey and D.C. Lobe. 1993. "The Inactivation of Hepatitis A Virus and Other Model Viruses by UV Irradiation." *Wat. Sci. Tech.*, 27:3-4:339-342.

Benedek, A., Bancsi, J. J., Malaiyandi, M. and Lancaster, E. A. 1979. "The Effect of Ozone on the Biological Degradation and Activated Carbon Adsorption of Natural and Synthetic Organics in Water. Part II. Adsorption." *Ozone Sci. Eng.*, 1:4:347.

Bergman R. A. 1996. "Cost of Membrane Softening in Florida", J. AWWA, 88:5:32.

Bolton, J. R. 1999. *Ultraviolet Applications Handbook*. Bolton Photosciences, Inc., Ayr, Ontario, Canada.

Bouwer, E. J. and Crowe, P. B. 1988. "Biological Processes in Drinking Water Treatment." *J. AWWA,* 80:9:82.

Bukhari, Z.; Hargy, T.H.; Bolton, J.R., Dussert B., and Clancy J.L. 1998. "Inactivation of *Cryptosporidium Parvum* Oocysts Using Medium-Pressure Ultraviolet Light." *Proceedings, 1998 Annual AWWA Conference,* Dallas, TX.

Bukhari, Z., T.M. Hargy, J.R. Bolton, B. Dussert and J.L. Clancy. 1999) "Medium-Pressure UV Light for Oocyst Inactivation." *J. AWWA,* 91:3:86-94.

Cairns, B. 1999. "Ultraviolet Water Disinfection." USEPA Workshop on UV Disinfection of Drinking Water, April 28-29, 1999, Arlington, VA.

Camel, V., and Bermond, A. 1999. "The Use of Ozone and Associated Oxidation Processes in Drinking Water Treatment." *Water Research,* 32:11:3208-3222.

Campbell, A. T., Robertson, L. J., and Smith, H. V. 1995b. "Inactivation of Oocysts of *Cryptosporidium parvum* by Ultraviolet Irradiation." *Wat. Res.*, 29:2583.

Campbell, S., B.W. Lykins, J.A. Goodrich, D. Post and T. Lay. 1995a. "Package Plants for Small Systems: A Field Study." *J. AWWA,* 87:11:39-47.

Carlson, M. and D. Hardy. 1998. "Controlling DBPs with Monochloramine." *J. AWWA,* 90:2:95- 105.

CH2M Hill. 1986. *Pilot Plant Report for Department of Public Utilities, Newport News, Virginia.* Vol. 1, Newport News, VA.

Chadik, P. A. and Amy, G. L. 1983. "Removing Trihalomethane Precursors from Various Natural Waters by Metal Coagulants." *J. AWWA*, 75:10:532.

Chadik, P. A. and Amy, G. L. 1987. "Molecular Weight Effects of THM Control by Coagulation and Adsorption." *J. Env. Eng.*, 113:6:1234.

Chang, J.C.H., S.F. Osoff, D.C. Lobe, M.H. Dorfman, C.M. Dumais, R.G. and J.D. Johnson. 1985. "UV Inactivation of Pathogenic and Indicator Organisms." *Applied and Environmental Microbiology*, 49:6:1361.

Chang, S. D. and Singer, P. C. 1991. "The Impact of Ozonation on Particle Stability And The Removal of TOC And THM Procursors." *J. AWWA*, 83:3:71.

Chellam, S., Jacangelo, J., Bonacquisti, T., Schauer, B. 1997. "Effect of Pretreatment on Surface Water Nanofiltration." *J. AWWA*, 89:10:77.

Chen, A. S. C., V. L. Snoeyink and F. Fiessinger. 1987. "Activated Alumina Adsorption of Dissolved Organic Compounds Before and After Ozonation." *Environ. Sci. Technol.*, 21:1:83.

Cho, J, Amy, G., Pellgrino, J. 1999. "Membrane Filtration of Natural Organic Matter: Initial Comparison of Rejection and Flux Decline Characteristics with Ultrafiltration and Nanofiltration Membranes." *Water Resources*, 33:11:2517-2526.

Chowdhury, Z.K., J. A. Roberson and D.M. Owen. 1997. "A National Evaluation of Enhanced Coagulation and Enhanced Softening." AWWA Annual Conference Proceedings, Atlanta, GA.

Clair, D., S. Randtke, P. Adams, and S. Shreve. 1997. "Microfiltration of a High-Turbidity Surface Water with Post- treatment by Nanofiltration and Reverse Osmosis," AWWA Membrane Technology Conference Proceedings, February 23 - 26, 1997, New Orleans, LA.

Clancy, J. 1999. "Watershed Monitoring for Determining Variability of *Giardia* and *Cryptosporidium* Concentrations." *1999 AWWA Water Quality Technology Conference Proceedings*, Tampa Bay, FL.

Clancy, J., Hargy, T., and Dyksen, J. 1998. UV Light Inactivation of *Cryptosporidium* Oocysts. *J. AWWA*, 90:9:92.

Clancy, J.L., Z. Bukhari, T.M. Hargy, J.R. Bolton, B.W. Dussert, and M.M. Marshall. 2000. "Using UV to Inactivate *Cryptosporidium*." *J.AWWA*,. 92:9:97.

Clark et al. 1994. "DBP Control in Drinking Water: Cost and Performance." *J. of Environmental Engineering*, 120:4:759.

Clark, R. M. 1987. "Modeling TOC Removal by GAC: The General Logistic Function." *J. AWWA*, 79:1:33.

Clark, R.M., J.Q. Adams, V. Sethi and M. Sivaganesan. 1998. “Control of Microbial Contaminants and Disinfection Byproducts for Drinking Water in the US: Cost and Performance.” *Aqua*, 47:6:255-265.

Clesceri, L. S., Greenberg, A. E. and Trussell, R. R. eds. 1989. *Standard Methods for the Examination of Water and Wastewater.* 17th Edition, AWWA, WPCF, APHA.

Collins, M. R., Amy, G. L. and King, P. H. 1985. “Removal of Organic Matter in Water Treatment.” *J. Env. Eng.*, 111(6), p. 850.

Colvin, C., C. Acker, B. Marinas, and J. Lozier. 1999. "Mechanisms Responsible for the Passage of Microorganisms through RO and NF Membranes," AWWA Membrane Technology Conference Proceedings, February 28 - March 3, 1999, Long Beach, CA.

Conley, W.R. 1961. “Experiences with Anthracite Sand Filters.” *J. AWWA*, 53 (12): 1473.

Conley, W.R., and R.W. Pitman. 1960. “Test Program for Filter Evaluation at Hanford.” *J. AWWA*, 52(2): 205.

Conlon, W.J. and S.A. McClellan. 1989. "Membrane Softening: A Treatment Process Comes of Age," J. AWWA, 81:11:47.

Cotton , C. A., Linden , K. G., Schmelling , D. C., Bell , C. F., and Darnault, C. 2001. “The Development, Application, and Cost Implications of the UV Dose Tables for LT2ESWTR Compliance.” *Proceedings,* Water Quality Technology Conference, Nashville, TN November 11-14, 2001.

Cowman, G.A. and P.C. Singer. 1996. “Effect of Bromide Ion on Haloacetic Acid Speciation Resulting from Chlorination and Chlorimination of Aquatic Humic Substances.” *Env. Sci. Tech* 30(1):16-24.

Crozes, G., Seacord, T. 1999. “Ultrafiltration to Meet Multiple Treatment Objectives in Lime Softening Plants.” AWWA Membrane Technology Conference Proceedings, Long Beach, CA.

Culp/Wesner/Culp. 1979. *Estimating Water Treatment Costs, Volume 2: Cost Curves Applicable to 1 to 200 mgd Treatment Plants,* CWC Engineering, San Clemente, CA.

Culp/Wesner/Culp. 1984. *Estimation of Small System Water Treatment Costs,* CWC Engineering Software, San Clemente, CA.

Culp/Wesner/Culp. 1994. *WATERCO$T Model - A Computer Program for Estimating Water and Wastewater Treatment Costs, Version 2.0*, CWC Engineering Software, San Clemente, CA.

Culp/Wesner/Culp. 2000. *WATERCO$T Model - A Computer Program for Estimating Water and Wastewater Treatment Costs, Version 3.0*, CWC Engineering Software, San Clemente, CA.

Dempsey, B. A., Ganho, R. M. and O'Melia, C. R. 1984. “The Coagulation of Humic Substances by Means of Aluminum Salts.” *J. AWWA*, 76:4:141.

Dempsey, B. A. and O'Melia, C. R. 1983. “The Protonation and Complexation of Four Fulvic Acid Fractions.” in *Aquatic and Terrestrial Humic Materials*, R.F. Christman and E.T.Gjessing eds., Ann Arbor, Michigan: Ann Arbor Sciences.

Dominngue, E.L., et al. 1988. “Effects of Three Oxidizing Biocides on Legionella Pneumophila Serogroup 1. *Applied Environmental Microbiology*, 40:11-30.

DPRA. 1993a. *Small Water System Byproducts Treatment and Disposal Cost Document*, Prepared for USEPA Office of Groundwater and Drinking Water.

DPRA. 1993b. *Water System Byproducts Treatment and Disposal Cost Document*, Prepared for USEPA Office of Groundwater and Drinking Water.

Driedger, A.M., S.A. Rubin, J.L. Rennecker and B.J. Marinas. 1999. “Inactivation of *Cryptosporidium parvum* Oocysts with Free Chlorine and Monochloramine in Single-step and Sequential Disinfection Schemes.” 1999 AWWA Annual Conference Proceedings, Chicago, IL.

Driedger, A.M., S.A. Rubin, J.L. Rennecker and B.J. Marinas. 2000. “Sequential Inactivation of *Cryptosporidium parvum* Oocysts with Ozone and Free Chlorine.” *Wat. Res*. 34:14:3591-3597.

Dryfuse, M. J., Miltner R. J., Summers, R. S. 1995. “The Removal of Molecular Size and Humic/Nonhumic Fractions of DBP Precursors by Optimized Coagulation.” Amer. Water Works Assoc. Annual Conference Proceedings, Anaheim, CA.

Dugan, N.R., Fox, K.R., Owens, J.H., and R.J. Miltner. 2001. “Controlling Cryptosporidium Oocysts Using Conventional Treatment.” *J. AWWA* 93.12: 64-76.

Dugan, N.R., K.R. Fox, R.J. Miltner, D.A. Lytle, D.J. Williams, C.J. Parrett, C.M. Feld, and J.H. Owens. 1999. “Control of *Cryptosporidium* oocysts by steady-state conventional treatment.” EPA Water Supply and Water Resources Division, Cincinnati. Annual Conference Proceedings of the American Water Works Association. #ACE99567.

Duguet, J. P., Dussert, B., Mallevialle, J. and Fiessinger, F. 1987. “Polymerization Effects of Ozone: Applications to the Removal of Phenolic Compounds From Industrial Wastewaters.” *Water Sci. Tech.*, 19:919.

Dulin, B. E. and Knocke, W. R. 1989. “The Impact of Incorporated Organic Matter on the Dewatering Characteristics of Aluminum Hydroxide Sludges.” *J.AWWA*, 81:5:74.

Duranceau, S., Thorner, K., McAleese, P. 1998. “The Olivenhain Water Supply Project and Integrated Membrane Systems.” Microfiltration II Conference of the National Water Research Institute Proceedings, San Diego, CA.

Edwards, M. 1997. “Predicting DOC Removal during Enhanced Coagulation.” *J. AWWA*, 89:5:78.

Edwards, M., M. Boller., M.M. Benjamin. 1993. “Effect of Pre-Ozonation on Removal of Organic Matter during Water Treatment Plant Operations.” *Water Science Technology*, 27:ll:37-45.

Edzwald, J. K. 1984. *Removal of Trihalomethane Precursors by Direct Filtration and Conventional Treatment*. USEPA Municipal Environmental Research Laboratory, Cincinnati, OH. Rpt. No. EPA/600/2-84/068, NTIS Publ. No. PB84-163278.

Edzwald, J. K. 1990. “Aluminum Coagulation of Natural Organic Matter,” 4th International Guthenburg Symposium on Chemical Treatment Proceedings, Madrid, Spain.

El-Rehaili, A. M. and Weber, W. J. 1987. “Correlation of Humic Substance Trihalomethane Formation Potential and Adsorption Behavior to Molecular Weight Distribution in Raw and Chemically

Emelko, M.B., Huck P.M, Douglas, I.P, and J. Van Den Oever. 2000. “*Cryptosporidium* and Microsphere Removal During Low Turbidity End-Of-Run and Early Breakthrough Filtration.” *Proceedings from AWWA Water Quality Technology Conference*. Treated Waters.” *Water Research*., 21:5:573.

Emelko, M.B., Huck, P.M., and R. M. Slawson. 1999. “Design and Operational Strategies for Optimizing *Cryptosporidium* Removal by Filters.” Conference proceedings of the AWWA Water Quality Technical Conference.

Escobar, I., Randall, A. 1999. “Influence of NF on Distribution Systems Biostability.” *J. AWWA*, 91:9:76.

Faust, S.D and O.M Aly. 1999. *Chemistry of Water Treatment, Second Edition*, Lewis Publishers, CRC Press, Boca Raton, FL.

Finch, G. 1999. “Inactivation of *C. parvum* and *G. muris* with Medium Pressure Ultraviolet Radiation.” USEPA Workshop on UV Disinfection of Drinking Water, April 28-29, 1999, Arlington, VA.

Finch, G.R. 1997. “Control of *Cryptosporidium* Through Chemical Disinfection: Current State-of-the-Art.” AWWARF Technology Transfer Conference, Portland, OR.

Finch, G.R., Black, E.K., and Gyurek, L.L. 1994. “Ozone and Chlorine Inactivation of *Cryptosporidium*.” WQTC, San Francisco, CA.

Finch, G.R., L.R.J. Liyanage, and M. Belosevic. 1995. “Effects of Chlorine Dioxide on *Cryptosporidium* and *Giardia*.” Third International Symposium on Chlorine Dioxide: Drinking Water, Process Water, and Wastewater Issues Conference Proceedings, AWWA and AWWARF, New Orleans, LA.

Fronk, C. A. 1987. “Destruction of Volatile Organic Contaminants in Drinking Water By Ozone Treatment.” *Ozone Sci. Eng*., 9:265.

Fu, L.F., Dempsey, B. 1997. “Effects of Charge and Coagulant Dose on NOM Removal and Membrane Fouling Mechanisms.” AWWA Membrane Technology Conference Proceedings, New Orleans, LA.

Fu, P. Ruiz, H., Lozier, J., Thomspon, K., Spangenberg, C. 1995. “A Pilot Study on Groundwater Natural Organics Removal by Low-Pressure Membranes.” *Desalination*, 102:47-56.

Gagliardo, P., S. Adham, Y. Chambers, B. Gallagher, M. Sobsey, and R. Trussel. 1999. "Development of an Innovative Method to Monitor the Integrity of a Membrane Water Repurifiation System," AWWA Membrane Technology Conference Proceedings, February 28 - March 3, 1999, Long Beach, CA.

Gagliardo, P., S. Adham, and R. Trussel. 1997. "Water Repurification Using Reverse Osmosis: Thin Film Composite vs. Cellulose Acetate Membranes," AWWA Membrane Technology Conference Proceedings, February 23 - 26, 1997, New Orleans, LA.

Glaze, W. H. et al. 1982. *Pilot-Scale Evaluation of Biological Activated Carbon for the Removal of THM Precursors*. USEPA Municipal Environmental Research Laboratory, Cincinnati, OH. Rpt. No. EPA/600/S2-82/046.

Glaze, W. H., Peyton, G. R., Huang, F. Y., Burleson, J. L. and Jones, P. C. 1980. *Oxidation of Water Supply Refractory Species By Ozone With Ultraviolet Radiation*. USEPA, Cincinnati, OH, EPA-600/2-80-110.

Glaze, W.H., H.S. Weinberg, and J.E. Cavanagh. 1993. "Evaluating the Formation of Brominated DBPs During Ozonation," J. AWWA, 85:1:96-103.

Glucina, K., J-M. Laine, and C. Robert. 1997. "Integrated Multi-Objective Membrane Systems for Surface Water Treatment," AWWA Membrane Technology Conference Proceedings, February 23 - 26, 1997, New Orleans, LA.

Goodrich, J.A, S.Y. Li, and B.W. Lykins. 1995. "Cost and Performance of Alternative Filtration Technologies for Small Communities." Proceedings of the 1995 American Water Works Association Annual Conference.

Grasso, D. and Weber, W. J. 1988. "Ozone Induced Particle Destabilization." *J. AWWA*, 80:8:73.

Gurol, M. D. and Singer, P. C. 1983. "Dynamics of Ozonation of Phenol. I. Experimental Observations." Water Research, 17(9):1173.

Gurol, M. D. and Singer, P. C. 1983. "Dynamics of Ozonation of Phenol. II. Mathematical Simulation." *Water Research*, 17(9):1173.

Gyurek, L.L., Li, H., Belosevic, M., and Finch, R,G. 1999. "Ozone Inactivation Kinetics of *Cryptosporidium* in Phosphate Buffer." *J. of Environmental Engineering*, 125(10):913.

Haag, W.R. and J. Hoigne (1983). "Ozonation of Bromide Containing Waters: Kinetics of Formation of Hypobromous Acid and Bromate," Environmental Science and Technology, 17:5:261.

Hagedorn, C., S.L. Robinson, J.R. Filtz, S.M. Grubss, T.A. Angier, and R.B. Reneau, Jr. 1999. "Determining sources of fecal pollution in a rural Virginia watershed with antibiotic resistance patterns in fecal streptococci." *Appl. Env. Micorbiology*, 65(12):5522-31.

Hagen, K. 1998. "Removal of Particles, Bacteria, and Parasites with Ultrafiltration for Drinking Water Treatment," Desalination, 119:85-91.

Hall, T. and B. Croll. 1996. "The UK Approach to *Cryptosporidium* Control in Water Treatment." *Proceedings AWWA Water Quality Technology Conference*. Boston: AWWA.

Hall, T., Pressdee, J., and E. Carrington 1994. "Removal of Cryptosporidium Oocysts By Water Treatment Processes." *Foundation for Water Research*.

Hargy, T.M. 2000. "UV Equipment Proven Against *Cryptosporidium*." *Water Conditioning and Purification*. March, p. 36-38.

Harrington, G. W. and DiGiano, F.A. 1989. "Adsorption Equilibria of Natural Organic Matter After Ozonation." *J. AWWA*, 81:6:93.

Havelaar, A.H., M. van Olphen, and J.F. Schijven. 1995. "Removal and inactivation of viruses by drinking water treatment processes under full-scale conditions." *Wat. Sci. Technol*., 31:55062.

Heneghan, K. and Clark, M. 1991. “Surface Water Treatment by Combined Ultrafiltration/PAC Adsorption/Coagulation for Removal of Natural Organics, Turbidity, and Bacteria. AWWA Membrane Technology Conference Proceedings, Orlando, FL.

Hofman, J.A., M.M. Beumer, E.T. Baars, J.P. van der Hoek and H.M.M. Kopers. 1998. "Enhanced Surface Water Treatment by Ultrafiltration," Desalination, 119:113-125.

Hoigne J., and H. Bader. 1976. Role of Hydroxyl Radical Reactions in Ozonation Processes in Aqueous Solutions, *Water Res*. 10: 377.

Hooper, S. M., Summers R. S., Hong S. 1996b. “A Systematic Evaluation of the Role of Influent TOC and pH on GAC Performance After Enhanced Coagulation.” American Water Works Assoc. Water Quality Technology Conference Proceedings, Boston, MA.

Hooper, S. M., Summers R. S., Solarik G., Hong S. 1996a. “GAC Performance for DBP Control: Effect of Influent Concentration, Seasonal Variation, and Pretreatment.” AWWA Conference Proceedings, Toronto, Canada.

Hooper, S. M., Summers R. S., Solarik G., Owen D. M. 1996c. “Improving GAC Performance by Optimized Coagulation.” *J. AWWA*, 88:8:107-120.

Hubel, R. E. and Edzwald, J. K. 1987. “Removing Trihalomethane Precursors by Coagulation.” *J.AWWA*, 79:7:98.

Huber, C. 1984. *Adsorption and Biologischer Abbau van Huminstoffen in Activkohlfiltern*. Dissertation (in German), Univ. Karlsruhe, West Germany.

Huck, P. M., Anderson, W. B., Rowley, S. M. and Daignault, S. A. 1990. “Formation and Removal of Selected Aldehydes in a Biological Drinking Water Treatment Process.” Presented at the 1990 Spring Conference of the International Ozone Association, Shreveport, LA.

Huey, B., Heckler, J., Joost, R., Crozes, G., Gallier, T. 1999. “Combination of Powdered Activated Carbon and Low Pressure Membrane Filtration: A Process Alternative for SRP Water Treatment.” AWWA Membrane Technology Conference Proceedings, Long Beach, CA.

Jacangelo, J.G., S. Adham, J-M. Laine. 1997. *Membrane Filtration for Microbial Removal.* Report No. 90715. AWWARF, Denver, CO.

Jacangelo, J.G, M.E. Aeita, K.E. Carns, E.W. Cummings, and J. Mallevialle. 1989a. "Assessing Hollow-Fiber Ultrafiltration for Particle Removal," J. AWWA, 81:11:68.

Jacangelo, J.G., J.M. Laine, K.E. Carns, E.W. Cummings and J. Mallevialle. 1991. "Low-Pressure Membrane Filtration for Removing Giardia and Microbial Indicators," J. AWWA, 83:9:97.

Jacangelo, J.G., J. M. Laine, E. W. Cummings, S.S. Adham. 1995. “UF with Pretreatment for Removing DBP Precursors.” *J. AWWA*, 87:3:100.

Jacangelo, J.G., N.L. Patania, K.M. Reagan, E.M. Aieta, S.W. Krasner, and M.J. McGuire. 1989b. Ozonation: Assessing Its Role in the Formation and Control of Disinfection By-Products," J. AWWA, 81:8:74.

Jack, A.M. and Clark, M.M. 1998. “Using PAC-UF to Treat a Low-Quality Surface Water.” *J. AWWA*, 90(11):83.

Jekel, M. R., and B.U. Ernst. 1981. “Einfluss von huminstoffen und ihrer ozonten produkte auf die electrotykoagulation von polystyrolatex.” *Vom Wasser*, 57:123-126.

Jodellah, A. M. and Weber, W. J. 1985. “Controlling Trihalomethane Formation Potential by Chemical Treatment and Adsorption.” *J. AWWA*, 77:10:95.

Johnson, D. E. and Randtke, S. J. 1983. “Removing Non-Volatile Organic Chlorine and Its Precursors by Coagulation and Softenin.” *J. AWWA*, 75:5:249.

Joret, J.C., V. Mennecart, C. Robert, B. Campagnon and P. Cervantes. 1997. “Inactivation of Indigenous Bacteria in Water by Ozone and Chlorine.” *Wat. Sci. Tech*, 35:11-12:81-86.

Junli, H., W. Li, R. Nanqi, M. Fang, and Juli. 1997. “Disinfection Effect of Chlorine Dioxide on Bateria in Water.” *Water Research*, 31:3:607-613.

Juranek, D. “Cryptosporidiosis: Sources of infection and guidelines for prevention.” *Clin. Infect. Dis.* 21(Suppl. 1) (1995): S57-S61.

Kaastrup, E. 1985. *Activated Carbon Adsorption of Humic Substances and the Influence of Preozonation on Such*. Dissertation, Univ. Trondheim, Norwegian Inst. Technol., Trondheim, Norway.

Karimi, A., Vickers, J., Harasick, R. 1999. “Microfiltration goes Hollywood: the Los Angeles Experience.” *J. AWWA*, 91:6:90-103.

Kashinkunti, R., K.G. Linden, G. Shin, D.H. Metz, M.D. Sobsey, M. Moran, and A. Samuelson. 2003. Achieving multi-barrier inactivation in Cincinnati: UV, byproducts, and biostability. *J. AWWA.* Submitted January 9, 2003.

Katzenelson, E., Kletter, E., Schechter, H., and Shuval, H. 1974. “Inactivation of Viruses and Bacteria by Ozone.” *J. AWWA*, 66:725-729.

Kavanaugh, M. C. 1978. “Modified Coagulation for Improved Removal of Trihalomethane Precursors.” *J. AWWA*, 70:11:613.

Kawamura, S. 2000. *Integrated Design and Operation of Water Treatment Facilities*. 2nd Edition, John Wiley & Sons, New York, NY.

Keller, J.W., Morin, R.A., and Scaffernoth, T.J. 1974. “Ozone Disinfection Pilot Plant Studies at Laconia, NH.” *J. AWWA*, 66:7:30.

Kinman, R.N. (1975). "Water and Wastewater Disinfection With Ozone," Crit. Rev. Environ. Control," 5:1:141-152.

Kirmeyer, G.J., G.W. Foust, G.L. Pierson, J.J. Simmler, M.W. LeChevallier. 1993. *Optimizing Chloramine Treatment*, Report No. 90620. AWWARF, Denver, CO.

Kirmeyer, G.J., L.H. Odell, J.G. Jacangelo, A. Wilczak, and R. Wolfe. 1995. *Nitrification Occurrence and Control in Chloraminated Water Systems.* Report No. 90669. AWWARF, Denver, CO.

Kittridge, D., Beaurivage, R. and Paris, D. 1983. *Granular Activated Carbon Adsorption and Fluid-Bed Reactivation at Manchester, New Hampshire*. USEPA Rpt. No. EPA/600/2-83/104. Cincinnati, OH.

Knocke, W. R. West, S. and Hoehn, R. C. 1986. “Effects of Low Temperature on the Removal of Trihalomethane Precursors by Coagulation.” *J. AWWA*, 78:4:189.

Knudson, G.B. 1985. Photoreactivation of UV-irradiated *Legionella Pneumoplila* and other *Legionella* species. *Applied and Environmental Microbiology* 49, No. 4: 975-980.

Koffskey, W. E. 1987. *Alternative Disinfectants and Granular Activated Carbon Effects on Trace Organic Contaminants*. USEPA Rpt. No. EPA/600/2-87/006, Cincinnati, OH.

Korich, D.G., J.R. Mead, M.S. Madore, N.A. Sinclair, and C.R. Sterling. 1990. “Effects of Ozone, Chlorine Dioxide, Chlorine, and Monochloramine on *Cryptosporidium parvum* Oocyst Viability.” *Applied Engineering and Microbiology*. 56:5:1423-1428.

Kornegay, B. H. 1979. “Control of Synthetic Organic Chemicals of Activated Carbon—Theory, Application and Regeneration Alternatives.” Presented at the Seminar on Control of Organic Chemicals in Drinking Water, sponsored by USEPA.

Krasner, S. et al. 1996. Issue paper prepared during USEPA Technologies Working Group Meetings.

Krasner, S.W., et al. 1989. "The Occurrence of Disinfection By-Products in U.S. Drinking Water, " J. AWWA, 81:8:41.

Krasner, S.W., W.H. Glaze, H.S. Weinberg, P.A. Daniel, and I.N. Najm. 1993. "Formation and Control of Bromate During Ozonation of Waters Containing Bromide," J. AWWA, 85:1:73.

Kruithof, J.C. P. Hiemstra, P. Kamp, J. van der Hoek, and J.C. Schippers. 1997. "Integrated Multi-Objective Membrane Systems for Control of Microbials and DBP-Precursors," AWWA Membrane Technology Conference Proceedings, February 23-26, 1997, New Orleans, LA.

Laine, J. M., Clark, M. M. and Mallevialle, J. 1990. “Ultrafiltration of Lake Water: Effect of Pretreatment On The Partitioning Of Organics, THMFP Flox.” *J. AWWA*, 82:12:82.

Langlais, B. et al. 1990. “New Developments: Ozone in Water and Wastewater Treatment. The CT Value Concept for Evaluation of Disinfection Process Efficiency; Particular Case of Ozonation for Inactivation of Some Protozoa, Free-Living Amoeba and *Cryptosporidium*.” IOA Pan-American Conference, Shreveport, LA.

Langlais, B.; Reckhow, D.A.; Brink, D.R. (Editors). 1991. Ozone in Drinking Water Treatment: Application and Engineering. AWWARF, Compagnie Generale Des Eaux, Lewis Publishers, Chelsea, MI.

Laurent, P., Servais, P., Gatel, D., Randon, G., Bonne, P., Cavard, J. 1999. “Microbiological Quality Before and After Nanofiltration.” *J. AWWA*, 91:10:62.

Lebeau, T., Lelievre, C., Buisson, H., Cleret, D., Van de Venter, L., Cote, P. 1998. “Immersed Membrane Filtration for the Production of Drinking Water: Combination with PAC for NOM and SOCs Removal.” *Desalination*, 117:219-231.

LeChevallier, M.W. 1998. “Benefits of Employing a Disinfectant Residual in Distribution Systems,” *Water Supply*, 16:3-4:61-73.

LeChevallier, M.W., W.D. Norton, and R.G. Lee. 1991. “Evaluation of a Method to Detect *Giardia* and *Cryptosporidium* in Water.” From *Monitoring Water in the 1990's: Meeting New Challenges*. ASTM STP 1102 J.R. Hall and G.D. Glysson, eds. American Society for Testing and Materials, Philadelphia.

Lee, M. C., Crittenden, J. C., Snoeyink, V. L. and Ari, M. 1983. “Design of Carbon Beds to Remove Humic Substances.” *J. Env. Eng.*, 109:3:631.

Lee, M. C., Snoeyink, V. L. and Crittenden, J. C. 1981. "Activated Carbon Adsorption of Humic Substances." *J. AWWA*, 73:8:440.

Lee, Y. and Hunter, J. V. 1985. "Effect of Ozonation and Chlorination on Environmental Protection Agency Priority Pollutants." *Water Chlorination: Chemistry, Environmental Impact and Health Effects*. Vol. 5. R. L. Jolley, R. J. Bull, W. P. Davis, S. Katz, M. H. Roberts and V. A. Jacobs(eds). Lewis Publishers, p. 1515.

Legube, B., Agbekodo, K., Cote, P., Bourbigot, M. 1995. "Removal of Organohalide Precursors by Nanofiltration." *Water Supply*, 13:2:171-181.

Leinhard, H. and Sontheimer, H. 1979. "Influence of Process Conditions on the Effect of Ozone Treatment of Organic Substances in Water." *Ozone Sci. Eng.*, 1:1:61.

Li, H., G.R. Finch, N. Neumann, and M. Belosevic. 1998. "Inactivation of *Cryptosporidium* by Chlorine Dioxide at 1^{o}C." Water Quality Technology Conference Proceedings, AWWA, San Diego, CA.

Li, S.Y., J.A. Goodrich, J.H. Owens, G.E. Willeke, F.W. Schaefer and R.M. Clark. 1997. "Reliability of Surrogates for Determining *Cryptosporidium* Removal," *J. AWWA*, 89:5:90-99.

Liao, M. Y. and Randtke, S. J. 1985. "Removing Fulvic Acid by Lime Softening." *J. AWWA*, 77:8:78.

Linden, K.G. 2002. Personal email communication by Laurel Passantino. April 24-May 6.

Linden, K.G., L. Batch, and C. Schulz. 2002b. UV Disinfection of filtered water supplies: water quality impacts on MS2 dose-response curves. Proceedings of the AWWA Annual Conference, June 16-20, New Orleans, LA.

Linden, K.G., G.A. Shin, G. Faubert, W. Cairns, and M.D. Sobsey. 2002a. UV disinfection of *Giardia lamblia* cysts in water. *Environmental Science and Technology* 36, No. 11: 2519-2522.

Linden, K. G., G.S. Soriano, and J.L. Darby. 1998. "Investigation of Disinfection Byproduct Formation. Following Low and Medium Pressure UV Irradiation of Wastewater." WEF Disinfection Conference Proceedings.

Lindenauer K. and J. Darby. 1994. "Ultraviolet disinfection of wastewater: Effect of Dose on Subsequent Photoreactivation." *Water Research*, 28:4:805-817.

Liyanage, L.R.J., G.R. Finch, and M. Belosevic. 1997a. "Synergistic Effects of Sequential Exposure of *Cryptosporidium* Oocysts to Chemical Disinfectants," 1997 International Symposium on Waterborne *Cryptosporidium* Proceedings, March 2-5, 1997, Newport Beach, CA, AWWA, Denver, CO.

Liyanage, L.R.J., G.R. Finch, and M. Belosevic. 1997b. "Sequential Disinfection of *Cryptosporidium parvum* by Ozone and Chlorine Dioxide," *Ozone Sci. Eng.*, 19:409-423.

Long, W.R. 1983. "Evaluation of Cartridge Filters for the Removal of *Giardia lamblia* Cyst Models from Drinking Water Systems." *J. Env. Health*, 45:5:220-225.

Lozier, J. 1998. "Implementation of Integrated Membrane Treatment: Lessons Learned from Three years of Operation in Barrow, Alaska." Microfiltration II Conference of the National Water Research Institute Proceedings, San Diego, CA.

Lozier, J., Jones, G., Bellamy, W. 1997. "Integrated Membrane Treatment in Alaska." *J. AWWA*, 89:10:50.

Luitweiler, J.P., T.L. Yohe, E. Crist, and X. Sun. 1991. "Performance Testing of Hollow-Fiber Membranes on a Groundwater," AWWA Membrane Technology Conference, Proceedings, Orlando, FL.

Lykins, B. W. and Griese, M. H. 1986. "Using Chlorine Dioxide for Trihalomethane Control." *J AWWA*, 78:6:88.

Mackey, E.D.; Cushing, R.S.; & G.F. Crozes. 2000. UV Disinfection Systems for the Inactivation of *Cryptosporidium*: Evaluating Practical Implementation Issues. *Proceedings*, 2000 Annual AWWA Conference, Denver, CO.

Malcolm Pirnie, Inc. 1988. Unpublished data.

Malcolm Pirnie, Inc. 1989. *Water Quality Master Plan*. Prepared for City of Phoenix, AZ.

Malcolm Pirnie, Inc. 1990. *City of San Diego Water Quality Report*, August 1990.

Malcolm Pirnie, Inc. 1993. *Very Small Systems Best Available Technology Cost Document*. Prepared for USEPA Office of Ground Water and Drinking Water.

Mallevialle, J., P.E. Odendaal, and M.R. Weisner, ED. 1996. *Water Treatment Membrane Processes.* AWWARF. Lyonnaise des Eaux, Water Research Commission of South Africa. McGraw Hill.

Malley, J.P., J.P. Show, and J.R. Ropp. 1996. *Evaluation of Byproducts Produced by Treatment of Groundwaters with Ultraviolet Irradiation.* Report No. 90685. AWWARF & AWWA, Denver, CO.

Malley, J.P, J.P. Shaw and J.R. Ropp. 1995. *Evaluation of by-products produced by treatment of groundwaters with ultraviolet irradiation.* Denver, CO.: AWWA Research Foundation.

Malley, J.R. 1999. “UV Disinfection’s Emerging Role in Drinking Water Treatment—Theories and Practical Questions.” USEPA Workshop on UV Disinfection of Drinking Water, April 28-29, 1999, Arlington, VA.

Malley, J.R. 1998. *Control of Microbes in Drinking Water, Chapter 13: Ultraviolet Disinfection*. Draft Chapter from ASCE Manual.

Maloney, S. W., Suffet, I. H., Bancroft, K. and Neukrug, H. M. 1985. “Ozone-GAC Following Conventional US Drinking Water Treatment.” *J. AWWA*, 77:8:66.

Marinas, J.B., Rennecker, L.J., Teefy, S., and Rice W.E. 1999. “Assessing Ozone Disinfection.” *J.AWWA*, 91:10:79.

Marriott, W. D., M. M. Clark, J. M. Laine. 1997. “Piloting for Optimal Operation of Ultrafiltration.” Annual AWWA Membrane Conference Proceedings, New Orleans, LA.

McCreary, J. J. and Snoeyink, V. L. 1980. “Characterization and Activated Carbon Adsorption of Several Humic Substances.” *Water Research*, 14:1:151.

McGuire, M. J., Davis, M. K., Liang, S., Tate, C. H., Aieta, E. M., Wallace, I. E., Wilkes, D. R., Crittenden, J. C. and Vaith, K. 1989. *Optimization and Economic Evaluation of Granular Activated Carbon for Organic Removal*, AWWA Research Foundation, Denver, CO.

McGuire, M.J.; Krasner, S.W.; Gramith, J.T. 1990. Comments on Bromide Levels in State Project Water and Impacts on Control of Disinfection Byproducts.

McGuire, M. J., Krasner, S. W., Reagan, K. M., Aieta, E. M., Jacangelo, J. G., Patania, N. L. and Gramith, K. M. 1989. *Disinfection By-Products in United States Drinking Waters*. Final Report for the USEPA and AMWA.

McTigue, N. E., M. LeChevallier, H. Arora, J. Clancy. 1998. National Assessment of Particle Removal by Filtration. Denver: American Water Works Association Research Foundation and AWWA. p. 266

Meals, D.W. 2001. “Water quality response to riparian restoration in an agricultural watershed in Vermont, USA.” *Water Sci. Technology,* 43(5): 175-82.

Medema, G.J., M.H.A. Juhasz-Hoterman, and J.A. Luitjen. 2000. “Removal of microorganisms by bank filtration in a gravel-sand soil.” Proceedings, International Riverbank Filtration Conference, November 2-4, Düsseldorf. W. Julich and J. Schubert, eds. Internationale Arbeitgemeinschaft der Wasserwerke im Rheineinzugsgebiet, Amsterdam, pp. 161-168.

Meng, Q and C. Gerba. 1996. “Comparative Inactivation of Enteric Adenoviruses, Poliovirus and Coliphages by Ultraviolet Irradiation.” *Water Research*, 30:11:2665-2668.

Miller, R. and Hartman, D. J. 1982. *Feasibility of Granular Activated Carbon and On-Site Reactivation*. USEPA Rpt. No. EPA/600/2-82/087, Cincinnati, OH.

Miltner, R., Rice E. W. and Stevens, A. A. 1990. “A Study of Ozone's Role in Disinfection By-Product Control.” Presented at the 1990 Spring Conference of the International Ozone Association, Shreveport, LA.

Mofidi, A. 1999. “Inactivation of *Cryptosporidium parvum* with Polychromatic UV Systems —Water Quality Monitoring.” USEPA Workshop on UV Disinfection of Drinking Water, April 28-29, 1999, Arlington, VA.

Montgomery, James M., Consulting Engineers, Inc. 1992. *Effect of Coagulation and Ozonation on the Formation of Disinfection Byproducts*. Prepared for the AWWA.

Mulford, L., Taylor, J., Nickerson, D., Chen, S-S. 1999. “NF Performance at Full and Pilot Scale.” *J. AWWA*, 91:6:64.

Najm, I.N and S.W. Krasner. 1995. "Effects of Bromide and Natural Organic Matter on the Formation of Ozonation By-Products," J. AWWA, 87:1.

Nakatsuka, S., Nakate, I., Miyano, T. 1996. “Drinking Water Treatment by Using Ultrafiltration Hollow Fiber Membranes.” *Desalination*, 106:55-61.

Neukrug, H. M., et al. 1983. *Removing Organics From Philadelphia Drinking Water by Combined Ozonation and Adsorption*. USEPA Municipal Environmental Research Laboratory, Cincinnati, OH. Rpt. No. EPA/600/S2-83/048, NTIS Publ. No. PB83-223370.

Neukrug, H. M., Smith, M. G., Maloney, S. W. and Suffet, I. H. 1984. “Biological Activated Carbon - At What Cost?” *J. AWWA*, 76:4:158.

Nowack, K.O., F.S. Cannon, and H. Arora. 1999. “Ferric Chloride plus GAC for Removing TOC.” *J. AWWA*, 91:2:65-78.

Oguma K., H. Katayama, H. Mitani, S. Morita, T. Hirata, and S. Ohgaki. 2001. Determination of pyrimidine dimers in *Escherichia coli* and *Cryptosporidium* parvum during UV light inactivation, photoreactivation and dark repair. *Applied and Environmental Microbiology* 67, No. 10: 4630-4637.

Olivieri, V., Parker Jr., D., Willinghan, G., Vickers, J. 1991. "Continuous Microfiltration of Surface Water." AWWA Membrane Technology Conference Proceedings, Orlando, FL.

Owens, J.H. et. al. 1994. "Pilot-Scale Ozone Inactivation of *Cryptosporidium* and *Giardia*." WQTC, San Francisco, CA.

Parrotta, M.J. and F. Bekdash. 1998. "UV Disinfection for Small Groundwater Supplies." *J. AWWA*, 90:2:71-81.

Passantino, L.B. and J.P. Malley. 2001. Impacts of turbidity and algal content of unfiltered drinking water supplies on the ultraviolet disinfection process. Proceedings of the 2001 AWWA Annual Conference, Washington, DC.

Patania, N.L., J.G. Jacangelo, L. Cummings, A. Wilczak, K. Riley, and J. Oppenheimer. 1995. "Optimization of Filtration for Cyst Removal." Denver: AWWA Research Foundation and AWWA.

Payment, Pierre, and E. Franco. 1993. "*Clostridium perfringens* and somatic coliphages as indicators of the efficiency of drinking water treatment for viruses and protozoan cysts." *Applied and Environmental Microbiology*. 59 (8): 2418-2424.

Peeters, J.E. et al. 1989. "Effect of Disinfection of Drinking Water with Ozone or Chlorine Dioxide on Survival of *Cryptosporidium Parvum* Oocysts." *Applied and Environmental Microbiology*, 55:6:1519-1522.

Pontius, F.W. and W.R. Diamond. 1999. "Complying with the Stage 1 D/DBP Rule." *J. AWWA*, 91:3:16-32.

Prados-Ramirez, M., Ciba, N., Bourbigot, M. 1993. "Available Techniques for Reducing Bromate in Drinking Water." International Water Supply Association International Conference Proceedings: Bromate and Water Treatment, Paris, France.

Prengle, H. W., Mauk, C. E. and Payne, J. E. 1976. "Ozone/UV Oxidation of Chlorinated Compounds in Water." Presented at the *International Ozone Institute Forum on Ozone Disinfection*. Chicago, IL.

Quinonez-Diaz, M.J., M.M. Karpiscak, E.D. Ellman, and C.P. Gerba. 2001. "Removal of pathogenic and indicator moicroorganisms by a constructed wetland receiving untreated domestic wastewater." *Journal of Environmental Science and Health, Part A, Toxic/Hazardous Substances and Environmental Engineering*, 36(7):1311-20.

Randtke, S. J. 1988. “Organic Contaminant Removal by Coagulation and Related Process Combinations.” *J. AWWA*, 80:5:40.

Randtke, S. J., Thiel, C. E., Liao, M. Y. and Yamaya, C. N. 1982. “Removing Soluble Organic Contaminants by Lime-Softening.” *J. AWWA*, 74:4:192.

Randtke, S. J. and Jepsen, C. P. 1981. “Chemical Pretreatment for Activated Carbon Absorption.” *J. AWWA*, 73:8:411.

Randtke, S. J. and Jepsen, C. P. 1982. “Effects of Salts on Activated Carbon Adsorption of Fulvic Acids.” *J. AWWA*, 74:2:84.

Rauth, A.M. 1965. The physical state of viral nucleic acid and the sensitivity of viruses to ultraviolet light. *Biophysical Journal* 5: 257-273.

Reckhow, D.A. and Singer, P.C. 1984. “The Removal of Organic Halide Precursors by Preozonation and Alum Coagulation.” *J. AWWA*, 76:4:151.

Reckhow, D. A. and Singer, P. C. 1990. “Chlorination By-Products in Drinking Waters: From Formation Potentials to Concentrations in the Finished Water.” *J. AWWA*, 82:4.

Reed, G.D. 1983. “Effects of Prechlorination on THM Formation and Microbial Growth in Pilot-Plant Units.” *J. AWWA*, 82:4:426.

Rennecker, J.L., B. Corona-Vasquez, A.M. Driedger and B.J. Marinas. 2000. “Synergism in Sequential Disinfection of *Cryptosporidium parvum*.” *Wat. Sci. Tech*., 41:7:47-52.

Rennecker, J.L., Marinas, J.B., Owens, H.J., and Rice, W.E. 1999. “Inactivation of *Cryptosporidium Parvum* Oocysts With Ozone.” *Water Resources*, 33:11:2481-2488.

Rice, E.W. and J.C. Hoff. 1981. “Inactivation of *Giardia lamblia* Cysts by Ultraviolet Irradiation.” *Appl. and Environ. Microbiol*. 42:3:546-547.

Rice, R.G., P.K. Overbeck and K.O. Larson. 1999. “Ozone, an Effective and Affordable Choice for Small Water Systems.” 1999 AWWA Annual Conference Proceedings, Chicago, IL.

Robeck, G.G., K. A. Dostal and R.L. Woodward. 1964. "Studies of Modifications in Water Filtration." J. AWWA, 56:2:198-213.

R.S. Means Company Inc. 1999. *RSMeans Facilities Construction Cost Data*, 14th annual ed. Kingston, MA.

SAB and USEPA. 1990. *Reducing risk: setting priorities and strategies for environmental protection.* Washington, DC.: U.S. EPA Science Advisory Board. SAB-EC-90-021.

Scanlan, P., Pohlman, B., Freeman, S., Spillman, B., Mark, J. 1997. “Membrane Filtration for the Removal of Color and TOC from Surface Water.” AWWA Membrane Technology Conference Proceedings, New Orleans, LA.

Schneider, O.D., E. Acs, Leggerio, and S. Nickols (1999). "The Use of Microfiltration for Backwash Water Treatment," AWWA Annual Conference Proceedings, June 20 - 24, 1999, Chicago, IL.

Semmens, M. J. and Ayers, K. 1985. “Removal by Coagulation of Trace Organics from Mississippi River Water.” *J. AWWA*, 77:5:79.

Semmens, M. J., Norgaard, G. E., Hohenstein, G. and Staples, A. B. 1986. “Influence of pH on the Removal of Organics by Granular Activated Carbon.” *J. AWWA*, 78:5:89.

Semmens, M. J. and Staples, A. B. 1986. “The Nature of Organics Removed During Treatment of Mississippi River Water.” *J. AWWA*, 78:2:76.

Semmens, M. J. and T. K. Field. 1980. “Coagulation: Experiences in Organics Removal.” *J. AWWA*, 72:8:476.

Seyde, V., D. Clark, E. Akiyoshi, A. Kalinsky, and C. Spangenberg. 1999. "Nanofiltration Process Microbial Challenge Studies," AWWA Membrane Technology Conference Proceedings, February 28 - March 3, 1999, Long Beach, CA.

Shaban, A.M., G.E. El-Taweel, and G.H. Ali. 1997. UV Ability to Inactivate Microorganisms Combined with Factors Affecting Radiation. *Wat. Sci. Tech*., 35:11-12:107-112.

Shin G.A., K.G. Linden, M.J. Arrowood, G. Faubert, and M.D. Sobsey. 2001. DNA repair of UV-irradiated Cryptosporidium parvum oocysts and Giardia lamblia cysts. Proceedings of the First International Ultraviolet Association Congress, June 14-16, Washington, D.C.

Shin, G., K.G. Linden, G. Faubert, M. Arrowood, and M.D. Sobsey. 2000a. “Inactivation of *Cryptosporidium parvum* Oocysts and *Giardia lamblia* Cysts by Monochromatic UV Radiation.” Proceedings of the IWA First International Congress, Health Related Microbiology, Paris, July 1-4, 2000.

Shin, G.A., Linden, K.G., and Sobsey, M.D. 2000b. Comparative Inactivation of *Cryptosporidium Parvum* Oocysts and Coliphage MS-2 by Monochromatic UV Radiation. Proc., Disinfection 2000, WEF Specialty Conference, New Orleans, LA. March 15-17, 2000.

Shukairy, H. M. and Summers, R. S. 1990. “The Impact of Preozonation and Biodegradation on the Formation of Halogenated Organic Compounds After Chlorination And Chloramination.” AWWA Annual Conference, Cincinnati, OH.

Siddiqui, M.S., G.L., Amy, and McCollum, L.J. 1996. “Bromate Destruction by UV Irradiation and Electric Arc Discharge.” *J. Ozone S&E*, 18:271-290.

Siddiqui, M.S., G.L. Amy and R. Rice. 1995. “Bromate Ion Formation in Drinking Water: A Critical Review.” *J. AWWA*, 87:10:58.

Siddiqui, M.S. and G.L. Amy. 1993. “Factors Affecting DBP Formation During Ozone-Bromide Reactions.” *J. AWWA*, 85:1:63-72.

Singer, P.C. 1988. *Alternative Oxidant and Disinfectant Treatment Strategies for Controlling Trihalomethane Formation*. USEPA Risk Reduction Engineering Laboratory,Cincinnati, OH. Rpt. No. EPA/600/2-88/044, NTIS Publ. No. PB88-238928.

Singer, P.C. and Chang, S.D. 1988. “Characterization of the Impact of Pre-Ozonation of Raw Drinking Water.” Presented at the 1988 Spring Technical Conference of the International Ozone Assoc., Monroe, MI.

Sinsabaugh, R.L., Hoehn, R.C., Knocke, W R. and Linkins, A.E. 1986a. “Removal of Dissolved Organic Carbon by Coagulation with Iron Sulfate.” *J. AWWA*, 78:5:74.

Sinsabaugh, R.L., Hoehn, R.C., Knocke, W.R. and Linkins, A.E. 1986b. “Precursor Size and Organic Halide Formation Rates in Raw and Coagulated Surface Waters.” *J. Env. Eng.*, 111:6:850.

Solarik G., Hooper S.M., Summers R.S., Owen D.M. 1996. “The Impact of Ozonation and Biotreatment on GAC Performance for NOM Removal and DBP Control.” American Water Works Association Conference Proceedings, Toronto, Ontario, Canada.

Solo-Gabriele, H., and S. Neumeister. 1996. “U.S. Outbreaks of Cryptosporidiosis.” *J. AWWA* 88:76-86.

Somiya, I., Yamada, H., Nozawa, E. and Mohri, M. 1986. “Biodegradability and GAC Adsorbability of Micropollutants by Preozonation.” *Ozone Sci. Eng*, 8:1:11.

Song, R., R. Minear, P. Westerhoff, and G. Amy (1995). "Bromate Formation and Minimization in Water Treatment," AWWA Water Quality Technology Conference Proceedings, New Orleans, LA.

Soroushian, F. and W.D. Bellamy. 2000. “Assessment of Ultraviolet Technology for Drinking Water Disinfection: Facts of Light.” Proceedings of the 2000 AWWA Annual Conference, Denver, CO.

Spangenberg, C., E. Akiyoshi, A. Kalinsky, V. Seyde, D. Clark and J. Taylor. 1999. "Insights on Recent Membrane Integrity Testing of an Organic Selective Nanofiltration and Hybrid Membrane Arrangement," AWWA Membrane Technology Conference Proceedings, February 28 - March 3, 1999, Long Beach, CA.

Speitel, G.E., Turakhia, M.H. and Lu, C.J. 1989. "Initiation of Micropollutant Biodegradation in Virgin GAC Columns." *J. AWWA*, 81:4:168.

Speitel, G. E., Patterson, A. M., Lu, C. J. and Thompson, R.C. 1989. "Aerobic Biodegradation of Chloroform and Trichloroethylene in Drinking Water Treatment." AWWA Annual Conference Proceedings, Los Angeles, CA.

Spencur, C. M. and Collins, M. R. 1990. "Modifications of Precoat Filter with Crushed Granular Activated Carbon and Amiona Resin Improves Organic Precursor Removal." 1990 AWWA Annual Conference Proceedings, p. 509.

Staehlin, J. and Hoigne, J. 1983. *Vom Wasser*. 61:337.

Staehlin, J. and Hoigne, J. 1985. "Decomposition of Ozone in the Presence of Organic Solutes Acting as Promoters and Inhibitors of Radical Chain Reactions." *Environ. Sci. Tech*., 19:1206.

Stevens, A.A., Moorek, L.A. and Miltner, R J. 1989. "Formation and Control of Non-Trihalomethane By-Products." *J. AWWA*, 81:8:54.

Summers, R.S. 1986. *Activated Carbon Adsorption of Humic Substances: Effect of Molecular Size and Heterodispersity*. Ph.D. Dissertation, Stanford Univ., Stanford, CA.

Summers, R.S. et al. 1997. "Removal of DBP Precursors by Granular Activated Carbon Adsorption." AWWA Research Foundation, Denver, CO.

Summers, R.S., Hong, S., Hooper, S., Solarik ,G. 1994. "Adsorption of Natural Organic Matter and Disinfection By-Product Precursors." American Water Works Association Annual Conference Proceedings, New York, NY.

Summers, R.S. and Roberts, P.V. 1988. "Activated Carbon Adsorption of Humic Substances. II. Size Exclusion and Electrostatic Interactions." *J. Colloid Interface Sci.*, 122:2:382.

Summers, R.S. and Roberts, P.V. 1982. "Performance of Granular Activated Carbon for Total Organic Carbon Removal." *J. AWWA*., 74:2:113-118.

Symons, J.M., G.E. Speitel, C. Hwang, S.W. Krasner, and S.E. Barrett. 1998. *Factors Affecting Disinfection Byproduct Formation During Chloramination.* AWWARF, Denver, CO.

Symons, J.M, G.E. Speitel, C.J. Hwang, S.W. Krasner, S.E. Barrett, A.C. Diehl, and R. Xia. 1996. "Factors Affecting Disinfection By-Product Formation During Chloramination," AWWA Water Quality Technology Conference Proceedings, Boston, MA.

Taylor, J.S., L.A. Mulford, S.J. Duranceau and W.M. Barret. 1989. "Cost and Performance of a Membrane Pilot Plant." J. AWWA, 81:11:52.

Taylor, J.S. D.M. Thompson and J.K Carswell. 1987. "Applying Membrane Processes to Groundwater Sources for Trihalomethane Precursor Control." J. AWWA, 79:8:72

Thurston, J.A., C.P. Gerba, K.E. Foster, M.M. Karpiscak. 2001. "Fate of indicator microorganisms, *Giardia*, and *Cryptosporidium* in subsurface flow constructed wetlands." *Wat. Res.*, 35:6(1547-51).

Trussel, R., P. Gagliardo, S. Adham, amd A. Olivieri. 1998. "Membranes as an Alternate to Disinfection," Microfiltration II Conference of the National Water Research Institute Proceedings, November 12 - 13, 1998, San Diego, CA.

Trussell, R.R. 1999. "Safeguarding Distribution System Integrity." *J. AWWA*, 91:1:46-54.

Tuepker, J.L., and C.A. Buescher, Jr. 1968. "Operation and Maintenance of Rapid Sand Mixed-Media Filters in a Lime Softening Plant." *J. AWWA*, 60 (12), 1377.

United States Bureau of Reclamation. 1997. "Survey of U.S. Costs and Water Rates for Desalination and Membrane Softening Plants," Water Treatment Technology Program Report No. 24, U.S. Bureau of Reclamation, Denver, CO.

U.S. Environmental Protection Agency. 1988. *In-House Pilot Studies for Control of Chlorination By-Products*. Organics Control Branch, Drinking Water Research Division, Risk Reduction Engineering Laboratory, Cincinnati, OH.

U.S. Environmental Protection Agency. 1990. *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources.* Science and Technology Branch Criteria and Standards Division Office of Drinking Water.

U.S. Environmental Protection Agency. 1996. *Ultraviolet Light Disinfection Technology in Drinking Water Application. An Overview*. EPA 811-R-96-002, EPA Office of Ground Water and Drinking Water.

U.S. Environmental Protection Agency. 1998a. *Small System Compliance Technology List for the Surface Water Treatment Rule and Total Coliform Rule*, EPA-815-R-98-001.

U.S. Environmental Protection Agency. 1998b. *National Primary Drinking Water Regulations: Interim Enhanced Surface Water Treatment*; Final Rule. Federal Register 63(241):69477-69521. December 16, 1998.

U.S. Environmental Protection Agency. 1999a. *Analysis of GAC Effluent Blending During the ICR Treatment Studies*, EPA 815-C-99-002, EPA Office of Ground Water and Drinking Water, Technical Support Center.

U.S. Environmental Protection Agency. 1999b. *Alternative Disinfectants and Oxidants Guidance Manual*, EPA 815-R-99-014, EPA Office of Water.

U.S. Environmental Protection Agency. 1999c. *Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual*, EPA 815-R-99-012, Office of Water.

U.S. Environmental Protection Agency. 2000a. *National Primary Drinking Water Regulations: Long Term 1 Enhanced Surface Water Treatment and Filter Backwash Rule: Proposed Rule. Federal Register* 65(69):19046-19094.

U.S. Environmental Protection Agency. 2000b. *Stage 2 Microbial and Disinfection Byproducts Federal Advisory Committee Agreement in Principal*. *Federal Register* 65(251): 83015. December 29, 2000.

U.S. Environmental Protection Agency. 2001a. *Low-Pressure membrane Filtration for Pathogen Removal: Application, Implementation, and Regulatory Issues,* EPA 815-C-01-001, Office of Water.

U.S. Environmental Protection Agency. 2001b. *National Primary Drinking Water Regulations; Filter Backwash Recycling Rule; Final Rule*. *Federal Register* 66(111): 31085-31105. June 8, 2001.

U.S. Environmental Protection Agency. 2002a. *National Primary Drinking Water Regulations: Long Term 1 Enhanced Surface Water Treatment and Filter Backwash Rule: FInal Rule. Federal Register* 67(9):1811-1844.

U.S. Environmental Protection Agency. 2002b. "SSO Case Study: Fairfax County, Virginia CMOM Program." www.epa.gov/npdes/sso/virginia/index.htm. Last updated January 2002. Downloaded January 22, 2002.

U.S. Environmental Protection Agency. 2005. *UV Disinfection Guidance Manual*, EPA. Office of Water.

Van der Kooij, D., Hijnenk, W.A.M. and Kruithof J.C. 1989. "The Effects of Ozonation, Biological Filtration, and Distribution on the Concentration of Easily Assimilable Organic Carbon (AOC) in Drinking Water." *Ozone Sci. Engr.*, 11:3:297.

Vaughn, J.M. et al. 1987. “Inactivation of Human and Simian Rotaviruses by Ozone.” *Appl. Env. Microbiology* 53:2218-2221.

Viessman, Warren Jr., and M.J. Hammer. 1993. *Water Supply and Pollution Control, Fifth Edition*, HarperCollins College Publishers, New York, NY.

Vik, E.A., Carlson, D.A., Eikum, A.S. and Gjessing, E.T. 1985. “Removing Aquatic Humus from Norwegian Lakes.” *J. AWWA*, 77:3:58.

von Sonntag, C. and H-P. Schuchmann. 1992. UV disinfection of drinking water and by-product formation—some basic considerations. *Journal of Water Supply Research and Technology* 41, No 2: 67-74.

Vrijenhoek, E.M., A.E. Childress, M. Elimelech, T.S. Tanaka and M.D. Beuhler. 1998. “Removing Particles and THM Precursors by Enhanced Coagulation.” *J. AWWA*, 90:4:139-150.

Wallace, J.L., Vahadi, B., Fernandes, B.L. and Boyden, B.H. 1988. “The Combination of Ozone/ Hydrogen Peroxide and Ozone/UV Radiation for Reduction of Trihalomethane Formation Potential in Surface Water.” *Ozone Sci. Eng.*, 10:1:103.

Wang, B., Tian, J., Yin, J. and Shi, G. 1989. “Ammonia, Nitrite, and Nitrate Nitrogen Removal from Polluted Source Water with Ozonation and BAC Processes.” *Ozone Sci. Engr*., 11:2:227.

Wang, J.Z., R. Song and S.A. Hubbs. 2000. “Particle removal through riverbank filtration process.” Proceedings, Water Quality Technology Conference, November 5-9, 2000; Salt Lake City, Utah. American Water Works Association, Denver, Colorado.

Wang, J.Z., R. Song and S.A. Hubbs. 2000. “Particle removal through riverbank filtration process.” Proceedings of International Riverbank Filtration Conference, November 2-4, Düsseldorf. W. Julich and J. Schubert, eds., Internationale Arbeitgemeinschaft der Wasserwerke im Rheineinzugsgebiet, Amsterdam, pp. 127-138.

Wang, J. Z., R.S. Summers, R.J. Miltner. 1995. “Biofiltration Performance Part 1, Relationships to Biomass.” *J. AWWA*, 87:12:55.

Weber, W. J. 1972. *Physicochemical Processes for Water Quality Control*, John Wiley & Sons, New York, NY.

Weber, W.J. and A.M. Jodellah. 1985. “Removing Humic Substances by Chemical Treatment and Adsorption.” *J. AWWA*, 77:(4):132.

Weber, W.J., Voice, T.C. and Jodellah, A. 1983. “Adsorption of Humic Substances: The Effects of Heterogeneity and System Characteristics.” *J. AWWA*, 75:12:612.

Werdehoff, K.S. and P.C. Singer. 1987. “Chlorine Dioxide Effects on THMFP, TOXFP, and the Formation of Inorganic By-Products,” *J.AWWA*, 79:9:107.

West, T., P. Daniel, P. Meyerhofer, A. DeGraca, S. Leonard, and C. Gerba. “Evaluation of *Cryptosporidium* Removal Through High-Rate Filtration.” *Proc. AWWA 1994 Annual Conference, Water Quality*. New York: AWWA, June 19-23, 1994.

Westerhoff, G. and Chowdhury, Z.K. 1996. “Water Treatment Systems.” Chapter in *Water Resources Handbook*, L.M. Mays ed., McGraw Hill, New York.

White G.C. 1999. *Handbook of Chlorination and Alternative Disinfectants*, John Wiley & Sons, Inc., New York, NY.

White, M.C., Thompson, J.D., Harrington, G.W., and Singer, P.C. 1997. “Evaluating Criteria for Enhanced Coagulation Compliance.” *J. AWWA*, 89:5:64.

Wiesner, M, Schroelling, D., Pickering, K. 1991. “Permeate Behavior and Filtrate Quality of Tubular Cermanic Membranes Used for Surface Water Treatment.” AWWA Membrane Technology Conference Proceedings, Orlando, FL.

Wiesner, M., Veerapaneni, R., Brejchova, D. 1992. “Improvements in Membrane Microfiltration Using Coagulation Pretreatment.” *Chemical Water and Wastewater Treatment II.* Springer-Verlag, New York, p. 281.

Wilson, B.R.; P.F. Roessler, E. Van Dellen, M. Abbaszadegan and C.P. Gerba. 1992. “Coliphage MS-2 as a UV Water Disinfection Efficacy Test Surrogate for Bacterial and Viral Pathogens.” Proceedings of 1992 Water Quality Technology Conference, Nov 15-19, Toronto, pp. 219.

Wood, P.R., Jackson, D.F., Gervers, J.A., Waddell, D.H. and Kaplan, L. 1980. *Removing Potential Organic Carcinogens and Precursors From Drinking Water*. USEPA Rpt. No. EPA/600/2-80/130 Cincinnati, OH.

Wright, H.B and W.L. Cairns. 1998. “Ultraviolet Water Disinfection.” Technical literature distributed by Trojan Technologies, Inc., London, Ontario, Canada.

Wuhrmann, K. and Meyrath, J. 1955. “The Bactericidal Action of Ozone Solution.” *J. Allgen. Pathol. Bakteriol.*, 18:1060.

Yoon, Y., Amy, G., Pellegrino, J., Cho, Jaeweon, C. 1999. "NOM Rejection by, and Flux-decline of, Nanofiltration (NF and Ultrafiltration (UF) Membranes: Scale-up Effects and Optimal Operating Conditions." AWWA Membrane Technology Conference Proceedings, Long Beach, CA.

Young, J. S. and Singer, P. C. 1979. "Chloroform Formation in Public Water Supplies: A Case Study." *J. AWWA*, 71:12:87.

Zheng, M, S.A. Andrews, and J.R. Bolton. 1999. Impacts of medium pressure UV on THM and HAA formation in pre-UV chlorinated drinking water. Water Quality Technology Conference, October 31-November 3, Tampa, FL.

Appendix A

Very Small Systems Model
Capital Cost Breakdown Summaries

Appendix A Contents

Below is an explanation of the abbreviations used in this appendix:

p - The cost belongs to the process cost category of capital cost breakdown
c - The cost belongs to the construction cost category of the capital cost breakdown
e - The cost belongs to the engineering cost category of the capital cost breakdown

Exhibit A1 - VSS Document Capital Cost Breakdown for Membrane Processes

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	56.97%	p
Installation	0.2500	14.24%	c
Sitework/Interface Piping	0.0750	4.27%	c
Standby Power	0.0625	3.56%	c
OH&P	0.1665	9.49%	e
Legal & Admin	0.0416	2.37%	e
Engineering	0.1596	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.7552	100.00%	

Exhibit A2 - VSS Document Capital Cost Breakdown for Ion Exchange Processes

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	54.78%	p
Installation	0.3000	16.43%	c
Sitework/Interface Piping	0.0780	4.27%	c
Standby Power	0.0650	3.56%	c
OH&P	0.1732	9.49%	e
Legal & Admin	0.0433	2.37%	e
Engineering	0.1659	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.8254	100.00%	

Exhibit A3 - VSS Document Capital Cost Breakdown for Chlorination

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	61.93%	p
Installation	0.1500	9.29%	c
Sitework/Interface Piping	0.0690	4.27%	c
Standby Power	0.0575	3.56%	c
OH&P	0.1532	9.49%	e
Legal & Admin	0.0383	2.37%	e
Engineering	0.1468	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.6148	100.00%	

Exhibit A4 - VSS Document Capital Cost Breakdown for Potassium Permanganate Feed

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	64.74%	p
Installation	0.1000	6.47%	c
Sitework/Interface Piping	0.0660	4.27%	c
Standby Power	0.0550	3.56%	c
OH&P	0.1465	9.49%	e
Legal & Admin	0.0366	2.37%	e
Engineering	0.1404	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.5446	100.00%	

Exhibit A5 - Typical VSS Document Capital Cost Breakdown

Component	Capital Cost Factor	Percent of Total Capital Cost	Capital Cost Breakdown Category
Equipment	1.0000	54.78%	p
Installation	0.3000	16.43%	c
Sitework/Interface Piping	0.0780	4.27%	c
Standby Power	0.0650	3.56%	c
OH&P	0.1732	9.49%	e
Legal & Admin	0.0433	2.37%	e
Engineering	0.1659	9.09%	e
Contigencies	0.0000	0.00%	c
Total	1.8254	100.00%	

Appendix B

Water Model
Capital Cost Breakdown Summaries

Appendix B Contents

Below is an explanation of the abbreviations used in this appendix:

p - The cost belongs to the process cost category of capital cost breakdown
c - The cost belongs to the construction cost category of the capital cost breakdown
e - The cost belongs to the engineering cost category of the capital cost breakdown

Exhibit B1.1 - Base Costs Obtained from the Water Model for Activated Alumina

Cost Component	Contactor Volume (ft^3)							Capital Cost Category
	32	71	126	283	385	502	754	
Excavation & Sitework	$4,700	$4,700	$4,700	$4,700	$4,700	$4,700	$4,700	c
Manufactured Equipment	$12,800	$23,900	$39,100	$50,600	$64,500	$72,900	$101,000	p
Activated Alumina	$1,400	$3,100	$5,400	$11,900	$15,400	$19,600	$29,400	p
Concrete	$400	$1,200	$1,800	$2,000	$2,500	$3,200	$4,100	p
Labor	$1,200	$1,500	$2,000	$2,800	$3,300	$3,400	$4,200	c
Pipes and Valves	$5,200	$6,500	$6,500	$8,400	$12,800	$13,300	$20,100	p
Electrical	$6,400	$6,400	$6,400	$8,000	$8,000	$8,500	$9,600	p
Housing	$8,700	$14,400	$16,900	$17,900	$24,800	$34,400	$43,900	p
Subtotal	$40,800	$61,700	$82,800	$106,300	$136,000	$160,000	$217,000	
Contingencies	$6,100	$9,300	$12,400	$15,900	$20,400	$24,000	$32,600	c
Total	$46,900	$71,000	$95,200	$122,200	$156,400	$184,000	$249,600	

Exhibit B1.2 - Water Model Base Construction Cost Analysis for Activated Alumina

Cost Component	Contactor Volume (ft^3)							Average Percent
	32	71	126	283	385	502	754	
Excavation & Sitework	10.02%	6.62%	4.94%	3.85%	3.01%	2.55%	1.88%	4.70%
Manufactured Equipment	27.29%	33.66%	41.07%	41.41%	41.24%	39.62%	40.46%	37.82%
Activated Alumina	2.99%	4.37%	5.67%	9.74%	9.85%	10.65%	11.78%	7.86%
Concrete	0.85%	1.69%	1.89%	1.64%	1.60%	1.74%	1.64%	1.58%
Labor	2.56%	2.11%	2.10%	2.29%	2.11%	1.85%	1.68%	2.10%
Pipes and Valves	11.09%	9.15%	6.83%	6.87%	8.18%	7.23%	8.05%	8.20%
Electrical	13.65%	9.01%	6.72%	6.55%	5.12%	4.62%	3.85%	7.07%
Housing	18.55%	20.28%	17.75%	14.65%	15.86%	18.70%	17.59%	17.62%
Contingencies	13.01%	13.10%	13.03%	13.01%	13.04%	13.04%	13.06%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B2.1 - Base Costs Obtained from the Water Model for Anion Exchange

Cost Component	Resin Volume (ft^3)						Capital Cost Category
	4	17	54	188	280	520	
Excavation & Sitework	$2,100	$2,100	$4,400	$4,400	$4,400	$5,300	c
Manufactured Equipment	$3,100	$8,600	$23,100	$64,100	$96,800	$164,800	p
Concrete	$300	$400	$5,500	$5,800	$6,000	$8,400	p
Steel	$0	$0	$7,800	$7,800	$7,800	$10,900	p
Labor	$400	$1,100	$12,100	$12,800	$12,900	$17,200	c
Pipes and Valves	$800	$800	$1,000	$2,600	$2,600	$3,100	p
Electrical	$3,100	$3,100	$3,100	$3,100	$3,100	$3,100	p
Housing	$5,600	$9,600	$11,100	$16,600	$19,200	$25,000	p
Subtotal	$15,400	$25,700	$68,100	$117,200	$152,800	$237,800	
Contingencies	$2,300	$3,900	$10,200	$17,600	$22,900	$35,700	c
Total	$17,700	$29,600	$78,300	$134,800	$175,700	$273,500	

Exhibit B2.2 - Water Model Base Construction Cost Analysis for Anion Exchange

Cost Component	Resin Volume (ft^3)						Average Percent
	4	17	54	188	280	520	
Excavation & Sitework	11.86%	7.09%	5.62%	3.26%	2.50%	1.94%	5.38%
Manufactured Equipment	17.51%	29.05%	29.50%	47.55%	55.09%	60.26%	39.83%
Concrete	1.69%	1.35%	7.02%	4.30%	3.41%	3.07%	3.48%
Steel	0.00%	0.00%	9.96%	5.79%	4.44%	3.99%	4.03%
Labor	2.26%	3.72%	15.45%	9.50%	7.34%	6.29%	7.43%
Pipes and Valves	4.52%	2.70%	1.28%	1.93%	1.48%	1.13%	2.17%
Electrical	17.51%	10.47%	3.96%	2.30%	1.76%	1.13%	6.19%
Housing	31.64%	32.43%	14.18%	12.31%	10.93%	9.14%	18.44%
Contingencies	12.99%	13.18%	13.03%	13.06%	13.03%	13.05%	13.06%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B3.1 - Base Costs Obtained from the Water Model for Basic Chemical Feed

Cost Component	Maximum Feed Rate (lb/day)							Capital Cost Category
	0.1-10	25	50	100	250	500	1000	
Dissolving Tank	$290	$430	$640	$910	$1,830	$2,200	$4,400	p
Mixer	$180	$200	$200	$240	$410	$620	$620	p
Metering Pump	$430	$700	$750	$1,230	$1,600	$1,670	$1,820	p
Pipes and Valves	$180	$180	$220	$220	$280	$280	$420	p
Labor	$180	$180	$240	$260	$300	$330	$400	c
Electrical	$80	$100	$150	$200	$250	$300	$400	p
Subtotal	$1,340	$1,790	$2,200	$3,060	$4,670	$5,400	$8,060	
Contingencies	$200	$270	$330	$460	$700	$810	$1,210	c
Total	$1,540	$2,060	$2,530	$3,520	$5,370	$6,210	$9,270	

Exhibit B3.2 - Water Model Base Construction Cost Analysis for Basic Chemical Feed

Cost Component	Maximum Feed Rate (lb/day)							Average Percent
	0.1-10	25	50	100	250	500	1000	
Dissolving Tank	18.83%	20.87%	25.30%	25.85%	34.08%	35.43%	47.46%	29.69%
Mixer	11.69%	9.71%	7.91%	6.82%	7.64%	9.98%	6.69%	8.63%
Metering Pump	27.92%	33.98%	29.64%	34.94%	29.80%	26.89%	19.63%	28.97%
Pipes and Valves	11.69%	8.74%	8.70%	6.25%	5.21%	4.51%	4.53%	7.09%
Labor	11.69%	8.74%	9.49%	7.39%	5.59%	5.31%	4.31%	7.50%
Electrical	5.19%	4.85%	5.93%	5.68%	4.66%	4.83%	4.31%	5.07%
Contingencies	12.99%	13.11%	13.04%	13.07%	13.04%	13.04%	13.05%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B4.1 - Base Costs Obtained from the Water Model for Chlorination

Cost Component	Cost	Capital Cost Category
Excavation & Sitework	$1,200	c
Manufactured Equipment	$2,700	p
Concrete	$300	p
Labor	$400	c
Pipes and Valves	$500	p
Electrical	$2,200	p
Housing	$7,800	p
Subtotal	$15,100	
Contingencies	$2,300	c
Total	$17,400	

Exhibit B4.2 - Water Model Base Construction Cost Analysis for Chlorination

Cost Component	Cost	Average Percent
Excavation & Sitework	6.90%	6.90%
Manufactured Equipment	15.52%	15.52%
Concrete	1.72%	1.72%
Labor	2.30%	2.30%
Pipes and Valves	2.87%	2.87%
Electrical	12.64%	12.64%
Housing	44.83%	44.83%
Contingencies	13.22%	13.22%
Total	100.00%	100.00%

Exhibit B5.1 - Base Costs Obtained from the Water Model for Underground Clearwell Storage

Cost Component	Design Capacity (gpd)					Capital Cost Category
	5,000	10,000	50,000	100,000	500,000	
Excavation & Sitework	$3,300	$5,700	$16,500	$25,300	$75,400	c
Concrete	$9,800	$16,500	$37,000	$64,000	$216,400	p
Steel	$300	$400	$500	$500	$600	p
Electrical	$2,600	$2,600	$2,600	$2,600	$2,600	p
Subtotal	$16,000	$25,200	$56,600	$92,400	$295,000	
Contingencies	$2,400	$3,800	$8,500	$13,900	$44,300	c
Total	$18,400	$29,000	$65,100	$106,300	$339,300	

Exhibit B5.2 - Water Model Base Construction Cost Analysis for Underground Clearwell Storage

Cost Component	Design Capacity (gpd)					Average Percent
	5,000	10,000	50,000	100,000	500,000	
Excavation & Sitework	17.93%	19.66%	25.35%	23.80%	22.22%	21.79%
Concrete	53.26%	56.90%	56.84%	60.21%	63.78%	58.20%
Steel	1.63%	1.38%	0.77%	0.47%	0.18%	0.88%
Electrical	14.13%	8.97%	3.99%	2.45%	0.77%	6.06%
Contingencies	13.04%	13.10%	13.06%	13.08%	13.06%	13.07%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B6.1 - Base Costs Obtained from the Water Model for Package Conventional Treatment

Cost Component	Filter Area (ft^2)						Capital Cost Category
	2	12	20	40	112	150	
Excavation & Sitework	$3,500	$3,500	$4,700	$5,800	$7,000	$9,300	c
Manufactured Equipment	$31,000	$44,900	$53,500	$111,300	$176,600	$190,500	p
Concrete	$1,000	$1,000	$1,500	$4,500	$5,700	$6,800	p
Labor	$9,900	$14,700	$17,500	$36,400	$57,800	$62,400	c
Pipes and Valves	$4,200	$8,300	$10,400	$20,900	$29,200	$41,700	p
Electrical	$3,200	$4,500	$5,300	$11,100	$17,600	$19,000	p
Housing	$18,600	$18,600	$23,400	$45,000	$47,500	$52,500	p
Subtotal	$71,400	$95,500	$116,300	$235,000	$341,400	$382,200	
Contingencies	$10,700	$14,300	$17,400	$35,300	$51,200	$57,300	c
Total	$82,100	$109,800	$133,700	$270,300	$392,600	$439,500	

Exhibit B6.2 - Water Model Base Construction Cost Analysis for Package Conventional Treatment

Cost Component	Filter Area (ft^2)						Average Percent
	2	12	20	40	112	150	
Excavation & Sitework	4.26%	3.19%	3.52%	2.15%	1.78%	2.12%	2.84%
Manufactured Equipment	37.76%	40.89%	40.01%	41.18%	44.98%	43.34%	41.36%
Concrete	1.22%	0.91%	1.12%	1.66%	1.45%	1.55%	1.32%
Labor	12.06%	13.39%	13.09%	13.47%	14.72%	14.20%	13.49%
Pipes and Valves	5.12%	7.56%	7.78%	7.73%	7.44%	9.49%	7.52%
Electrical	3.90%	4.10%	3.96%	4.11%	4.48%	4.32%	4.15%
Housing	22.66%	16.94%	17.50%	16.65%	12.10%	11.95%	16.30%
Contingencies	13.03%	13.02%	13.01%	13.06%	13.04%	13.04%	13.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B7.1 - Base Costs Obtained from the Water Model for Ferric Chloride Feed

Cost Component	Maximum Feed Rate (lb/day)							Capital Cost Category
	1	10	25	50	100	250	750	
Storage Tank	$0	$0	$0	$0	$360	$780	$2,040	p
Wooden Stairway	$0	$0	$0	$0	$0	$300	$300	p
Metering Pump	$390	$390	$390	$390	$390	$1,090	$1,100	p
Pipes and Valves	$180	$180	$180	$180	$220	$280	$280	p
Labor	$120	$120	$130	$130	$210	$360	$410	c
Electrical	$80	$80	$80	$80	$100	$120	$120	p
Subtotal	$770	$770	$780	$780	$1,280	$2,930	$4,250	
Contingencies	$120	$120	$120	$120	$190	$440	$640	c
Total	$890	$890	$900	$900	$1,470	$3,370	$4,890	

Exhibit B7.2 - Water Model Base Construction Cost Analysis for Ferric Chloride Feed

Cost Component	Maximum Feed Rate (lb/day)							Average Percent
	1	10	25	50	100	250	750	
Storage Tank	0.00%	0.00%	0.00%	0.00%	24.49%	23.15%	41.72%	12.76%
Wooden Stairway	0.00%	0.00%	0.00%	0.00%	0.00%	8.90%	6.13%	2.15%
Metering Pump	43.82%	43.82%	43.33%	43.33%	26.53%	32.34%	22.49%	36.53%
Pipes and Valves	20.22%	20.22%	20.00%	20.00%	14.97%	8.31%	5.73%	15.64%
Labor	13.48%	13.48%	14.44%	14.44%	14.29%	10.68%	8.38%	12.74%
Electrical	8.99%	8.99%	8.89%	8.89%	6.80%	3.56%	2.45%	6.94%
Contingencies	13.48%	13.48%	13.33%	13.33%	12.93%	13.06%	13.09%	13.24%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B8.1 - Base Costs Obtained from the Water Model for Package Lime Softening

Cost Component	Design Capacity (gpd)					Capital Cost Category
	15,000	150,000	430,000	750,000	1,000,000	
Excavation & Sitework	$3,500	$5,800	$6,700	$8,400	$9,800	c
Manufactured Equipment	$33,200	$49,800	$66,300	$86,200	$103,800	p
Concrete	$1,100	$2,500	$3,200	$5,900	$7,000	p
Labor	$14,000	$18,200	$28,000	$36,400	$43,800	c
Pipes and Valves	$5,200	$10,400	$14,100	$16,700	$45,900	p
Electrical	$8,500	$12,200	$17,000	$18,900	$26,700	p
Housing	$8,800	$16,400	$19,800	$30,000	$33,000	p
Subtotal	$74,300	$115,300	$155,100	$202,500	$270,000	
Contingencies	$11,100	$17,300	$23,300	$30,400	$40,500	c
Total	$85,400	$132,600	$178,400	$232,900	$310,500	

Exhibit B8.2 - Water Model Base Construction Cost Analysis for Package Lime Softening

Cost Component	Design Capacity (gpd)					Average Percent
	15,000	150,000	430,000	750,000	1,000,000	
Excavation & Sitework	4.10%	4.37%	3.76%	3.61%	3.16%	3.80%
Manufactured Equipment	38.88%	37.56%	37.16%	37.01%	33.43%	36.81%
Concrete	1.29%	1.89%	1.79%	2.53%	2.25%	1.95%
Labor	16.39%	13.73%	15.70%	15.63%	14.11%	15.11%
Pipes and Valves	6.09%	7.84%	7.90%	7.17%	14.78%	8.76%
Electrical	9.95%	9.20%	9.53%	8.12%	8.60%	9.08%
Housing	10.30%	12.37%	11.10%	12.88%	10.63%	11.46%
Contingencies	13.00%	13.05%	13.06%	13.05%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B9.1 - Base Costs Obtained from the Water Model for Permanganate Feed

Cost Component	Maximum Feed Rate (lb/day)						Capital Cost Category
	0.5-5	12.5	25	50	125	250	
Dissolving Tank	$290	$430	$640	$910	$1,830	$2,200	p
Mixer	$180	$200	$200	$240	$410	$620	p
Metering Pump	$430	$700	$750	$1,230	$1,600	$1,670	p
Pipes and Valves	$180	$180	$220	$220	$280	$280	p
Labor	$180	$180	$240	$260	$300	$330	c
Electrical	$80	$100	$150	$200	$250	$300	p
Subtotal	$1,340	$1,790	$2,200	$3,060	$4,670	$5,400	
Contingencies	$200	$270	$330	$460	$700	$810	c
Total	$1,540	$2,060	$2,530	$3,520	$5,370	$6,210	

Exhibit B9.2 - Water Model Base Construction Cost Analysis for Permanganate Feed

Cost Component	Maximum Feed Rate (lb/day)						Average Percent
	0.5-5	12.5	25	50	125	250	
Excavation & Sitework	18.83%	20.87%	25.30%	25.85%	34.08%	35.43%	26.73%
Manufactured Equipment	11.69%	9.71%	7.91%	6.82%	7.64%	9.98%	8.96%
Concrete	27.92%	33.98%	29.64%	34.94%	29.80%	26.89%	30.53%
Labor	11.69%	8.74%	8.70%	6.25%	5.21%	4.51%	7.52%
Pipes and Valves	11.69%	8.74%	9.49%	7.39%	5.59%	5.31%	8.03%
Electrical	5.19%	4.85%	5.93%	5.68%	4.66%	4.83%	5.19%
Contingencies	12.99%	13.11%	13.04%	13.07%	13.04%	13.04%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B10.1 - Base Costs Obtained from the Water Model for Polymer Feed

Cost Component	Maximum Feed Rate (lb/day)					Capital Cost Category
	0.6	1	2.1	4.2	10.4	
Mixing Tank	$290	$430	$640	$910	$1,830	p
Mixer	$850	$850	$200	$1,050	$1,050	p
Metering Pump	$640	$700	$750	$1,230	$1,600	p
Pipes and Valves	$180	$180	$220	$220	$280	p
Labor	$180	$180	$240	$260	$300	c
Electrical	$80	$100	$150	$200	$250	p
Subtotal	$2,220	$2,440	$2,200	$3,870	$5,310	
Contingencies	$330	$370	$330	$580	$800	c
Total	$2,550	$2,810	$2,530	$4,450	$6,110	

Exhibit B10.2 - Water Model Base Construction Cost Analysis for Polymer Feed

Cost Component	Maximum Feed Rate (lb/day)					Average Percent
	0.6	1	2.1	4.2	10.4	
Mixing Tank	11.37%	15.30%	25.30%	20.45%	29.95%	20.47%
Mixer	33.33%	30.25%	7.91%	23.60%	17.18%	22.45%
Metering Pump	25.10%	24.91%	29.64%	27.64%	26.19%	26.70%
Pipes and Valves	7.06%	6.41%	8.70%	4.94%	4.58%	6.34%
Labor	7.06%	6.41%	9.49%	5.84%	4.91%	6.74%
Electrical	3.14%	3.56%	5.93%	4.49%	4.09%	4.24%
Contingencies	12.94%	13.17%	13.04%	13.03%	13.09%	13.06%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B11.1 - Base Costs Obtained from the Water Model for Raw Water Pumping

Cost Component	Design Capacity (gpd)					Capital Cost Category
	28,800	144,000	504,000	720,000	1,008,000	
Excavation & Sitework	$11,700	$11,700	$12,300	$12,300	$12,800	c
Manufactured Equipment	$6,600	$7,800	$11,800	$12,600	$16,500	p
Concrete	$500	$500	$1,100	$1,100	$1,500	p
Labor	$3,700	$3,800	$5,800	$6,200	$8,500	c
Pipes and Valves	$1,500	$1,800	$2,700	$3,600	$4,500	p
Electrical	$800	$800	$1,400	$1,600	$2,100	p
Subtotal	$24,800	$26,400	$35,100	$37,400	$45,900	
Contingencies	$3,700	$4,000	$5,300	$5,600	$6,900	c
Total	$28,500	$30,400	$40,400	$43,000	$52,800	

Exhibit B11.2 - Water Model Base Construction Cost Analysis for Raw Water Pumping

Cost Component	Design Capacity (gpd)					Average Percent
	28,800	144,000	504,000	720,000	1,008,000	
Excavation & Sitework	41.05%	38.49%	30.45%	28.60%	24.24%	32.57%
Manufactured Equipment	23.16%	25.66%	29.21%	29.30%	31.25%	27.72%
Concrete	1.75%	1.64%	2.72%	2.56%	2.84%	2.30%
Labor	12.98%	12.50%	14.36%	14.42%	16.10%	14.07%
Pipes and Valves	5.26%	5.92%	6.68%	8.37%	8.52%	6.95%
Electrical	2.81%	2.63%	3.47%	3.72%	3.98%	3.32%
Contingencies	12.98%	13.16%	13.12%	13.02%	13.07%	13.07%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B12.1 - Base Costs Obtained from the Water Model for Package Reverse Osmosis

Cost Component	Plant Capacity (gpd)						Capital Cost Category
	2,500	10,000	50,000	100,000	500,000	1,000,000	
Manufactured Equipment	$20,300	$30,000	$69,600	$123,000	$454,800	$877,400	p
Labor	$800	$1,200	$1,500	$2,800	$7,500	$14,600	c
Electrical	$3,200	$4,600	$10,700	$18,700	$45,900	$62,100	p
Housing	$11,900	$13,900	$16,400	$18,500	$38,400	$52,500	p
Subtotal	$36,200	$49,700	$98,200	$163,000	$546,600	$1,006,600	
Contingencies	$5,400	$7,500	$14,700	$24,500	$82,000	$151,000	c
Total	$41,600	$57,200	$112,900	$187,500	$628,600	$1,157,600	

Exhibit B12.2 - Water Model Base Construction Cost Analysis for Package Reverse Osmosis

Cost Component	Plant Capacity (gpd)						Average Percent
	2,500	10,000	50,000	100,000	500,000	1,000,000	
Manufactured Equipment	48.80%	52.45%	61.65%	65.60%	72.35%	75.79%	62.77%
Labor	1.92%	2.10%	1.33%	1.49%	1.19%	1.26%	1.55%
Electrical	7.69%	8.04%	9.48%	9.97%	7.30%	5.36%	7.98%
Housing	28.61%	24.30%	14.53%	9.87%	6.11%	4.54%	14.66%
Contingencies	12.98%	13.11%	13.02%	13.07%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B13.1 - Base Costs Obtained from the Water Model for Sodium Hydroxide Feed

Cost Component	Maximum Feed Rate (lb/day)							Capital Cost Category
	0.8	4	8	42	83	417	834	
Storage and Feed Tanks	$60	$60	$90	$970	$2,040	$3,560	$6,940	p
Heating and Insulation	$0	$0	$0	$200	$410	$950	$1,620	p
Mixer	$0	$0	$0	$180	$240	$620	$640	p
Stairway	$0	$0	$0	$0	$0	$300	$600	p
Man. Transfer Pump	$100	$100	$100	$0	$0	$0	$0	p
Pipes and Valves	$310	$310	$310	$470	$470	$530	$790	p
Metering Pump	$390	$390	$390	$390	$410	$1,090	$1,100	p
Containment Wall	$120	$120	$150	$270	$400	$600	$880	p
Labor	$280	$280	$280	$420	$480	$650	$860	c
Electrical	$80	$80	$80	$100	$100	$120	$120	p
Subtotal	$1,340	$1,340	$1,400	$3,000	$4,550	$8,420	$13,550	
Contingencies	$200	$200	$210	$450	$680	$1,260	$2,030	c
Total	$1,540	$1,540	$1,610	$3,450	$5,230	$9,680	$15,580	

Exhibit B13.2 - Water Model Base Construction Cost Analysis for Sodium Hydroxide Feed

Cost Component	Maximum Feed Rate (lb/day)							Average Percent
	0.8	4	8	42	83	417	834	
Storage and Feed Tanks	3.90%	3.90%	5.59%	28.12%	39.01%	36.78%	44.54%	23.12%
Heating and Insulation	0.00%	0.00%	0.00%	5.80%	7.84%	9.81%	10.40%	4.84%
Mixer	0.00%	0.00%	0.00%	5.22%	4.59%	6.40%	4.11%	2.90%
Stairway	0.00%	0.00%	0.00%	0.00%	0.00%	3.10%	3.85%	0.99%
Man. Transfer Pump	6.49%	6.49%	6.21%	0.00%	0.00%	0.00%	0.00%	2.74%
Pipes and Valves	20.13%	20.13%	19.25%	13.62%	8.99%	5.48%	5.07%	13.24%
Metering Pump	25.32%	25.32%	24.22%	11.30%	7.84%	11.26%	7.06%	16.05%
Containment Wall	7.79%	7.79%	9.32%	7.83%	7.65%	6.20%	5.65%	7.46%
Labor	18.18%	18.18%	17.39%	12.17%	9.18%	6.71%	5.52%	12.48%
Electrical	5.19%	5.19%	4.97%	2.90%	1.91%	1.24%	0.77%	3.17%
Contingencies	12.99%	12.99%	13.04%	13.04%	13.00%	13.02%	13.03%	13.02%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit B14.1 - Base Costs Obtained from the Water Model for Package Ultrafiltration

Cost Component	Membrane Area (ft^2)						Capital Cost Category
	30	424	1,431	3,604	7,155	14,310	
Excavation & Sitework	$1,300	$2,400	$4,100	$5,700	$10,200	$14,900	c
Manufactured Equipment	$5,500	$25,300	$65,600	$129,800	$23,900	$415,100	p
Concrete	$1,800	$3,700	$5,800	$10,200	$16,700	$28,800	p
Labor	$1,100	$5,200	$13,500	$26,900	$49,500	$85,900	c
Pipes and Valves	$500	$1,100	$2,200	$3,800	$4,500	$6,200	p
Electrical	$1,500	$5,600	$13,300	$25,800	$48,100	$85,300	p
Housing	$7,800	$14,600	$21,700	$29,000	$40,800	$56,000	p
Subtotal	$19,500	$57,900	$126,200	$231,200	$193,700	$692,200	
Contingencies	$2,900	$8,700	$18,900	$34,700	$29,100	$103,800	c
Total	$22,400	$66,600	$145,100	$265,900	$222,800	$796,000	

Exhibit B14.2 - Water Model Base Construction Cost Analysis for Package Ultrafiltration

Cost Component	Membrane Area (ft^2)						Average Percent
	30	424	1,431	3,604	7,155	14,310	
Excavation & Sitework	5.80%	3.60%	2.83%	2.14%	4.58%	1.87%	3.47%
Manufactured Equipment	24.55%	37.99%	45.21%	48.82%	10.73%	52.15%	36.57%
Concrete	8.04%	5.56%	4.00%	3.84%	7.50%	3.62%	5.42%
Labor	4.91%	7.81%	9.30%	10.12%	22.22%	10.79%	10.86%
Pipes and Valves	2.23%	1.65%	1.52%	1.43%	2.02%	0.78%	1.60%
Electrical	6.70%	8.41%	9.17%	9.70%	21.59%	10.72%	11.05%
Housing	34.82%	21.92%	14.96%	10.91%	18.31%	7.04%	17.99%
Contingencies	12.95%	13.06%	13.03%	13.05%	13.06%	13.04%	13.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Appendix C

W/W Cost Model
Capital Cost Breakdown Summaries

Appendix C Contents

Exhibit Name	Exhibit Number
WATER Model Base Construction Cost Analysis for In-Plant Pumping	C14.2
Base Costs Obtained from the WATER Model for Ion Exchange	C15.1
WATER Model Base Construction Cost Analysis for Ion Exchange	C15.2
Base Costs Obtained from the WATER Model for Lime Feed with Recalcination	C16.1
WATER Model Base Construction Cost Analysis for Lime Feed with Recalcination	C16.2
Base Costs Obtained from the WATER Model for Permanganate Feed Systems	C17.1
WATER Model Base Construction Cost Analysis for Permanganate Feed Systems	C17.2
Base Costs Obtained from the WATER Model for Polymer Feed Systems	C18.1
WATER Model Base Construction Cost Analysis for Polymer Feed Systems	C18.2
Base Costs Obtained from the WATER Model for Rapid Mix, G=900	C19.1
WATER Model Base Construction Cost Analysis for Rapid Mix, G=900	C19.2
Base Costs Obtained from the WATER Model for Recarbonation, Liquid Carbon Dioxide	C20.1
WATER Model Base Construction Cost Analysis for Recarbonation, Liquid Carbon Dioxide	C20.2
Base Costs Obtained from the WATER Model for Recarbonation Basins	C21.1
WATER Model Base Construction Cost Analysis for Recarbonation Basins	C21.2
Base Costs Obtained from the WATER Model for Rectangular Clarifiers	C22.1
WATER Model Base Construction Cost Analysis for Rectangular Clarifiers	C22.2
Base Costs Obtained from the WATER Model for Reverse Osmosis	C23.1
WATER Model Base Construction Cost Analysis for Reverse Osmosis	C23.2
Base Costs Obtained from the WATER Model for Sodium Hydroxide Feed Systems	C24.1
WATER Model Base Construction Cost Analysis for Sodium Hydroxide Feed Systems	C24.2
Base Costs Obtained from the WATER Model for Sulfuric Acid Feed Systems	C25.1
WATER Model Base Construction Cost Analysis for Sulfuric Acid Feed Systems	C25.2
Base Costs Obtained from the WATER Model for Tube Settling Modules	C26.1
WATER Model Base Construction Cost Analysis for Tube Settling Modules	C26.2
Base Costs Obtained from the WATER Model for Wash Water Surge Basins	C27.1
WATER Model Base Construction Cost Analysis for Wash Water Surge Basins	C27.2

Below is an explanation of the abbreviations used in this appendix:

p - The cost belongs to the process cost category of capital cost breakdown
c - The cost belongs to the construction cost category of the capital cost breakdown
e - The cost belongs to the engineering cost category of the capital cost breakdown

Exhibit C1.1 - Base Costs Obtained from the WATER Model for Activated Alumina

Cost Component	Plant Capacity (mgd)						Capital Cost Category
	0.7	2.0	6.8	27	54	135	
Manufactured Equipment	$26,760	$44,580	$138,330	$522,210	$1,031,270	$2,564,560	p
Activated Alumina	$8,300	$14,770	$83,080	$332,310	$664,610	$1,661,530	p
Labor	$10,280	$13,490	$48,010	$192,020	$384,060	$1,282,370	c
Pipes and Valves	$16,260	$19,320	$69,030	$273,210	$542,650	$1,368,060	p
Electrical	$10,050	$11,360	$22,300	$60,300	$119,030	$284,750	p
Housing	$6,960	$27,630	$62,120	$210,980	$374,840	$744,320	p
Contingencies	$11,790	$19,670	$63,430	$238,650	$467,470	$1,185,840	c
Total	$90,400	$150,820	$486,300	$1,829,680	$3,583,930	$9,091,430	

Exhibit C1.2 - WATER Model Base Construction Cost Analysis for Activated Alumina

Cost Component	Plant Capacity (mgd)						Average Percent
	0.7	2.0	6.8	27	54	135	
Manufactured Equipment	29.60%	29.56%	28.45%	28.54%	28.77%	28.21%	28.86%
Activated Alumina	9.18%	9.79%	17.08%	18.16%	18.54%	18.28%	15.17%
Labor	11.37%	8.94%	9.87%	10.49%	10.72%	14.11%	10.92%
Pipes and Valves	17.99%	12.81%	14.19%	14.93%	15.14%	15.05%	15.02%
Electrical	11.12%	7.53%	4.59%	3.30%	3.32%	3.13%	5.50%
Housing	7.70%	18.32%	12.77%	11.53%	10.46%	8.19%	11.49%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C2.1 - Base Costs Obtained from the WATER Model for Ammonia Feed Systems

Cost Component	Feed Capacity (lb/day)					Capital Cost Category
	250	500	1,000	2,500	5,000	
Manufactured Equipment	$13,260	$19,520	$30,450	$38,830	$59,200	p
Labor	$3,990	$5,680	$9,250	$10,620	$13,870	c
Pipes and Valves	$2,390	$3,520	$5,500	$7,000	$10,670	p
Electrical	$3,250	$3,770	$6,180	$8,480	$10,990	p
Housing	$4,500	$4,500	$4,500	$4,500	$6,430	p
Contingencies	$4,110	$5,550	$8,380	$10,410	$15,170	c
Total	$31,500	$42,540	$64,260	$79,840	$116,330	

Exhibit C2.2 - WATER Model Base Construction Cost Analysis for Ammonia Feed Systems

Cost Component	Feed Capacity (lb/day)					Average Percent
	250	500	1,000	2,500	5,000	
Manufactured Equipment	42.10%	45.89%	47.39%	48.63%	50.89%	46.98%
Labor	12.67%	13.35%	14.39%	13.30%	11.92%	13.13%
Pipes and Valves	7.59%	8.27%	8.56%	8.77%	9.17%	8.47%
Electrical	10.32%	8.86%	9.62%	10.62%	9.45%	9.77%
Housing	14.29%	10.58%	7.00%	5.64%	5.53%	8.61%
Contingencies	13.05%	13.05%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C3.1 - Base Costs Obtained from the WATER Model for Backwash Water Pumping

Cost Component	Pumping Capacity (mgd(gpm))					Capital Cost Category
	1,260 (1.8)	3,150 (4.5)	6,300 (9.1)	18,000 (25.9)	22,950 (33)	
Manufactured Equipment	$11,400	$14,600	$38,380	$76,780	$95,970	p
Labor	$3,050	$4,410	$4,880	$9,290	$12,440	c
Pipes and Valves	$9,780	$17,690	$17,690	$33,390	$44,780	p
Electrical	$13,350	$16,040	$16,740	$28,070	$33,250	p
Contingencies	$5,640	$7,910	$11,650	$22,130	$27,970	c
Total	$43,220	$60,650	$89,340	$169,660	$214,410	

Exhibit C3.2 - WATER Model Base Construction Cost Analysis for Backwash Water Pumping

Cost Component	Pumping Capacity (mgd(gpm))					Average Percent
	1,260 (1.8)	3,150 (4.5)	6,300 (9.1)	18,000 (25.9)	22,950 (33)	
Manufactured Equipment	26.38%	24.07%	42.96%	45.26%	44.76%	36.68%
Labor	7.06%	7.27%	5.46%	5.48%	5.80%	6.21%
Pipes and Valves	22.63%	29.17%	19.80%	19.68%	20.89%	22.43%
Electrical	30.89%	26.45%	18.74%	16.54%	15.51%	21.63%
Contingencies	13.05%	13.04%	13.04%	13.04%	13.05%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C4.1 - Base Costs Obtained from the WATER Model for Chemical Sludge Pumping

Cost Component	Capacity (gpm)						Capital Cost Category
	20	100	500	1,000	5,000	10,000	
Excavation & Sitework	$470	$600	$810	$970	$1,840	$2,220	c
Manufactured Equipment	$4,370	$6,230	$8,210	$10,390	$23,320	$38,440	p
Concrete	$1,500	$2,210	$3,220	$4,100	$9,270	$12,310	p
Steel	$1,510	$2,130	$3,120	$3,940	$8,640	$11,070	p
Labor	$5,280	$8,060	$12,880	$17,400	$47,850	$64,720	c
Pipes and Valves	$2,560	$4,570	$10,870	$18,190	$42,810	$79,060	p
Electrical	$6,290	$7,390	$7,880	$9,380	$10,380	$12,510	p
Housing	$5,880	$5,880	$5,880	$8,100	$8,100	$11,700	p
Contingencies	$4,180	$5,560	$7,930	$10,870	$22,830	$34,800	c
Total	$32,040	$42,630	$60,800	$83,340	$175,040	$266,830	

Exhibit C4.2 - WATER Model Base Construction Cost Analysis for Chemical Sludge Pumping

Cost Component	Capacity (gpm)						Average Percent
	20	100	500	1,000	5,000	10,000	
Excavation & Sitework	1.47%	1.41%	1.33%	1.16%	1.05%	0.83%	1.21%
Manufactured Equipment	13.64%	14.61%	13.50%	12.47%	13.32%	14.41%	13.66%
Concrete	4.68%	5.18%	5.30%	4.92%	5.30%	4.61%	5.00%
Steel	4.71%	5.00%	5.13%	4.73%	4.94%	4.15%	4.78%
Labor	16.48%	18.91%	21.18%	20.88%	27.34%	24.26%	21.51%
Pipes and Valves	7.99%	10.72%	17.88%	21.83%	24.46%	29.63%	18.75%
Electrical	19.63%	17.34%	12.96%	11.26%	5.93%	4.69%	11.97%
Housing	18.35%	13.79%	9.67%	9.72%	4.63%	4.38%	10.09%
Contingencies	13.05%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C5.1 - Base Costs Obtained from the WATER Model for Chlorination

Cost Component	Chlorine Feed Capacity (lb/day)						Capital Cost Category
	10	500	1,000	2,000	5,000	10,000	
Manufactured Equipment	$6,760	$21,630	$41,630	$65,950	$76,780	$114,360	p
Labor	$820	$2,610	$5,030	$7,960	$9,270	$13,810	c
Pipes and Valves	$540	$1,710	$3,300	$5,230	$6,080	$9,060	p
Electrical	$770	$2,450	$4,710	$7,460	$8,690	$12,940	p
Housing	$2,430	$18,360	$27,760	$46,550	$100,440	$186,490	p
Contingencies	$1,700	$7,010	$12,360	$19,970	$30,190	$50,500	c
Total	$13,020	$53,770	$94,790	$153,120	$231,450	$387,160	

Exhibit C5.2 - WATER Model Base Construction Cost Analysis for Chlorination

Cost Component	Chlorine Feed Capacity (lb/day)						Average Percent
	10	500	1,000	2,000	5,000	10,000	
Manufactured Equipment	51.92%	40.23%	43.92%	43.07%	33.17%	29.54%	40.31%
Labor	6.30%	4.85%	5.31%	5.20%	4.01%	3.57%	4.87%
Pipes and Valves	4.15%	3.18%	3.48%	3.42%	2.63%	2.34%	3.20%
Electrical	5.91%	4.56%	4.97%	4.87%	3.75%	3.34%	4.57%
Housing	18.66%	34.15%	29.29%	30.40%	43.40%	48.17%	34.01%
Contingencies	13.06%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C6.1 - Base Costs Obtained from the WATER Model for Circular Clarifiers

Cost Component	Surface Area (SA=ft^2) and Diameter (D=ft)							Capital Cost Category
	SA=707 D=30	SA=1,590 D=45	SA=5,027 D=80	SA=10,387 D=115	SA=15,393 D=140	SA=22,698 D=170	SA=31,416 D=200	
Excavation & Sitework	$1,530	$2,430	$4,900	$7,860	$10,280	$13,520	$17,130	c
Manufactured Equipment	$28,740	$34,410	$69,580	$97,180	$132,350	$189,060	$226,980	p
Concrete	$4,860	$7,710	$15,480	$24,800	$32,400	$42,560	$53,860	p
Steel	$14,160	$21,090	$67,240	$129,250	$188,720	$249,570	$335,140	p
Labor	$10,770	$16,180	$30,960	$46,980	$60,110	$77,640	$96,320	c
Pipes and Valves	$8,090	$8,420	$11,540	$15,660	$21,590	$26,590	$42,520	p
Electrical	$5,940	$5,940	$7,560	$8,270	$10,870	$12,370	$13,060	p
Contingencies	$11,110	$14,430	$31,090	$49,500	$68,450	$91,700	$117,750	c
Total	$85,200	$110,610	$238,350	$379,500	$524,770	$703,010	$902,760	

Exhibit C6.2 - WATER Model Base Construction Cost Analysis for Circular Clarifiers

Cost Component	Surface Area (SA=ft^2) and Diameter (D=ft)							Average Percent
	SA=707 D=30	SA=1,590 D=45	SA=5,027 D=80	SA=10,387 D=115	SA=15,393 D=140	SA=22,698 D=170	SA=31,416 D=200	
Excavation & Sitework	1.80%	2.20%	2.06%	2.07%	1.96%	1.92%	1.90%	1.99%
Manufactured Equipment	33.73%	31.11%	29.19%	25.61%	25.22%	26.89%	25.14%	28.13%
Concrete	5.70%	6.97%	6.49%	6.53%	6.17%	6.05%	5.97%	6.27%
Steel	16.62%	19.07%	28.21%	34.06%	35.96%	35.50%	37.12%	29.51%
Labor	12.64%	14.63%	12.99%	12.38%	11.45%	11.04%	10.67%	12.26%
Pipes and Valves	9.50%	7.61%	4.84%	4.13%	4.11%	3.78%	4.71%	5.53%
Electrical	6.97%	5.37%	3.17%	2.18%	2.07%	1.76%	1.45%	3.28%
Contingencies	13.04%	13.05%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C7.1 - Base Costs Obtained from the WATER Model for Clearwell Storage

Cost Component	Capacity (gal)						Capital Cost Category
	10,000	50,000	100,000	500,000	1,000,000	7,500,000	
Excavation & Sitework	$140	$190	$410	$2,030	$19,440	$30,020	c
Concrete	$8,250	$14,430	$23,280	$66,330	$105,520	$622,500	p
Steel	$5,700	$9,240	$14,550	$32,670	$113,050	$350,700	p
Labor	$13,050	$21,480	$35,040	$84,090	$109,290	$394,160	p
Electrical	$1,270	$1,270	$6,010	$6,010	$9,800	$9,800	p
Contingencies	$4,260	$6,990	$11,890	$28,670	$53,570	$211,080	c
Total	$32,670	$53,600	$91,180	$219,800	$410,670	$1,618,260	

Exhibit C7.2 - WATER Model Base Construction Cost Analysis for Clearwell Storage

Cost Component	Capacity (gal)						Average Percent
	10,000	50,000	100,000	500,000	1,000,000	7,500,000	
Excavation & Sitework	0.43%	0.35%	0.45%	0.92%	4.73%	1.86%	1.46%
Concrete	25.25%	26.92%	25.53%	30.18%	25.69%	38.47%	28.67%
Steel	17.45%	17.24%	15.96%	14.86%	27.53%	21.67%	19.12%
Labor	39.94%	40.07%	38.43%	38.26%	26.61%	24.36%	34.61%
Electrical	3.89%	2.37%	6.59%	2.73%	2.39%	0.61%	3.10%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C8.1 - Base Costs Obtained from the WATER Model for Ferric Chloride Feed Systems*

Cost Component	Feed Capacity (lb/hr)				Capital Cost Category
	10.7	107	1,070	5,350	
Manufactured Equipment	$7,500	$13,100	$33,560	$160,940	p
Labor	$420	$1,130	$2,430	$12,160	c
Pipes and Valves	$2,000	$2,500	$3,000	$15,000	p
Electrical	$1,110	$2,260	$4,960	$19,000	p
Housing	$6,000	$13,300	$51,270	$174,590	p
Contingencies	$2,550	$4,840	$14,280	$57,250	c
Total	$19,580	$37,130	$109,500	$438,940	

*Numbers were unavailable for ferric chloride. However, numbers presented for ferrous sulfate and ferric sulfate were identical.
It was assumed that these same relationships apply to ferric chloride

Exhibit C8.2 - WATER Model Base Construction Cost Analysis for Ferric Chloride Feed Systems*

Cost Component	Feed Capacity (lb/hr)				Average Percent
	10.7	107	1,070	5,350	
Manufactured Equipment	38.30%	35.28%	30.65%	36.67%	35.22%
Labor	2.15%	3.04%	2.22%	2.77%	2.54%
Pipes and Valves	10.21%	6.73%	2.74%	3.42%	5.78%
Electrical	5.67%	6.09%	4.53%	4.33%	5.15%
Housing	30.64%	35.82%	46.82%	39.78%	38.27%
Contingencies	13.02%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

*Numbers were unavailable for ferric chloride. However, numbers presented for ferrous sulfate and ferric sulfate were identical.
It was assumed that these same relationships apply to ferric chloride

Exhibit C9.1 - Base Costs Obtained from the WATER Model for Finished Water Pumping

Cost Component	Plant Capacity (mgd)				Capital Cost Category
	1.5	15	150	300	
Manufactured Equipment	$15,410	$89,700	$567,600	$1,142,350	p
Labor	$3,880	$11,580	$80,400	$158,840	c
Pipes and Valves	$5,200	$16,570	$139,200	$270,100	p
Electrical	$7,180	$38,450	$210,490	$400,230	p
Contingencies	$4,750	$23,450	$149,650	$295,730	c
Total	$36,420	$179,750	$1,147,340	$2,267,250	

Exhibit C9.2 - WATER Model Base Construction Cost Analysis for Finished Water Pumping

Cost Component	Plant Capacity (mgd)				Average Percent
	1.5	15	150	300	
Manufactured Equipment	42.31%	49.90%	49.47%	50.38%	48.02%
Labor	10.65%	6.44%	7.01%	7.01%	7.78%
Pipes and Valves	14.28%	9.22%	12.13%	11.91%	11.89%
Electrical	19.71%	21.39%	18.35%	17.65%	19.28%
Contingencies	13.04%	13.05%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C10.1 - Base Costs Obtained from the WATER Model for Gravity Filtration

Cost Component	Total Filter Area (FA-ft^2) and Plant Flow (Q=mgd)						Capital Cost Category
	FA=140 Q=1	FA=700 Q=5	FA=1,400 Q=10	FA=7,000 Q=50	FA=14,000 Q=100	FA=28,000 Q=200	
Excavation & Sitework	$1,950	$3,620	$5,520	$16,220	$25,590	$43,410	c
Manufactured Equipment	$26,360	$56,960	$78,300	$305,170	$529,360	$982,390	p
Concrete	$13,400	$27,040	$41,660	$95,490	$154,790	$275,570	p
Steel	$11,550	$19,960	$30,120	$73,530	$123,160	$209,960	p
Labor	$40,580	$88,490	$150,870	$356,380	$508,980	$1,000,670	c
Pipes and Valves	$20,580	$79,020	$127,340	$420,670	$590,150	$1,125,500	p
Electrical	$13,390	$38,410	$38,410	$99,140	$168,840	$265,310	p
Housing	$17,400	$40,480	$70,590	$291,940	$514,330	$968,520	p
Contingencies	$21,780	$53,100	$81,420	$248,780	$392,280	$730,700	c
Total	$166,990	$407,080	$624,230	$1,907,320	$3,007,480	$5,602,030	

Exhibit C10.2 - WATER Model Base Construction Cost Analysis for Gravity Filtration

Cost Component	Total Filter Area (FA-ft^2) and Plant Flow (Q=mgd)						Average Percent
	FA=140 Q=1	FA=700 Q=5	FA=1,400 Q=10	FA=7,000 Q=50	FA=14,000 Q=100	FA=28,000 Q=200	
Excavation & Sitework	1.17%	0.89%	0.88%	0.85%	0.85%	0.77%	0.90%
Manufactured Equipment	15.79%	13.99%	12.54%	16.00%	17.60%	17.54%	15.58%
Concrete	8.02%	6.64%	6.67%	5.01%	5.15%	4.92%	6.07%
Steel	6.92%	4.90%	4.83%	3.86%	4.10%	3.75%	4.72%
Labor	24.30%	21.74%	24.17%	18.68%	16.92%	17.86%	20.61%
Pipes and Valves	12.32%	19.41%	20.40%	22.06%	19.62%	20.09%	18.98%
Electrical	8.02%	9.44%	6.15%	5.20%	5.61%	4.74%	6.53%
Housing	10.42%	9.94%	11.31%	15.31%	17.10%	17.29%	13.56%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C11.1 - Base Costs Obtained from the WATER Model for Horizontal Paddle, G=50

Cost Component	Total Basin Volume (ft^3)						Capital Cost Category
	1,800	10,000	25,000	100,000	500,000	1,000,000	
Excavation & Sitework	$470	$2,550	$4,290	$9,970	$40,080	$77,640	p
Manufactured Equipment	$12,140	$28,250	$35,410	$74,400	$220,800	$433,640	p
Concrete	$1,400	$7,610	$12,740	$29,770	$120,280	$232,960	p
Steel	$2,360	$12,550	$20,440	$46,500	$175,290	$339,510	p
Labor	$7,080	$20,220	$29,420	$75,460	$221,200	$439,770	c
Electrical	$6,980	$28,320	$28,320	$28,320	$141,610	$283,220	p
Contingencies	$4,560	$14,930	$19,590	$39,660	$137,890	$271,010	c
Total	$34,990	$114,430	$150,210	$304,080	$1,057,150	$2,077,750	

Exhibit C11.2 - WATER Model Base Construction Cost Analysis for Horizontal Paddle, G=50

Cost Component	Total Basin Volume (ft^3)						Average Percent
	1,800	10,000	25,000	100,000	500,000	1,000,000	
Excavation & Sitework	1.34%	2.23%	2.86%	3.28%	3.79%	3.74%	2.87%
Manufactured Equipment	34.70%	24.69%	23.57%	24.47%	20.89%	20.87%	24.86%
Concrete	4.00%	6.65%	8.48%	9.79%	11.38%	11.21%	8.59%
Steel	6.74%	10.97%	13.61%	15.29%	16.58%	16.34%	13.26%
Labor	20.23%	17.67%	19.59%	24.82%	20.92%	21.17%	20.73%
Electrical	19.95%	24.75%	18.85%	9.31%	13.40%	13.63%	16.65%
Contingencies	13.03%	13.05%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C12.1 - Base Costs Obtained from the WATER Model for Horizontal Paddle, G=80

Cost Component	Total Basin Volume (ft^3)					Capital Cost Category
	1,800	10,000	25,000	100,000	500,000	
Excavation & Sitework	$470	$2,550	$4,290	$9,970	$40,080	c
Manufactured Equipment	$12,140	$34,210	$44,360	$115,770	$427,670	p
Concrete	$1,400	$7,610	$12,740	$29,770	$120,280	p
Steel	$2,360	$12,550	$20,440	$46,500	$175,290	p
Labor	$7,080	$22,190	$32,370	$90,170	$289,520	p
Electrical	$6,980	$28,320	$28,320	$28,320	$141,610	p
Contingencies	$4,560	$16,110	$21,380	$48,080	$179,170	c
Total	$34,990	$123,540	$163,900	$368,580	$1,373,620	

Exhibit C12.2 - WATER Model Base Construction Cost Analysis for Horizontal Paddle, G=80

Cost Component	Total Basin Volume (ft^3)					Average Percent
	1,800	10,000	25,000	100,000	500,000	
Excavation & Sitework	1.34%	2.06%	2.62%	2.70%	2.92%	2.33%
Manufactured Equipment	34.70%	27.69%	27.07%	31.41%	31.13%	30.40%
Concrete	4.00%	6.16%	7.77%	8.08%	8.76%	6.95%
Steel	6.74%	10.16%	12.47%	12.62%	12.76%	10.95%
Labor	20.23%	17.96%	19.75%	24.46%	21.08%	20.70%
Electrical	19.95%	22.92%	17.28%	7.68%	10.31%	15.63%
Contingencies	13.03%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C13.1 - Base Costs Obtained from the WATER Model for Hydraulic Surface Wash

Cost Component	Total Filter Area (ft^2)						Capital Cost Category
	140	700	1,400	7,000	14,000	28,000	
Manufactured Equipment	$9,170	$12,050	$35,090	$82,010	$172,440	$401,200	p
Labor	$1,300	$2,770	$5,170	$14,710	$29,430	$66,600	c
Pipes and Valves	$2,570	$5,100	$7,020	$13,390	$32,290	$59,870	p
Electrical	$12,670	$17,920	$20,440	$37,900	$61,120	$92,360	p
Contingencies	$3,860	$5,680	$10,160	$22,200	$44,290	$93,000	c
Total	$29,570	$43,520	$77,880	$170,210	$339,570	$713,030	

Exhibit C13.2 - WATER Model Base Construction Cost Analysis for Hydraulic Surface Wash

Cost Component	Total Filter Area (ft^2)						Average Percent
	140	700	1,400	7,000	14,000	28,000	
Manufactured Equipment	31.01%	27.69%	45.06%	48.18%	50.78%	56.27%	43.16%
Labor	4.40%	6.36%	6.64%	8.64%	8.67%	9.34%	7.34%
Pipes and Valves	8.69%	11.72%	9.01%	7.87%	9.51%	8.40%	9.20%
Electrical	42.85%	41.18%	26.25%	22.27%	18.00%	12.95%	27.25%
Contingencies	13.05%	13.05%	13.05%	13.04%	13.04%	13.04%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C14.1 - Base Costs Obtained from the WATER Model for In-Plant Pumping

Cost Component	Pumping Capacity (mgd)						Capital Cost Category
	1	5	10	50	100	200	
Excavation & Sitework	$100	$100	$130	$360	$600	$1,030	c
Manufactured Equipment	$6,300	$9,110	$14,780	$48,650	$83,400	$152,900	p
Concrete	$970	$970	$1,510	$4,770	$8,030	$14,090	p
Steel	$1,610	$1,610	$2,450	$7,630	$12,500	$21,330	p
Labor	$5,570	$10,410	$24,070	$63,330	$129,130	$331,030	c
Pipes and Valves	$5,090	$12,330	$16,300	$60,230	$114,200	$222,080	p
Electrical	$3,170	$4,930	$7,390	$25,760	$47,240	$89,360	p
Housing	$1,500	$1,500	$3,000	$14,520	$28,830	$58,080	p
Contingencies	$3,650	$6,140	$10,440	$33,790	$63,590	$133,490	c
Total	$27,960	$47,100	$80,070	$259,040	$487,520	$1,023,390	

Exhibit C14.2 - WATER Model Base Construction Cost Analysis for In-Plant Pumping

Cost Component	Pumping Capacity (mgd)						Average Percent
	1	5	10	50	100	200	
Excavation & Sitework	0.36%	0.21%	0.16%	0.14%	0.12%	0.10%	0.18%
Manufactured Equipment	22.53%	19.34%	18.46%	18.78%	17.11%	14.94%	18.53%
Concrete	3.47%	2.06%	1.89%	1.84%	1.65%	1.38%	2.05%
Steel	5.76%	3.42%	3.06%	2.95%	2.56%	2.08%	3.31%
Labor	19.92%	22.10%	30.06%	24.45%	26.49%	32.35%	25.89%
Pipes and Valves	18.20%	26.18%	20.36%	23.25%	23.42%	21.70%	22.19%
Electrical	11.34%	10.47%	9.23%	9.94%	9.69%	8.73%	9.90%
Housing	5.36%	3.18%	3.75%	5.61%	5.91%	5.68%	4.92%
Contingencies	13.05%	13.04%	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C15.1 - Base Costs Obtained from the WATER Model for Ion Exchange

Cost Component	Plant Capacity (mgd)				Capital Cost Category
	1.1	3.7	6.1	12.3	
Excavation & Sitework	$740	$1,140	$1,470	$1,970	c
Manufactured Equipment	$39,960	$89,580	$137,770	$258,230	p
Media	$92,790	$313,160	$521,940	$1,043,880	p
Concrete	$2,410	$3,580	$4,750	$6,320	p
Steel	$3,830	$5,680	$7,530	$9,950	p
Labor	$17,420	$33,510	$61,460	$125,080	c
Pipes and Valves	$14,040	$38,780	$69,740	$139,480	p
Electrical	$27,700	$38,510	$60,820	$120,210	p
Housing	$21,920	$35,660	$57,440	$79,820	p
Contingencies	$33,120	$83,940	$138,440	$267,740	c
Total	$253,930	$643,540	$1,061,360	$2,052,680	

Exhibit C15.2 - WATER Model Base Construction Cost Analysis for Ion Exchange

Cost Component	Plant Capacity (mgd)				Average Percent
	1.1	3.7	6.1	12.3	
Excavation & Sitework	0.29%	0.18%	0.14%	0.10%	0.18%
Manufactured Equipment	15.74%	13.92%	12.98%	12.58%	13.80%
Media	36.54%	48.66%	49.18%	50.85%	46.31%
Concrete	0.95%	0.56%	0.45%	0.31%	0.57%
Steel	1.51%	0.88%	0.71%	0.48%	0.90%
Labor	6.86%	5.21%	5.79%	6.09%	5.99%
Pipes and Valves	5.53%	6.03%	6.57%	6.80%	6.23%
Electrical	10.91%	5.98%	5.73%	5.86%	7.12%
Housing	8.63%	5.54%	5.41%	3.89%	5.87%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C16.1 - Base Costs Obtained from the WATER Model for Lime Feed with Recalcination

Cost Component	Feed Capacity (lb/hr)		Capital Cost Category
	1,000	10,000	
Manufactured Equipment	$48,870	$80,660	p
Labor	$1,510	$3,060	c
Pipes and Valves	$3,120	$6,250	p
Electrical	$6,880	$12,320	p
Housing	$9,450	$26,250	p
Contingencies	$10,470	$19,280	c
Total	$80,300	$147,820	

Exhibit C16.2 - WATER Model Base Construction Cost Analysis for Lime Feed with Recalcination

Cost Component	Feed Capacity (lb/hr)		Average Percent
	1,000	10,000	
Manufactured Equipment	60.86%	54.57%	57.71%
Labor	1.88%	2.07%	1.98%
Pipes and Valves	3.89%	4.23%	4.06%
Electrical	8.57%	8.33%	8.45%
Housing	11.77%	17.76%	14.76%
Contingencies	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%

Exhibit C17.1 - Base Costs Obtained from the WATER Model for Permanganate Feed Systems

Cost Component	Feed Capacity (lb/day)				Capital Cost Category
	1	10	100	500	
Manufactured Equipment	$2,340	$2,600	$3,380	$5,220	p
Labor	$480	$480	$540	$770	c
Pipes and Valves	$970	$970	$970	$970	p
Electrical	$3,190	$3,190	$3,190	$3,190	p
Housing	$1,260	$1,580	$1,950	$2,940	p
Contingencies	$1,240	$1,320	$1,500	$1,960	c
Total	$9,480	$10,140	$11,530	$15,050	

Exhibit C17.2 - WATER Model Base Construction Cost Analysis for Permanganate Feed Systems

Cost Component	Feed Capacity (lb/day)				Average Percent
	1	10	100	500	
Manufactured Equipment	24.68%	25.64%	29.31%	34.68%	28.58%
Labor	5.06%	4.73%	4.68%	5.12%	4.90%
Pipes and Valves	10.23%	9.57%	8.41%	6.45%	8.66%
Electrical	33.65%	31.46%	27.67%	21.20%	28.49%
Housing	13.29%	15.58%	16.91%	19.53%	16.33%
Contingencies	13.08%	13.02%	13.01%	13.02%	13.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C18.1 - Base Costs Obtained from the WATER Model for Polymer Feed Systems

Cost Component	Feed Capacity (lb/hr)				Capital Cost Category
	1	10	100	200	
Manufactured Equipment	$11,670	$11,670	$14,730	$18,970	p
Labor	$700	$700	$700	$760	c
Pipes and Valves	$280	$280	$280	$300	p
Electrical	$1,290	$1,290	$1,290	$1,290	p
Housing	$3,600	$3,600	$4,050	$4,500	p
Contingencies	$2,630	$2,630	$3,160	$3,870	c
Total	$20,170	$20,170	$24,210	$29,690	

Exhibit C18.2 - WATER Model Base Construction Cost Analysis for Polymer Feed Systems

Cost Component	Feed Capacity (lb/hr)				Average Percent
	1	10	100	200	
Manufactured Equipment	57.86%	57.86%	60.84%	63.89%	60.11%
Labor	3.47%	3.47%	2.89%	2.56%	3.10%
Pipes and Valves	1.39%	1.39%	1.16%	1.01%	1.24%
Electrical	6.40%	6.40%	5.33%	4.34%	5.62%
Housing	17.85%	17.85%	16.73%	15.16%	16.90%
Contingencies	13.04%	13.04%	13.05%	13.03%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C19.1 - Base Costs Obtained from the WATER Model for Rapid Mix, G=900

Cost Component	Basin Volume (ft^3)						Capital Cost Category
	100	500	1,000	5,000	10,000	20,000	
Excavation & Sitework	$220	$380	$490	$1,360	$2,720	$5,460	c
Manufactured Equipment	$4,310	$9,830	$14,760	$66,840	$133,670	$267,340	p
Concrete	$390	$870	$1,280	$3,610	$7,220	$14,450	p
Steel	$570	$1,350	$2,010	$5,600	$11,180	$22,360	p
Labor	$1,230	$2,300	$3,410	$13,140	$26,280	$52,550	c
Electrical	$6,980	$6,980	$7,180	$7,470	$8,760	$16,100	p
Contingencies	$2,060	$3,260	$4,370	$14,700	$28,470	$56,740	c
Total	$15,760	$24,970	$33,500	$112,720	$218,300	$435,000	

Exhibit C19.2 - WATER Model Base Construction Cost Analysis for Rapid Mix, G=900

Cost Component	Basin Volume (ft^3)						Average Percent
	100	500	1,000	5,000	10,000	20,000	
Excavation & Sitework	1.40%	1.52%	1.46%	1.21%	1.25%	1.26%	1.35%
Manufactured Equipment	27.35%	39.37%	44.06%	59.30%	61.23%	61.46%	48.79%
Concrete	2.47%	3.48%	3.82%	3.20%	3.31%	3.32%	3.27%
Steel	3.62%	5.41%	6.00%	4.97%	5.12%	5.14%	5.04%
Labor	7.80%	9.21%	10.18%	11.66%	12.04%	12.08%	10.50%
Electrical	44.29%	27.95%	21.43%	6.63%	4.01%	3.70%	18.00%
Contingencies	13.07%	13.06%	13.04%	13.04%	13.04%	13.04%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C20.1 - Base Costs Obtained from the WATER Model for Recarbonation, Liquid Carbon Dioxide

Cost Component	Installed Capacity (lb/day)						Capital Cost Category
	380	750	1,500	3,750	7,500	15,000	
Manufactured Equipment	$27,000	$31,000	$35,250	$49,250	$73,000	$141,000	p
Labor	$7,650	$8,780	$12,170	$17,330	$28,990	$58,010	c
Pipes and Valves	$1,530	$2,340	$4,620	$8,710	$16,940	$37,540	p
Housing	$7,360	$7,360	$7,360	$7,360	$8,450	$8,900	p
Contingencies	$6,530	$7,420	$8,910	$12,400	$19,110	$36,820	c
Total	$50,070	$56,900	$68,310	$95,050	$146,490	$282,270	

Exhibit C20.2 - WATER Model Base Construction Cost Analysis for Recarbonation, Liquid Carbon Dioxide

Cost Component	Installed Capacity (lb/day)						Average Percent
	380	750	1,500	3,750	7,500	15,000	
Manufactured Equipment	53.92%	54.48%	51.60%	51.81%	49.83%	49.95%	51.93%
Labor	15.28%	15.43%	17.82%	18.23%	19.79%	20.55%	17.85%
Pipes and Valves	3.06%	4.11%	6.76%	9.16%	11.56%	13.30%	7.99%
Housing	14.70%	12.93%	10.77%	7.74%	5.77%	3.15%	9.18%
Contingencies	13.04%	13.04%	13.04%	13.05%	13.05%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C21.1 - Base Costs Obtained from the WATER Model for Recarbonation Basins

Cost Component	Single Basin Volume (ft^3)							Capital Cost Category
	770	1,375	2,750	5,630	8,800	17,600	35,200	
Excavation & Sitework	$520	$620	$980	$1,390	$1,790	$3,050	$5,570	c
Concrete	$1,380	$1,860	$2,820	$4,050	$5,190	$8,570	$15,320	p
Steel	$2,250	$3,010	$4,670	$6,560	$8,320	$13,960	$25,240	p
Labor	$2,830	$3,800	$5,730	$8,090	$10,240	$16,740	$29,730	c
Pipes and Valves	$90	$130	$250	$480	$680	$1,360	$3,360	p
Contingencies	$1,060	$1,410	$2,170	$3,090	$3,930	$6,550	$11,880	c
Total	$8,130	$10,830	$16,620	$23,660	$30,150	$50,230	$91,100	

Exhibit C21.2 - WATER Model Base Construction Cost Analysis for Recarbonation Basins

Cost Component	Single Basin Volume (ft^3)							Average Percent
	770	1,375	2,750	5,630	8,800	17,600	35,200	
Excavation & Sitework	6.40%	5.72%	5.90%	5.87%	5.94%	6.07%	6.11%	6.00%
Concrete	16.97%	17.17%	16.97%	17.12%	17.21%	17.06%	16.82%	17.05%
Steel	27.68%	27.79%	28.10%	27.73%	27.60%	27.79%	27.71%	27.77%
Labor	34.81%	35.09%	34.48%	34.19%	33.96%	33.33%	32.63%	34.07%
Pipes and Valves	1.11%	1.20%	1.50%	2.03%	2.26%	2.71%	3.69%	2.07%
Contingencies	13.04%	13.02%	13.06%	13.06%	13.03%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C22.1 - Base Costs Obtained from the WATER Model for Rectangular Clarifiers

Cost Component	Area (A=ft^2) and Length x Width (LW=ftxft)						Capital Cost Category
	A=240 LW=30x8	A=600 LW=60x10	A=1260 LW=90x14	A=2240 LW=140x16	A=3600 LW=200x18	A=4800 LW=240x20	
Excavation & Sitework	$1,060	$2,000	$3,060	$4,680	$6,670	$8,090	c
Manufactured Equipment	$8,540	$12,080	$24,470	$32,020	$53,110	$63,440	p
Concrete	$2,970	$5,490	$8,430	$12,820	$18,190	$22,070	p
Steel	$6,400	$13,110	$19,440	$32,620	$51,250	$69,680	p
Labor	$6,220	$11,260	$17,320	$26,390	$37,570	$45,300	c
Pipes and Valves	$6,960	$7,400	$9,100	$12,500	$16,100	$21,450	p
Electrical	$1,510	$1,760	$1,860	$2,020	$2,110	$2,400	p
Contingencies	$5,050	$7,970	$12,550	$18,460	$27,750	$34,860	c
Total	$38,710	$61,070	$96,230	$141,510	$212,750	$267,290	

Exhibit C22.2 - WATER Model Base Construction Cost Analysis for Rectangular Clarifiers

Cost Component	Area (A=ft^2) and Length x Width (LW=ftxft)						Average Percent
	A=240 LW=30x8	A=600 LW=60x10	A=1260 LW=90x14	A=2240 LW=140x16	A=3600 LW=200x18	A=4800 LW=240x20	
Excavation & Sitework	2.74%	3.27%	3.18%	3.31%	3.14%	3.03%	3.11%
Manufactured Equipment	22.06%	19.78%	25.43%	22.63%	24.96%	23.73%	23.10%
Concrete	7.67%	8.99%	8.76%	9.06%	8.55%	8.26%	8.55%
Steel	16.53%	21.47%	20.20%	23.05%	24.09%	26.07%	21.90%
Labor	16.07%	18.44%	18.00%	18.65%	17.66%	16.95%	17.63%
Pipes and Valves	17.98%	12.12%	9.46%	8.83%	7.57%	8.02%	10.66%
Electrical	3.90%	2.88%	1.93%	1.43%	0.99%	0.90%	2.01%
Contingencies	13.05%	13.05%	13.04%	13.05%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C23.1 - Base Costs Obtained from the WATER Model for Reverse Osmosis

Cost Component	Plant Capacity (mgd)				Capital Cost Category
	1.0	10	100	200	
Manufactured Equipment	$474,210	$3,458,480	$29,174,260	$56,438,930	p
Labor	$70,420	$346,850	$2,312,340	$2,837,870	c
Electrical	$65,740	$486,270	$3,635,690	$6,947,480	p
Housing	$64,260	$462,650	$2,409,660	$4,176,740	p
Contingencies	$101,190	$713,140	$5,629,790	$10,560,150	c
Total	$775,820	$5,467,390	$43,161,740	$80,961,170	

Exhibit C23.2 - WATER Model Base Construction Cost Analysis for Reverse Osmosis

Cost Component	Plant Capacity (mgd)				Average Percent
	1.0	10	100	200	
Manufactured Equipment	61.12%	63.26%	67.59%	69.71%	65.42%
Labor	9.08%	6.34%	5.36%	3.51%	6.07%
Electrical	8.47%	8.89%	8.42%	8.58%	8.59%
Housing	8.28%	8.46%	5.58%	5.16%	6.87%
Contingencies	13.04%	13.04%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C24.1 - Base Costs Obtained from the WATER Model for Sodium Hydroxide Feed Systems

Cost Component	Feed Capacity (lb/day)				Capital Cost Category
	10	100	1,000	10000	
Manufactured Equipment	$6,440	$7,010	$5,720	$19,450	p
Labor	$640	$640	$790	$4,120	c
Pipes and Valves	$850	$850	$850	$850	p
Electrical	$3,190	$3,190	$3,190	$3,460	p
Housing	$1,010	$2,100	$8,400	$48,380	p
Contingencies	$1,820	$2,070	$2,840	$11,440	c
Total	$13,950	$15,860	$21,790	$87,700	

Exhibit C24.2 - WATER Model Base Construction Cost Analysis for Sodium Hydroxide Feed Systems

Cost Component	Feed Capacity (lb/day)				Average Percent
	10	100	1,000	10,000	
Manufactured Equipment	46.16%	44.20%	26.25%	22.18%	34.70%
Labor	4.59%	4.04%	3.63%	4.70%	4.24%
Pipes and Valves	6.09%	5.36%	3.90%	0.97%	4.08%
Electrical	22.87%	20.11%	14.64%	3.95%	15.39%
Housing	7.24%	13.24%	38.55%	55.17%	28.55%
Contingencies	13.05%	13.05%	13.03%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C25.1 - Base Costs Obtained from the WATER Model for Sulfuric Acid Feed Systems

Cost Component	Feed Capacity (gpd)				Capital Cost Category
	10	100	1000	5000	
Manufactured Equipment	$1,560	$3,440	$12,400	$41,000	p
Labor	$640	$820	$2,840	$11,840	c
Pipes and Valves	$1,090	$1,090	$2,150	$2,150	p
Electrical	$1,670	$2,920	$2,920	$2,920	p
Housing	$2,520	$1,560	$1,560	$1,560	p
Contingencies	$1,120	$1,470	$3,280	$8,920	c
Total	$8,600	$11,300	$25,150	$68,390	

Exhibit C25.2 - WATER Model Base Construction Cost Analysis for Sulfuric Acid Feed Systems

Cost Component	Feed Capacity (gpd)				Average Percent
	10	100	1000	5000	
Manufactured Equipment	18.14%	30.44%	49.30%	59.95%	39.46%
Labor	7.44%	7.26%	11.29%	17.31%	10.83%
Pipes and Valves	12.67%	9.65%	8.55%	3.14%	8.50%
Electrical	19.42%	25.84%	11.61%	4.27%	15.28%
Housing	29.30%	13.81%	6.20%	2.28%	12.90%
Contingencies	13.02%	13.01%	13.04%	13.04%	13.03%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C26.1 - Base Costs Obtained from the WATER Model for Tube Settling Modules

Cost Component	Tube Module Area (ft^2)					Capital Cost Category
	280	2,800	14,000	28,000	56,000	
Manufactured Equipment	$4,200	$31,000	$147,000	$282,000	$504,000	p
Steel	$2,000	$19,500	$95,000	$155,000	$300,000	p
Labor	$2,500	$11,200	$49,000	$95,000	$224,000	c
Contingencies	$1,300	$9,300	$43,700	$79,800	$154,200	c
Total	$10,000	$71,000	$334,700	$611,800	$1,182,200	

Exhibit C26.2 - WATER Model Base Construction Cost Analysis for Tube Settling Modules

Cost Component	Tube Module Area (ft^2)					Average Percent
	280	2,800	14,000	28,000	56,000	
Manufactured Equipment	42.00%	43.66%	43.92%	46.09%	42.63%	43.66%
Steel	20.00%	27.46%	28.38%	25.34%	25.38%	25.31%
Labor	25.00%	15.77%	14.64%	15.53%	18.95%	17.98%
Contingencies	13.00%	13.10%	13.06%	13.04%	13.04%	13.05%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Exhibit C27.1 - Base Costs Obtained from the WATER Model for Wash Water Surge Basins

Cost Component	Capacity (gal)				Capital Cost Category
	10,000	50,000	100,000	500,000	
Excavation & Sitework	$200	$520	$1,250	$4,400	c
Concrete	$11,560	$39,310	$71,480	$143,680	p
Steel	$7,990	$25,170	$44,680	$70,770	p
Labor	$18,270	$58,500	$107,590	$182,150	c
Pipes and Valves	$5,500	$7,500	$11,000	$16,000	p
Electrical	$1,300	$1,300	$6,000	$6,000	p
Contingencies	$6,720	$19,850	$36,300	$63,450	c
Total	$51,540	$152,150	$278,300	$486,450	

Exhibit C27.2 - WATER Model Base Construction Cost Analysis for Wash Water Surge Basins

Cost Component	Capacity (gal)				Average Percent
	10,000	50,000	100,000	500,000	
Excavation & Sitework	0.39%	0.34%	0.45%	0.90%	0.52%
Concrete	22.43%	25.84%	25.68%	29.54%	25.87%
Steel	15.50%	16.54%	16.05%	14.55%	15.66%
Labor	35.45%	38.45%	38.66%	37.44%	37.50%
Pipes and Valves	10.67%	4.93%	3.95%	3.29%	5.71%
Electrical	2.52%	0.85%	2.16%	1.23%	1.69%
Contingencies	13.04%	13.05%	13.04%	13.04%	13.04%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Appendix D

Technology Cost Curves

Appendix D
Unit Costs Graphs

Costs for independent flows are presented in the main text of this document. This appendix provides graphs of those points and displays the lines that were used to predict costs for flows other than those costed. This appendix provides the following information:

- Capital unit cost estimates for a wide range of design flows (in tabular and graphical forms)
- O&M unit cost estimates for a wide range of average daily flows (in tabular and graphical forms)

The range of design and average flows is intended to cover all possible system flows. When flows fall in between the design or average daily flows used to estimate unit costs, straight line interpolation can be used to estimate the capital or O&M cost. Design costs were calculated for points ranging between 0.007 MGD and 520 MGD. For plants with flows less than 0.007 MGD the value for 0.007 MGD was used. For plants with flows greater than 520 MGD, the costs are calculated by extrapolating a straight line between the last two calculated cost points. Points are included in the graphs at 0.0001 MGD and 1500 MGD to show these assumptions. Likewise for average daily flows, points were calculated between 0.0015 MGD and 350 MGD. Points outside this range show the assumptions used to extrapolate costs.

The Appendix D Contents (shown on the next page) describes the exhibits in this appendix. Each exhibit lists the constraints and design criteria for the technology, presents a table showing the unit cost estimates for each design or average flow point, and graphically displays each point to illustrate the way in which the costs increase with flow. All graphs are in Log-Log scale.

Appendix D Contents

Technology	Cost Type	Exhibit Number
Chloramines (Ammonia dose = 0.55 mg/L)	Capital	D.1
	O&M	D.2
Chloramines (Ammonia dose = 0.15 mg/L)	Capital	D.3
	O&M	D.4
Chlorine Dioxide (ClO_2 Dose = 1.25 mg/L)	Capital	D.5
	O&M	D.6
UV (40 mJ/cm^2)	Capital	D.7
	O&M	D.8
UV (200 mJ/cm^2)	Capital	D.9
	O&M	D.10
Ozone, 0.5-Log Inactivation of *Cryptosporidium*	Capital	D.11
	O&M	D.12
Ozone, 1.0-Log Inactivation of *Cryptosporidium*	Capital	D.13
	O&M	D.14
Ozone, 2.0-Log Inactivation of *Cryptosporidium*	Capital	D.15
	O&M	D.16
Microfiltration/Ultrafiltration (MF/UF)	Capital	D.17
	O&M	D.18
Bag Filters	Capital	D.19
	O&M	D.20
Cartridge Filters	Capital	D.21
	O&M	D.22
Bank Filtration	Capital	D.23
Second Stage Filtration	Capital	D.24
	O&M	D.25
Pre-Sedimentation with Coagulant	Capital	D.26
	O&M	D.27
Watershed Control	Capital	D.28
	O&M	D.29
Combined Filter Performance	Capital	D.30
	O&M	D.31
GAC10-360	Capital	D.32
	O&M	D.33
GAC20-90	Capital	D.34
	O&M	D.35
GAC20-240	Capital	D.36
	O&M	D.37
Nanofiltration	Capital	D.38
	O&M	D.39

Exhibit D.1 - Capital Costs for Switching to Chloramines
Surface Water Plants

Constraints: It can be used alone or in conjunction with the other technologies
Design Criteria:
1) Ammonia dose = 0.55 mg/L

Design Flow (mgd)	Capital Cost ($)
0.0001	$29,104
0.0070	$29,104
0.0220	$29,104
0.0370	$29,104
0.0910	$29,104
0.1800	$30,604
0.2700	$37,939
0.3600	$38,858
0.6800	$42,127
1.0000	$53,396
1.2000	$83,772
2.0000	$83,772
3.5000	$83,772
7.0000	$83,772
17.0000	$98,772
22.0000	$133,907
76.0000	$397,173
210.0000	$492,039
430.0000	$590,780
520.0000	$736,773
1,500.0000	$2,326,467

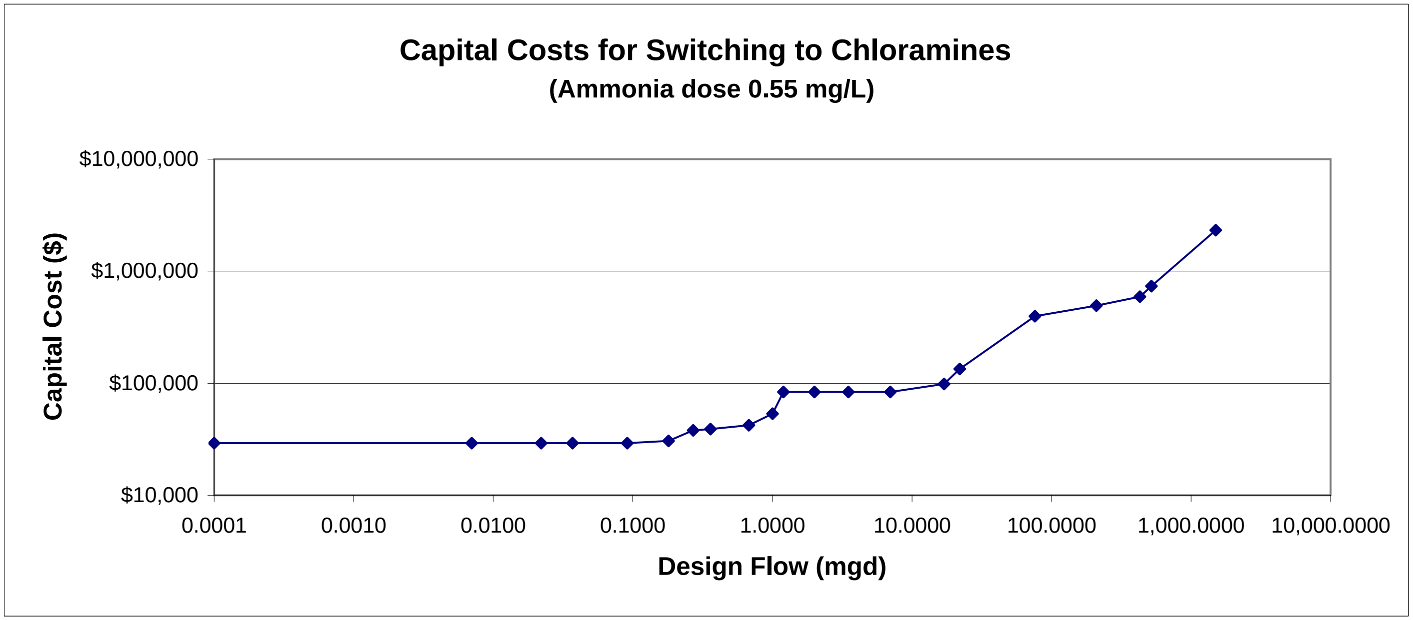


Exhibit D.2 - O&M Costs for Switching to Chloramines
Surface Water Plants

Constraints: It can be used alone or in conjunction with the other technologies
Design Criteria:

1) Ammonia dose = 0.55 mg/L

Average Flow (mgd)	O&M cost ($)
0.00005	$1,362
0.00150	$1,362
0.00540	$1,366
0.00950	$1,370
0.02500	$1,483
0.05400	$1,515
0.08400	$3,014
0.11000	$3,041
0.23000	$3,077
0.35000	$4,443
0.41000	$6,000
0.77000	$6,747
1.40000	$8,102
3.00000	$10,536
7.80000	$15,491
11.00000	$18,954
38.00000	$31,538
120.00000	$80,340
270.00000	$161,502
350.00000	$204,728
750.00000	$420,859

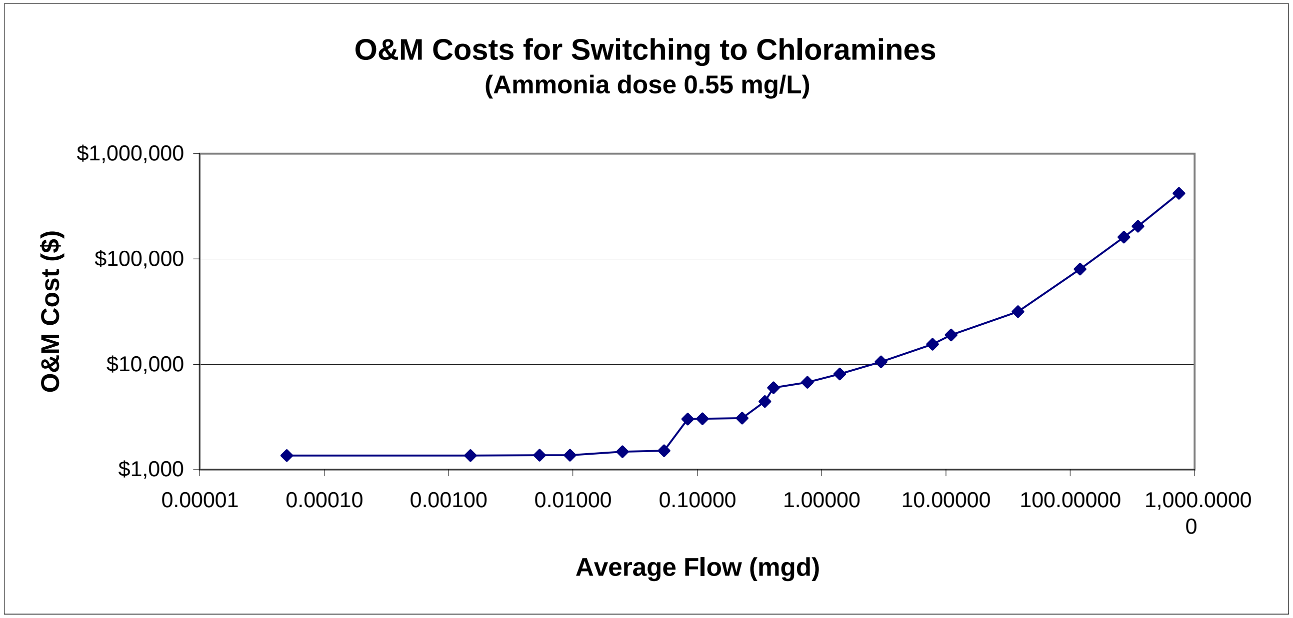


Exhibit D.3 - Capital Costs for Switching to Chloramines
Ground Water Plants

Constraints: It can be used alone or in conjunction with the other technologies
Design Criteria:
1) Ammonia dose = 0.15 mg/L

Design Flow (mgd)	Capital Cost ($)
0.0001	$29,104
0.0070	$29,104
0.0220	$29,104
0.0370	$29,104
0.0910	$29,104
0.1800	$30,604
0.2700	$37,939
0.3600	$38,858
0.6800	$42,127
1.0000	$53,396
1.2000	$83,772
2.0000	$83,772
3.5000	$83,772
7.0000	$83,772
17.0000	$98,772
22.0000	$98,772
76.0000	$98,772
210.0000	$158,907
430.0000	$428,047
520.0000	$428,047
1,500.0000	$428,047

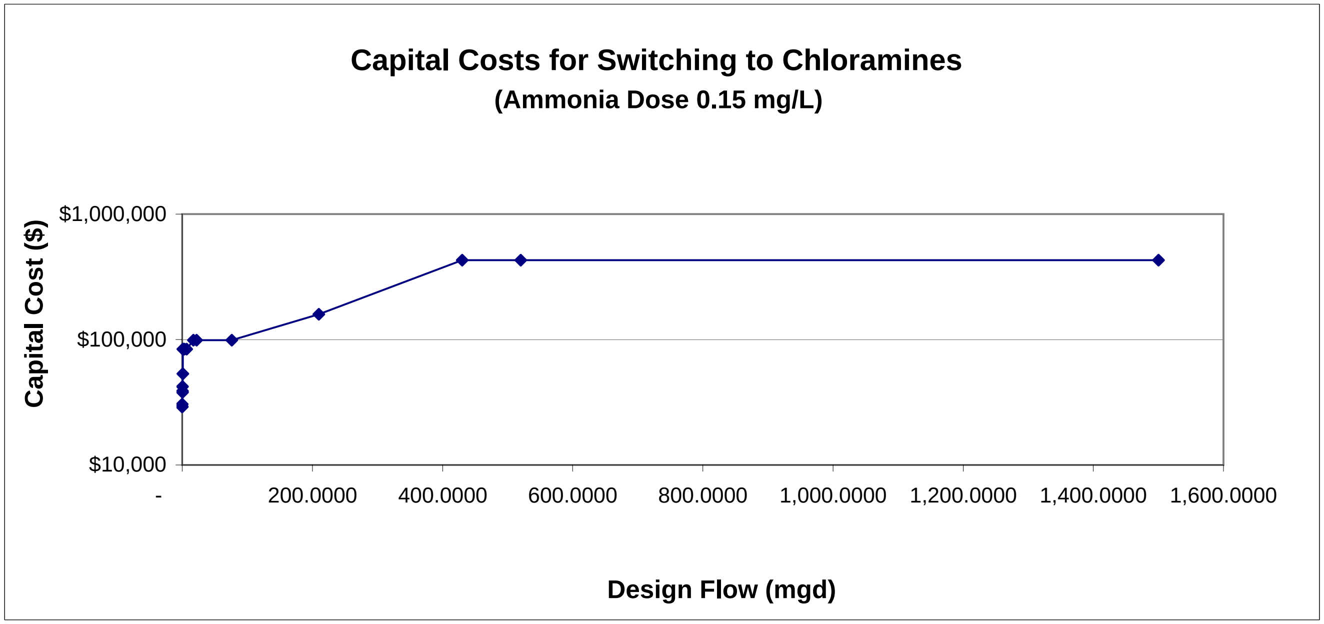


Exhibit D.4 - O&M Costs for Switching to Chloramines
Ground Water Plants

Constraints: It can be used alone or in conjunction with the other technologies
Design Criteria:
1) Ammonia dose = 0.15 mg/L

Average Flow (mgd)	O&M Cost ($)
0.00005	$1,361
0.00150	$1,361
0.00540	$1,362
0.00950	$1,363
0.02500	$1,463
0.05400	$1,472
0.08400	$2,949
0.11000	$2,956
0.23000	$2,966
0.35000	$4,274
0.41000	$5,743
0.77000	$6,266
1.40000	$7,231
3.00000	$8,688
7.80000	$11,333
11.00000	$12,887
38.00000	$23,579
120.00000	$46,355
270.00000	$73,620
350.00000	$87,174
750.00000	$154,948

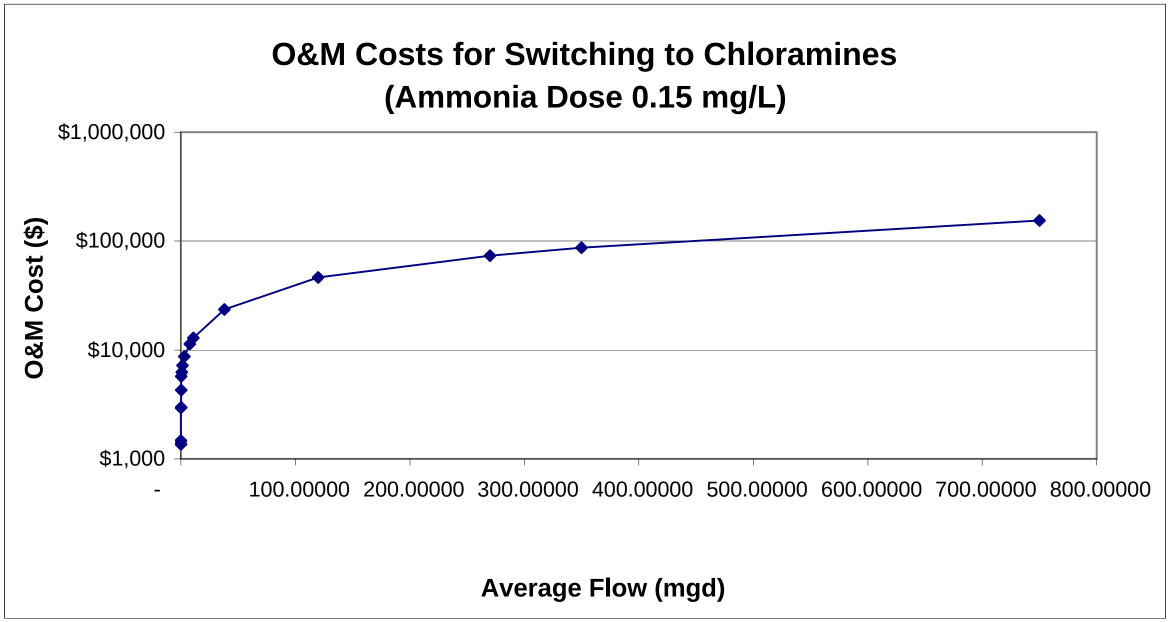


Exhibit D.5 - Capital Costs for Chlorine Dioxide

Constraints: Not practical for systems serving 500 or fewer people
Design Criteria:

1) ClO_2 dose = 1.25 mg/L

Design Flow (mgd)	Capital Cost ($)
0.0001	Data Not Used
0.0070	Data Not Used
0.0220	Data Not Used
0.0370	Data Not Used
0.0910	$32,427
0.1800	$38,370
0.2700	$39,172
0.3600	$40,066
0.6800	$43,005
1.0000	$40,035
1.2000	$80,585
2.0000	$82,054
3.5000	$191,088
7.0000	$211,473
17.0000	$268,223
22.0000	$296,568
76.0000	$603,425
210.0000	$897,449
430.0000	$1,245,987
520.0000	$1,368,982
1,500.0000	$2,708,268

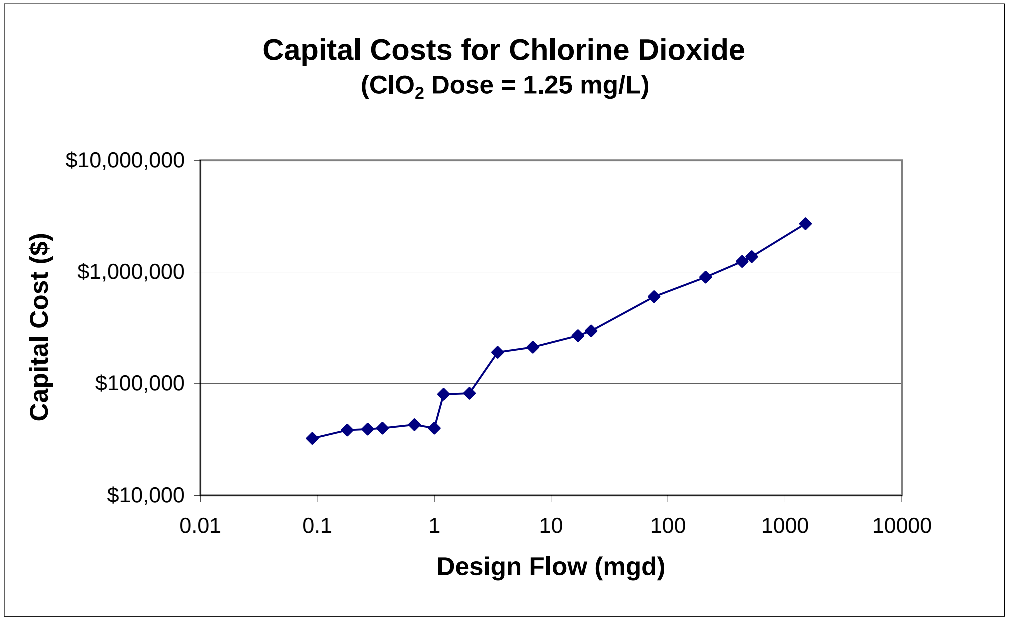


Exhibit D.6 - O&M Costs for Chlorine Dioxide

Constraints: Not practical for systems serving 500 or fewer people
Design Criteria:

1) ClO_2 dose = 1.25 mg/L

Average Flow (mgd)	O&M Cost ($)
0.00005	Data Not Used
0.00150	Data Not Used
0.00540	Data Not Used
0.00950	Data Not Used
0.02500	$14,093
0.05400	$15,204
0.08400	$16,721
0.11000	$16,999
0.23000	$17,812
0.35000	$18,571
0.41000	$18,984
0.77000	$21,638
1.40000	$22,001
3.00000	$25,392
7.80000	$35,939
11.00000	$42,336
38.00000	$87,061
120.00000	$216,813
270.00000	$446,533
350.00000	$561,934
750.00000	$1,138,937

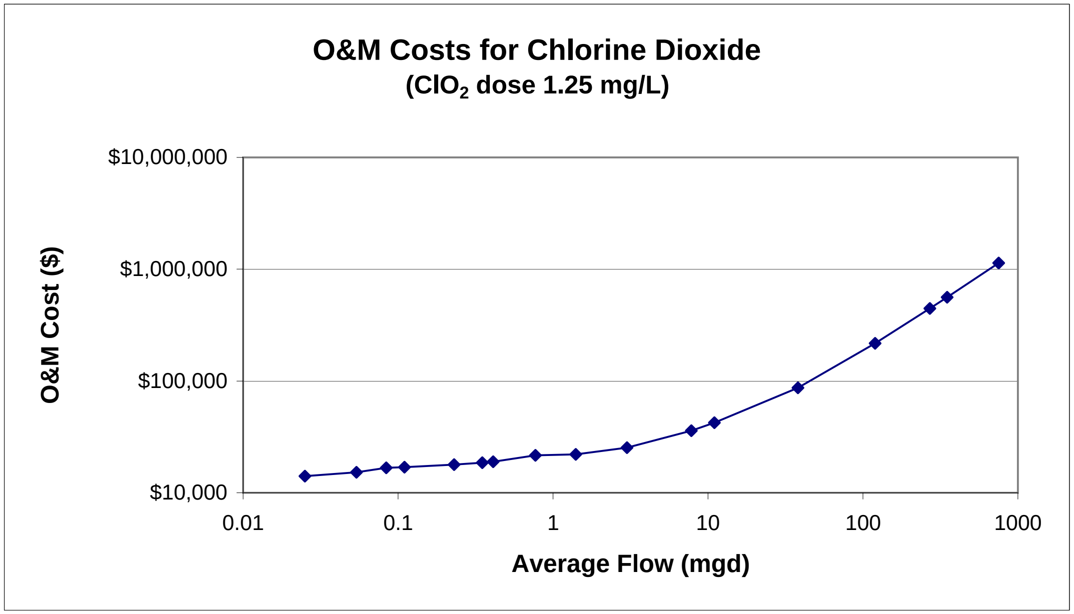


Exhibit D.7 - Capital Costs for UV (40 mJ/cm^2)

Constraints: None
Design Criteria:

1) UV $_{254}$ = 0.051 cm^{-1}, Turbidity = 0.1 NTU, Alkalinity = 60 mg/L $CaCO_3$, Hardness = 100 mg/L $CaCO_3$
2) UV dose = 40 mJ/cm^2

Design Flow (mgd)	Capital Cost ($)
0.0001	$10,195
0.0070	$10,195
0.0220	$13,034
0.0370	$15,834
0.0910	$25,596
0.1800	$40,597
0.2700	$54,386
0.3600	$66,790
0.6800	$99,661
1.0000	$310,154
1.2000	$313,662
2.0000	$333,331
3.5000	$362,965
7.0000	$544,728
17.0000	$1,342,022
22.0000	$1,933,041
76.0000	$3,367,751
210.0000	$8,074,450
430.0000	$15,798,603
520.0000	$18,601,681
1,500.0000	$49,124,085

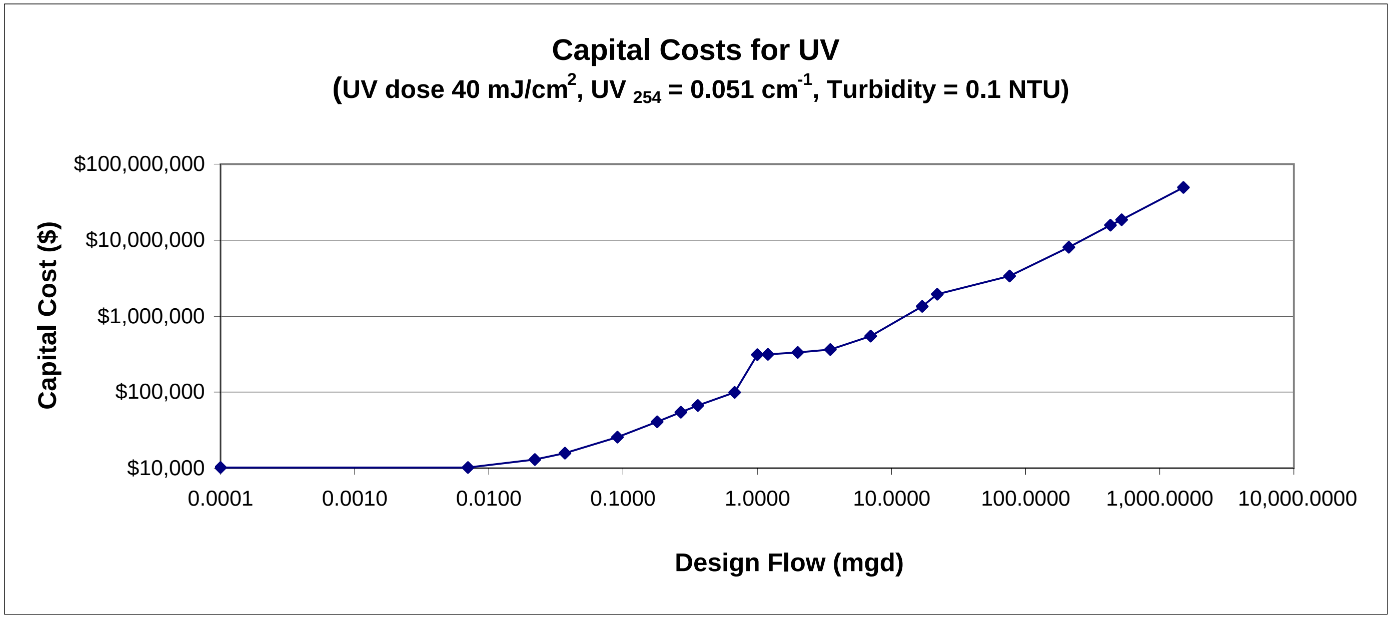


Exhibit D.8 O&M Costs for UV (40 mJ/cm^2)

Constraints: None
Design Criteria:

1) UV $_{254}$ = 0.051 cm^{-1}, Turbidity = 0.1 NTU, Alkalinity = 60 mg/L $CaCO_3$, Hardness = 100 mg/L $CaCO_3$
2) UV dose = 40 mJ/cm^2

Average Flow (mgd)	O&M Cost ($)
0.00005	$3,350
0.00150	$3,350
0.00540	$3,380
0.00950	$3,769
0.02500	$4,549
0.05400	$4,736
0.08400	$6,115
0.11000	$6,493
0.23000	$8,152
0.35000	$9,016
0.41000	$9,450
0.77000	$11,512
1.40000	$13,979
3.00000	$16,183
7.80000	$22,908
11.00000	$27,531
38.00000	$66,755
120.00000	$188,219
270.00000	$422,455
350.00000	$551,123
750.00000	$1,194,464

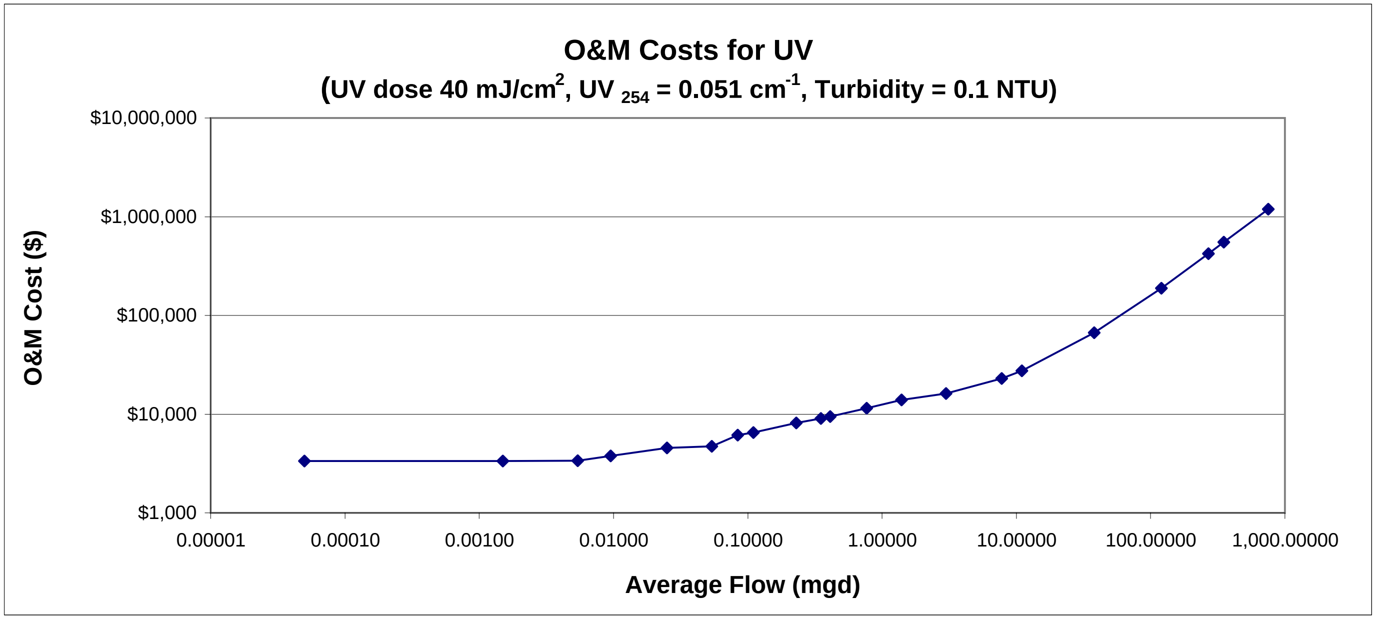
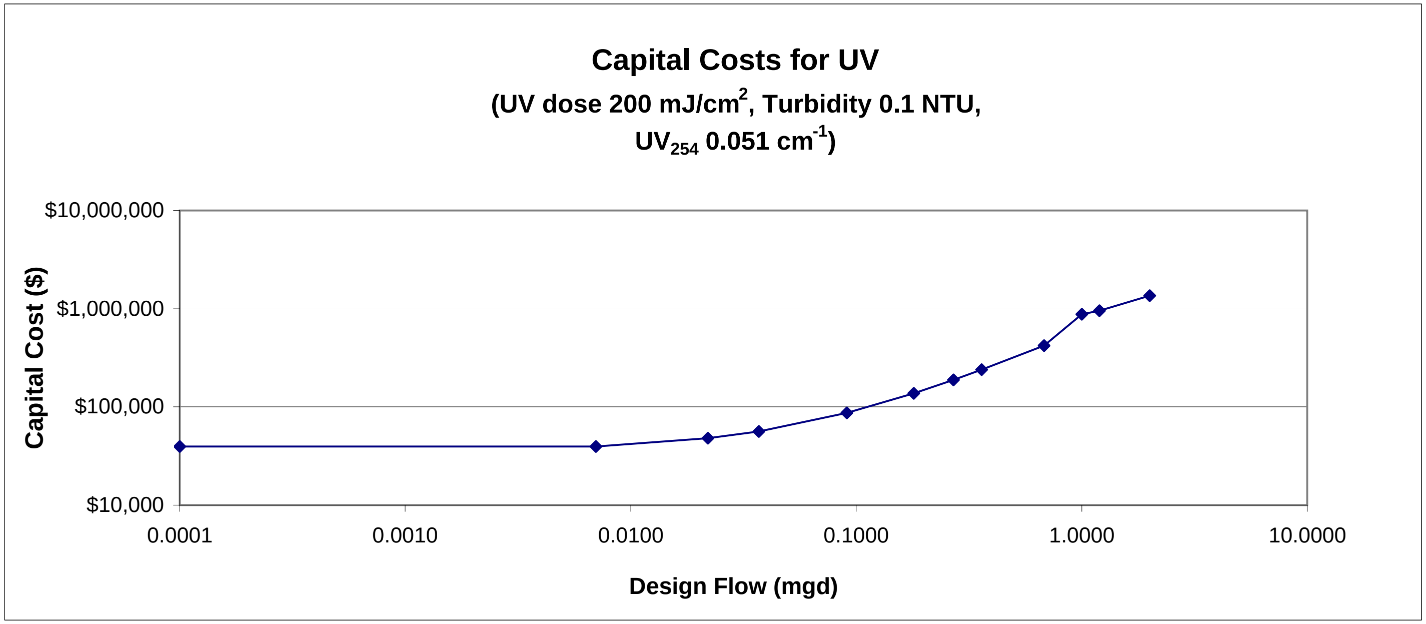


Exhibit D.9 Capital Costs for UV (200 mJ/cm^2)

Constraints: None
Design Criteria:

1) UV_{254} = 0.051 cm^{-1}, Turbidity = 0.1 NTU
2) Alkalinity = 60 mg/L $CaCO_3$, Hardness = 100 mg/L $CaCO_3$
3) UV dose = 200 mJ/cm^2

Design Flow (mgd)	Capital Cost ($)
0.0001	$39,390
0.0070	$39,390
0.0220	$47,873
0.0370	$56,357
0.0910	$86,898
0.1800	$137,234
0.2700	$188,136
0.3600	$239,038
0.6800	$420,021
1.0000	$878,383
1.2000	$953,078
2.0000	$1,354,307
3.5000	Not Applicable
7.0000	Not Applicable
17.0000	Not Applicable
22.0000	Not Applicable
76.0000	Not Applicable
210.0000	Not Applicable
430.0000	Not Applicable
520.0000	Not Applicable
1,500.0000	Not Applicable



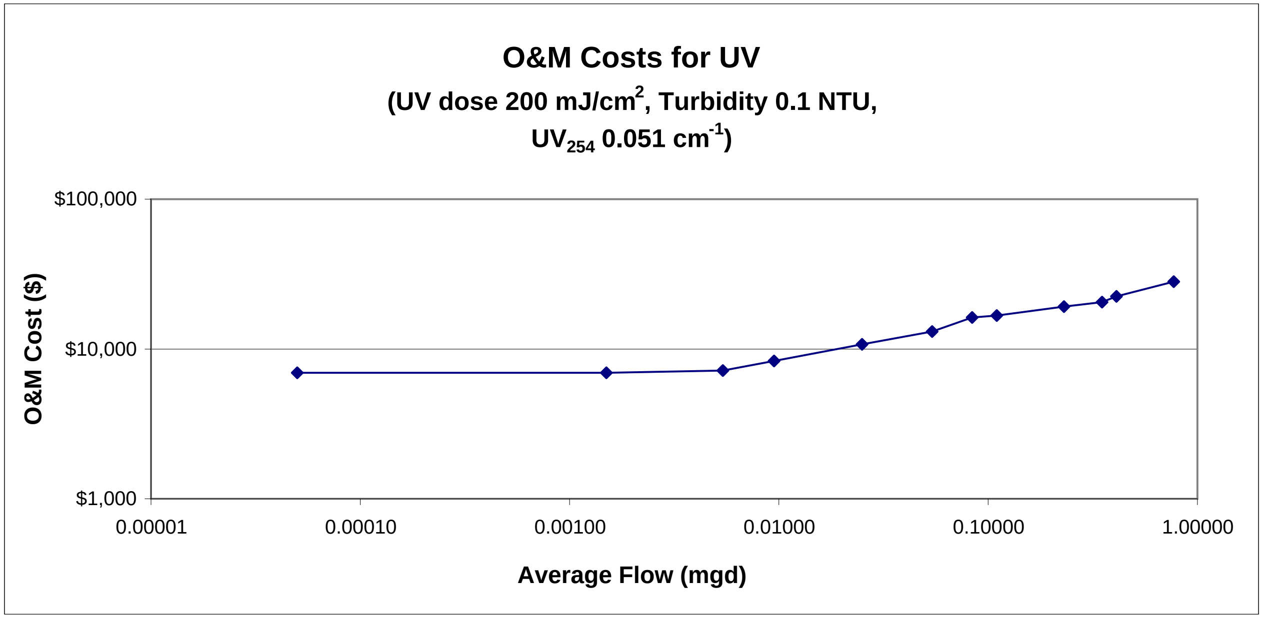
Note: EPA updated the 40 mJ/cm2 UV unit costs based on data obtained for recent installations of this technology. Similar data for 200 mJ/cm2 UV systems were not available within the time frame required to include in this analysis.

Exhibit D.10 - O&M Costs for UV (200 mJ/cm^2)

Constraints: None
Design Criteria:

1) UV $_{254}$ = 0.051 cm^-1, Turbidity = 0.1 NTU
2) Alkalinity = 60 mg/L $CaCO_3$, Hardness = 100 mg/L $CaCO_3$
3) UV dose = 200 mJ/cm^2

Average Flow (mgd)	O&M Cost ($)
0.00005	$6,919
0.00150	$6,919
0.00540	$7,189
0.00950	$8,324
0.02500	$10,751
0.05400	$13,065
0.08400	$16,203
0.11000	$16,739
0.23000	$19,155
0.35000	$20,522
0.41000	$22,415
0.77000	$28,089
1.40000	Not Applicable
3.00000	Not Applicable
7.80000	Not Applicable
11.00000	Not Applicable
38.00000	Not Applicable
120.00000	Not Applicable
270.00000	Not Applicable
350.00000	Not Applicable
750.00000	Not Applicable



Note: EPA updated the 40 mJ/cm2 UV unit costs based on data obtained for recent installations of this technology. Similar data for 200 mJ/cm2 UV systems were not available within the time frame required to include in this analysis.

Exhibit D.11 - Capital Costs for Ozone
0.5-Log Inactivation of *Cryptosporidium*

Constraints: Not practical for systems serving 100 or fewer people
Design Criteria:

1) Contact time = 12 minutes
2) Ozone maximum dose = 3.19 mg/L

Design Flow (mgd)	Capital Cost ($)
0.0001	Data Not Used
0.0070	Data Not Used
0.0220	Data Not Used
0.0370	Data Not Used
0.0910	$322,787
0.1800	$382,874
0.2700	$438,785
0.3600	$493,394
0.6800	$675,951
1.0000	$804,614
1.2000	$902,391
2.0000	$1,226,541
3.5000	$1,595,373
7.0000	$2,357,412
17.0000	$3,946,957
22.0000	$4,546,365
76.0000	$12,628,950
210.0000	$26,317,852
430.0000	$44,918,178
520.0000	$53,248,978
1,500.0000	$143,962,124

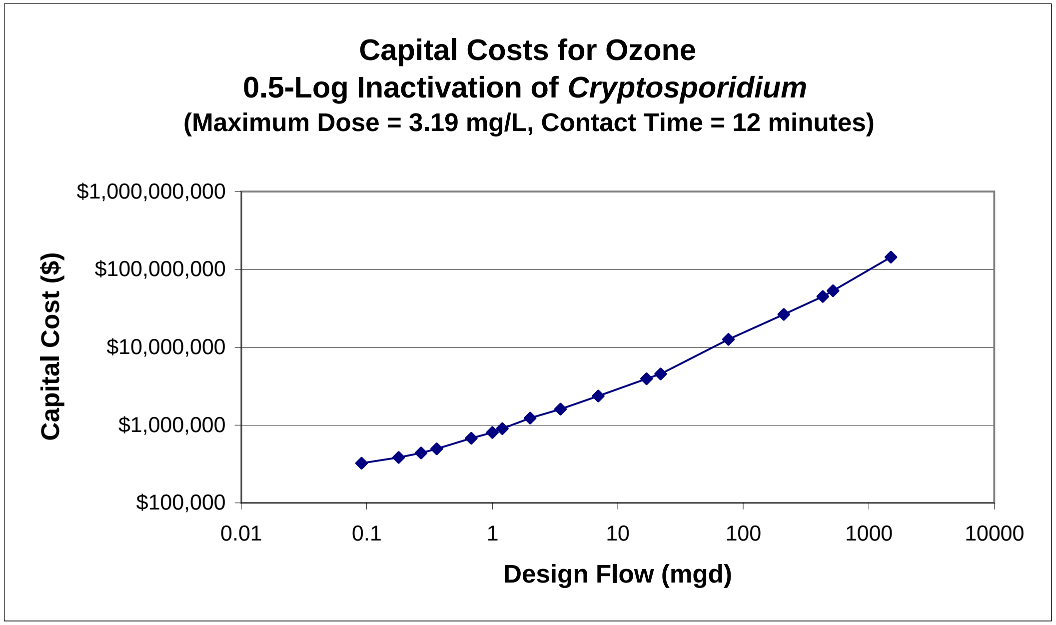


Exhibit D.12 - O&M Costs for Ozone
0.5-Log Inactivation of *Cryptosporidium*

Constraints: Not practical for systems serving 100 or fewer people
Design Criteria:

1) Contact time = 12 minutes
2) Ozone average dose = 1.78 mg/L

Average Flow (mgd)	O&M Cost ($)
0.00005	Data Not Used
0.00150	Data Not Used
0.00540	Data Not Used
0.00950	Data Not Used
0.02500	$55,520
0.05400	$55,884
0.08400	$59,391
0.11000	$59,737
0.23000	$61,152
0.35000	$62,566
0.41000	$63,350
0.77000	$67,621
1.40000	$77,719
3.00000	$95,346
7.80000	$145,700
11.00000	$177,752
38.00000	$464,832
120.00000	$1,377,320
270.00000	$2,871,997
350.00000	$3,662,456
750.00000	$7,614,752

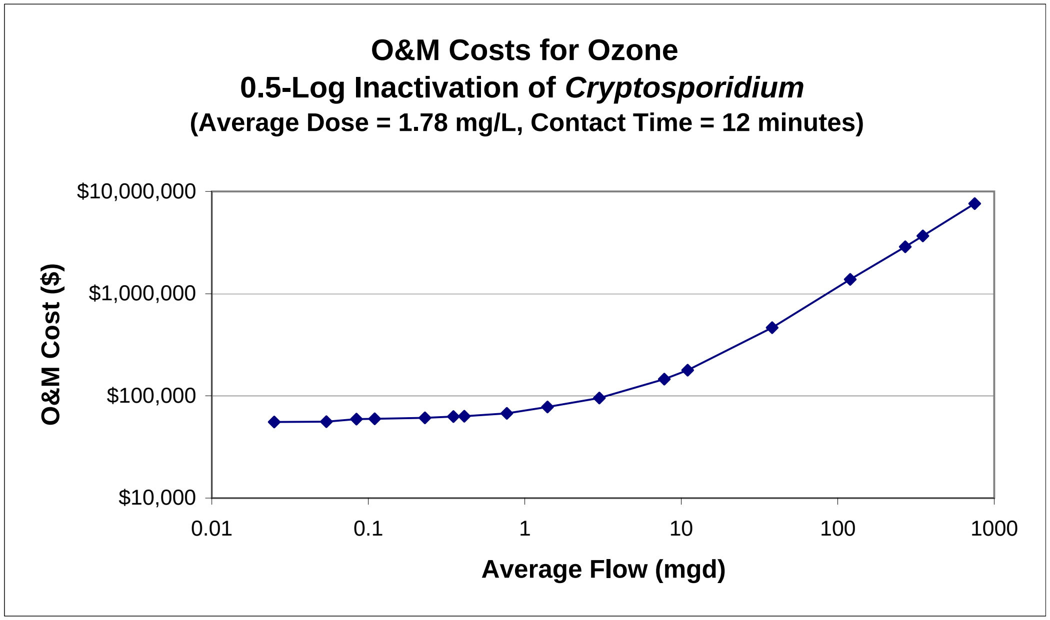


Exhibit D.13 - Capital Costs for Ozone
1.0-Log Inactivation of *Cryptosporidium*

Constraints: Not practical for systems serving 100 or fewer people
Design Criteria:
1) Contact time = 12 minutes
2) Ozone maximum dose = 5.00 mg/L

Design Flow (mgd)	Capital Cost ($)
0.0001	Data Not Used
0.0070	Data Not Used
0.0220	Data Not Used
0.0370	Data Not Used
0.0910	$351,943
0.1800	$440,546
0.2700	$525,292
0.3600	$608,737
0.6800	$893,979
1.0000	$1,043,133
1.2000	$1,119,608
2.0000	$1,416,784
3.5000	$1,922,483
7.0000	$2,912,264
17.0000	$4,697,222
22.0000	$5,517,296
76.0000	$15,011,417
210.0000	$30,378,296
430.0000	$55,716,052
520.0000	$66,369,920
1,500.0000	$182,378,707

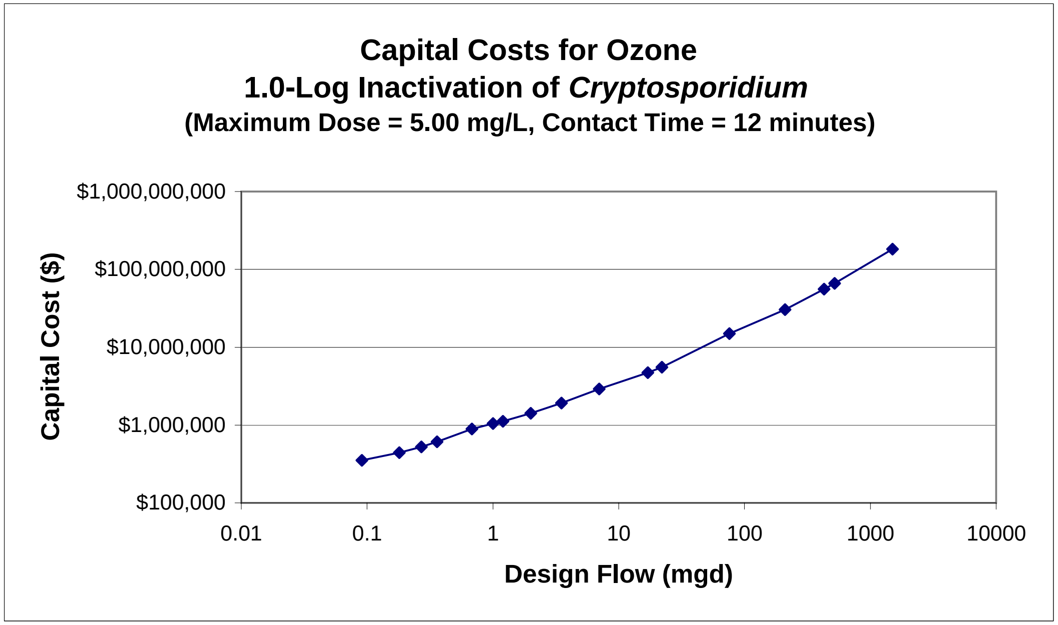


Exhibit D.14 - O&M Costs for Ozone
1.0-Log Inactivation of *Cryptosporidium*

Constraints: Not practical for systems serving 100 or fewer people
Design Criteria:

1) Contact time = 12 minutes
2) Ozone average dose = 2.75 mg/L

Average Flow (mgd)	O&M Cost ($)
0.00005	Data Not Used
0.00150	Data Not Used
0.00540	Data Not Used
0.00950	Data Not Used
0.02500	$55,827
0.05400	$56,438
0.08400	$60,197
0.11000	$60,781
0.23000	$63,138
0.35000	$65,357
0.41000	$66,210
0.77000	$75,885
1.40000	$87,731
3.00000	$115,823
7.80000	$194,432
11.00000	$245,991
38.00000	$694,758
120.00000	$2,083,382
270.00000	$4,473,882
350.00000	$5,734,314
750.00000	$12,036,475

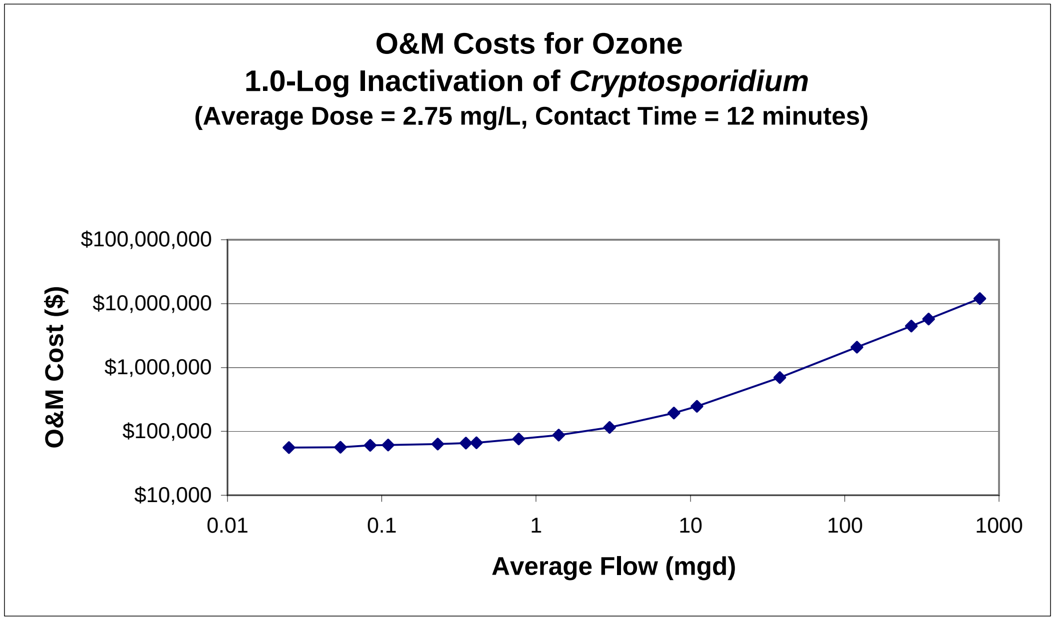


Exhibit D.15 - Capital Costs for Ozone
2.0-Log Inactivation of *Cryptosporidium*

Constraints: Not practical for systems serving 100 or fewer people
Design Criteria:
1) Contact time = 12 minutes
2) Ozone maximum dose = 7.50 mg/L

Design Flow (mgd)	Capital Cost ($)
0.0001	Data Not Used
0.0070	Data Not Used
0.0220	Data Not Used
0.0370	Data Not Used
0.0910	$372,391
0.1800	$480,993
0.2700	$585,963
0.3600	$689,631
0.6800	$1,069,196
1.0000	$1,107,713
1.2000	$1,200,916
2.0000	$1,547,877
3.5000	$2,151,897
7.0000	$3,124,381
17.0000	$5,223,408
22.0000	$6,291,141
76.0000	$16,720,757
210.0000	$34,225,903
430.0000	$63,362,091
520.0000	$75,616,293
1,500.0000	$209,050,936

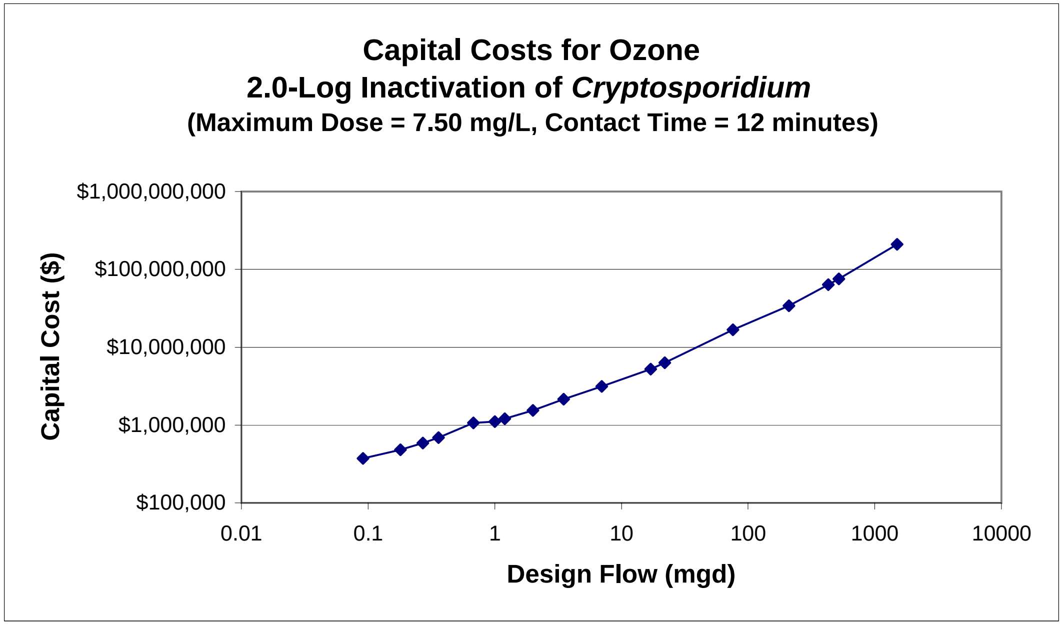


Exhibit D.16 - O&M Costs for Ozone
2.0-Log Inactivation of *Cryptosporidium*

Constraints: Not practical for systems serving 100 or fewer people
Design Criteria:
1) Contact time = 12 minutes
2) Ozone average dose = 3.91 mg/L

Average Flow (mgd)	O&M Cost ($)
0.00005	Data Not Used
0.00150	Data Not Used
0.00540	Data Not Used
0.00950	Data Not Used
0.02500	$56,096
0.05400	$56,900
0.08400	$60,858
0.11000	$61,627
0.23000	$64,836
0.35000	$66,956
0.41000	$68,079
0.77000	$74,291
1.40000	$85,473
3.00000	$211,156
7.80000	$424,479
11.00000	$541,290
38.00000	$1,710,724
120.00000	$4,846,200
270.00000	$10,067,081
350.00000	$12,436,352
750.00000	$24,282,705

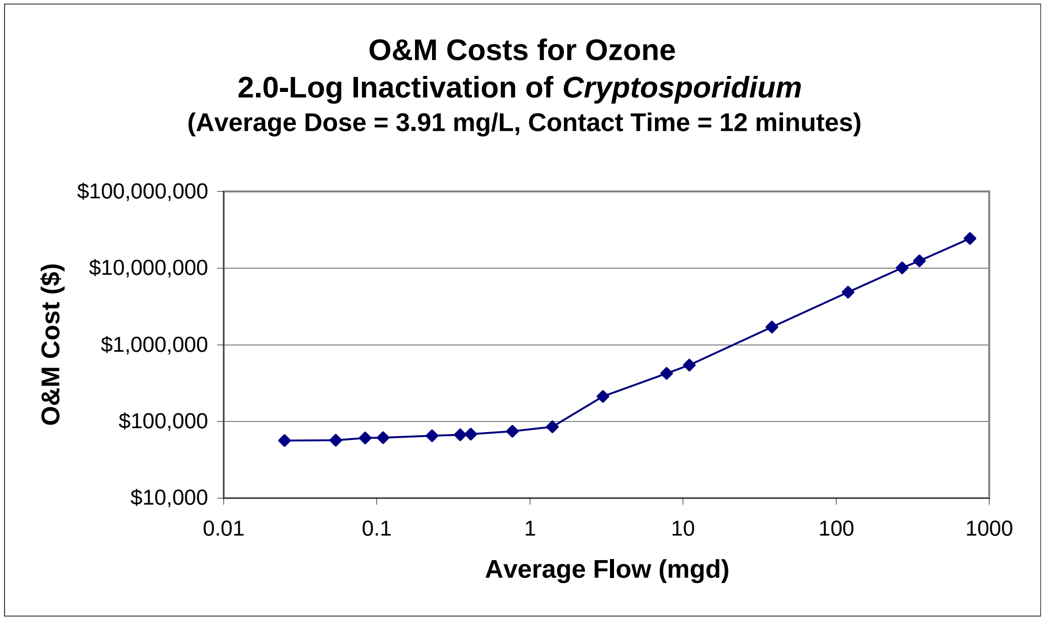


Exhibit D.17 - Capital Costs for Microfiltration/Ultrafiltration (MF/UF)

Constraints: None
Design Criteria:
1) Water temp. 10 degrees C
2) Sanitary Sewer Discharge

Design Flow (mgd)	Capital Cost ($)
0.0001	$131,478
0.0070	$131,478
0.0220	$214,432
0.0370	$270,819
0.0910	$409,983
0.1800	$628,117
0.2700	$748,563
0.3600	$850,970
0.6800	$1,133,988
1.0000	$1,594,911
1.2000	$1,738,505
2.0000	$2,720,593
3.5000	$4,142,559
7.0000	$7,382,351
17.0000	$15,991,348
22.0000	$20,058,196
76.0000	$61,150,358
210.0000	$153,184,031
430.0000	$293,759,889
520.0000	$349,252,221
1,500.0000	$953,502,064

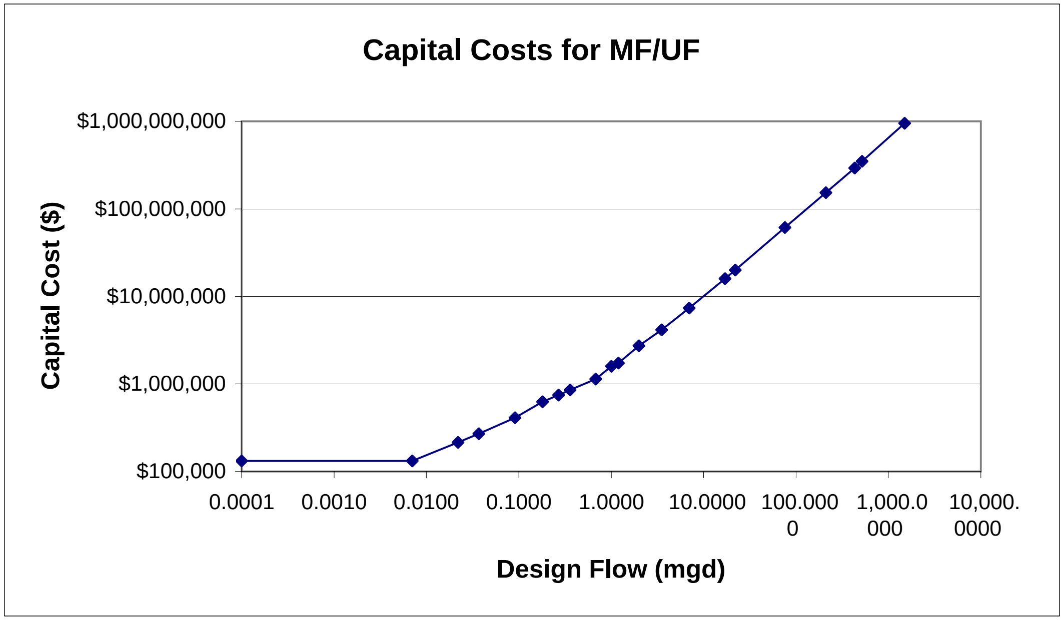


Exhibit D.18 - O&M Costs for Microfiltration/Ultrafiltration (MF/UF)

Constraints: None

Design Criteria:

1) Water temp. 10 degrees C

2) Sanitary Sewer Discharge

Average Flow (mgd)	O&M Cost ($)
0.00005	$6,230
0.00150	$6,230
0.00540	$6,686
0.00950	$7,156
0.02500	$9,329
0.05400	$22,042
0.08400	$26,348
0.11000	$29,272
0.23000	$41,522
0.35000	$69,214
0.41000	$75,317
0.77000	$106,798
1.40000	$164,173
3.00000	$324,393
7.80000	$786,427
11.00000	$1,034,793
38.00000	$3,301,730
120.00000	$9,888,387
270.00000	$21,519,157
350.00000	$27,300,426
750.00000	$56,206,770

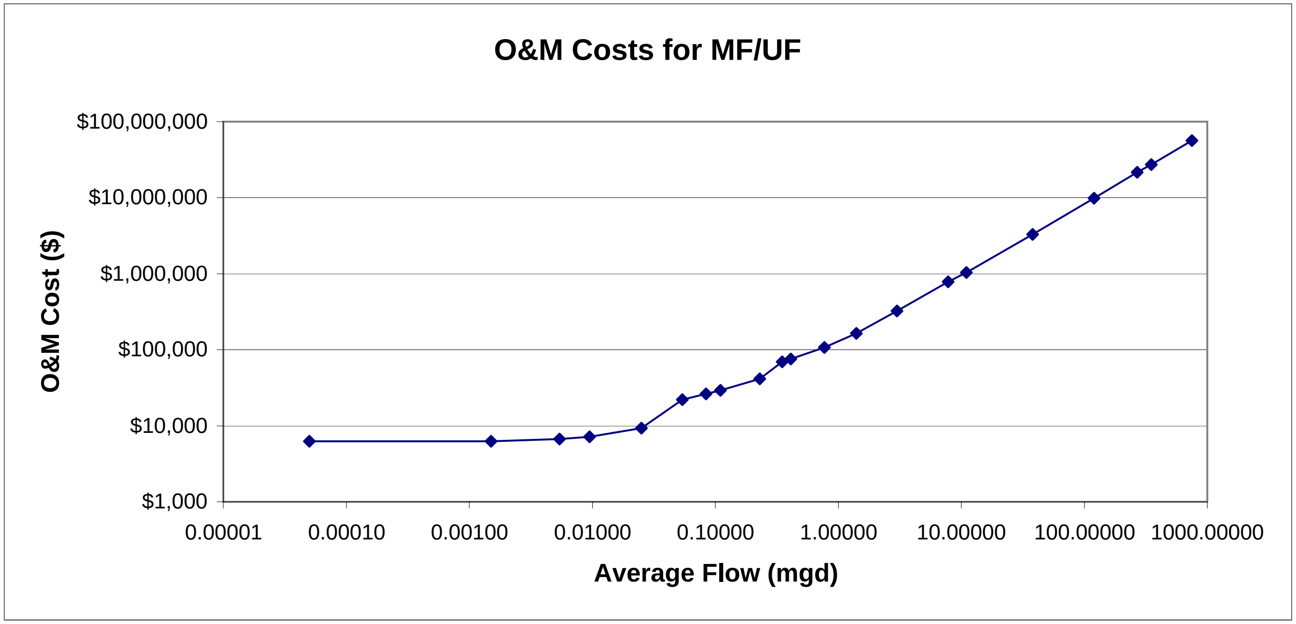


Exhibit D.19 - Capital Costs for Bag Filtration

Design Criteria:

1) Nominal pore size = 1 micron

Design Flow (mgd)	Capital Cost ($)
0.0001	$10,280
0.0070	$10,280
0.0220	$10,420
0.0370	$12,828
0.0910	$13,320
0.1800	$19,487
0.2700	$23,424
0.3600	$28,771
0.6800	$42,479
1.0000	$65,653
1.2000	$75,011
2.0000	$136,788
3.5000	Data Not Used
7.0000	Data Not Used
17.0000	Data Not Used
22.0000	Data Not Used
76.0000	Data Not Used
210.0000	Data Not Used
430.0000	Data Not Used
520.0000	Data Not Used
1,500.0000	Data Not Used

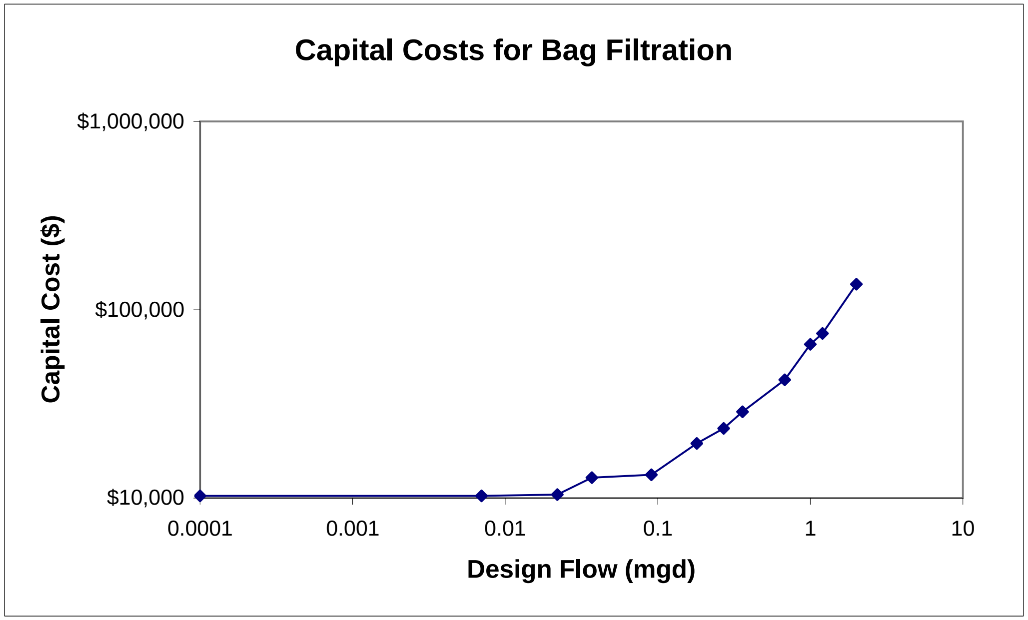


Exhibit D.20 - O&M Costs for Bag Filtration

Design Criteria:

1) Nominal pore size = 1 micron

Average Flow (mgd)	O&M Cost ($)
0.00005	$479
0.00150	$479
0.00540	$481
0.00950	$701
0.02500	$732
0.05400	$962
0.08400	$1,223
0.11000	$1,673
0.23000	$2,602
0.35000	$3,956
0.41000	$4,851
0.77000	$8,151
1.40000	Data Not Used
3.00000	Data Not Used
7.80000	Data Not Used
11.00000	Data Not Used
38.00000	Data Not Used
120.00000	Data Not Used
270.00000	Data Not Used
350.00000	Data Not Used
750.00000	Data Not Used

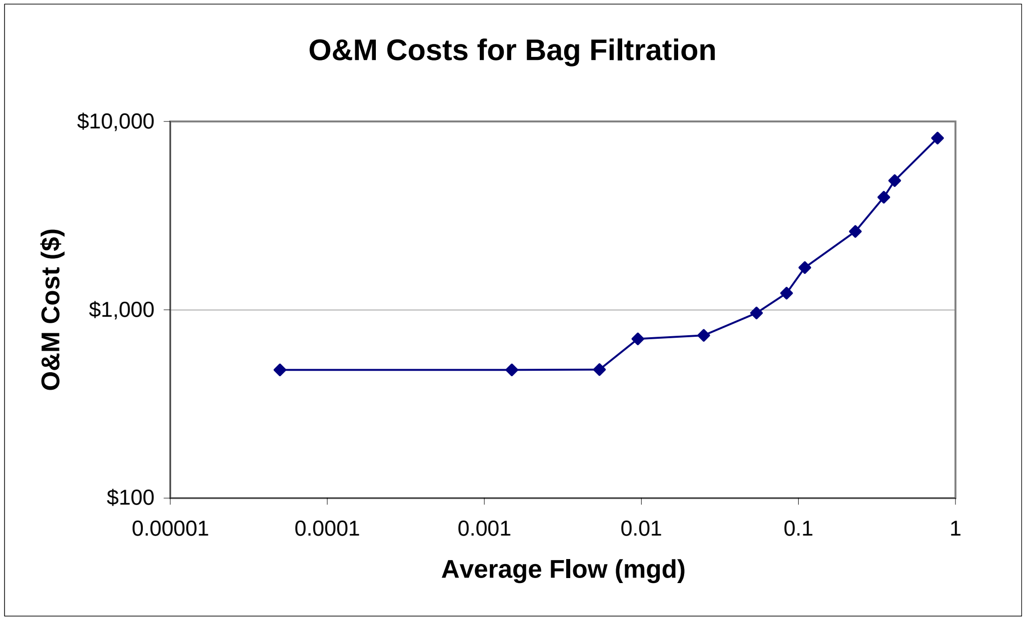


Exhibit D.21 - Capital Costs for Cartridge Filtration

Design Criteria:

1) Nominal pore size = 1 micron

Design Flow (mgd)	Capital Cost ($)
0.0001	$10,465
0.0070	$10,465
0.0220	$10,605
0.0370	$13,196
0.0910	$17,256
0.1800	$24,024
0.2700	$31,479
0.3600	$43,699
0.6800	$73,535
1.0000	$111,151
1.2000	$136,393
2.0000	$265,089
3.5000	Data Not Used
7.0000	Data Not Used
17.0000	Data Not Used
22.0000	Data Not Used
76.0000	Data Not Used
210.0000	Data Not Used
430.0000	Data Not Used
520.0000	Data Not Used
1,500.0000	Data Not Used

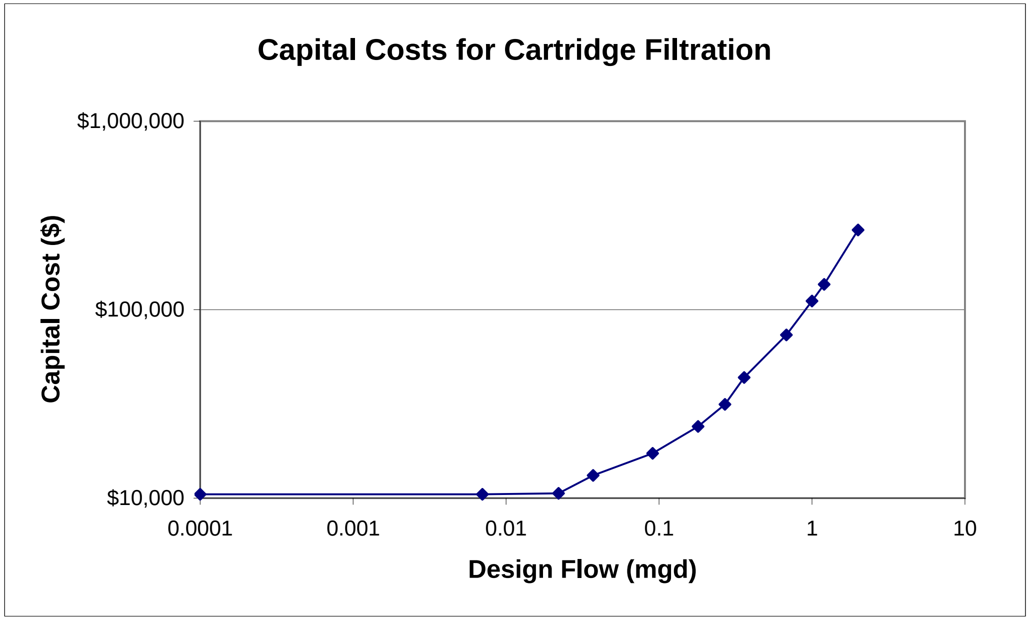


Exhibit D.22 - O&M Costs for Cartrige Filtration

Design Criteria:

1) Nominal pore size = 1 micron

Average Flow (mgd)	O&M Cost ($)
0.00005	$680
0.00150	$680
0.00540	$682
0.00950	$1,099
0.02500	$1,465
0.05400	$2,808
0.08400	$4,596
0.11000	$5,621
0.23000	$9,821
0.35000	$14,315
0.41000	$18,075
0.77000	$28,189
1.40000	Data Not Used
3.00000	Data Not Used
7.80000	Data Not Used
11.00000	Data Not Used
38.00000	Data Not Used
120.00000	Data Not Used
270.00000	Data Not Used
350.00000	Data Not Used
750.00000	Data Not Used

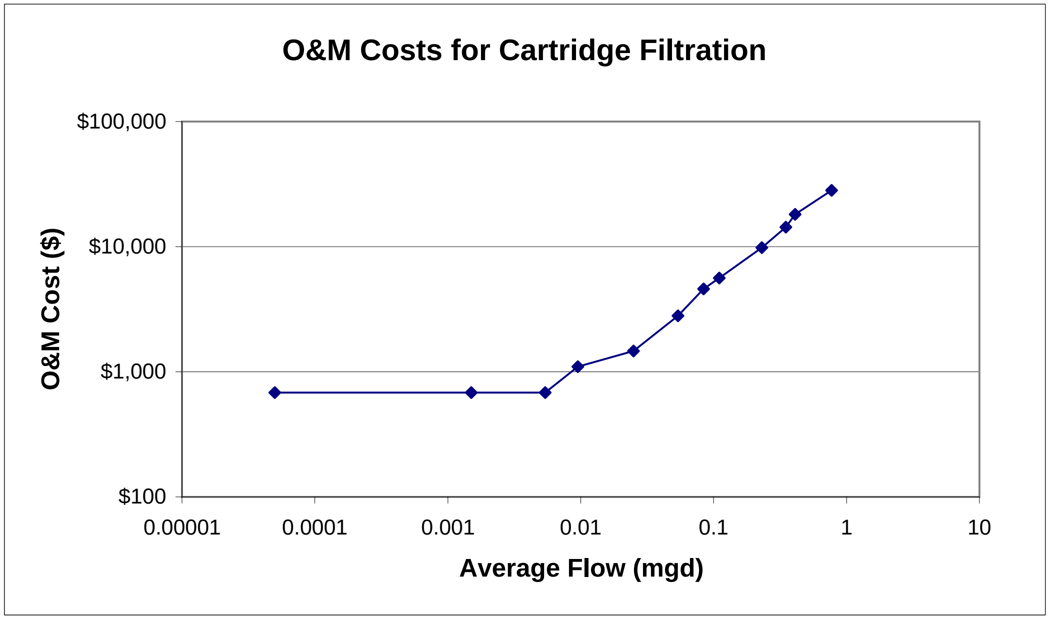


Exhibit D.23 - Capital Costs for Bank Filtration

Design Flow (mgd)	Capital Cost ($)
0.0001	$150,000
0.0070	$150,000
0.0220	$150,000
0.0370	$150,000
0.0910	$150,000
0.1800	$150,000
0.2700	$150,000
0.3600	$150,000
0.6800	$150,000
1.0000	$224,684
1.2000	$271,361
2.0000	$458,070
3.5000	$808,149
7.0000	$1,625,000
17.0000	$3,382,246
22.0000	$4,260,870
76.0000	$13,750,000
210.0000	$37,297,101
430.0000	$75,956,522
520.0000	$91,771,739
1,500.0000	$263,981,884

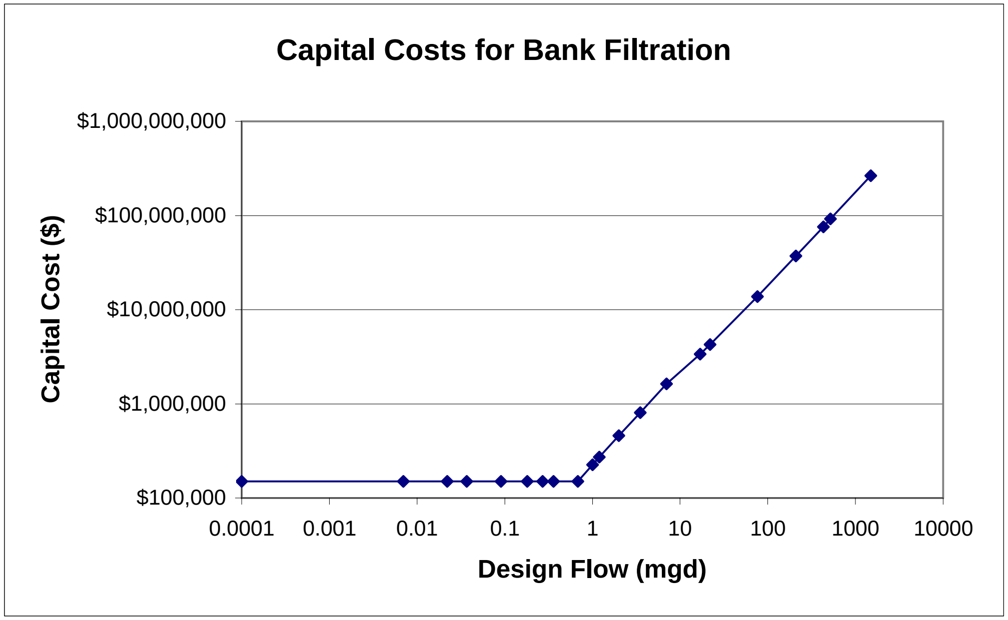


Exhibit D.24 - Capital Costs for Secondary Filters

Design Flow (mgd)	Capital Cost ($)
0.0001	$1,106,000
0.0070	$1,106,000
0.0220	$1,106,000
0.0370	$1,106,000
0.0910	$1,106,000
0.1800	$1,106,000
0.2700	$1,106,000
0.3600	$1,106,000
0.6800	$1,106,000
1.0000	$1,331,013
1.2000	$1,471,646
2.0000	$2,034,177
3.5000	$3,088,924
7.0000	$5,550,000
17.0000	$7,731,159
22.0000	$8,821,739
76.0000	$20,600,000
210.0000	$49,827,536
430.0000	$97,813,043
520.0000	$117,443,478
1,500.0000	$331,197,101

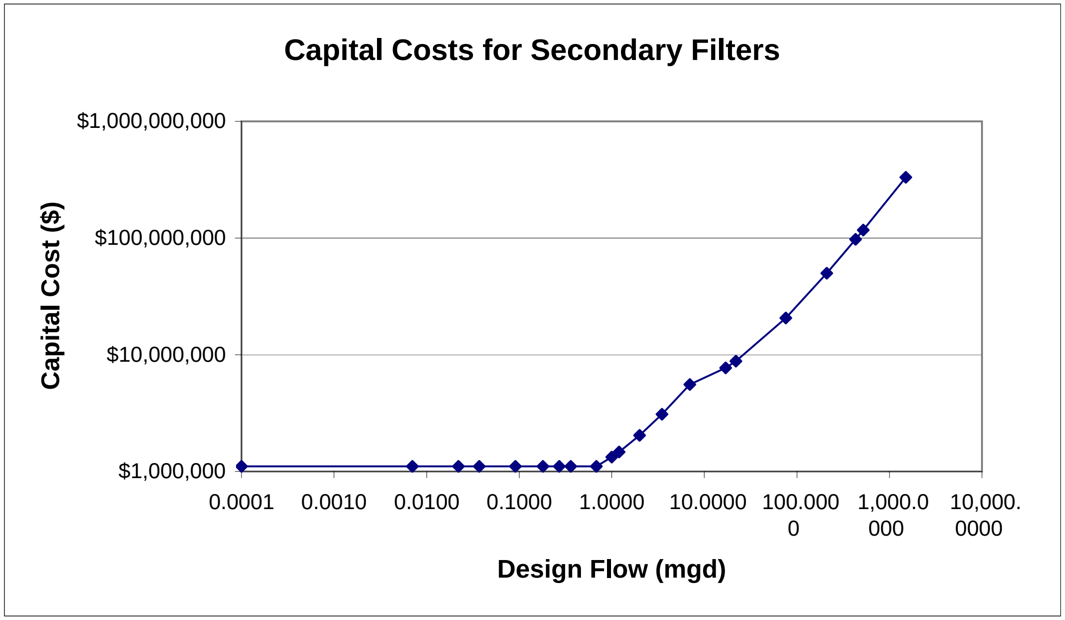


Exhibit D.25 - O&M Costs for Secondary Filters

Average Flow (mgd)	O&M Cost ($)
0.00005	$62,300
0.00150	$62,300
0.00540	$62,300
0.00950	$62,300
0.02500	$62,300
0.05400	$62,300
0.08400	$62,300
0.11000	$62,300
0.23000	$62,300
0.35000	$66,034
0.41000	$67,901
0.77000	$79,104
1.40000	$98,709
3.00000	$148,500
7.80000	$182,031
11.00000	$204,386
38.00000	$393,000
120.00000	$965,829
270.00000	$2,013,686
350.00000	$2,572,543
750.00000	$5,366,829

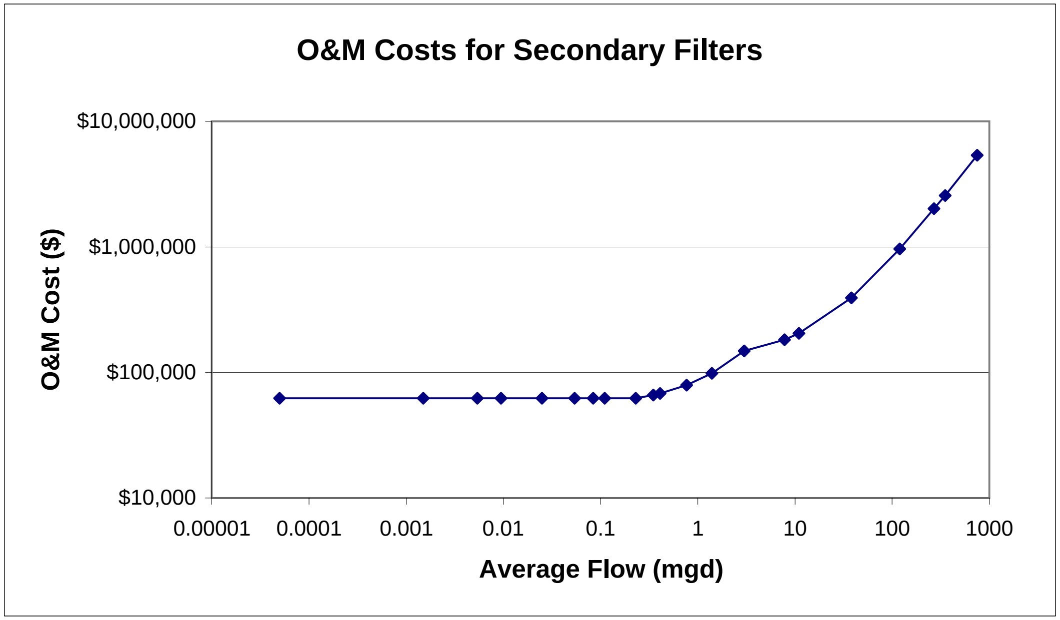


Exhibit D.26 - Capital Costs for Pre-sedimentation with Coagulant

Design Flow (mgd)	Capital Cost ($)
0.0001	$1,200,000
0.0070	$1,200,000
0.0220	$1,200,000
0.0370	$1,200,000
0.0910	$1,200,000
0.1800	$1,200,000
0.2700	$1,200,000
0.3600	$1,200,000
0.6800	$1,200,000
1.0000	$1,326,582
1.2000	$1,405,696
2.0000	$1,722,152
3.5000	$2,315,506
7.0000	$3,700,000
17.0000	$6,859,420
22.0000	$8,439,130
76.0000	$25,500,000
210.0000	$67,836,232
430.0000	$137,343,478
520.0000	$165,778,261
1,500.0000	$475,401,449

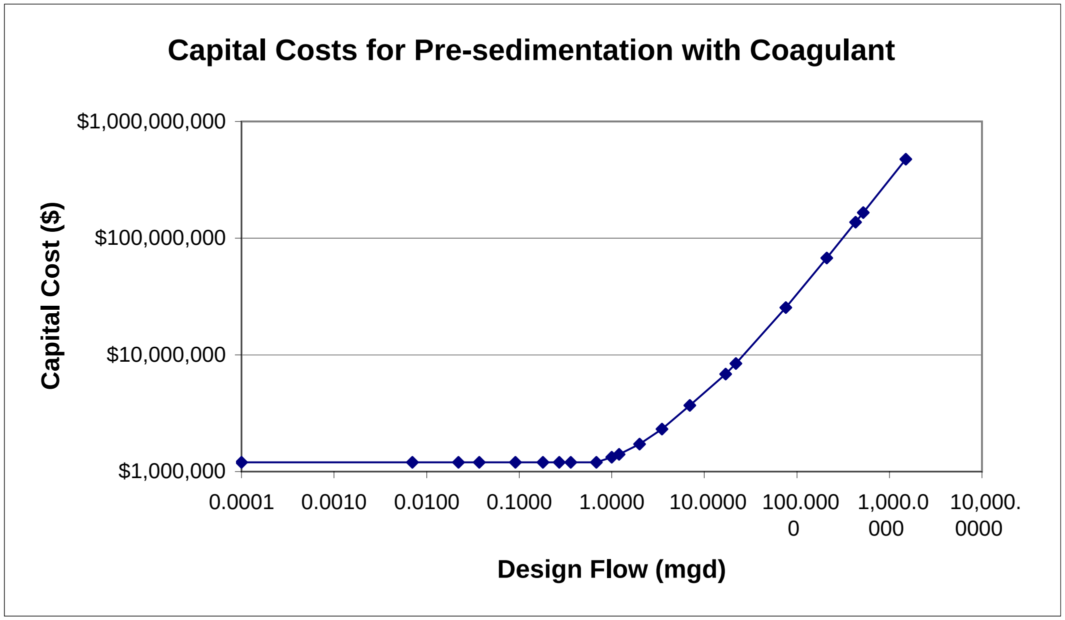


Exhibit D.27 - O&M Costs for Pre-sedimentation with Coagulant

Average Flow (mgd)	O&M Cost ($)
0.00005	$37,000
0.00150	$37,000
0.00540	$37,000
0.00950	$37,000
0.02500	$37,000
0.05400	$37,000
0.08400	$37,000
0.11000	$37,000
0.23000	$37,000
0.35000	$40,552
0.41000	$42,329
0.77000	$52,986
1.40000	$71,635
3.00000	$119,000
7.80000	$179,480
11.00000	$219,800
38.00000	$560,000
120.00000	$1,593,200
270.00000	$3,483,200
350.00000	$4,491,200
750.00000	$9,531,200

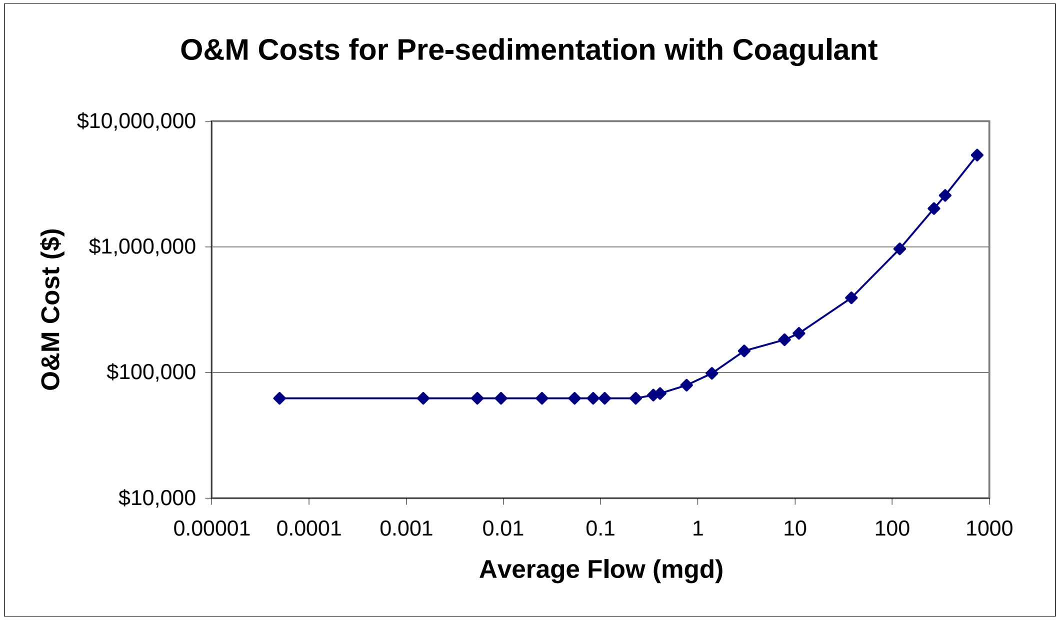


Exhibit D.28 - Capital Costs for Watershed Control

Design Flow (mgd)	Capital Cost ($)
0.0001	$250,000
0.0070	$250,000
0.0220	$250,000
0.0370	$250,000
0.0910	$250,000
0.1800	$250,000
0.2700	$250,000
0.3600	$250,000
0.6800	$250,000
1.0000	$262,658
1.2000	$270,570
2.0000	$302,215
3.5000	$361,551
7.0000	$500,000
17.0000	$572,464
22.0000	$608,696
76.0000	$1,000,000
210.0000	$1,971,014
430.0000	$3,565,217
520.0000	$4,217,391
1,500.0000	$11,318,841

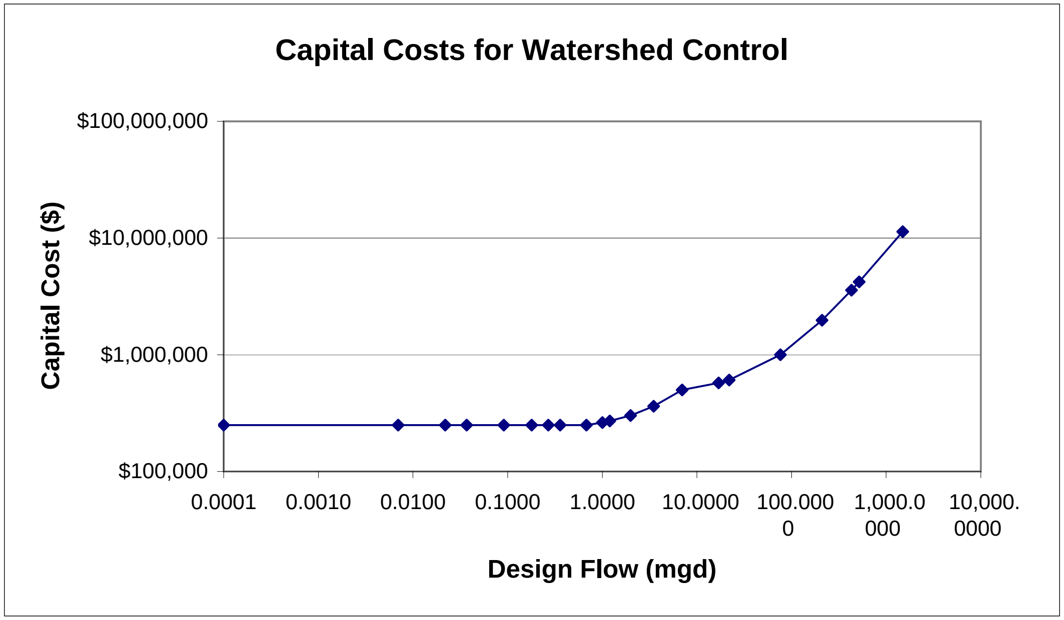


Exhibit D.29 - O&M Costs for Watershed Control

Average Flow (mgd)	O&M Cost ($)
0.00005	$350,000
0.00150	$350,000
0.00540	$350,000
0.00950	$350,000
0.02500	$350,000
0.05400	$350,000
0.08400	$350,000
0.11000	$350,000
0.23000	$350,000
0.35000	$378,159
0.41000	$392,238
0.77000	$476,715
1.40000	$624,549
3.00000	$1,000,000
7.80000	$1,205,714
11.00000	$1,342,857
38.00000	$2,500,000
120.00000	$6,014,286
270.00000	$12,442,857
350.00000	$15,871,429
750.00000	$33,014,286

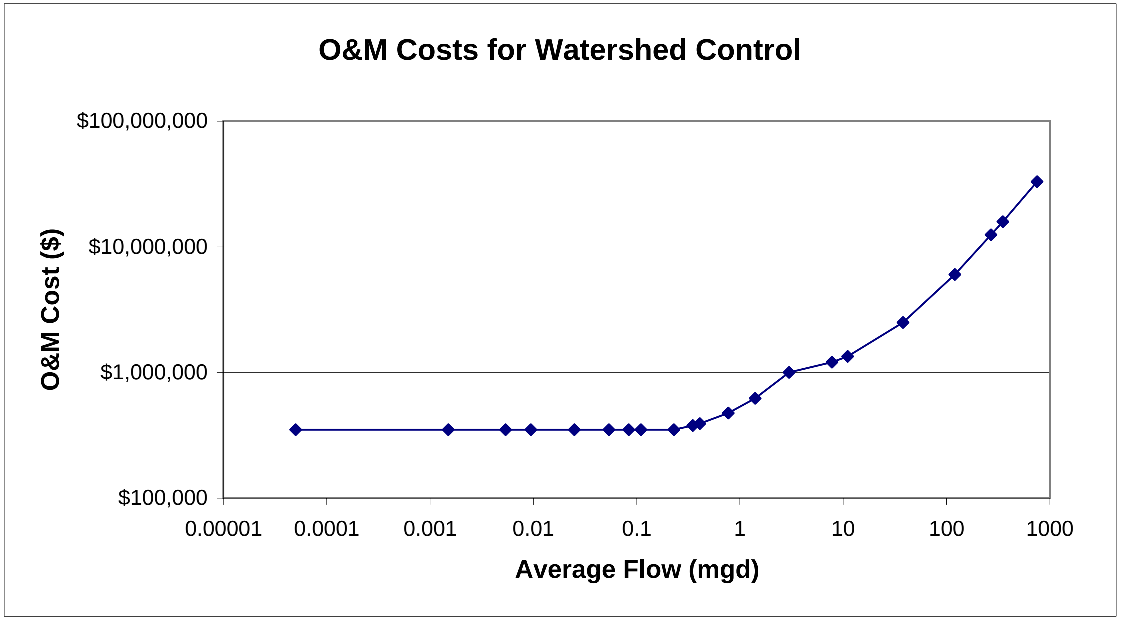


Exhibit D.30 - Capital Costs for Combined Filter Performance

Constraints: Not practical for systems serving fewer than 500 people

Design Criteria:

1) See *Technologies and Costs for Control of Microbial Contaminants and Disinfection Byproducts* ch. 3.3.11

Design Flow (mgd)	Capital Cost ($)
0.0001	Data Not Used
0.0070	Data Not Used
0.0220	Data Not Used
0.0370	Data Not Used
0.0910	Data Not Used
0.1800	$9,986
0.2500	$17,840
0.3600	$19,764
0.6300	$24,486
1.0000	$30,133
1.2000	$33,186
1.8100	$42,497
3.5000	$58,321
6.9000	$90,156
17.0000	$136,850
19.8700	$150,119
77.5000	$653,715
210.0000	$1,069,457
430.0000	$1,759,746
575.4100	$2,215,996
1,500.0000	$5,117,060

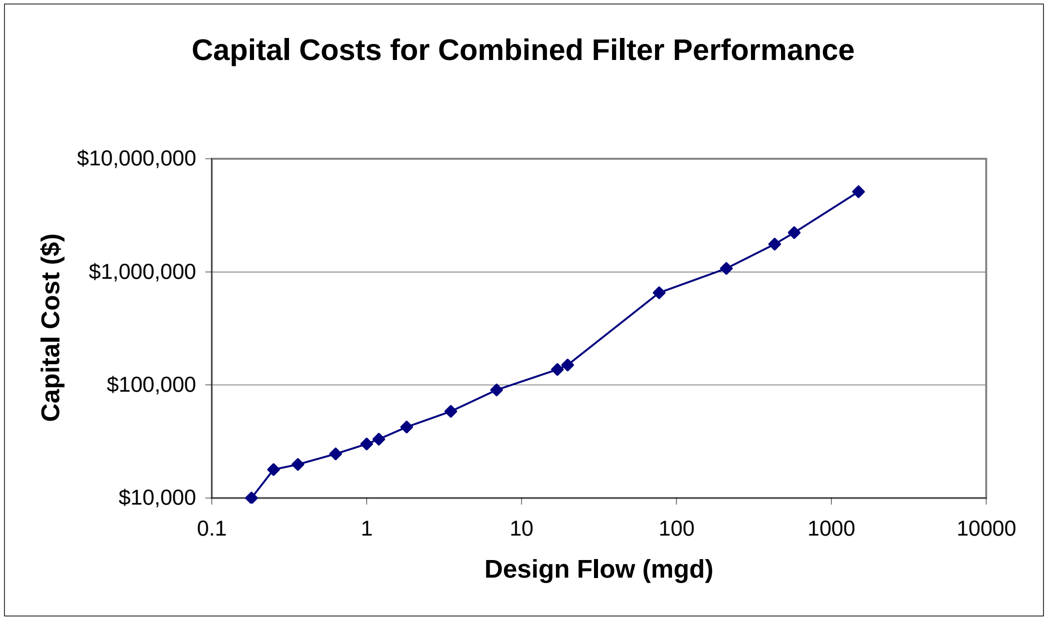


Exhibit D.31 - O&M Costs for Combined Filter Performance

Constraints: Not practical for systems serving fewer than 500 people
Design Criteria:
1) See *Technologies and Costs for Control of Microbial Contaminants and Disinfection Byproducts* ch. 3.3.11

Average Flow (mgd)	O&M Cost ($)
0.00005	Data Not Used
0.00150	Data Not Used
0.00540	Data Not Used
0.00950	Data Not Used
0.02500	Data Not Used
0.05400	$7,090
0.09300	$16,626
0.11000	$16,698
0.25000	$17,295
0.35000	$20,227
0.41000	$21,986
0.75000	$31,954
1.40000	$33,036
3.00000	$35,702
7.80000	$58,854
9.10000	$65,124
37.90000	$133,775
120.00000	$161,628
270.00000	$212,517
307.00000	$225,069
750.00000	$375,359

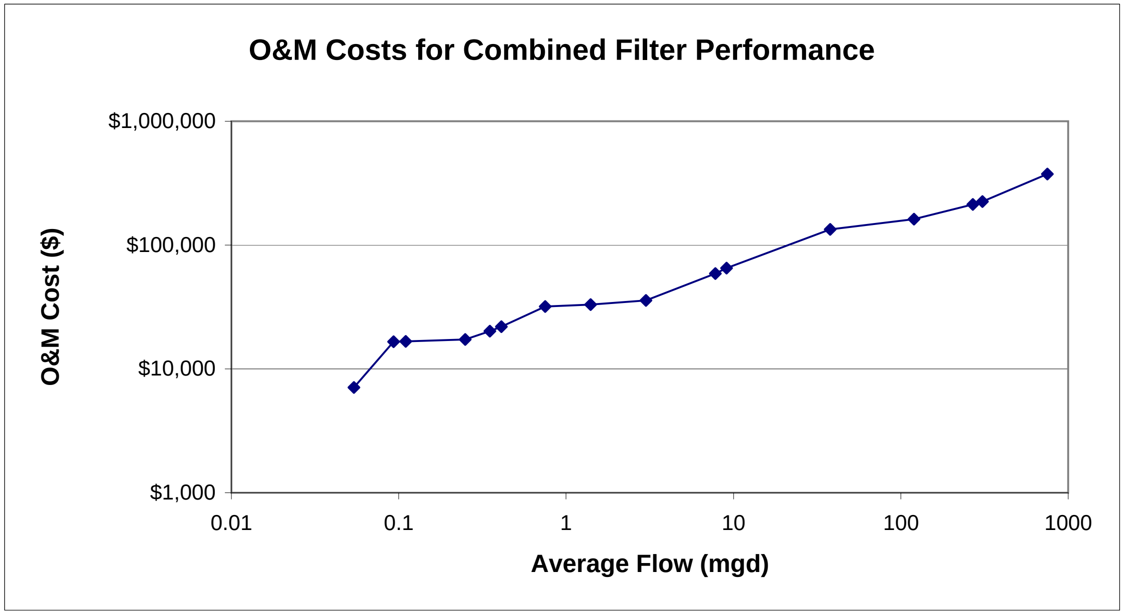


Exhibit D.32 - Capital Costs for GAC10
Surface Water Plants

Constraints: Not practical for systems serving 10,000 or fewer people
Design Criteria:
1) Reactivation frequency = 360 days
2) Onsite generation

Design Flow (mgd)	Capital Cost ($)
0.0001	Not Applicable
0.0070	Not Applicable
0.0220	Not Applicable
0.0370	$63,046
0.0910	$101,302
0.1800	$159,645
0.2700	$215,163
0.3600	$269,400
0.6800	$452,926
1.0000	$783,808
1.2000	$999,248
2.0000	$1,385,099
3.5000	$2,014,217
7.0000	$3,258,534
17.0000	$6,140,593
22.0000	$7,400,352
76.0000	$18,311,317
210.0000	$38,194,366
430.0000	$64,571,358
520.0000	$74,261,694
1,500.0000	$179,778,692

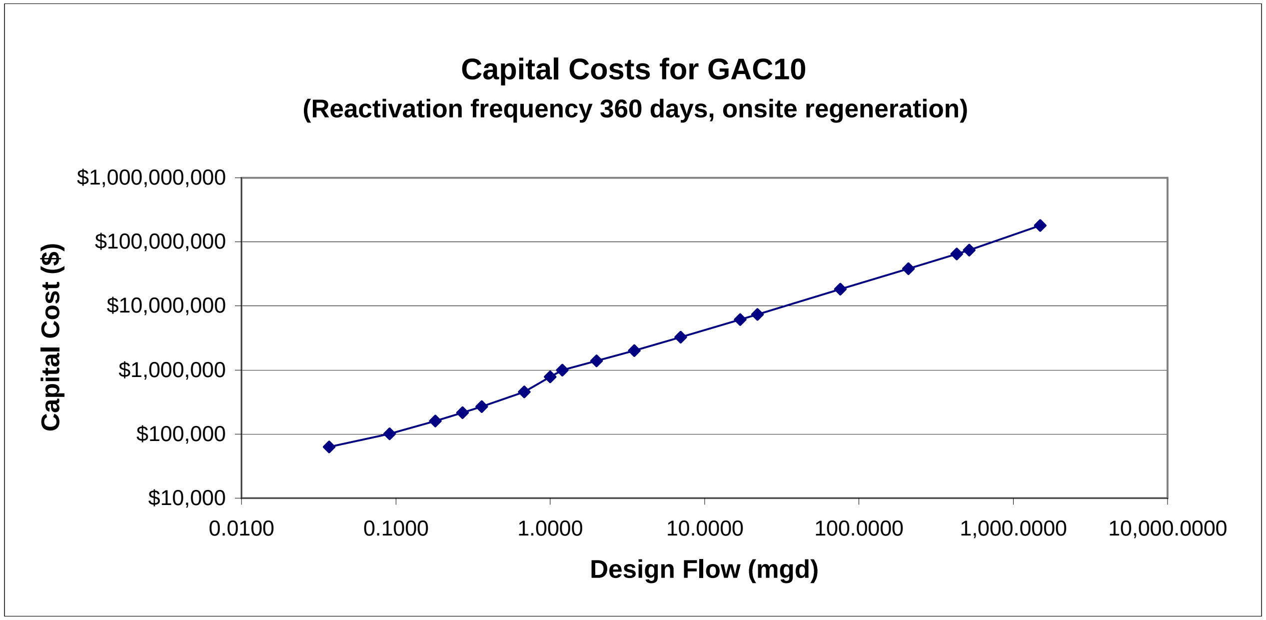


Exhibit D.33 - O&M Costs for GAC10
Surface Water Plants

Constraints: Not practical for systems serving 10,000 or fewer people
Design Criteria:
1) Reactivation frequency = 360 days
2) Onsite generation

Average Flow (mgd)	O&M Cost ($)
0.00005	Not Applicable
0.00150	Not Applicable
0.00540	Not Applicable
0.00950	$12,360
0.02500	$19,485
0.05400	$27,213
0.08400	$30,798
0.11000	$34,808
0.23000	$46,000
0.35000	$57,078
0.41000	$51,809
0.77000	$61,887
1.40000	$79,158
3.00000	$120,100
7.80000	$227,710
11.00000	$280,625
38.00000	$709,287
120.00000	$1,952,120
270.00000	$4,368,760
350.00000	$5,584,876
750.00000	$11,665,453

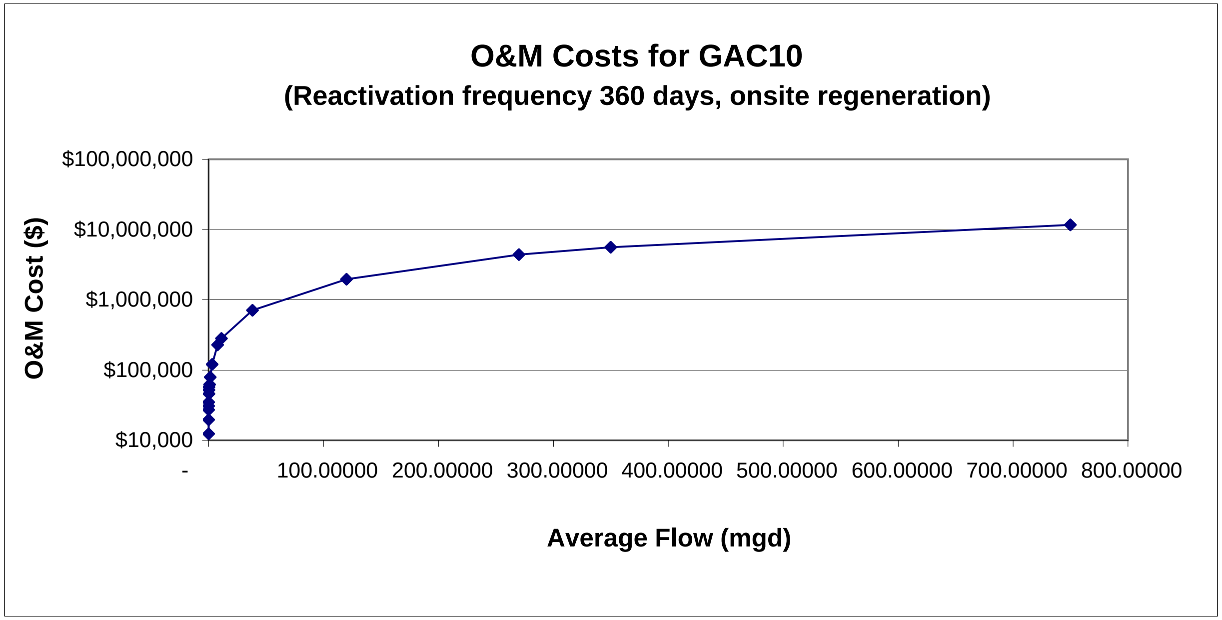


Exhibit D.34 - Capital Costs for GAC20
Surface Water Plants

Constraints: None
Design Criteria:

1) Reactivation frequency = 90 days
2) Onsite generation for systems serving more than 10,000 people
3) Media replacement for systems serving 10,000 or fewer people

Design Flow (mgd)	Capital Cost ($)
0.0001	$36,117
0.0070	$36,117
0.0220	$53,091
0.0370	$70,491
0.0910	$137,932
0.1800	$241,793
0.2700	$340,528
0.3600	$435,155
0.6800	$739,387
1.0000	$1,228,620
1.2000	$1,551,122
2.0000	$2,203,728
3.5000	$3,275,153
7.0000	$5,411,638
17.0000	$10,411,502
22.0000	$12,611,714
76.0000	$31,503,622
210.0000	$67,096,117
430.0000	$114,813,572
520.0000	$132,437,789
1,500.0000	$324,345,925

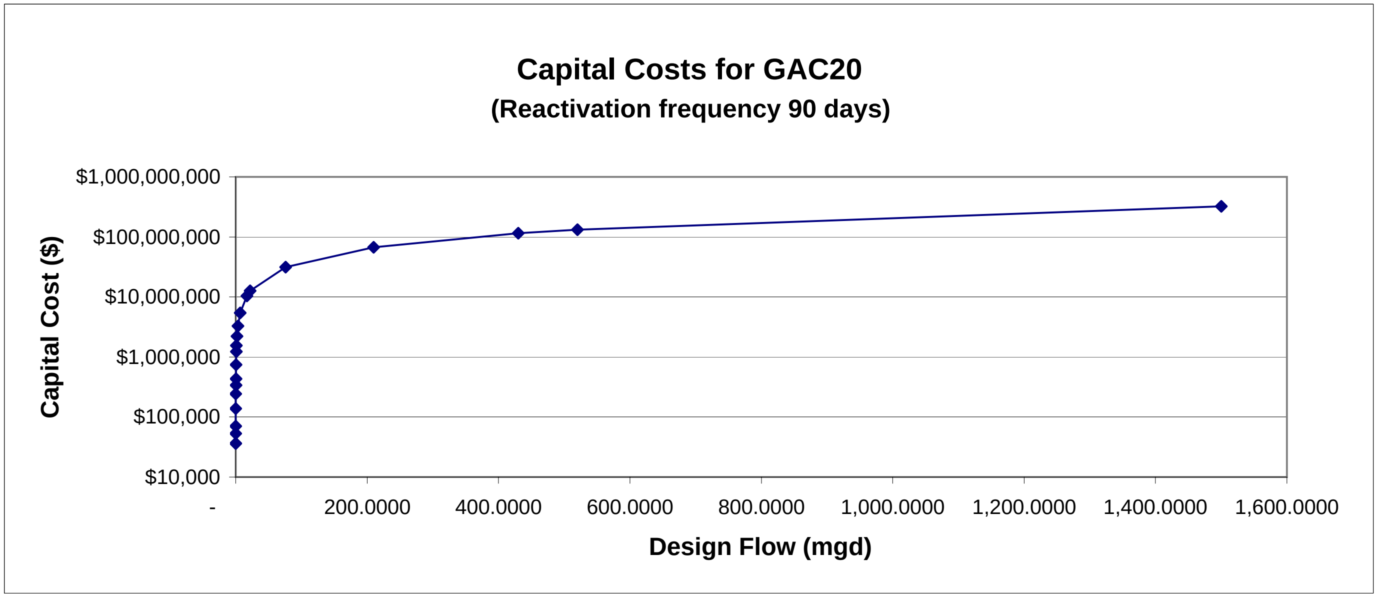


Exhibit D.35 - O&M Costs for GAC20
Surface Water Plants

Constraints: None
Design Criteria:

1) Reactivation frequency = 90 days
2) Onsite generation for systems serving more than 10,000 people
3) Media replacement for systems serving 10,000 or fewer people

Average Flow (mgd)	O&M Cost ($)
0.00005	$9,222
0.00150	$9,222
0.00540	$18,223
0.00950	$25,644
0.02500	$47,782
0.05400	$47,639
0.08400	$61,728
0.11000	$74,417
0.23000	$123,691
0.35000	$171,149
0.41000	$177,242
0.77000	$199,489
1.40000	$237,836
3.00000	$330,703
7.80000	$656,235
11.00000	$863,063
38.00000	$2,448,311
120.00000	$6,727,479
270.00000	$14,362,281
350.00000	$18,123,898
750.00000	$36,931,984

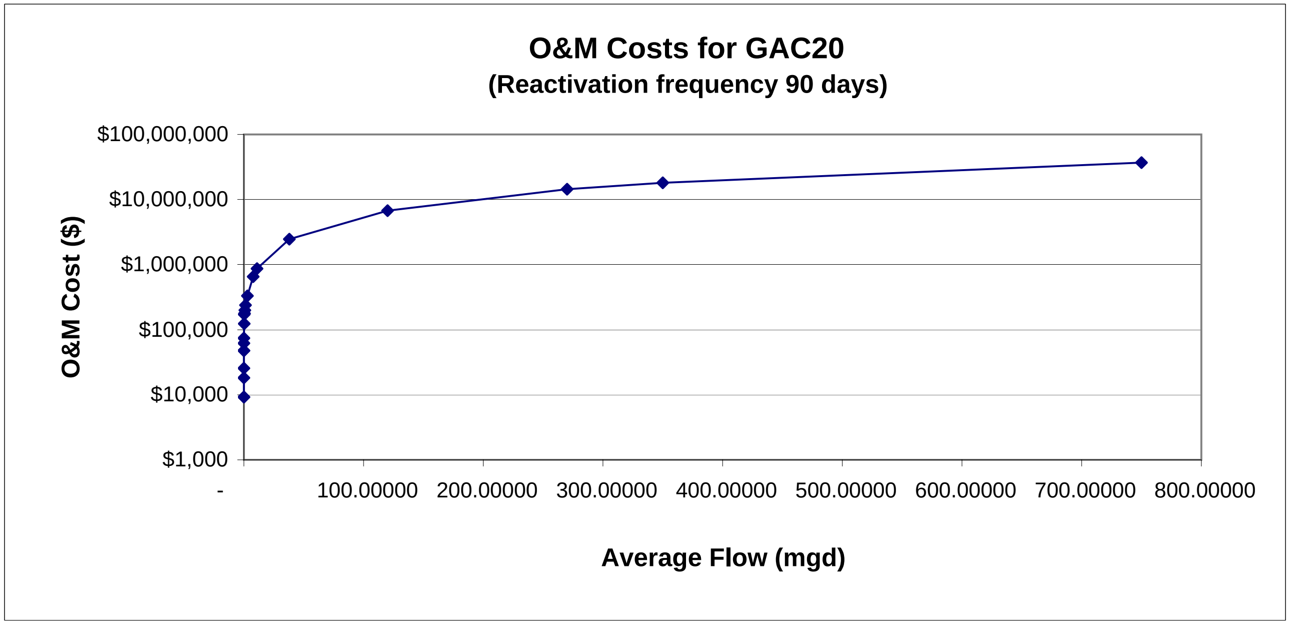


Exhibit D.36 - Capital Costs for GAC20
Ground Water Plants

Constraints: None
Design Criteria:

1) Reactivation frequency = 240 days
2) Onsite regeneration for systems serving more than 10,000 people
3) Media replacement for systems serving 10,000 or fewer people

Design Flow (mgd)	Capital Cost ($)
0.0001	$36,117
0.0070	$36,117
0.0220	$53,091
0.0370	$70,491
0.0910	$137,932
0.1800	$241,793
0.2700	$340,528
0.3600	$435,155
0.6800	$739,387
1.0000	$1,228,620
1.2000	$1,351,323
2.0000	$1,931,036
3.5000	$2,894,585
7.0000	$4,844,129
17.0000	$9,491,603
22.0000	$11,561,478
76.0000	$29,712,377
210.0000	$64,708,727
430.0000	$112,528,561
520.0000	$130,362,039
1,500.0000	$324,548,797

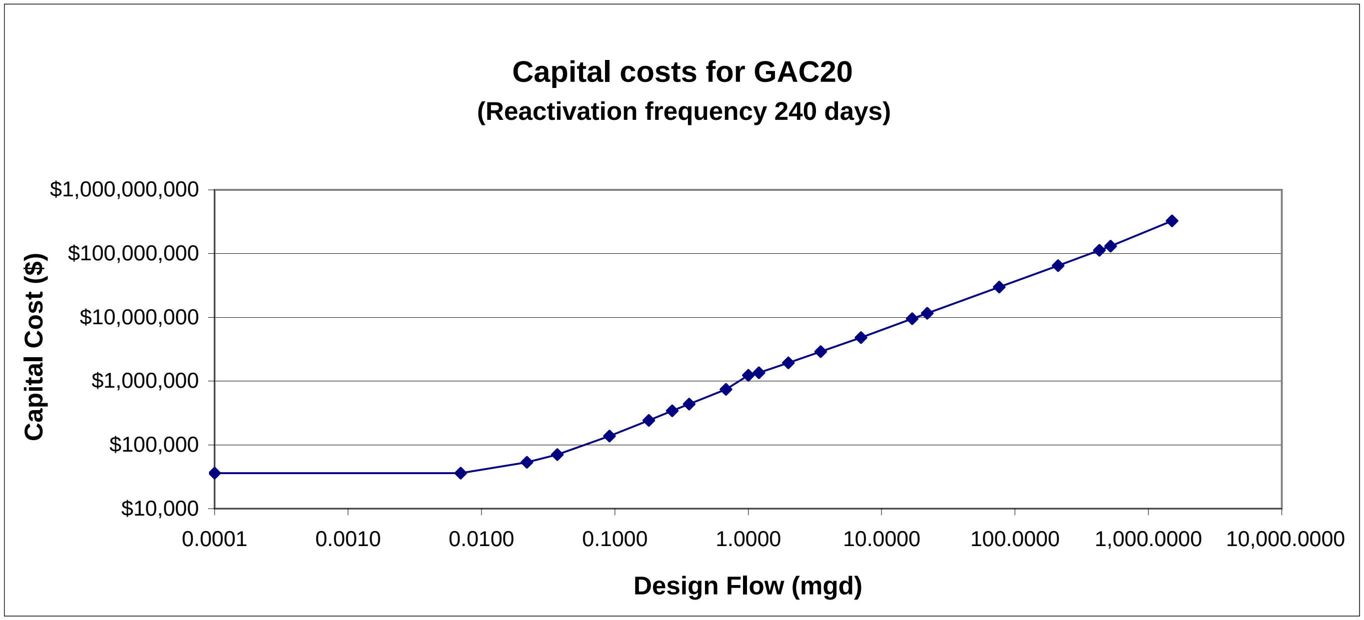


Exhibit D.37 - O&M Costs for GAC20
Ground Water Plants

Constraints: None
Design Criteria:

1) Reactivation frequency = 240 days
2) Onsite regeneration for systems serving more than 10,000 people
3) Media replacement for systems serving 10,000 or fewer people

Average Flow (mgd)	O&M Cost ($)
0.00005	$6,673
0.00150	$6,673
0.00540	$11,206
0.00950	$14,742
0.02500	$24,752
0.05400	$35,068
0.08400	$42,835
0.11000	$50,123
0.23000	$75,023
0.35000	$98,679
0.41000	$96,623
0.77000	$110,575
1.40000	$134,831
3.00000	$193,396
7.80000	$367,103
11.00000	$469,818
38.00000	$1,294,938
120.00000	$3,624,295
270.00000	$7,945,037
350.00000	$9,865,622
750.00000	$19,468,547

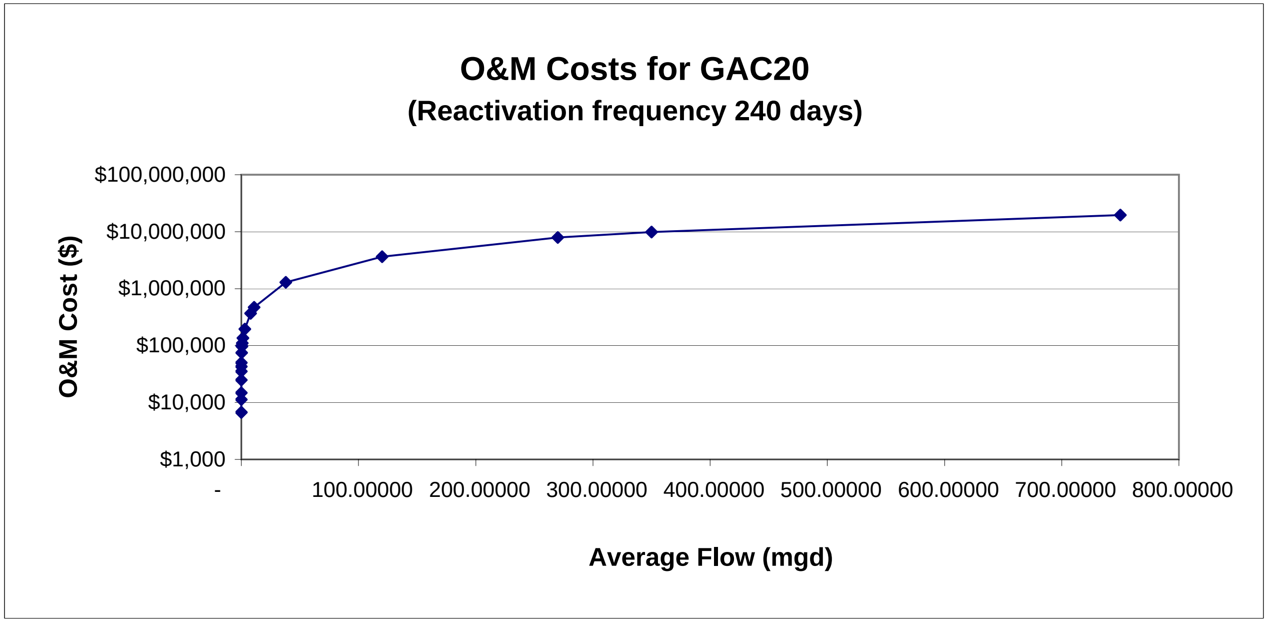


Exhibit D.38 - Capital Costs for Nanofiltration
Surface Water Plants

Constraints: None
Design Criteria:
1) Water temp. 10 degrees C
2) Ocean discharge

Design Flow (mgd)	Capital Cost ($)
0.0001	$51,894
0.0070	$51,894
0.0220	$69,241
0.0370	$86,588
0.0910	$156,079
0.1800	$222,829
0.2700	$315,937
0.3600	$357,087
0.6800	$663,375
1.0000	$912,423
1.2000	$1,080,532
2.0000	$2,018,579
3.5000	$3,404,129
7.0000	$6,745,258
17.0000	$15,456,118
22.0000	$19,862,964
76.0000	$57,558,238
210.0000	$129,659,099
430.0000	$265,356,059
520.0000	$318,914,577
1,500.0000	$902,107,327

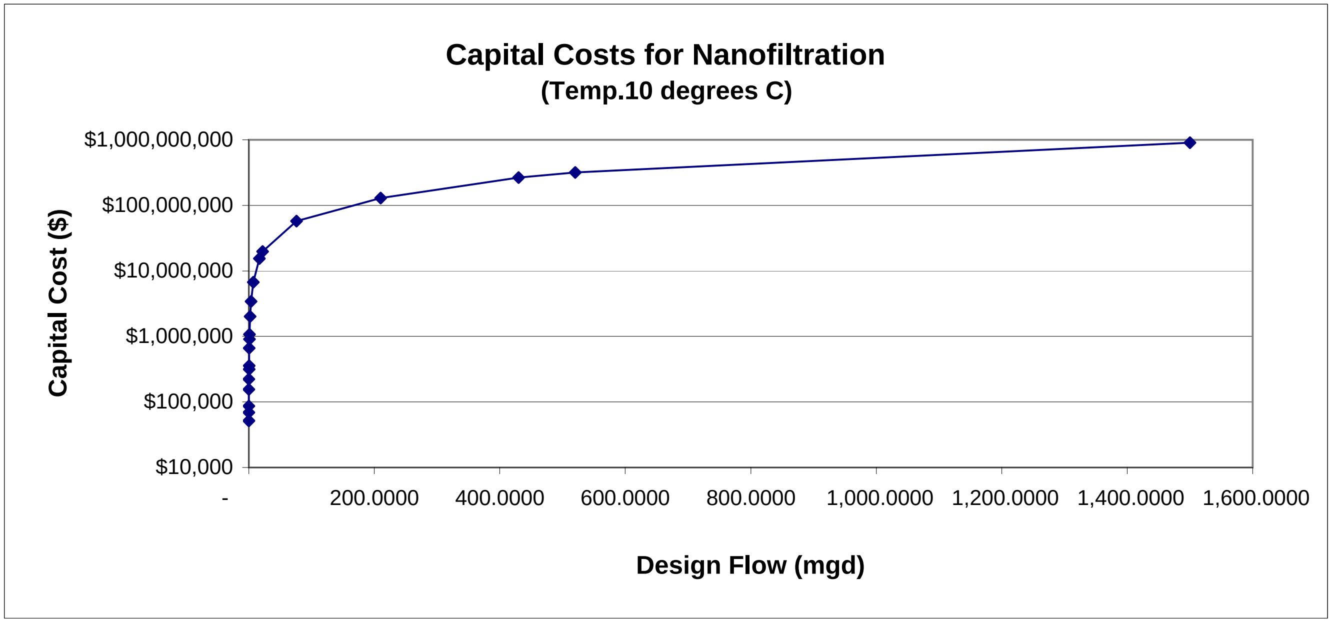


Exhibit D.39 - O&M Costs for Nanofiltration
Surface Water Plants

Constraints: None
Design Criteria:
1) Water temp. 10 degrees C
2) Ocean discharge

Average Flow (mgd)	O&M Cost ($)
0.00005	$6,909
0.00150	$6,909
0.00540	$7,937
0.00950	$9,025
0.02500	$13,703
0.05400	$29,539
0.08400	$37,904
0.11000	$43,223
0.23000	$70,725
0.35000	$112,309
0.41000	$126,572
0.77000	$205,817
1.40000	$343,298
3.00000	$710,894
7.80000	$1,780,761
11.00000	$2,429,844
38.00000	$7,914,024
120.00000	$23,845,168
270.00000	$52,975,344
350.00000	$68,097,181
750.00000	$143,706,367