United States Environmental Protection Agency

Technology and Cost Document for the Final Ground Water Rule

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Contents

List of Exhibits

List of Acronyms and Abbreviations

A^0	Angstrom
adj.	adjustment
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
BCI	Building Cost Index
BLS	Bureau of Labor Statistics
BMP	Best Management Practice
BPJ	Best Professional Judgment
BVP	bovine parovirus
°C	degrees centrigrade
C	Residual Disinfectant Concentration (in mg/L)
CAP	Total Capital Cost
CCCBFP	Cross-Connection Control and Backflow Prevention
CIP	Clean In-Place
cm	centimeter
CPI	Consumer Price Index
CSTR	Continuous Stirred-tank Reactor
CSU	California State University
CT	product of the residual disinfectant concentration (C) & the disinfectant contact time (T)
CWC	Culp/Wesner/Culp
CWS	Community Water System
CY	Cubic Yard
DBP	Disinfection Byproduct
EA	Economic Analysis
ECBO	Enteric Cytopathogenic Bovine Orphan
ECI	Employment Cost Index
E&I	Electrical and Instrumentation
ENR	Engineering News Record
ft	foot or feet
ft^2	square feet
gal	gallons
gpd	gallons per day
gpd/ft^2	gallons per day per square feet
gpm	gallons per minute
GWR	Ground Water Rule
GWSS	Ground Water Supply Survey
GWUDI	Ground Water Under Direct Influence of Surface Water
HAA	Haloacetic Acid
HAV	Hepatitis A Virus
HCC	hepatitus contagiosa
hp	Horsepower
HPC	Heterotrophic Plate Count
hr	hour
HSA	Hydrogeologic Sensitivity Assessment
HVAC	Heating, Ventilation, and Air Conditioning

I&C	Instrumentation and Controls
ICP	Inductively Coupled Plasma
ICR	Information Collection Rule
IESWTR	Interim Enhanced Surface Water Treatment Rule
in	inch
IT	Irradiance Multiplied by Time
kgal	kilogallons
kg/mg	kilograms per milligram
kgpd	kilogallons per day
kW	kilowatt
kWh	kilowatt hours
kWh/ft^2/yr	kilowatt hour per square foot per year
kWh/lb	kilowatt hour per pound
lb	pound
lb/day	pounds per day
lb/kg	pounds per kilogram
LF	Linear Foot
L/gal	liter per gallon
LOX	Liquid Oxygen
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
µm	micrometer
µmhos/cm	micromhos per centimeter
MCL	Maximum Contaminant Level
MF	Microfiltration
mgd	million gallons per day
mg/g	milligrams per gram
mg/L	milligrams per liter
mg-min/L	milligrams minute per liter
mm	millimeters
NCWS	Noncommunity Water System
NDWAC	National Drinking Water Advisory Council
NETA	National Environmental Training Association
NF	Nanofiltration
nm	nanometers
NOM	Natural Organic Matter
NPDES	National Pollutant Discharge Elimination System
NPDWR	National Primary Drinking Water Regulations
NRC	National Research Council
NV	Newcastle Disease Virus
NWQA	National Water Quality Association
O.C.	on center
OEM	Original Equipment Manufacturer
O&M	Operation and Maintenance
O&P	Overhead and Profit
ORP	Oxidation-Reduction Potential
PLC	Programmable Logic Control
POE	Point-of-Entry
POTW	Publicly Owned Treatment Works

POU	Point-of-Use
PPI	Producer Price Index
ppm	parts per million
PSA	Pressure Swing Absorption
psi	pounds per square inch
P&V	Pipes and Valves
PVC	polyvinyl chloride
PWS	Public Water System
Q_{10}	factor by which disinfection rates increase for each 10°C rise in water temperature
rpm	revolutions per minute
SDWA	Safe Drinking Water Act
SDWIS	Safe Drinking Water Information System
SWAP	Source Water Assessment Program
SWTR	Surface Water Treatment Rule
T	Disinfectant Contact Time (in minutes)
TDH	Total Dynamic Head
TDP	Technology Design Panel
TDS	Total Dissolved Solids
THM	Trihalomethane
TTHMs	Total Trihalomethanes
TOC	Total Organic Carbon
UIC	Underground Injection Control
UF	Ultrafiltration
UFTREECO	University of Florida Training, Research, and Education for Environmental Occupations Center
U.S.	United States
USGS	United States Geological Survey
USEPA	United States Environmental Protection Agency
VS	Vesicular Somatitis
VSS	Very Small Systems
WEF	Water Environment Federation
WIDB	Water Industry Database
W/W	Water and Wastewater Model

List of Chemical Formulae

$CaCO_3$	calcium carbonate
$Ca(OCl)_2$	calcium hypochlorite
Cl	chlorine
Cl^-	chloride ion
ClO_2	chlorine dioxide
ClO_2^-	chlorite
ClO_3^-	chlorate
Fe^{2+}	iron (II)
H^+	hydrogen ion
HO_2	hydrogen dioxide
HO_3	hydrogen trioxide
HO^{C}	hydroxyl free radical
$HClO_2$	chlorous acid
$HClO_3$	chloric acid
HCO_3^{C}	bicarbonate free radical
HCO_3^-	bicarbonate ion
H_2O_2	hydrogen peroxide
HCl	hydrogen chloride or hydrochloric acid
$HOCl$	hypochlorous acid
H_2S	hydrogen sulfide
H_2SO_4	hydrogen sulfate
Mn^{2+}	manganese (II)
Mn^{4+}	manganese (IV)
$NaCl$	sodium chloride
$NaClO_2$	sodium chlorite
$NaClO_3$	sodium chlorate
$NaOCl$	sodium hypochlorite
O_2	molecular oxygen
O_2^-	molecular oxygen unstable reactive intermediate
O_3	ozone
O_3^-	ozone unstable reactive intermediate
OCl^-	hypochlorite ion
OH^-	hydroxyl ion

1. Introduction

1.1 Purpose of the Document

This document is one of several technical documents prepared in support of the Ground Water Rule (GWR) The document describes treatment technologies and best management practices (BMPs) that ground water systems can consider as corrective actions or safeguards to reduce or eliminate microbial risks. The document also presents the estimated costs associated with their installation, implementation, and operation.

1.2 Statement of Statutory Requirements

The United States Environmental Protection Agency (EPA) has the responsibility to develop a ground water rule which not only specifies the appropriate use of disinfection but, just as important, also addresses other components of ground water systems to assure protection of public health. Section 1412(b)(1)(A) of the Safe Drinking Water Act (SDWA) requires EPA to establish National Primary Drinking Water Regulations (NPDWRs) for contaminants that "may have an adverse effect on the health of persons," are "known to occur or there is a substantial likelihood that the contaminant will occur in public water systems with a frequency and at levels of public health concern," and for which, "in the sole judgment of the Administrator, regulation of such contaminant presents a meaningful opportunity for health risk reductions for persons served by public water systems." Section 1412(b)(8) requires the EPA to develop regulations specifying the use of disinfectants for ground water systems as necessary.

1.3 Document Organization

This document is organized into five chapters as follows:

- **Chapter 1. Introduction** discusses the purpose and organization of the document, presents an overview of the treatment technologies and BMPs described in the document, and explains how the information provided in this document support the development of the GWR. A detailed description and derivation of costs for these technologies and practices are presented in the following chapters of this document.

- **Chapter 2. Introduction to Water Treatment Technologies** describes well-established pathogen inactivation and removal technologies applicable to reduce microbial risks fromground water sources, including evaluations of efficacy data and advantages and disadvantages for each technology. A discussion of the potential impact of certain technologies on the levels of disinfection byproducts (DBPs) in finished water is also presented to enable evaluation of the risk/risk trade-offs associated with chemical disinfection. Where applicable, the chapter considers waste disposal and operations and maintenance (O&M) requirements for the treatment technologies discussed.

- **Chapter 3. Costs for Treatment Technologies** presents design criteria, costing methodologies, and unit cost elements for treatment technologies. The design criteria presented address those elements used in the costing methodologies. Costs for each technology include both capital and O&M costs.

- **Chapter 4. Introduction to Best Management Practices** describes ten different BMPs that prevent, eliminate, or reduce contamination within ground water systems, and notes advantages and disadvantages or limitations of each. A description and discussion of implementation issues is also presented for each BMP.

- **Chapter 5. Costs for Best Management Practices** presents costs for each of the BMPs discussed in Chapter 4. This chapter outlines assumptions and describes oversight costs, where relevant, for systems, States, or EPA.

- **Appendix A. Cost Equation Coefficients** presents the linear coefficients used to calculate costs for each of the treatment technologies for which costs were calculated.

1.4 Treatment Technologies

Treatment technologies are water treatment processes that provide public health protection by achieving a specified level of contaminant removal or, in the case of microbial contamination, inactivation or removal. The contaminants of concern for the GWR are viruses and bacteria. Modes of treatment technologies include: centralized treatment facilities, prefabricated and designed package treatment units or plants (decentralized or remotely operated), and point-of-entry (POE) devices. Some of these technologies may be used on an interim basis to provide temporary disinfection until permanent changes can be implemented.

An important consideration to the practical use of any treatment technique is the economic feasibility of the selected treatment technique and financial capability of the public water system (PWS). Some of the technologies identified for use to meet GWR requirements are more complex and expensive than others, but because of site-specific conditions and system size, may be more applicable for eliminating microbial contamination. Some water systems (e.g., the smallest) cannot use certain technologies due to operational complexity, manpower or training requirements, economic considerations, or other local conditions or requirements. In accordance with SDWA requirements, EPA must evaluate and list affordable treatment techniques for small public water supplies serving populations of: 25 to 500 people; 501 to 3,300 people; and 3,301 to 10,000 people.

Under the GWR, treatment techniques will not include point-of-use (POU) devices since section 1412(b)(4)(E)(42 U.S.C.300g-1(b)(4)(E)) of the SDWA directs EPA not to list any POU treatment technology to achieve compliance with a maximum contaminant level or treatment technique requirement for a microbial contaminant (or an indicator of a microbial contaminant). Given the importance of disinfection, it is important to note that the National Research Council (NRC) cites that surface water disinfection using point-of-entry (POE) and POU systems is generally regarded as inappropriate (NRC, 1997) because the use of POE devices weaken the systems assurance that public health is being protected and customer access to some devices may make maintenance difficult. Other factors such as management and monitoring frequency of POE and POU systems may make disinfection with POE and POU systems less practical than centralized treatment at the community level (NRC, 1997).

Viruses are the target microbial pathogen for ground water sources because they are more mobile in an underground setting, and are usually more resistant to inactivation and less amenable to filtration processes than bacteria. EPA believes that protection against viruses will provide additional protection against bacteria co-occurring in contaminated ground water. The 4-log inactivation or removal of viruses is the standard of comparison for this document because it is consistent with the disinfection treatment objectives for drinking water from surface water sources (USEPA, 1991a). Protozoa, such as

Cryptosporidium, are more resistant to conventional disinfection methods than bacteria and viruses, but are not the target microorganism for disinfection in ground water because the filtering action of the soil or aquifer media immobilizes protozoa. Any ground water source that does contain protozoa is defined as ground water under the direct influence of surface water (GWUDI). GWUDI sources are regulated the same as surface water sources under EPA regulations such as the Surface Water Treatment Rule (SWTR), the Interim Enhanced Surface Water Treatment Rule (IESWTR), Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR), and Long Term 2 Enhanced Surface Water Treatment Rule (LT2).

This document provides information on treatment techniques that PWSs could use for primary pathogen inactivation and removal. Information on some technologies that may be utilized as secondary disinfection technologies is also presented, although it is not required in the rule. Primary disinfection technologies are capable of achieving a mandatory log inactivation, or removal of pathogenic or indicator microorganisms prior to distribution. Secondary disinfection technologies are capable of providing a residual disinfectant in the distribution system. In order to meet the GWR requirements, a treatment technology must, at a minimum, satisfy the following criteria:

- Field scale applications of the technology or projections from field or pilot studies are available, and it is reasonable to assume that the technology will perform in a similar manner under most field conditions

- The technology is compatible with other treatment technologies (e.g., technologies for iron and manganese removal)

- The technology can achieve effective contaminant inactivation or removal (i.e. 4-log virus inactivation)

Exhibit 1.1 lists the treatment technologies described in this document and classifies them by chemical (chlorine and non-chlorine based) and physical methods.

Exhibit 1.1 Treatment Technologies

Chlorine Based Treatment Technologies	Non-Chlorine Based Chemical Treatment Technologies	Physical or Irradiation Process (Non-Chemical) Based Treatment Technologies
Gas chlorination Hypochlorination Chlorine dioxide Anodic oxidation	Ozonation	Nanofiltration (NF)

Although all of the technologies listed in Exhibit 1.1 are evaluated in this document, the selection of any particular technology in response to GWR requirements is dependent on a variety of site specific characteristics. Some technologies which were considered but not included are chloramines, reverse osmosis, and UV. Chloramines were not considered because they cannot reasonably achieve 4-log virus inactivation. Reverse Osmosis was not included because nanofiltration is a similar technology and can achieve the treatment goals at a much lower cost. UV was not included because current validation procedures do not allow for validation of reactors for 4-log virus inactivation. Although systems could employ 2 reactors in series or UV in series with another technology, these options would be more expensive than those described in this document.

1.5 Best Management Practices

There are numerous sanitation practices or BMPs that can be used to prevent, identify, and correct situations that may cause microbial contamination of a ground water supply. Implementation of BMPs may represent cost effective methods for achieving (or helping to achieve) the health protection requirements of the GWR.

This document classifies BMPs into assessment and corrective action BMPs. Assessment BMPs, such as sanitary surveys and hydrogeologic sensitivity assessments, are measures performed to identify the components of PWSs that are vulnerable to the introduction of contamination. Systems implement assessment BMPs to screen or prioritize defects or vulnerabilities in order to protect public health. Assessment BMPs do not in and of themselves result in improved water quality. Corrective action BMPs, which are divided into significant deficiency, source water, and additional corrective actions, are measures performed to protect a system from a source of contamination. This document limits the discussion on BMPs to those measures that a system may implement to address microbial contamination.

1.6 Use of the Information Presented in this Document

Readers may use the information presented in this document to evaluate the effectiveness, costs, and operational constraints of technologies available to PWSs for inactivation or removal of microbial contaminants from drinking water drawn from ground water sources or to remedy a significant deficiency. Similar evaluations may also be made for technologies used to correct significant deficiencies that may lead to microbial contamination of drinking water drawn from ground water sources. In addition, evaluations can be conducted of BMPs used to prevent, identify, and correct situations that may cause microbial contamination of a ground water supply.

Information presented in this document also serves as a foundation for making comparisons between regulatory alternatives developed by EPA, States, and other interested parties. The information is meant to be used for evaluation and comparison purposes at the national level only and not as direct input into system-specific design or budget preparation for non-EPA entities.

2. Introduction to Treatment Technologies

2.1 Introduction

This chapter discusses chemical inactivation technologies and physical removal technologies that may be used to address microbial contaminants in response to Ground Water Rule (GWR) requirements. For each technology, a description and brief discussion illustrate the technology's efficiency in eliminating microbial contaminants as well as the advantages and disadvantages of its use. An assessment is also presented regarding how widely each technology is utilized. The treatment technologies described are gas chlorination, hypochlorination, chlorine dioxide, on-site oxidant generation (anodic oxidation), ozonation, and nanofiltration (NF).

General evaluations are made based on published research to determine the relative effectiveness of each technology based upon the ability to achieve 4-log inactivation or removal of viruses from ground water. In general, viruses are more resistant to disinfection than bacteria and protecting against viruses should also ensure sufficient protection against the presence of bacteria in contaminated ground water.

Research regarding the disinfection properties of specific chemical-based technologies often correlate the product of the residual disinfectant concentration, C (in milligrams per liter [mg/L]), and the residual disinfectant contact time, T (in minutes) (CT) values to the log inactivation of pathogens. The SWTR formally established the concept of CT in chemical disinfection as the primary method for determining inactivation levels (USEPA, 1989a). The time from the point of disinfectant application to the point of residual disinfectant measurement, or between points of residual measurement, is the contact time. The following EPA documents present a detailed description of the application of the CT concepts to disinfection practices:

- The preamble to the SWTR. *Federal Register*; June 29, 1989; p. 274–86 (USEPA, 1989a).
- SWTR Guidance Manual (USEPA, 1991a; AWWA, 1991b).

Although eliminating the source of contamination is a viable alternative for some ground water supplies, the most widely used method of microbial control among public water supplies is chemical disinfection (USEPA, 1997a; SDWIS, 1997). Systems use disinfection to inactivate, remove, or kill disease-causing microorganisms. Chemical methods may inactivate microorganisms in several ways:

- By causing damage to the cell wall which causes alterations in cell permeability and affects nutrient and ion transport.
- By causing alteration of the cell protoplasm, denaturing the cell components, and precipitating important cell proteins.
- By oxidizing functional groups in enzymes, oxidizing minerals essential for cell growth, and disrupting electron transfer mechanisms within the cell genetic material (AWWA and ASCE, 1990).

For example, an increase in the oxidation-reduction potential (ORP) of the cellular environment could disrupt protein synthesis within the cell and consequently inactivate it (Metcalf and Eddy, 1991).

Adding oxidizing chemicals to water is the most common disinfection treatment method; however, physical methods may provide similar results. Membrane treatment methods such as NF do not inactivate microbes by impacting their metabolic processes, but rather remove microorganisms through physical mechanisms such as straining and electrostatic repulsion.

2.2 Chlorine-Based Treatment Technologies

This section presents the general chemistry and CT information for the following chlorine-based disinfection technologies:

- Chlorine gas (Section 2.2.2)
- Hypochlorite (Section 2.2.3)
- Temporary Hypochlorination (2.2.4)
- Chlorine Dioxide (Section 2.2.5)
- Anodic Oxidation (Section 2.2.6)

The chemistries of chlorine gas, hypochlorite and anodic oxidation are similar; they all react with water to form the disinfecting agents - hypochlorous acid (HOCl) and hypochlorite ion (OCl^-). Since they require similar doses and contact time, they can achieve inactivation rates with similar CT values. The other chlorine-based disinfectant, chlorine dioxide, differs in its disinfection mechanisms.

Chlorine dioxide (ClO_2) is a more powerful oxidizing agent than chlorine, and does not react with water. ClO_2 is not as effective against viruses as other chlorine-based technologies. However, the effects of pH and temperature on CT values are similar to those on chlorine.

2.2.1 The Concept of Chlorine Residual

During gas chlorination and hypochlorination, chlorine reacts with water to form HOCl and OCl^-, the free chlorine residuals that are the disinfecting agents. This process is known as hydrolysis and occurs as follows:

$$Cl_2(g) + H_2O \rightleftharpoons HOCl + H^+ + Cl^-$$

Next, ionization occurs:

$$HOCl \rightleftharpoons H^+ + OCl^-$$

These equations indicate the release of one or two protons. pH levels in drinking water typically drop between 0.5 and 1.5 pH units as a result of chlorination during typical operations.

In the hypochlorination process, sodium hypochlorite or calcium hypochlorite in solution ionize directly to form hypochlorite ion as follows:

$$NaOCl \rightleftharpoons Na^{+} + OCl^{-}$$

$$Ca(OCl)_2 \rightleftharpoons Ca^{++} + 2OCl^{-}$$

Reaction with water can produce HOCl and hydroxide ion:

$$H_2O + OCl^{-} \rightleftharpoons HOCl + OH^{-}$$

2.2.1.1 Chlorine Dose and Contact Time

As discussed in section 2.1, CT values are the product of residual disinfectant concentration and contact time. When chlorine is added to water, it reacts with inorganic ions and compounds such as iron (Fe^{2+}), manganese (Mn^{2+}), and hydrogen sulfide (H_2S) found in the water and in some system structural materials. Therefore, the chlorine is not fully available for disinfection. The amount of chlorine needed to react with these substances is known as chlorine demand. The chlorine dose (in mg/L) is the amount of chlorine added to satisfy the chlorine demand and provide a free chlorine residual up to the end of the contact period:

Chlorine dose = chlorine demand + free available residual chlorine

To illustrate the effects of chlorine demand, water with a chlorine demand of 0.5 mg/L and a residual requirement of 0.5 mg/L needs a dosage of 1 mg/L of free chlorine. Typical chlorine dosages for ground water systems range from 0.2 to 4 mg/L.

For daily plant operation, calculations of the amount of chlorine needed to satisfy the chlorine demand are in pounds per day. For example, the following equation calculates the amount of chlorine required to satisfy a 1.0 mg/L dosage:

$$Cl_2 \; \frac{lbs}{day} = Average\ Flow\ (gpd) \times dose \left(\frac{mg}{L}\right) \times \frac{1\ kg}{1{,}000{,}000\ mg} \times \frac{lb}{0.45\ kg} \times \frac{3.78\ L}{gal}$$

Systems must allow sufficient contact time for attaining the necessary CT values to achieve proper disinfection of bacteria and viruses. For a given water, the longer the chlorine remains in the water, the greater the inactivation of microorganisms. Depending on the necessary contact time and particular types of treatment in place, systems can apply disinfectants anywhere between the wellhead and the first customer.

Attainment of contact times occurs in the distribution system or in contact basins designed specifically for the task. Types of contact basins include clear wells and treated water reservoirs with flow-through piping. A basin with at least four compartments and baffle walls that distribute flow across the cross-section of the basin is ideal. Baffle walls minimize flow short-circuiting and maximize the utilization of the basin volume. Baffle walls also reduce inlet and outlet flow velocities, distribute water over the basin’s cross section and simulate a plug-flow reactor (Montgomery, 1985; WEF and ASCE, 1992).

Small water systems can have difficulty attaining sufficient contact time, especially for those systems that employ package plants or have limited space for water storage (NRC, 1997). These systems may meet CT values by using enlarged or existing discharge pipes and contact basins dedicated to the disinfection process. Applying chlorine in combination with other functions such as fluoridation and water storage also assists systems in meeting CT values. For example, for small systems serving a population of about 10,000 people, storage tanks with capacities of up to 30,000 gallons may suffice and a change in the system's pumping structure may not be required. The following calculation demonstrates this point (assuming a per capita flow of 150 gallons per day (gpd) and a contact time of 28 minutes):

$$10{,}000\ people \times 150\ gpd \times 28\ \min \div 1{,}440\ (\frac{\min}{day}) = 30{,}000\ gal$$

Exhibit 2.1 presents the required CT values established by the SWTR that achieve 2-, 3- and 4-log inactivation of viruses with chlorine.

Exhibit 2.1 CT Values for Inactivation of Viruses by Free Chlorine (mg-min/L)

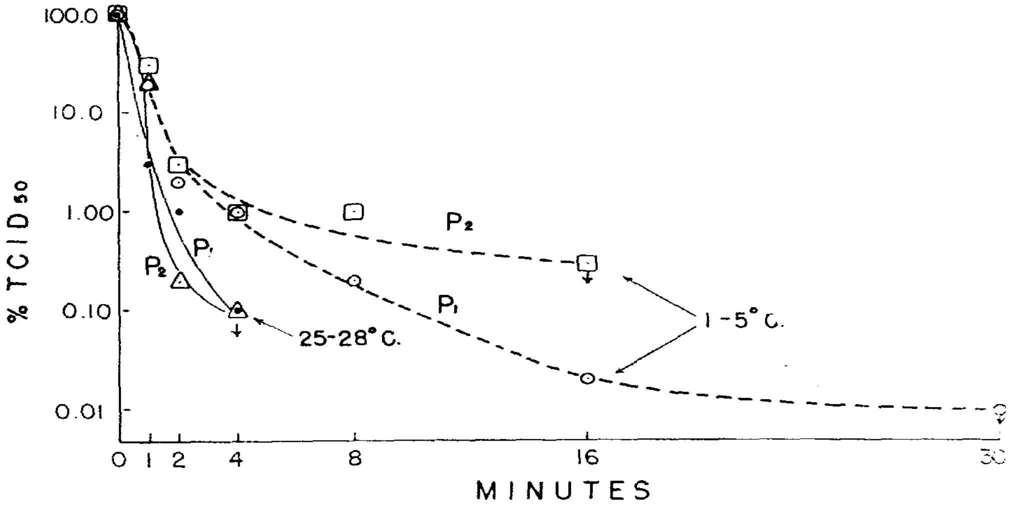
	Log Inactivation[1]					
	2.0		**3.0**		**4.0**	
Temperature °C	**pH 6 – 9**	**pH 10**	**pH 6 – 9**	**pH 10**	**pH 6 – 9**	**pH 10**
0.5	6	45	9	66	12	90
5	4	30	6	44	8	60
10	3	22	4	33	6	45
15	2	15	3	22	4	30
20	1	11	2	16	3	22
25	1	7	1	11	2	15

[1] Presents data for inactivation of Hepatitis A virus (HAV) at pH = 6, 7, 8, 9 and 10 and temperature = 0.5, 5, 10, 15, 20 and 25 degrees centigrade (°C). CT values include a safety factor of 3. To adjust for other temperatures, simply double the CT value for each 10°C drop in temperature.
Sources: USEPA, 1991a; AWWA, 1991b.

Higher temperatures and lower pH values (less than 8) correspond to lower CT requirements to achieve a given level of inactivation. CT values generally increase by a factor of at least two to three times for each 10°C fall in temperature. In other words, disinfection efficiency (measured as a percent loss in inactivation) decreases with the decrease in temperature (USEPA, 1991a; AWWA, 1991b). Water treatment chemistry literature defines a Q_{10} value as the factor by which disinfection rates increase for each 10°C rise in water temperature (the Q_{10} empirical common rule). For temperatures below 5°C, disinfection efficiency might be much less than that which follows the Q_{10} empirical common rule. However, studies have not conclusively quantified disinfection efficiencies in waters with temperatures below 5°C (USEPA, 1986). Exhibit 2.2 presents the effects of temperature on disinfection efficiency of polioviruses. Many other factors such as the degree of mixing and turbidity may also affect CT values for chlorination.

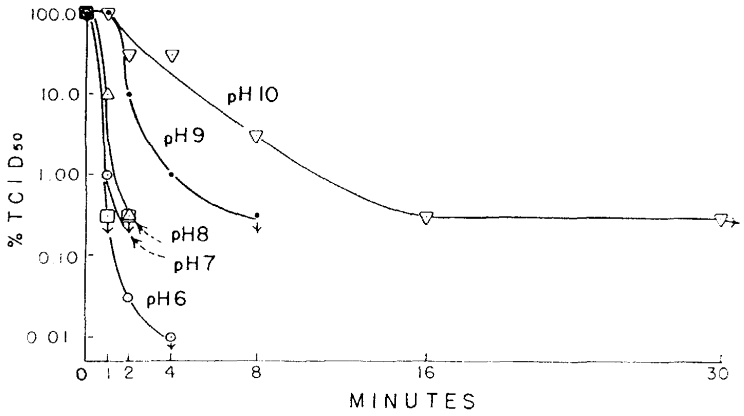
The pH of the water is an important factor in determining virus and bacteria inactivation since the $OCl^!$ and HOCl proportions change dramatically over a pH level range between 6 to 10. The biocidal effectiveness of free chlorine decreases with an increase in pH. HOCl is one and a half to three times more effective than $OCl^!$ as a disinfectant. At a pH of 6, HOCl comprises 98 percent of the $HOCl/OCl^!$ pair. As pH increases, $OCl^!$ is more prevalent, and at a pH level of 10, the $HOCl/OCl^!$ pair consists of over 99 percent $OCl^!$. Temperature slightly affects this equilibrium; lower temperatures slightly favor a higher proportion of HOCl (USEPA, 1986), which in turn increases disinfection efficiency. However, lower temperatures may often cause microorganisms to clump together as the viscosity and surface tension of water increases. This may result in them being shielded from the disinfectant. As a result, the stronger germicidal effect of the higher $HOCl/OCl^-$ ratio may get eroded slightly. Exhibit 2.3 demonstrates the decreased disinfection efficiency of Coxsackie B5 virus by free chlorine at increased pH.

Exhibit 2.2 Inactivation of Poliovirus 1 (Mahoney) and Poliovirus 2 (MEF_1) at pH 7, at 1 to 5°C and 25 to 28°C, with 0.20 to 0.30 ppm Free Residual Chlorine (P_1 = Poliovirus 1, P_2 = Poliovirus 2)



Source: Kelly and Sanderson, 1958.

Exhibit 2.3 Inactivation of Coxsackie B5 Virus at pH 6 to 10 at 25 to 28°C with 0.24 to 0.29 ppm Free Residual Chlorine



Source: Kelly and Sanderson, 1958.

In general, research shows disinfection by chlorination is most efficient with relatively high values for the chlorine residual, contact time, water temperature, and degree of mixing combined with relatively low values for pH, and an absence of interfering substances. But high residuals are limited by DBP Rules. The CT product exhibits the possibility for effective disinfection with low chlorine residuals when combining long contact times with other factors beneficial for disinfection, such as low pH (around 6) and high temperatures.

2.2.2 Chlorine Gas

2.2.2.1 Background

Systems conduct chlorine gas disinfection by injecting chlorine gas into the water stream. In general, large systems are more likely to use chlorine gas, since safety, space, and operational requirements necessary for chlorine gas disinfection may be beyond the operational capabilities of many small systems.

2.2.2.2 Description

A gas chlorination facility consists of chlorine (liquified/pressurized) cylinders, a scale, an evaporator (if the chlorine is drawn from 1-ton cylinders, or if the daily chlorine capacity exceeds 4,000 pounds (lbs/day)), a chlorinator, a control and residual analyzer unit, a combined gas line and gas blow-off valve, injectors, and diffusers. Systems must store chlorination equipment away from other treatment facilities and chemicals because chlorine gas is hazardous and corrosive. Systems must also supply safety equipment, such as a leak detector, scrubber, and ventilation system and have a reliable electricity supply. Contact basins often help systems attain sufficient contact times (Montgomery, 1985; White, 1986).

Evaporating liquid chlorine using pressure feed or vacuum feed methods generates chlorine gas used for drinking water applications. In the pressure feed method, diffusers release chlorine to the water. In the vacuum feed method, the system supersaturates a small flow of water with chlorine and subsequently returns it to the main water flow. Generally, systems prefer the vacuum feed method over the pressure feed method because the vacuum feed method uses negative pressure, which is less likely to result in a chlorine gas leak.

Systems store chlorine as a liquified or pressurized gas in cylinders. For relatively small cylinders tubing from the top of the chlorine cylinders to the chlorinator transfers the chlorine gas. The cylinders are set on platform scales to measure dosage by the loss of weight. Chlorine cylinders have specific withdrawal rates (about 40 lbs/day for a 150-lb cylinder). The withdrawal rate is the maximum amount of chlorine gas a user can withdraw from the tank given the ambient water temperature and the liquid chlorine temperature without freezing the liquid. For one-ton cylinders, users draw liquid chlorine from the bottom of the cylinders and transport the liquid to an evaporator for conversion into a gas (AWWA and ASCE, 1990).

A chlorinator is a supply metering device for chlorine gas controlled by regulated pressure (i.e., pressure feed method) and/or variable orifices (i.e., vacuum feed method). A system may manually or automatically regulate the chlorine feed rate. A manual control chlorinator is sufficient for a small plant or well water supply. In the vacuum feed method, the rate-control-valve of the regulator controls the flow rate. The control unit also includes a gas release valve for ventilation in the event of gas leaks (Viessman and Hammer, 1993). Injectors in the vacuum feed method use the pressurized water supply to create a vacuum that draws chlorine gas at a set dosage through the regulator to the throat of the injector to mix with water (Montgomery, 1985). After injection, throttling valves, or flow indicators, send the solution to the point(s) of chlorination. In the pressure feed method the metering pump sends a set amount of gas directly into the main water line under a specific pressure.

Systems may inject chlorine directly into the main plant flow, with or without the aid of diffusers. Diffusers disperse chlorine across the cross section of the flow. Small pipes (less than 500-mm diameter or 20 in) generally do not need diffusers. Montgomery (1985) recommends diffusers and supplemental mixing for waters with a chlorine demand greater than 1 mg/L.

2.2.2.3 Operation and Maintenance

The general elements of operation and maintenance (O&M) for a chlorination facility are labor, energy, and materials. The time spent on operation activities varies by the size of the facility and the degree of automation at the facility. O&M costs include daily operation, preventive maintenance, and periodic personnel training and certification.

Operation of a gas chlorination facility includes checking and replacing the chlorine cylinders when necessary, checking the valves and flow meters, and monitoring for a chlorine residual. For some systems, residual analyzers monitor the chlorine levels in treated water. Many analyzer systems, often automated, include alarm signals for chlorine residuals that are too low or too high. These analyzers require a continuous sample stream generated by sample pumps.

Personnel require training in the operation of gas chlorination systems. The costs of operator training and certification may be an important cost factor for very small systems. Besides treatment plant operation training, operators also need training on safety procedures and hazardous materials handling. Safety precautions for gas chlorination systems include: checking for leaks in the chlorine cylinders and the gas chlorination transport tubing, replacing gaskets, and the annual cleaning of interior parts (AWWA, 1991a). Chlorine gas leaks are very dangerous, and therefore, systems must routinely monitor the system for leaks. Necessary safety equipment includes a ventilation system and scrubbers, a shower and eye wash, and chlorine gas detectors. In case of emergency, systems must also supply gas masks or self-contained breathing apparatuses and store them outside of the chlorine cylinder storage area.

The final element of O&M of the chlorination facility involves the materials required for routine operation, including chlorine gas, cleaning chemicals, and replacement parts.

2.2.2.4 Microbial Inactivation Capabilities

Gas chlorination is a well-established disinfection technology for inactivating pathogenic viruses and bacteria. Chlorine disinfection can achieve 4-log or greater inactivation of viruses and bacteria. In addition, EPA lists chlorine disinfection as a compliance technology for all system sizes in the SWTR. The SWTR and SWTR Guidance Manual cite a number of studies conducted to demonstrate these capabilities (USEPA, 1991a; AWWA, 1991b).

2.2.2.5 Advantages and Disadvantages

Many systems use chlorine gas disinfection to inactivate viruses and bacteria while providing a distribution system disinfectant residual. Chlorine controls biological growth in water treatment plants, water storage basins, pipelines, reservoirs, provides taste and odor control, enhances color removal, and oxidizes iron and manganese to facilitate their removal through subsequent unit processes such as green-sand filtration. Gas chlorination systems are also flexible and, when properly maintained, reliable.

One disadvantage of chlorination is that chlorine gas is toxic. At low levels, chlorine gas causes eye irritation and respiratory problems; at high doses, serious injury or even death can occur. Chlorine gas systems require regular maintenance and special safety precautions, such as a separate storage space, ventilation, and scrubbing facilities. Liquid chlorine pressure tanks could present an explosion hazard if not handled carefully. Plant operators are required to have hazardous materials training and must wear protective clothing when working with chlorine gas.

Provision of adequate contact facilities may in some cases be impractical and/or cost-prohibitive. Some small systems may not be able to afford the construction of new basins or oversized pipes to meet CT requirements.

Another disadvantage of chlorine gas, along with other chlorine compounds, is the formation of disinfection byproducts (DBPs). The formation of DBPs depends upon the presence of disinfection byproduct precursors in raw water, indicated by the presence of Total Organic Carbon (TOC) or bromide ion. Harmful byproducts form under certain temperature and pH conditions, chlorine residual concentrations, and contact times with raw water containing these precursors. Some known byproducts include trihalomethanes (THMs), haloacetic acids (HAAs), chloral hydrate, chlorophenols, haloacetonitriles, carboxylic acids, ketones, and chloropicrin. Other uncharacterized chlorinated and oxidized intermediates and byproducts may also be formed. Depending on these same raw water conditions, chlorine may also leave an unpleasant taste and odor in finished water.

2.2.3 Hypochlorite

2.2.3.1 Background

In comparison to chlorine gas, the storage and handling of hypochlorite is safer, and for this reason many small systems that chlorinate their water prefer to use hypochlorite. Systems achieve hypochlorite disinfection by injecting sodium or calcium hypochlorite solution (obtained by dissolving granules in water to produce a stock solution) into the water stream.

Sodium hypochlorite (NaOCl) is commercially available in solution form containing up to 10 to 16 percent available chlorine (i.e., the percentage by weight of chlorine available from the commercial grade chemical such as sodium hypochlorite). Calcium hypochlorite ($Ca(OCl)_2$) is a solid compound that dissolves easily in water and comes in tablet, granular, or powder forms containing at least 65 percent available chlorine (USEPA, 1991b). Calcium hypochlorite is also available as a solution. Water treatment plants more commonly purchase hypochlorite stock supplies in the granular or tablet form than the solution form. Produced from lime, sodium and calcium hypochlorite may contain impurities with varying concentrations of iron, chromium, and lead (USEPA, 1986).

2.2.3.2 Description

A hypochlorite facility consists of a solution tank, a pressure feed or vacuum feed system (hypochlorinator) with a flow meter and controls, and a contact basin. The pressure feed system also includes a diaphragm pump, which is run with electric or hydraulic power. The vacuum feed system also includes the use of a venturi tube.

At the beginning of the process, the user mixes calcium or sodium hypochlorite granules with water in a solution tank. An inflow water supply line from the main water line feeds water into the chlorine solution tank. In the pressure feed method, the metering pump sends a set amount of solution into the main water line through a chlorine discharge line and back to the main water line. Chlorinator controls such as in-line digital residual monitoring electrodes monitor the chlorine concentrations, while the water supply pumping unit controls the rate of water injection (USEPA, 1991a; AWWA, 1991b; EPA, 1993a).

The vacuum feed method employs the same type of system as the pressure feed method; however, the flow of water through the vacuum regulates the flow of chlorine. Water in the system draws in the chlorine solution by creating a vacuum as it passes through a venturi tube. An increased flow through the pipe adds chlorine solution to the system. For this reason, the vacuum feed system, once in place, is less likely to cause overdosing or underdosing than the pressure feed system.

A contact basin can be used to increase contact time if the distribution system pipes or existing basins do not provide for it adequately. Since small systems generally use hypochlorite, manufacturers sell them package systems sized according to necessary chlorine flow requirements. White (1986) suggests that systems requiring three lbs/day or less of chlorine and treating 200,000 gpd with a 2 mg/L dose-rate use hypochlorination since it is most economical for systems of this size.

2.2.3.3 Operation and Maintenance

The general elements of O&M for a hypochlorination facility are labor, energy, and materials. The time spent on operation activities varies by the size and the degree of automation of the facility. O&M costs include daily operation, preventive maintenance, personnel training, and in some cases operator certification.

Hypochlorination systems require daily monitoring of the flow meters and chlorine residual analyzer, preparation and addition of hypochlorite solution to the solution tank, replacement of the gaskets, valves and diaphragms, and regular cleaning and backwashing. The solution container also requires periodic cleaning.

The cost of training and certification for the operator may be an important cost factor for very small systems even though the handling of hypochlorite does not require hazardous materials training. Nonetheless, hypochlorite does require careful handling. Contact with hypochlorite can burn the skin and may cause damage to the eyes. Safety procedures for hypochlorite include wearing gloves and a nose mask when handling calcium hypochlorite. Systems must store hypochlorite in airtight, corrosion-resistant containers located in a cool place because hypochlorite solids and solution decompose rapidly in heat and because calcium hypochlorite reacts with moisture.

Most of the O&M power costs can be attributed to the operation of pumps/motors. Control panels and automated residual analyzers also require an energy source.

The final element of O&M for a hypochlorination facility includes the materials needed to ensure adequate equipment function. These materials include cleaning chemicals and replacement parts for periodic maintenance and repairs.

2.2.3.4 Microbial Inactivation Capabilities

Hypochlorination is an effective, well-established disinfection technology used in the inactivation of viruses and bacteria.

2.2.3.5 Advantages and Disadvantages

Hypochlorite can be as effective as chlorine gas, and in some cases, sodium or calcium hypochlorite may be more advantageous than gaseous chlorine for small systems because they are easier to handle, need less equipment compared to chlorine gas, and because spills and leaks of hypochlorite can be more easily managed and contained than chlorine gas leaks.

Hypochlorites tend to increase the pH level, rendering them potentially less effective than free chlorine at the same dose. They are also more expensive to purchase than chlorine gas and have a shorter shelf-life, which can affect the feed rate and dosage. High concentrations of hypochlorite solutions are unstable and can produce chlorite ions or chlorate byproducts.

Calcium and sodium hypochlorite solutions are corrosive and require procedures for cautious storage and handling. Using calcium hypochlorite in powder form requires dust control practices to guard against breathing calcium hypochlorite dust and minimizing skin exposure. Skin exposure is particularly dangerous during the hot season when operators are sweating, allowing absorption into pores. For the same reasons, systems must store calcium hypochlorite in corrosion-resistant containers to minimize the possibility of inadvertent exposure. In addition, containers must be stored in a cool, dark place, since hypochlorites degrade over time, particularly if exposed to heat and light.

2.2.4 Temporary Hypochlorination

2.2.4.1 Background and Description

If a system is found to have a serious deficiency or fecal contamination, it may take time for the system to design and install a corrective action. In the mean time, the system cannot serve the contaminated water to its customers. The Primacy agency may require the system to apply 4-log virus disinfection until the contamination is eliminated or a corrective action is put in place. It is assumed that in the case of this interim disinfection, hypochlorination will be used because it is easier to install and operate than gaseous chlorination or other disinfection methods and the least costly of the treatment methods.

2.2.4.2 Implementation Issues

Temporary hypochlorination will perform in the same manner as the permanent hypochlorination described above. The main difference is that the facilities will need to be portable as they will most likely be installed directly at a well site. Operators will need to travel to the well site to take chlorine residuals and periodically refill the tank.

2.2.4.3 Advantages and Limitations

Temporary hypochlorination will enable a system to continue serving water while allowing the system to come up with a permanent solution to a significant deficiency or contamination problem. It will protect customers against microbial contaminants but may not remove other potential contaminants (e.g. arsenic, iron). If the wells have high dissolved iron or manganese concentrations, precipitation in the distribution system could occur leading to customer complaints. Systems may also get customer objections to newly chlorinated systems.

2.2.5 Chlorine Dioxide

2.2.5.1 Background

Chlorine dioxide (ClO_2) is unstable, both as a compressed gas and as a concentrated aqueous solution, and therefore requires on-site generation for use as a drinking water disinfectant (Masschelein, 1992). Under atmospheric conditions, ClO_2 is a yellow to red colored gas with an unpleasant odor. Chlorine dioxide is a powerful oxidizing agent. One of the more widely used procedures for synthesizing ClO_2 is the chlorine-chlorite process of the acidification of $NaClO_2$. The overall reaction is:

$$5NaClO_2 + 4HCl \leftrightharpoons 4ClO_2 + 5NaCl + 2H_2O$$

Mechanistically, this process occurs by a series of coupled reactions, some of which may involve the *in-situ* formation of chlorine, the catalysis by chloride, and the oxidation of chlorite by chlorine (Noack and Doerr, 1979; Gordon, et al., 1972). The yield of the reaction and its rate are improved by low pH values, in which both gaseous chlorine and chlorous acid formation are favored. During the acid-chlorite reaction, the following side reactions also occur:

$$5ClO_2^- + 5H^+ \leftrightharpoons 3ClO_3^- + Cl_2 + 3H^+ + H_2O$$
$$4ClO_2^- + 4H^+ \leftrightharpoons 2Cl_2 + 3O_2 + 2H_2O$$
$$4HClO_2 \leftrightharpoons 2ClO_2 + HClO_3 + HCl + H_2O$$

If reaction stoichiometry is met, then close to 100 percent of the conversion of chlorite may occur, and a final pH below 0.5 will result. The overall chemistry of ClO_2 in acidic waters can be summarized as:

$$ClO_2 + 5e^- + 4H^+ \leftrightharpoons Cl^- + 2H_2O$$

At pH values near neutral or basic, the following base catalyzed reaction occurs (e.g., ClO_2 reduces to chlorite):

$$2ClO_2 + 2OH^- \leftrightharpoons ClO_2^- + ClO_3^- + H_2O$$

2.2.5.2 Description

A ClO_2 generation system consists of a closed-loop or vacuum generator with a metering pump and gravity flow or diaphragm pump, storage tanks for sodium chlorite or sodium chlorate, equipment for gaseous chlorine addition, and a control panel that includes an alarm and shutdown system. Systems generate ClO_2 for drinking water application either by reacting:

- Chlorine gas with sodium chlorite ($NaClO_2$) solution
- Chlorine gas with solid sodium chlorite
- Sodium chlorite with hydrochloric acid (HCl)
- Sodium chlorate ($NaClO_3$) with “other reactants” such as H_2O_2 and H_2SO_4

For drinking water applications, the most frequently used method of generating chlorine dioxide in the United States is by reacting a solution of sodium chlorite with chlorine gas:

$$2NaClO_2 + Cl_2\ (g) \rightleftharpoons 2ClO_2 + 2NaCl$$

One mole of chlorine is required to react completely with 2 moles of sodium chlorite (i.e., 0.78 part of Cl_2 per part of $NaClO_2$ by weight). Chlorine is normally overdosed to ensure the near complete conversion of sodium chlorite. The excess chlorine in solution is converted to hypochlorous acid which lowers the pH and increases chlorine dioxide production efficiency. As stated above, to generate chlorine dioxide, systems use sodium chlorite in a solid or liquid form. Solid sodium chlorite is only 80 percent pure, while sodium chlorite solution is 25 to 32 percent sodium chlorite by weight. Systems prefer to use liquid sodium chlorite, however, due to the hazardous nature of solid sodium chlorite. As long as the production of chlorine dioxide generates a 95 percent yield, with no more than 5 percent excess chlorine in the effluent, THM production will not occur (AWWA and ASCE, 1990). A properly operated and maintained system will consistently attain a 95 percent yield.

In gaseous chlorine/sodium chlorite solution generation, the liquid sodium chlorite vaporizes and travels to a reaction chamber through a metering pump. The chlorine gas mixes with water and travels to the generator's reaction chamber where the two components react under a vacuum at a pH of 7. The chlorine dioxide forms in the reaction chamber and travels to a contact chamber to ensure ample contact time for disinfection before pumping the water through the distribution system. The design of this system may use an eductor to add chlorine gas and sodium chlorite solution to the water stream before it enters the reaction chamber.

An "enrichment loop" or "closed loop" system is another type of ClO_2 generation system. This generator employs a circulating water loop that ensures the introduction of high levels of dissolved chlorine at a low pH into the reaction chamber. A pump transfers the sodium chlorite from a solution tank to the reactor.

A newer technology reacts solid sodium chlorite with gaseous chlorine to produce chlorine dioxide gas with less than or equal to 1 percent free chlorine. This generator reacts dilute, humidified Cl_2 with $NaClO_2$ in a sealed reactor cartridge. The amount of chlorine dioxide produced is a function of the feed rate of chlorine and may range from 0 to 100 percent. This process generates chlorine dioxide gas free of the chlorite and chlorate ions often produced in other types of generation systems with poor generation efficiency (Hoehn et al., 1996; Berringer et al., 1996).

Manufacturers also make small wall-mounted units for chlorine dioxide generation. These units generate chlorine dioxide through both the chlorine-chlorite process and the acid-chlorite process. Wall-mounted models for the chlorine-chlorite process include flow rate meters that regulate the flows from the gaseous chlorine supply and the sodium chlorite supply to the reaction zone. The ClO_2 contacts the water in the eductor and receives more contact time in the absorption column before flowing out to the water supply. Wall-mounted units using the acid chlorite generation process have a similar configuration (CSU, 1996).

2.2.5.3 Operation and Maintenance

The time spent on operation activities varies by the size and the degree of automation of the facility. O&M cost categories are daily operation, preventive maintenance, personnel training, and certification.

The operation of a chlorine dioxide system requires a trained staff and continuous plant monitoring. Operators require training in system start-up and shutdown, operation, equipment cleaning, and feed pump and rotameter calibration. Daily operation of the system requires adjustments of flow meters and rotameters that control the flow of Cl_2 gas and $NaClO_2$ solution. The enrichment loop system is more complex, requiring additional maintenance of the pumps and assembly associated with the recirculating loop. Also, operators require training in the O&M of gas chlorinators.

ClO_2 generator efficiency requires frequent tuning, and the generator requires recalibration if the production rate needs to be varied. Inefficient generators cause excess free chlorine resulting in the formation of chlorite and chlorate ions. Generator systems employing chlorine gas/solid sodium chlorite reactions ensure the presence of excess solid sodium chlorite, thereby limiting the presence of free chlorine in the reactor cartridge (Berringer et al., 1996).

The cost of operator training and certification may be an important cost factor for small systems. Operators require training in the operation and safety procedures for a chlorine dioxide generation system, including hazardous materials training for the handling of chlorine gas, HCl, and $NaClO_2$. Chlorine dioxide spontaneously combusts at concentrations exceeding 10 percent by volume in air. Operation of the generation system also requires proper handling and storage of chlorine gas cylinders and sodium chlorite. Sodium chlorite may explode upon contact with oxidizable or combustible materials and needs separate storage tanks in enclosed fireproof buildings with a water source nearby for assistance in the event of a spill. In addition, systems should have chlorine gas detectors, floor drains, and emergency gas masks available on-site (Corbitt, 1990).

The materials necessary to ensure adequate equipment function comprise the final O&M component of the ClO_2 facility. These include:

- chemicals that depend on the method used to generate ClO_2 (i.e., chlorine gas, $NaClO_2$, $NaClO_3$, HCl, H_2O_2, and H_2SO_4),
- cleaning chemicals, and
- replacement parts.

2.2.5.4 Microbial Inactivation Capabilities

Chlorine dioxide is a powerful disinfectant and is effective against viruses, bacteria, and highly resistant protozoa (e.g., *Cryptosporidium parvum*). EPA lists chlorine dioxide as a compliance technology for the SWTR. The SWTR Guidance Manual (USEPA, 1991a; AWWA, 1991b) provides CT values for inactivation of viruses as shown in Exhibit 2.4.

Exhibit 2.4 CT Values (mg-min/L) for Inactivation of Viruses[1] by Chlorine Dioxide for pH 6 to 9

Inactivation	Temperature					
	# 1°C	5°C	10°C	15°C	20°C	25°C
2 Log	8.4	5.6	4.2	2.8	2.1	1.4
3 Log	25.6	17.1	12.8	8.6	6.4	4.3
4 Log	50.1	33.4	25.1	16.7	12.5	8.4

[1] Studies pertain to the Hepatitis A virus.

Source: USEPA, 1991a; AWWA, 1991b.

As with many other disinfectants, pH and temperature affect the efficiency of ClO_2. In general, the disinfection efficiency of ClO_2 decreases as temperature decreases (Troyan and Hansen, 1989). Decreases in temperature cause microorganisms to clump together as surface tension and the viscosity of water increase. Consequently, they get shielded from the disinfectant, resulting in lowered disinfection efficiency. For some protozoan cysts, researchers have found ClO_2 to increase in effectiveness with an increase in pH levels (Troyan and Hansen, 1989). Experiments by LeChevallier et al. (1996) suggest oocysts inactivate more rapidly at a pH level of 8 than at a pH level of 6. However, other research studies show chlorine dioxide’s oxidizing potential decreases linearly as pH increases, although its effectiveness on viruses and bacteria does not decrease (Masschelein, 1992). This may make it very effective in inactivating viruses typically found in ground water sources at pH values high enough for final distribution.

2.2.5.5 Advantages and Disadvantages

In addition to its use as a disinfectant, chlorine dioxide can also oxidize metals such as iron (Fe) and manganese (Mn), and control taste, odor, and color (Corbitt, 1990). Chlorine dioxide is advantageous over most other disinfectants since it effectively disinfects over a wide pH range and has a persistent residual. Chlorine dioxide does not produce problematic disinfection byproducts such as THMs, unless too much chlorine is added during generation. Previously considered too complex for most small systems, the availability of wall mounted units simplifies chlorine dioxide generation (CSU, 1996) making chlorine dioxide generators more feasible for smaller systems, as long as staff are well trained in their use.

Chlorine dioxide does, however, have its disadvantages. Some major concerns with chlorine dioxide are its instability, the production of chlorite (ClO_2^-) and chlorate (ClO_3^-) during the generation process, and the incomplete generation of ClO_2 resulting in the presence of unreacted chlorite and chlorate in water (Sawyer et al., 1994). Researchers note human health problems associated with these byproducts (LeChevallier et al., 1996; USEPA, 1992a). Chlorine dioxide requires longer contact times for virus inactivation relative to *Giardia*. Hence, chlorine dioxide systems aimed specifically at virus inactivation require higher capital investment than chlorine-based systems.

Finally, the maintenance of chlorine dioxide as a disinfection technology must address many safety issues and is therefore more expensive to implement than chlorine (USEPA, 2003). Chlorine dioxide requires a separate, explosion-proof storage area and a highly trained staff to prevent accidents. Due to this, it is rarely used in systems serving populations less than 100 and is scarcely used by systems serving populations less than 1,000 (USEPA, 2003).

2.2.6 Anodic Oxidation

2.2.6.1 Background

The anodic oxidation (on-site oxidant generation) disinfection process uses electrolysis of sodium chloride in water by sending an electric current through the salt water. A reaction follows producing various oxidants for disinfection or oxidation of pollutants in raw water (Bradford and Baker, 1994). A cation exchange membrane separates the oxidants generated at the anode from the reactants at the cathode. Oxidants presumed to be produced include hypochlorite ion (OCl^-), HOCl, ozone (O_3), chlorine dioxide (ClO_2), and hydrogen peroxide (H_2O_2). Bradford and Baker (1994) studied the anodic oxidation process and confirmed the presence of HOCl, OCl^-, ClO_2 and O_3 in the oxidant stream. However, they were unable to verify the presence of H_2O_2. The verification of concentrations of oxidants produced at the anode requires additional research. The presence of multiple oxidants enhances the oxidizing strength of the solution such that it is a more effective disinfectant than a solution containing a single oxidant or disinfecting agent.

2.2.6.2 Description

Anodic oxidation units are package units that generally consist of a storage tank, oxidant generator (or cell) and storage tank, an injector, a control panel, and necessary pumps and piping.

Additional system requirements include housing space for the equipment and an electric power supply or solar panels. To ensure proper operation of the anodic oxidation system, the raw water source requires removal of hardness prior to disinfection. Water with a conductivity of more than 150 :mhos/cm requires a water softener (MIOX, 1997). Additionally, some substances that may occur in the source water exert a chlorine demand. System designers must account for these substances, which include organics, iron, manganese, and sulfides.

Energy required for the production of chlorine from salt varies among devices from different manufacturers. Smith and Loveless, Inc. (1996) indicate that for their units, using 3.5 kilowatts (kW) of electricity and 3.5 pounds of sodium chloride (NaCl) can produce 1 pound of chlorine. Units manufactured by Chemical Services Company, Inc. (CSC, 1996) require 3.5 lbs of salt, 2.5 kW of electricity, and 15 gallons of water to produce 1 pound of chlorine. Units from MIOX, Inc., vary in their efficiency; the higher the treated flow, the more efficient the treatment unit (MIOX, 1997). The system uses food grade salt with granules less than 0.5 millimeters (mm), containing no additives or inhibitors.

Some generators work well using sea water as a raw material. Smith and Loveless, Inc. (1996) indicate this disinfection technology is ideal for use at sea and at shorelines where sea water provides the raw material for generating oxidants on-site. For most manufacturers, the sea water models and salt models differ from one another. Salt intakes and production efficiencies vary by manufacturer. Exhibit 2.5 summarizes the oxidant production capabilities based on salt consumption for four of MIOX's models, assuming a need for a dosage of 1 ppm chlorine equivalent to obtain a proper residual.

Exhibit 2.5 Oxidant Production Efficiency of Four of MIOX's Models

	MIOX Brine Pump System	MIOX Model SAL-20	MIOX Model SAL-30	MIOX Model SAL-40
Gallons per day treated at 1 ppm dosage	25,000	250,000	330,000	600,000
Salt consumption	1 lb/hr	3 lbs/hr	3 lbs/hr	3.5 lbs/hr
Daily free available chlorine production	0.5 lbs/day	1.7 lbs/day	3.7 lbs/day	7 lbs/day

Source: Vendor Estimates.

Several systems have successfully used anodic oxidations to maintain a residual throughout the distribution system. Hamm (2002) summarized research from several systems using anodic oxidation and found that systems achieved an average dose reduction of 30 percent while still maintaining adequate residuals over lengths of pipe as long as 9 miles. Minimizing solution storage is critical to maintaining a residual. Under most conditions, injection of the solution generated into the raw water stream is immediate. Extended periods of storage in the pH range 4.5 to 8.8 allows the solution to breakdown. When stored for up to 10 hours prior to disinfection, the solution requires an upward pH adjustment prior to storage (Bradford, 1995). An increase in temperature also increases the rate of oxidant breakdown. Therefore, systems should store the generated solution in a relatively cool location.

2.2.6.3 Operation and Maintenance

The general O&M elements of an anodic oxidation facility are labor, energy and materials. O&M of an anodic oxidation facility includes daily operation, preventive maintenance, and personnel training and certification. Systems purchase anodic oxidation units as a package, spending minimal operational time. Operation requires salt addition and routine control panel checks. Because some treatment and regulatory requirements necessitate the presence of a residual disinfectant, operation also requires analysis of treated water for a chlorine residual. The demand on the electrodes used in the process is high. Efficient unit function requires electrode resistance to electric and chemical corrosion, and the absence of heavy metals.

The manufacturer generally provides the O&M training on anodic oxidation package units (MIOX, 1997; CSC, 1996). Generator and pump operations require a stable energy source and smaller units can be solar powered. Efficiency increases with unit size, requiring less salt and less energy per pound of chlorine generated.

The final O&M component for the facility are the materials required to ensure that the equipment functions adequately. The consumable materials required include salt, cleaning chemicals, and small replacement parts for periodic maintenance and repairs.

2.2.6.4 Microbial Inactivation Efficiencies

Early research by Mahnel (1978) determined the effectiveness of anodic oxidation on inactivating viruses. Mahnel tested 11 viruses at concentrations up to 10^4 infectious units/mL in non-chlorinated tap water. Anodic oxidation inactivated all 11 viruses. The degree of contamination did not affect the results, although the virus inactivation occurred more easily in water with a higher conductivity and a greater current density. The 11 viruses included poliovirus, enteric cytopathogenic bovine orphan (ECBO), Sindbis, influenza-A, Vesicular Somatitis (VS), bovine parvovirus (BPV), reovirus, Newcastle Disease Virus (NV), hepatitus contagiosa canis (HCC), pseudowut, and vacciniavirus.

Current research shows that anodic oxidation can be more effective than chlorine in the disinfection of bacteria, viruses, and protozoa (MIOX, 1997; Venczel et al., 1997; USEPA, 1997b). Research by Bradford and Baker (1994) suggests the anodic oxidation solution is capable of greater than 4-log inactivation of *Vibrio cholerae* and f-2 bacteriophage, as well as a 3- to 5-log inactivation of *E. coli*. Venczel et al. (1997) also showed on-site oxidant generation was effective in inactivating viruses such as MS-2 and bacteria such as *E. coli* and *V. cholerae*.

Anodic oxidation may provide more effective disinfection than chlorine gas, with lower contact times. However, CT values for anodic oxidation are unknown. The efficiency of anodic oxidation on pathogen inactivation requires further study and clarification (Venczel et al, 1997; USEPA, 1997b). The ability of anodic oxidation to produce mixed oxidants also requires further study. Until more CT information is available, EPA suggests using CT values for chlorine. Although these are conservative values, they will ensure adequate time for disinfection. The MIOX manufacturers specify the units (by lbs) of chlorine produced for every unit of salt, electricity, and water consumed. This information could be used to calculate the CT value and ensure the minimum level of disinfection needed.

2.2.6.5 Advantages and Disadvantages

As stated in section 2.2.5.4, anodic oxidation disinfection is effective against bacteria and viruses. Anodic oxidation disinfection is simple and reliable. The principles behind anodic oxidation disinfection enable these systems to operate with potentially lower health or environmental impacts than traditional chlorination methods. Specifically, there is no hazardous substance handling involved in this disinfection process, thus reducing the risk of leaks and potential health impacts. When compared to other disinfection technologies, anodic oxidation systems are cost-effective at design flows around one million gallons per day (mgd) and slightly greater.

The compact, packaged anodic oxidation units provide additional benefits for systems with limited space, especially small systems. EPA lists anodic oxidation as a small-system technology for compliance with the SWTR (USEPA 1997b).

Case studies of water systems using anodic oxidation verify that anodic oxidation produces fewer total trihalomethanes (TTHMs) than disinfection with chlorine gas (Daniel, 1995; MIOX, 1997). Laboratory research suggests varying results regarding TTHM production. Research by Bradford and Baker (1993) demonstrated that anodic oxidation reduces TTHM production by 50 percent in comparison to free chlorine, while research at the University of North Carolina (Venczel et al., 1997) found that anodic oxidation and free chlorine produced similar levels of TTHM.

The main disadvantage of anodic oxidation is higher O&M costs associated with high electrical power requirements.

2.3 Chlorine-Free Treatment Technologies

This section discusses the following chlorine-free disinfection and pathogen removal technologies: ozone and NF. Many systems use NF for the removal of contaminants other than microbial contaminants and its applicability for the removal of pathogenic organisms is very promising.

2.3.1 Ozone

2.3.1.1 Background

According to survey data from the International Ozone Association (Dimitriou, 1997) more than 60 ground water treatment plants in the United States currently use ozonation. The majority of these plants use ozone for oxidation of iron and manganese and control of taste and odor. More than a dozen systems use ozone primarily for disinfection. Ozone disinfection is uncommon among very small community and noncommunity water systems. One noncommunity water system uses a wall-mounted ozone generator with an automatic shutdown mechanism that is used in case of an ozone leak.

2.3.1.2 Description

Ozone disinfection systems require some basic components including an oxygen source, air blower, dust filter, air compressor, cooler and dryer, electric power supply, ozone generating equipment, ozone contactor, filter system, off-gas collector/controller (also known as an ozone destruction unit), control panel with an ozone gas detector and alarm, and a residual monitoring system. Because ozone is a hazardous compound, a separate building often houses the system (Viessman and Hammer, 1993; Masschelein, 1992).

The components of an ozone disinfection system comprise four main process categories, which are described below (DeMers and Renner, 1992).

Feed-Gas: A system requires an oxygen source to generate ozone. The oxygen source can be natural clean dry air, oxygen-enriched air, or oxygen gas. Most systems prefer oxygen gas as an oxygen source because it requires no preparation or treatment before use as a feed gas. The use of air requires devices to dehumidify and clean the air of dust and other impurities. Using humid, dirty air will result in the formation of undesirable byproducts along with the ozone. In addition, excess humidity can affect the ozone production yield (Viessman and Hammer, 1993; Masschelein, 1992). The use of dry or water-ring compressors dehumidifies the air. The compressors require high-quality stainless steel construction. Chemical dehumidifiers such as $CaCl_2$, silica gel, or activated alumina can eliminate the remaining humidity. For small systems producing less than 100-lbs of ozone per day the preferred oxygen source is air because of the safety issues and costs associated with handling liquid oxygen (USEPA, 1993a).

Ozone Generation: The second step in the disinfection process is ozone generation. Electric voltage controls the rate of ozone production. There are many types of ozone generators including: horizontal and vertical dielectric (non-conducting) glass tubes (Welsbach Tube and Megos and Wedeco ozonators), and glass or ceramic plate dielectric generators (Otto Plate Ozonator). Horizontal dieletric glass tube ozonators are widely used for water treatment. This ozonator is a glass tube, sealed at one end, that forces gas to flow through the discharge gap. The dielectric glass is coated with aluminum on the inside, which acts as the second electrode (Masschelein, 1992). In glass or ceramic plate generators, the generation of ozone occurs between the plates. All ozonators produce heat, therefore cooling is important. Cooling the tubes or plates increases the efficiency of ozone production (AWWA, 1990a).

Ozone Contacting/Absorption: The third and most important step in the ozone disinfection process is ozone contacting and absorption. Currently, ozone systems require separate contactors. Ozone transfer into water allows for disinfection in the contactor. The most commonly used contactor is a bubble diffuser contactor which consists of a countercurrent tank with a porous diffuser. The primary reasons for the common usage of bubble diffuser contactors include: no requirements for additional energy (except initial gas compression), proven performance, high transfer rates, and process flexibility. Moreover, bubble diffuser contactors have no moving parts.

To achieve 85 to 95 percent transfer efficiency, bubble diffuser contactors typically require 18- to 22-ft water depths. Since not all of the ozone transfers to the water, systems contain the off-gas by a covered basin. Continuous stirred-tank reactors (CSTR) and baffled chambers are additional types of contact basins. An axially submerged turbine in countercurrent flow can also act as a contactor. The system includes a flow tube with baffles to provide for sufficient contact time. A pump forces the liquid and gas in a co-current flow (i.e., in the same direction). Baffles create turbulence and increase the rate of gas-liquid mass transfer (USEPA, 1991a; AWWA, 1991b). Because ozone reaction with materials in the water produces suspended solids and colloidal particles, systems should filter to retain the colloidal particles and suspended solids. Ozone in water is corrosive, therefore contact basins should consist of concrete with at least American National Standards Institute (ANSI) 304 stainless steel reinforcing beams. Systems should use ozone resistant pipe material and inert polymer gaskets (AWWA, 1990a).

Off-Gas Destruction: The final process in ozone disinfection is destruction of the unused ozone. Excess ozone may pass through a valve to the off-gas controller, or ozone destruction unit. Off-gas routing to a secondary disinfection contactor is also possible. Excess ozone from this unit then travels to an ozone destruction unit (CCC, 1991). This destruction unit converts the ozone to oxygen by passing the ozone through a metallic oxide catalytic converter. Other off-gas destruction units destroy ozone by heat, heat-catalyst, and/or activated carbon. Because ozone is a toxic gas, ozone existing in the decomposer exit should be less than 0.1 percent by volume. For safety reasons, systems should regularly monitor flue gases.

2.3.1.3 Operation and Maintenance

The general O&M needs for an ozonation facility are labor, energy, and materials. The three O&M cost categories are: daily operation, preventive maintenance, and personnel training. The time spent on operation activities varies by the size of the facility. Although ozone generators are complex, they use complete automation, and require modest amounts of time for routine maintenance. Well-trained technicians require preventive maintenance and repair training to operate the ozone generator. This includes checking the generator and keeping system parts clean. Ozone is a strong oxidizer, therefore the system parts require cleaning to prevent corrosion. Parts requiring occasional cleaning are the ozone contacting unit and the ozone exhaust gas destruction unit. Other parts for the dehumidifying process also require cleaning and maintenance. In addition, users must clean the air preparation or oxygen feed, and dehumidify the saturated desiccant. Removing these areas from the ozonation process and heating them accomplishes these tasks.

Ozone leaks in and around the ozone generation facility may create a health hazard to operators of the treatment plant and may destroy or enhance the wear of other equipment materials. Therefore, facilities must apply strict safety measures, install an ozone gas detector, and periodically check alarms.

The materials needed to ensure the equipment functions adequately comprise the final O&M component of the ozonation facility. Materials include cleaning chemicals, replacement parts, and additional necessary supplies for periodic maintenance, system cleaning, and unanticipated breakdowns.

2.3.1.4 Microbial Inactivation Capabilities

Ozone is a powerful oxidant that reacts rapidly with organic and inorganic compounds in water, although a slower reaction occurs with organic materials than with inorganic compounds. Ozone does not react with water, but instead decomposes quickly in water to produce oxygen and hydroxyl free radicals, which in most waters act as the main participants in oxidizing most organic and inorganic molecules in the water. This decomposition does not leave a disinfection residual, but ozone has a high disinfection capacity due to its high oxidation potential (Rice et al., 1981; Masschelein, 1992).

Ozone decomposition is enhanced by a variety of factors such as high pH, humic materials, and transition metal ions. Decomposition of water yields hydroxyl ion (OH^-) (i.e., $2H_2O \rightarrow H_3O^+ + OH^-$) which initiates the following sequence of reactions:

$$OH^- + O_3 \rightarrow HO_2 + O_2^- \tag{1}$$

$$HO_2 \rightleftharpoons H^+ + O_2^- \tag{2}$$

$$O_2^- + O_3 \rightarrow O_2 + O_3^- \tag{3}$$

$$O_3^- + H^+ \rightarrow HO_3 \tag{4}$$

$$HO_3 \rightarrow O_2 + HO\cdot \tag{5}$$

$$HO\cdot + O_3 \rightarrow HO_2 + O_2 \tag{6}$$

This is a chain reaction mechanism since the HO_2 generated in step 6 can initiate a new chain through steps 2-6. Since the hydroxyl radical ($HO\cdot$) is a very powerful oxidizing species, when O_3 decomposes, its oxidizing power is not necessarily lost if the hydroxyl radical can be efficiently utilized.

Bicarbonate increases the lifetime of O_3 by stopping the chain mechanism by reacting with the OH radical intermediate as follows:

$$HO\cdot + HCO_3^- \rightarrow OH^- + HCO_3\cdot$$

The $HCO_3\cdot$ radical is a relatively unreactive radical that cannot propagate the chain. Thus, waters high in bicarbonate alkalinity and low in other contaminants will retain an O_3 residual for longer periods than low alkalinity, high-TOC waters (Staehelin and Hoigne, 1985; Hoigne and Bader, 1983). Only under high bicarbonate alkalinity does O_3 assert itself as a somewhat dominant oxidizing species; otherwise the disinfection power comes mainly from the $HO\cdot$ free radical.

Typical ozone doses for ground water sources range from 1 to 3 ppm. For color removal in some waters, doses may be as high as 8 ppm; however, this only occurs under extraordinary circumstances. In terms of oxidation of organic matter, Masschelein (1992) suggests using 0.15 to 0.2 mg ozone per mg/L of TOC. The SWTR lists ozonation as a disinfection technology able to achieve the required 4-log virus and 3-log protozoa inactivation. Exhibit 2.6 provides CT values for virus inactivation by ozone.

Exhibit 2.6 CT Values (mg of O_3-min/L) for Virus Inactivation by Ozone

Inactivation	Temperature					
	# 1°C	5°C	10°C	15°C	20°C	25°C
2-Log	0.9	0.6	0.5	0.3	0.25	0.15
3-Log	1.4	0.9	0.8	0.5	0.4	0.25
4-Log	1.8	1.2	1.0	0.6	0.5	0.3

Sources: USEPA, 1991a; AWWA, 1991b.

Hall and Sobsey (1993) studied the inactivation of HAV and MS-2 by ozone and an ozone/ hydrogen peroxide combination at a pH range of 6 to 10. The researchers found that both HAV and MS-2 became inactive after five seconds at an ozone concentration of 0.4 mg/L. Using these short contact times an applied ozone dose between 0.3 and 2 mg/L will achieve 3.9- to 6-log virus inactivation. In addition, when applying ozone for five minutes Finch et al. (1992) found 3-log inactivation of *Giardia muris* and enteric viruses using an ozone residual of 0.5 mg/L, and 4-log inactivation of *Giardia muris* and enteric viruses using an ozone residual of 0.6 mg/L.

2.3.1.5 Advantages and Disadvantages

Ozone has powerful disinfection capabilities. Its high diffusion characteristics make it one of the most efficient chemical disinfectants with its contact time of only a few minutes. For this reason, the SWTR lists ozone as a treatment technology for all public water systems (PWSs) (USEPA, 1997b). Ozone inactivates microbes without forming THMs. Ozone also oxidizes iron and manganese, and improves the taste, odor, and color of raw water. It enhances the biodegradability of natural and synthetic organic compounds and destroys many organic compounds. Production of ozone from air requires no storage space for chemicals. Due to its relatively short half-life and safety issues, ozone may require on-site production. Due to the difficulty in determining an adequate dose, ozone is most beneficial to systems with a constant demand or little demand fluctuation, such as ground water systems.

Disadvantages of ozone include its relatively high cost and complexity in its use (AWWA, 1990a). Ozone decomposes quickly in water and therefore does not provide an adequate residual to protect against recontamination in distribution or water storage systems. Therefore, secondary disinfection may be required. If the source water has a high bromide concentration, ozonation in conjunction with chlorination could result in high concentrations of brominated DBPs in finished waters. Ozonation also results in significant bromate ion production if the source water has high bromide levels.

Water containing large amounts of organic matter and bromide may increase ozone demand and the potential for byproduct formation. However, high natural organic matter (NOM) content in raw waters is generally not a concern for most ground water systems. Moreover, the placement of a carbon filter before or after the ozonation process can reduce ozonation byproducts. The pre-ozonation carbon filter removes the NOM that serves as a precursor to the formation of byproducts. Byproduct formation depends on pH and the ratio of ozone to bromide and TOC to bromide, as well as ozone to TOC. Depending on the amount of organic matter and bromide present, byproducts such as nitrates, oxalic acids, carboxylic acids, sulfonic acids, nitrophenols, aldehydes and ketones may form. Ozone can cause incomplete oxidation of some organic compounds and ozone may react with unsaturated aliphatic or aromatic compounds to form acids, ketones, and alcohols. This material can serve as a carbon source for bacteria in the distribution system, increasing the amount of biofilm growth in the system. At a pH greater than 9, ozone may form toxic phenolic structures in the presence of the redox salts, such as iron, manganese, and copper aromatics (Eckenfelder, 1991).

2.3.2 Nanofiltration

2.3.2.1 Background

NF employs very high pressures and thin film membranes to filter particles of sizes on the order of 10 nanometers (nm). Viruses range in size from 20 nm to 900 nm. NF membranes have pore sizes that are much smaller than those of microfiltration (MF) or ultrafiltration (UF) and typically remove particles between (5 to 10 nm) (USEPA, 1993a). NF membranes used for potable water applications typically use molecular weight cut-offs of 200 to 400 daltons (i.e., approximately 2 to 4 nm).

2.3.2.2 Description

Manufacturers often use a variety of cellulose and non-cellulose materials, including cellulose acetate, cellulose diacetate, cellulose triacetate, polyamide, other aromatic polyamides, polyetheramides, polyetheramines, and polyetherurea in the construction of NF membranes. NF systems employ pressures between 70 psi and 150 psi and flux rates ranging from 15 to 25 gallons per day per square feet (gpd/ft^2). However, this may not necessarily limit NF to small systems applications. Membranes vary in size and can be configured to treat large volumes of water.

An NF membrane system train consists of chemical addition for pretreatment and pH adjustment, a cartridge filter for removal of large particles that may foul the membrane system, medium to high pressure booster pumps for the feedwater, membrane vessels, a disposal system for concentrate, a degasifier, a clearwell for the addition of post-treatment disinfection and softening agents, and a transfer pump to water storage or to the distribution system.

2.3.2.3 Operation and Maintenance

The general O&M elements for an NF facility are labor, energy, and materials. O&M cost categories include daily operation, preventive maintenance, residual disposal, and periodic personnel training.

Operation of an NF facility requires cleaning the pretreatment filters, disinfecting and cleaning the membrane to prevent fouling, and checking the system to ensure proper operation. Systems must also prevent membrane scaling through chemical cleaning. Depending on influent water quality, the membrane may require cleaning every few days to every few months.

For an NF system, the quantity of residual concentrate directly relates to the recovery of the membrane system. The periodic application of treatment residuals consisting of chemical cleaning solutions and backwash water removes solids from the membrane surface. Systems discharge membrane concentrates to surface waters such as lakes, rivers and oceans (requiring a National Pollutant Discharge Elimination System (NPDES) permit), injection wells (under the Underground Injection Control (UIC) program), sewers or Publicly Owned Treatment Works (POTWs) (possibly requiring State or local permits), or evaporation ponds. Federal, State and local authorities, regulations, and permitting requirements regulate disposal methods. Disposal costs and geographic location are additional factors affecting the membrane type selection and disposal options for a plant.

NF's high operating costs are primarily due to its high energy and materials requirements. NF also requires the use of many materials and chemicals to prevent membrane fouling and to ensure adequate system functions. Membranes are expected to have at least a 3 to 5-year lifespan; replacement costs for the membranes are considerable (see Chapter 3 for costing details).

2.3.2.4 Microbial Removal Capabilities

In drinking water applications, NF is a common technology for water softening and NOM reduction. Additionally, NF is very efficient in simultaneously controlling THM precursors, hardness, and microbial contamination (USEPA, 1993a; Morin, 1994). Because of its very small pore size, NF can remove both large (e.g., *Giardia lamblia*) and very small microorganisms (e.g., enteric viruses) (AWWA, 1990a).

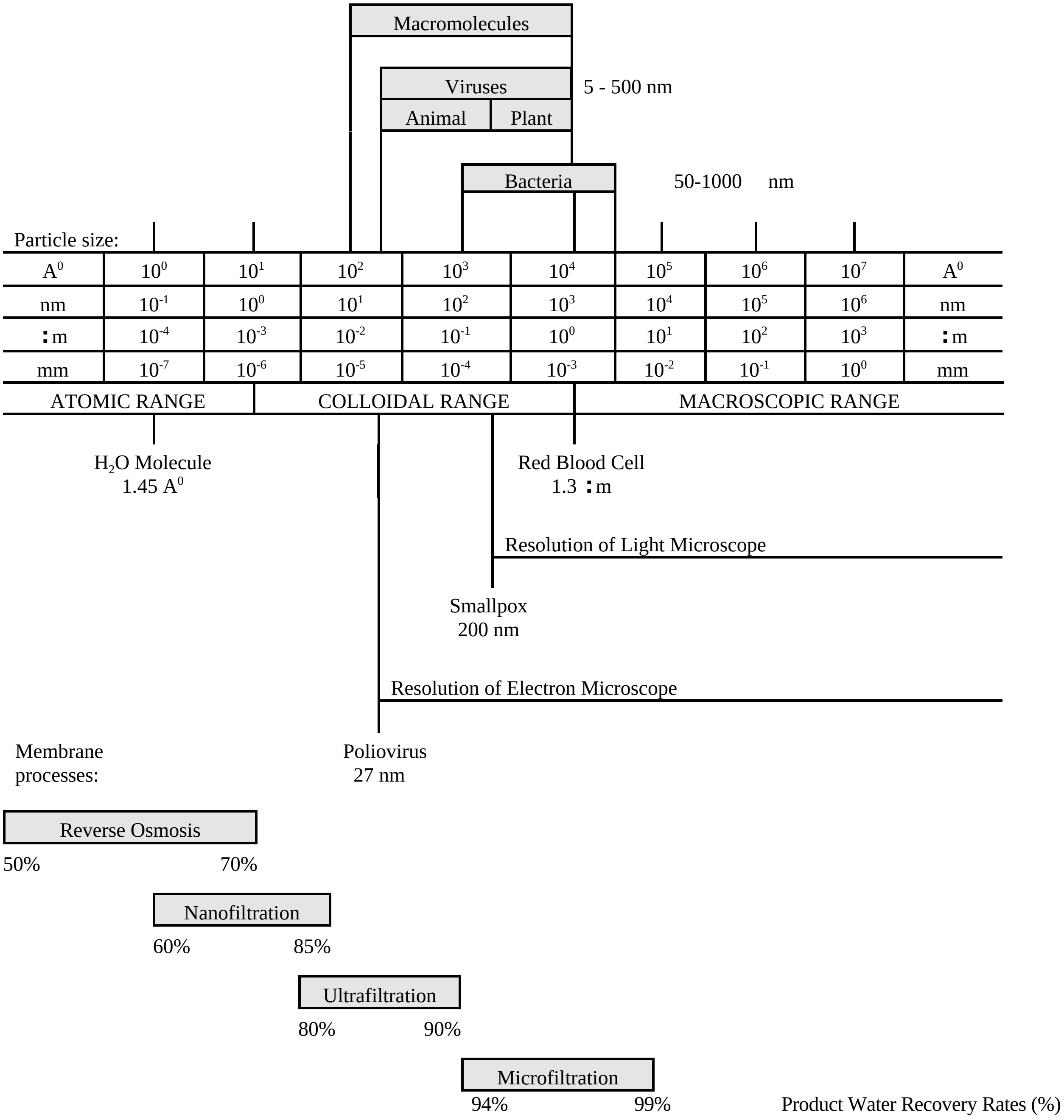
2.3.2.5 Advantages and Disadvantages

NF membranes can achieve absolute pathogen removal. NF membranes can also remove some colloidal material and organics, and are extremely effective in removing disinfection byproduct precursors (Exhibit 2.7). Due to improvements in synthetic membrane materials, NF membranes can remove DBP precursors in addition to organics and some total dissolved solids (TDS). Although capital costs for membrane technologies are high, the ease of adding additional modular components allows for future increases in treatment capacity with reduced capital costs (Hillis et al., 1996).

O&M costs for NF membranes are high because operation requires skilled and intensive labor to perform activities such as chemical cleaning and pretreatment for turbidity and suspended solids. NF membranes have up to a 90 percent recovery rate.

NF membranes do not provide any residual disinfection to control microbial growth in the distribution system or inactivate contaminants introduced to the water supply after filtration. Systems that require a disinfectant residual must use a secondary disinfection technology in conjunction with NF.

Exhibit 2.7 Particle Sizes and Membrane Process Ranges



Particle size:

A^0	10^0	10^1	10^2	10^3	10^4	10^5	10^6	10^7	A^0
nm	10^{-1}	10^0	10^1	10^2	10^3	10^4	10^5	10^6	nm
µm	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^0	10^1	10^2	10^3	µm
mm	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^0	mm

2.4 Applicability Matrix

Exhibit 2.8 presents a matrix summarizing key attributes for the drinking water treatment technologies discussed in the preceding sections of this chapter. For each technology, the matrix lists the inactivation or removal efficiency for a specific virus and contact time necessary to achieve the described inactivation or removal. The matrix also indicates whether the technology is capable of maintaining a disinfectant residual and if the technology employs hazardous materials.

Exhibit 2.8 Applicability of Drinking Water Treatment Technologies for Virus Inactivation or Removal

Technology	Virus	Inactivation or Removal Efficiency	CT (min-mg/L)[1]	Ability to Maintain a Residual	Hazardous Materials
Gaseous Chlorine	HAV	4- log	4	Yes	Yes
Sodium Hypochlorite	HAV	4- log	4	Yes	No
Calcium Hypochlorite	HAV	4- log	4	Yes	No
Anodic Oxidation[2]	HAV	4-log	4	Yes	No
Chlorine Dioxide	HAV	4-log	16.7	Yes	Yes
Ozone	poliovirus	4-log	0.6	No	Yes
Nanofiltration	NA	absolute	NA	No	No

[1] Contact times assuming a temperature of 15°C, a pH of 6–9 for use in the GWR preamble for comparison purposes only.

2.5 Risk/Risk Trade-Offs

2.5.1 Formation of Disinfection By-products

Several disinfection processes can lead to the formation of DBPs. DBPs have been associated with potential health risks, including adverse reproductive and developmental effects and cancer. Systems treating water for microbial contaminants must consider the potential for DBP formation when selecting a disinfection technology or other corrective action. DBPs are a result of reactions of the organic matter in source water with free chlorine and bromide, if present. This reaction continues to occur over time, and residence time in the distribution system becomes an important factor. The remainder of section 2.5.1 presents the occurrence of DBP precursors (TOC and bromide) and DBPs (THMs and HAAs). Generally, DBP concentrations in disinfected ground water systems are low relative to surface water systems because of lower precursor levels in ground water sources.

2.5.1.1 Sources of Data

Several data sources are available for analyses of precursor and DBP data. These data sources are described below, followed by summaries of key data from each source.

Information Collection Rule: The Information Collection Rule (ICR) data collection focused on large PWSs, which serve populations of at least 100,000 people. About 300 PWSs (both surface and ground water systems) operating approximately 500 treatment plants participated in this extensive data collection. Out of these 500 plants, 129 are classified as ground water plants (i.e., using only ground water). A more limited set of ICR requirements covered ground water systems serving 50,000 to 100,000 people. Over an 18-month period, PWSs monitored influent water quality parameters affecting DBP formation and DBP levels in the treatment plant and the distribution system. PWSs also provided operational data and descriptions of their treatment plant design. Systems began monitoring in July 1997 and completed monitoring in December 1998. Summaries of ICR precursor and DBP data are presented in Exhibits 2.9 through 2.11.

Water Utility Database (WATER:\STATS): Published by the American Water Works Association (AWWA), WATER\:STATS is derived from the AWWA Water Industry Database (WIDB) resulting from a 1996 survey of approximately 900 water utilities, mostly entities serving at least 10,000 people (approximately 30 systems in the database serve fewer than 10,000 people). The effort collected a range of financial and operational information on these systems, including data on the occurrence of DBPs in finished water (however, many systems did not respond to all questions). WATER:\STATS does not contain individual sample results; rather it contains minimum, maximum, and average values reported by each system. The WATER:\STATS data presented in this document are of TOC and TTHM data from medium and large ground water systems. Summaries of WATER:\STATS precursor and DBP data are presented in Exhibits 2.9 and 2.11.

The Ground Water Supply Survey (GWSS): This survey, conducted by EPA in 1981–82, was designed to collect treatment, influent water quality, and finished water contaminant occurrence information on 979 small, medium, and large ground water systems from across the United States. Although THM data from this survey are available, they are probably not representative of current THM levels for large and medium systems because they were collected more than 20 years ago. In addition, the TTHM data were collected only at the entry point to the distribution system and THM concentrations continue to increase through the distribution system. A summary of GWSS TOC data is presented in Exhibit 2.9.

AWWA Survey (1998): In January 1997, McGuire Environmental Consultants conducted an AWWA survey of 298 ICR systems (see description of the ICR above). Data were collected from ground water systems serving more than 50,000 people in the United States. Two hundred seventy-five utilities provided three months of TOC data collected in September, October, and November 1996. A summary of AWWA Survey (1998) TOC data (based on 110 ground water plants) is presented in Exhibit 2.9.

Exhibit 2.9 TOC Concentrations (mg/L) in Influent Water

Data Source	Mean	Median	90th Percentile	Range
ICR	1.67	0.23	4.15	0-15.9
Water:\Stats - Large systems	2.0	1.0	3.5	0-14
Water:\Stats - Medium systems	2.3	0.8	7.0	0-25
GWSS[1] - Large Systems	1.06	0.5	2.0	0-11
GWSS[1] - Medium Systems	1.32	0.7	3.2	0-14
GWSS[1] - Small Systems	1.18	0.6	2.9	0-18
AWWA (1998)	1.35	0.76	N/A	0-12.9

[1] GWSS TOC data taken from the finished water.

Exhibit 2.10 Bromide Concentrations (mg/L) in Influent Water

Data Source	Mean	Median	90th Percentile	Range
ICR	0.10	0.06	0.19	0-1.32

Exhibit 2.11 THMs (mg/L) in Distribution System Water for Disinfecting Ground Water Systems

Data Source	Mean	Median	90th Percentile	Range
ICR[1]	45.1	40.1	80.6	0-236
Water:\Stats - Large systems	24	12	57	0-91
Water:\Stats - Medium systems	19	10	50	0-121

[1] ICR statistics are of Distribution System Average, which is the average of four locations in a given plant's distribution system for a given sample period.

2.5.2 Colored Water

Another potential problem involved in installing disinfection treatment technologies is the possibility of the disinfectant reacting with pipes and pipe scales to produce colored water.

2.5.2.1 Definition of Problem

The chemistry involved in disinfecting previously undisinfected ground waters can, in some cases, cause concerns such as increased nuisance complaints from customers and potential violations of the SDWA color standards for PWSs. Oxidization of certain metals, such as iron and manganese, present in source waters may be the source of color problems. It is also possible that oxidation of the existing corrosion scales in a cast iron or ductile iron pipe may release metals that color the water. Color does not itself pose a health risk. However, color requirements must be met in order to provide water for some industries including beverage production, dairy and food processing, paper manufacturing, and textiles. In domestic water, color is aesthetically undesirable and may dull clothes or stain fixtures. The scales may also absorb or contain regulated contaminants.

The risk of colored water problems will cause many systems to be more careful when implementing corrective actions such as changing the disinfectant and/or dose. Some research exists that provides specific information on the number of systems potentially affected in certain areas. For example, iron is a common ground water problem in at least 20 States (USGS, 1990-1996).

2.5.2.2 Potential Sources of Ground Water Quality Problems

There are several potential sources of water quality problems associated with implementing disinfection of certain ground waters. The copper, iron, and manganese in ground water supplies result in customer complaints, particularly in conjunction with chlorination. Manganese can be far more problematic than iron and produces substantial manganese oxide deposits in distribution mains resulting in occasional customer complaints regarding laundry staining. In the case of ferrous iron in corrosion scales oxidized by chlorination, colored water can appear due to the more oxidized state of iron. Corrosion scales exist at the surface of the pipe which consist of oxidized pipe metals and other minerals, such as calcite, which form from constituents in the water. In some instances, more complex interactions can occur. In one case, chlorination released high levels of copper particulates and sorbed mostly insoluble arsenic onto the copper particulates causing arsenic levels to approach 5 mg/L (Reiber et al., 1997).

2.5.2.3 Potential Impacts On Water Quality

Disinfection of ground water can affect drinking water quality, resulting in an increase in customer complaints due to nuisance color problems (as opposed to potential health risks). As mentioned above, a major cause of colored water is the presence of precipitates (particulates) that form due to the oxidation of metals by a disinfectant. This could occur through a reaction of the disinfectant with dissolved metals in the water supply or though the disruption of corrosion scales in the distribution system. Oxidizing these scales with chlorine can release large amounts of metals into the water until the system reaches chemical stability (i.e., the system has re-equilibrated). This re-equilibration could take anywhere between a few weeks to several months and could result in violations of SDWA regulations (e.g. the Lead and Copper Rule). SDWA compliance issues such as chemical reactions that release regulated contaminants at levels exceeding their MCLs need to be addressed as well. The impact of these chemicals may not be known because systems do not typically monitor for such contaminants in the distribution system with the exception of lead and copper. Another key issue related to SDWA compliance is the impact of reduced disinfection and increased microbial risk due to oxidizing the metals with chlorine, (i.e., high chlorine demand). Decreased levels of disinfection effectiveness result if metals in the water or in corrosion scales exert a significant disinfectant demand. The result of decreased disinfection can cause a potential violation of the TCR due to bacterial growth and the consequent release of viable coliforms from biofilms.

2.5.2.4 Mitigation of Ground Water Disinfection Impacts

Increased knowledge of a distribution system can help operators prevent and/or mitigate the adverse impacts of ground water disinfection. A discussion of several of these knowledge areas is presented below.

History of Ground Water Quality: An awareness of the ground water quality will assist systems in understanding the possible range of issues they could face when initiating disinfection. Trace metals present at concentrations well below an MCL can accumulate in scales and result in concentrations exceeding the MCL if the scales are released into the distribution system. Therefore, a historical analysis of the ground water quality can identify potential problems for the system before they arise. Waters high in manganese concentrations, for example, will be strong candidates for colored water. This is because manganese in ground water will form a colloidal precipitate when oxidized to the most stable (Mn^{4+}) oxidation state. Manganese coloration persists because the oxidation is relatively slow in water with a pH below nine, which is typical in most ground water supplies (Sawyer and McCarty, 1967).

Characterization of Distribution System Materials: The type of distribution system materials used determines the potential for colored water problems that may occur when implementing disinfection. Water distribution systems consist of a variety of metal surfaces including steel, cast and ductile iron, zinc, copper, lead, and a number of specialty alloys. Systems use many of these metals because of their overall corrosion resistance. Nonetheless, all metal surfaces form a corrosion scale unique to the metal type. Non-metallic distribution pipe materials include concrete and PVC piping.

The metals distribution in different scales are indicative of the respective pipe material. Cast iron specimens, as expected, are high in iron. Typically galvanized iron pipe scale is high in iron and also contains zinc. Corrosion scales consist largely of the oxidized metal, but will generally contain calcite and other minerals. On some metal surfaces scales may be quite thin; in the case of copper, scales are often less than 0.2 mm. On cast iron surfaces the scales are large, frequently exceeding a depth of 1 centimeter (cm). In even a relatively small distribution system, the existing corrosion scales will contain several tons of metal oxides, while in large systems the corrosion scales can represent a massive reservoir of metals measured in kilotons (Reiber, et. al., 1997).

Assessment of Impacts: Systems can directly monitor impacts of disinfection by measuring corrosion scales and their stabilities. To measure corrosion scales, systems can obtain a variety of pipe samples from different portions of the distribution system to analyze the suspect constituent and metals contents. These include a sampling of copper tubing from galvanized iron service lines that provide water to many of the homes and sections of galvanized iron pipe from the distribution system. Samples should represent areas that have been in service over long periods in order to provide the appropriate data (i.e., corrosion scales that adequately represent the corrosion history of the system). Scales may be analyzed by removing the scale down to the pipe wall, drying and powdering it, and then dissolving the powder in nitric acid. This is followed by an inductively coupled plasma (ICP) analysis to determine the metal constituents. The results are normalized by presenting the individual metals as the respective metal mass per unit of total metal in the scale in milligrams per gram (mg/g).

Corrosion scale stability can be measured based on redox potential. Redox potential is the measure of the relative oxidative conditions in a particular environment. A variety of factors affect the redox potential including dissolved minerals, gases, and the electrochemical state of the surfaces in contact with the water. In a water distribution system temperature, pH, dissolved oxygen, microbial activity, and the presence of disinfectants such as chlorine typically influence the redox potential the most. This is important since many of the compounds in natural waters may exist in a variety of different oxidation states. By convention, an oxidizing environment has a high redox potential, while a reducing environment has a low redox potential. Clearly, a water distribution system with high dissolved oxygen and substantial chlorine residual has a high redox potential. The more oxidized forms of minerals or metal surfaces in contact with this water will tend to predominate in favor over reduced forms.

Prior to chlorination, most systems have relatively low redox potentials. Dissolved oxygen at the wellheads is typically low and measured dissolved oxygen in the distribution system will generally be very low (<1.0 mg/L). The historical absence of chlorine and low dissolved oxygen levels will probably allow for reducing micro-environments to develop at the pipe walls and in the corrosion scales where stagnation conditions predominate. This would suggest the existence of semi-reduced (i.e., not at their highest oxidative state) forms. Chlorination will change the redox potential of the system, causing a re-equilibration of the corrosion scales on residential copper plumbing surfaces. Disinfection converts the more voluminous reduced-based scales to oxidized-based scales resulting in the loss of the bulk of metal oxides stored in the scale. When conversion is complete, the resulting corrosion scale adheres and protects the underlying metal. The length of time for conversion is generally unknown, but would likely require up to months of continuous chlorine exposure (Reiber, et. al., 1997).

3. Costs for Treatment Technologies

3.1 Introduction

To provide input to the Ground Water Rule (GWR) Economic Analysis (EA), the United States Environmental Protection Agency (EPA) developed unit cost estimates for each of the ground water disinfection technologies expected to be employed for meeting rule requirements. This chapter describes the derivation of capital and operations and maintenance (O&M) unit costs for six treatment technologies. Historically, the outputs of three EPA Cost Models [i.e., the Very Small Systems Model (VSS), the Water Cost Model (Water), and the Water Wastewater Model (W/W)] have been used to estimate most unit technology costs. In this document, however, a modified approach is used. The following approaches were adopted to develop the cost estimates for GWR technologies:

- Cost Model Approach—modified outputs from the EPA Cost Models are used as stand-alone estimates

- Cost Build-Up Approach—manufacturer and/or vendor estimates along with engineered costs are used in conjunction with cost model parameters for certain capital cost components

Exhibit 3.1 summarizes the technologies that were costed in this document and the specific methodology adopted for each.

Exhibit 3.1 Technologies Costed and Methodology Adopted

Technology	Costing Methodology Used
Gas Chlorination	Cost Model Approach
Hypochlorination	Cost Model Approach
Temporary Hypochlorination	Cost Build-Up Approach
Chlorine Dioxide	Combination of Cost Build-Up and Cost Model Approaches
Anodic Oxidation	Cost Model Approach
Ozonation	Cost Build-Up Approach
Nanofiltration (NF)	Cost Build-Up Approach

For each of the treatment technologies listed in Exhibit 3.1, EPA estimated costs based on 19 flow categories. These 19 flow categories correspond to different system sizes. Exhibit 3.2 presents these flow categories.

Exhibit 3.2 Flow Categories Used for Cost Estimates

Design Flow (mgd)	Average Flow (mgd)
0.007	0.0015
0.022	0.0054
0.037	0.0095
0.091	0.025
0.18	0.054
0.27	0.084
0.36	0.11
0.68	0.23
1.0	0.3
1.2	0.41
2.0	0.77
3.5	1.4
7.0	3.0
17	7.8
22	11
76	38
210	120
430	270
520	350

The remaining sections in this chapter provide more detail on the costing process.

- Section 3.2 provides descriptions of the three cost models.
- Section 3.3 provides detail on the two GWR unit technology cost estimation methodologies (i.e., the Cost Model and Cost Build-Up approaches).
- Section 3.4 describes the assumptions used for estimating certain indirect or “additional” capital cost items.
- Section 3.5 presents example calculations for all three cost models that illustrate how the “raw” model outputs were modified (based on methodologies discussed in section 3.3) to produce the final capital cost estimates.

- Section 3.6 presents costs for storage tanks including finished water pumping.

- Section 3.7 presents the derivation of capital and O&M costs for each of the six GWR technologies.

3.2 Description and Application of the Cost Models

EPA developed the cost equations for the W/W and Water Models using data from manufacturers, actual plant construction data, and other published data ((Culp/Wesner/ Culp 1984); Culp/Wesner/Culp 1979). The *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie Inc., 1993) provides the basis for the equations used in the VSS Model.

To develop technology costs, all three Cost Models require user-specified inputs such as design and average flows, chemical dose, and cost indices. These three Cost Models, hereafter referred to as the "models", were used to estimate technology costs for particular system sizes.

- The W/W Model is used for design flows greater than 1.0 million gallons per day (mgd)

- The Water Model is used for design flows from 0.1 mgd to 1.0 mgd[1]

- The VSS Model is used for design flows less than 0.1 mgd

The following sections describe each of the three models in more detail.

3.2.1 Water and Wastewater (W/W) Model

EPA used the latest version (i.e., version 3.0 in the "Windows" operating system) of the *W/W Costs and Design Criteria Guidelines* software (CWC, 2000) to develop costs for drinking water systems serving more than 3,300 people (i.e., systems with design flows greater than 1 mgd). Information contained in a four volume report provides the documentation for this software (Culp/Wesner/Culp 1979). EPA obtained unit cost estimates by selecting the appropriate unit processes within the model.

W/W Model Structure

The W/W Model generates capital and annual O&M costs based on treatment technology, design and average daily flows, and chemical dose. The program calculates these costs based on capital and unit cost factors assigned by the user.

Capital costs include the following:

- Construction (e.g., equipment, labor, pipes/valves, electrical, housing)

- Sitework

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[1] Normally, the ideal applicability range for the Water Model is 0.27-1.0 mgd. Ideally, linear interpolation would be appropriate for the "transition zone" between the Water and VSS Models (i.e., 0.1 to 0.27 mgd). However, the Water Model has been found to be applicable for design flows as low as 0.1 mgd (USEPA, 1979). Thus, in this document, the Water Model is used for the "transition zone" of 0.1 to 0.27 mgd.

- Subsurface
- Standby power
- General contractor overhead and profit
- Engineering
- Land (assumed to be zero, unless noted)
- Legal, fiscal and administrative services
- Interest during construction

O&M costs include the following:

- Energy (e.g, electricity, fuel and natural gas)
- Maintenance material (e.g, periodic replacement throughout useful life)
- Labor
- Chemicals

W/W Model Inputs

The W/W Model is capable of estimating costs for the price level of any given year by entering appropriate cost indices and adjustment factors. The W/W Model requires standard indices and unit costs from the Bureau of Labor Statistics (BLS) and the Engineering News Record (ENR) to calculate and update costs. Exhibits 3.3 - 3.5 present capital and unit cost factors, national average building cost indices, and chemical costs used to generate capital and annual O&M costs. These represent year 2003 (average) numbers. The BLS indices listed in Exhibit 3.3 are based in 1967 dollars. The BLS Commodity Indices in Exhibit 3.3 reflect specific producer price index (PPI) listings. Due to the 1986 review of the industrial price methodology, these indices were re-based in 1982 dollars. However, the W/W Model requires BLS indices based on 1967 dollars and all BLS cost factors used in the model are recalculated to represent the 1967 base level.

Exhibit 3.3 Applicable Unit Costs and BLS Cost Indices (2003 dollars/indices)

Cost Index/Parameter	Index Value
Engineering Percent	Varies (see Exhibit 3.7)
Sitework, Interface Piping Percent	Varies (see Exhibit 3.7)
Standby Power Percent[3,5]	5%
Subsurface Sitework Percent[1,3,4]	10%
Land Cost ($/Acre)[6]	0.0
Electricity ($/kWh)[7]	0.076
Labor ($/hr)[7]	27.01
Diesel Fuel ($/gal)[7]	1.78
Natural Gas ($/ft^2)[7]	0.0092
Building Energy (kWh/ft^2/yr)[9]	102.6
Building/Housing ($/ft^2)[10]	51.1
BLS Commodity Code No. 3000[2,7] (PPI for Finished Goods)	414.2
BLS Commodity Code No. 114[2,7]	482.6
BLS Commodity Code No. 132[2,7]	502.5
BLS Commodity Code No. 1017[2,7]	397.3
BLS Commodity Code No. 1149[2,7]	533.8
BLS Commodity Code No. 117[2,7]	371.7

Sources:

[1] Subsurface Sitework is a construction cost contingency factor developed for excavation work.

[2] Commodity codes reflect specific PPI listings and a 1967 base year: No. 114: PPI for general purpose machinery and equipment; No. 132: PPI for nonmetallic mineral products (e.g., concrete and related products); No. 1017: PPI for metals and metal products; No. 1149: PPI for miscellaneous general purpose machinery and equipment; No. 117: PPI for electrical machinery and equipment.

[3] Percentage of construction costs.

[4] USEPA, 1993a.

[5] USEPA, 1992b.

[6] Assumes available land on-site for certain technologies. For others, land costs have been added separately (see section 3.4).

[7] Bureau of Labor Statistics (BLS, 2001). This labor rate only used for model calculations. For labor rate for other factors see Ex 3.6.

[8] USEPA, 1984.

[9] USEPA, 2003.

[10] R.S. Means (2000) cost updated to 2003 dollars using the ENR BCI (see Exhibit 3.4).

The ENR indices (2003 price level) listed in Exhibit 3.4 measure how much it costs to purchase goods and services compared to costs in the base year. The W/W Model required the following ENR indices as inputs: skilled labor, building costs, and materials. Exhibit 3.5 presents the cost of chemicals used in the W/W Model.

Exhibit 3.4 ENR Cost Indices

Cost Index/Parameter	2003 Index Value
ENR Skilled Labor Index	5,947.72
ENR Building Costs Index	3,693.00
ENR Materials Index	2,120.23

Source: www.enr.com

Exhibit 3.5 Chemical Costs (2003 dollars)

Chemical	Cost
Chlorine gas, 1-ton cylinder and bulk	$296.8 per ton
Chlorine gas, 150-lb cylinder	$636 per ton
Hexametaphosphate	$1,378 per ton
Sodium Chlorite	$344.5 per ton
Sodium Hypochlorite, 12 % chlorine	$1,192.5 per ton
Sulfuric Acid	$106 per ton

Source: Based on vendor estimates (USEPA, 2005).

The capital cost estimates based on the model outputs were then modified in a manner discussed in Sections 3.3 and 3.4 to obtain the final capital costs.

3.2.2 Water Model

The Water Model estimates water treatment costs for small to medium-sized drinking water systems serving between 1,000 and 3,300 people (i.e., systems with design flows between 0.1 mgd and 1 mgd). The model covers 45 different unit treatment processes. The document titled *Estimation of Small System Water Treatment Costs* (Culp/Wesner/ Culp 1984) contains a printout of the source code for the Water Model in FORTRAN. A spreadsheet version of the model is also available and was used for generating the cost numbers in this document.

Water Model Structure

The Water Model generates capital and annual O&M costs based on treatment technology, design and average daily flows, and chemical dose. The spreadsheet version of the model has a cost generating subroutine and a separate data file for each applicable technology that holds the user defined inputs. The program calculates these costs based on capital and unit cost factors assigned by the user. EPA selected unit processes for each technology based on processes used in prior technology and cost documents and engineering judgement. When the model did not include a particular unit process as an individual model process, EPA combined several model processes essential in achieving the treatment objective of the analyzed technology. The list of capital and O&M cost items included in the Water Model are the same for those used in the W/W Model (see Section 3.2.1).

Water Model Inputs

The inputs and processes required by the Water Model to estimate costs for a given time (i.e., price level) are the same as those used for the W/W Model (see Section 3.2.1 and Exhibits 3.3 - 3.5). Process-related input coefficients (such as minimum and maximum chemical dosages, detention times, etc.) differ from those used in the W/W Model and were obtained by EPA from the data file titled CRV_DAT.xls listed in *Estimation of Small System Water Treatment Costs* (Culp/Wesner/ Culp 1984).

The capital cost estimates based on the model outputs were then modified in a manner discussed in Sections 3.3 and 3.4 to obtain the final capital costs.

3.2.3 Very Small Systems (VSS) Model

The VSS Model is most applicable for very small systems serving fewer than 1,000 people (i.e, systems with design flows less than 0.1 mgd). The *Very Small Systems Best Available Technology Cost Document* (Malcolm Pirnie Inc., 1993) provides the basis for the equations used to estimate costs. This document compiles input from members of the National Water Quality Association (NWQA), academia, EPA , information collected from original equipment manufacturers (OEMs), the Water Model (USEPA, 1984), and very small system installations to establish design parameters used to size process equipment and to calculate annual O&M costs.

VSS Model Structure

In order to develop capital and annual O&M costs for very small systems the source information discussed above is used to develop technology-specific cost equations that are a function of systems' flows and labor costs. The VSS Model uses these cost equations to estimate technology-specific total capital costs.

VSS Model Inputs

To develop total capital costs, the VSS Model applies a cost factor to specific equipment costs. Since the VSS Model uses equipment costs as a basis for total capital costs, a cost factor is used to obtain building costs (e.g., engineering, installation, contractor overhead and profit, legal, fiscal and administrative, sitework, electricity, and standby power). This differs from the W/W and Water Models, which estimate costs for each of these components separately. The VSS document (Malcolm Pirnie Inc., 1993) provides these building cost estimates (presented as percentage of total capital cost).

O&M costs were also developed using OEM information and include costs for chemicals, power, labor, and replacement parts. The chemical costs used were identical to those used in the W/W and Water Models (see Exhibit 3.5). Labor costs for very small systems vary depending on the amount of time allotted for system personnel to inspect, operate, and maintain the facility. Therefore, the number of labor hours is a variable (along with average daily flow) in the VSS O&M cost equations.

The VSS Model also takes into account treatment plant site development (building, road, fencing, and land acquisition), wellhead rehabilitation, and distribution system O&M costs. These costs are estimated as a function of the size of process equipment and the need for the equipment to be installed in a building (Malcolm Pirnie Inc., 1993).

Adjustments to Model Outputs

EPA adjusted the capital and O&M cost outputs from the models to a year 2003 price level. Based on the ENR Building Cost Index (BCI), a capital cost adjustment factor of was applied to the capital costs. The BLS Consumer Price Index (CPI) was applied to the O&M costs. The BCI is more applicable to projects involving construction; whereas, the CPI is more applicable to instances where labor forms a substantial part of the total costs. Therefore, the BCI was used to adjust the capital costs, and the CPI was used for adjusting the O&M costs.

The adjusted (to 2003 dollars) capital cost estimates were then modified in a manner discussed in Sections 3.3 and Section 3.4 to obtain final capital cost estimates.

3.3 General Costing Methodology

Following the re-authorization of the SDWA 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 (sponsored by EPA in November, 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, 1998).

In 2001, the National Drinking Water Advisory Council (NDWAC) convened the Arsenic Cost Working Group to review the cost methodologies, assumptions, and information underlying the system-size specific cost estimates presented in the Arsenic Technologies and Costs Document (December, 2000), as well as the aggregated national cost estimates for the Arsenic in Drinking Water Rule. As part of the review, the NDWAC made several recommendations (National Drinking Water Advisory Council, 2001) that have since been incorporated into the cost approach applied for the Arsenic Rule. This document incorporates both the TDP and NDWAC recommendations in the capital unit cost estimates for the GWR, as appropriate.[2]

3.3.1 Estimates Using Cost Models Approach

Capital Costs

The capital cost output from the cost models consists of three elements:

- **Process costs** which include manufactured equipment, concrete, steel, electrical and instrumentation, and pipes and valves.
- **Construction costs** which include installation, sitework and excavation, subsurface considerations, standby power, contingencies, and interest during construction.
- **Engineering costs** which include general contractor overhead and profit, engineering fees, and legal, fiscal, and administrative fees.

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[2] This approach updates the costing approach used in the 1999 proposed Cost and Technology Document for the Ground Water Rule.

The TDP recommended that total capital cost estimates be based on process costs, which can then be multiplied by a specific cost factor to estimate total capital costs (i.e., extract the process cost from the model output and multiply it by a factor to arrive at the total cost). The TDP believed that the process cost component of the model outputs was the most reliable component and hence recommended the methodology described. 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 Nanofiltration, the following multiplier was used:

- Nanofiltration: 1.67

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 pre-assembled modular systems such as membrane units. Nanofiltration also requires relatively more expensive equipment, but is usually easier to install.

Some costs are not included in the model outputs. Other "additional" indirect capital costs such as land, permitting, piloting, operator training, housing, and public education are included (where indicated) in the estimates presented in this chapter, but are added to the direct capital cost *after* application of the NDWAC-recommended adjustment factors to the total process costs. Section 3.4 describes these "additional" indirect costs. Section 3.5 discusses this costing methodology in more detail through example calculations.

Annual O&M costs

O&M costs are obtained directly from the model outputs. Unlike the capital costs, no cost factors are applied to the O&M cost outputs from the models. Labor costs vary by size category and are shown in Exhibit 3.6. Electricity costs are assumed to be $0.076/kWh for all flows.

Exhibit 3.6 Labor Rates for PWS Operators

Size of PWS	Labor Rate (2003 $)
25 - 100	$ 21.44
101 - 500	$ 23.09
500 - 3,300	$ 24.74
3,301 - 10,000	$ 25.34
10,001 - 100,000	$ 26.05
> 100,000	$ 31.26

Source: Labor Costs for National Drinking Water Rules (USEPA 2003)

Summary of Cost Model Approach

Total Capital Cost:
Total Capital Cost = Direct Cost + Indirect Cost
where,

Direct Cost = The "process" cost item from model output × the appropriate NDWAC-recommended cost factor multiplier.

Indirect Cost = Additional cost items such as land, permitting, piloting, operator training, housing, and public education (see Section 3.4 for details), to which the NDWAC-recommended cost factor multiplier is NOT applied.

Annual O&M Cost:
Obtained directly from model outputs.
No cost factors applied.
Labor rate: varies by system size
Electricity unit cost: $0.076/kWh

3.3.2 Estimates Using a Cost Build-Up Approach

Capital Costs

To estimate capital costs for those technologies where cost model estimates were found to be inaccurate based on "best professional judgement" (BPJ), 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. These process costs were then multiplied by the capital cost factors as discussed above. The capital cost factors account for the engineering and construction costs. The breakouts showing the allocation of the factors are shown in Exhibit 3.7.

Exhibit 3.7 Additions to Preliminary Process Cost Estimates

Component	For Nanofiltration Systems	For Design Flows < 1 mgd	For Design Flows ≥ 1 mgd
Site work	10%	25%	15%
Contractor Overhead & Profit (O&P)	10%	20%	10%
Contingencies	15%	30%	20%
Engineering and design	10%	25%	15%
Mobilization and bonding	5%	5%	3%
Legal and administrative	0%	15%	10%
Interest during construction	7%	10%	7%
Installation	10%	20%	20%

Percentage refers to percentage of the “preliminary” process cost estimate.
Source: Best Professional Judgement.

Total capital costs are derived from the total process costs by applying the NDWAC-recommended cost factors (the same as those discussed under *Capital Costs* in section 3.3.1). Indirect capital costs such as land, permitting, piloting, operator training, housing, and public education are included (where indicated) in the estimates presented in this chapter. However, they are added to the direct capital cost *after* the application of the NDWAC-recommended cost factors to the total process cost. Section 3.4 describes these “additional” indirect costs, and Section 3.5 discusses this costing methodology in more detail through example calculations.

Annual O&M Costs

Annual O&M costs are mainly comprised of chemical, material, labor, and electricity/energy costs. Chemical costs are computed using vendors’ quotes after estimating the annual chemical requirements based on the chemical doses applied and average flow rates. Material, labor, and electricity costs are derived either from best professional judgement or directly from cost model input parameters. Where Model parameters are used, no cost factors are applied to those outputs (unlike the capital costs), except to update values to a 2003 price level. Labor costs are from Exhibit 3.6 and electricity costs are assumed to be $0.076/kWh.

Summary of Cost Build-Up Methodology

Total Capital Cost:
Total Capital Cost = Direct Cost + Indirect Cost
where,

Direct Cost = (Process cost estimated from engineering principles and manufacturers' quotes + the cost of the other components listed in Exhibit 3.6) and/or (Process costs from the cost models) × the appropriate NDWAC-recommended cost factor multiplier.

Indirect Cost = "Additional" cost items such as land, permitting, piloting, operator training, housing, and public education (see Section 3.4 for details), to which the NDWAC-recommended cost factor multiplier is NOT applied.

Annual O&M Cost:
Chemical cost: vendor estimates for unit costs in conjunction with annual chemical usage based on the chemical dose applied and average flow.

Materials, labor, and electricity: directly from model parameters or based on best professional judgement/vendor estimate. If cost models are used, no cost factors are applied.
Labor rate: varies by system size.
Electricity unit cost: $0.076/kWh.

3.3.3 Waste Disposal Costs

The GWR technologies identified and costed in this chapter generate little or no waste, with the exception of NF, which produces sufficient volumes of waste to warrant consideration. Therefore, wastewater treatment and disposal costs are included for this technology.

The W/W, Water, and VSS Models do not account for expenses incurred for waste disposal facilities; therefore, the NF waste disposal costs are based on engineering judgement and are added as a line item in the cost build-up structure *after* the application of NDWAC-recommended cost factors.

3.4 "Additional" Cost Items

Based on the recommendations of the TDP and NDWAC cost working groups, capital cost estimates presented in this chapter include additional costs associated with permitting, pilot testing, land, housing, operator training, and public education. This section describes the approach used to incorporate each of these items into unit cost estimates.

3.4.1 Permitting

The cost to assemble a permit application can be highly variable and usually varies by technology. Some permits can require extensive studies (e.g., Environmental Assessments or Environmental Impact Statements). Technologies requiring extensive environmental impact studies or permit applications for handling treatment residuals (e.g., National Pollutant Discharge Elimination System (NPDES) permits) can also be expensive and require legal assistance that leads to increased costs. Costs are also affected by whether a system has the expertise in-house to develop and submit the necessary permit applications. Otherwise, additional consulting services may be required. The NDWAC working group recommended that permitting costs for GWR technologies requiring a permit be calculated as 3 percent of the total process cost, with a minimum of $2,500 and a maximum of $500,000. For chlorination technologies (i.e. gas chlorination and hypochlorination), which require minor process modifications, permitting costs are included as a part of the engineering fees (included in the capital cost factor).

3.4.2 Piloting

The NDWAC working group recommended that the costs of pilot tests be included for all technologies. Piloting costs can be widely variable depending on treatment options and the extent to which pilot studies are necessary. For example, many pilot studies evaluate multiple technologies that can lead to increased costs. For the purposes of this document, it was assumed piloting would not be necessary for those technologies requiring relatively minor process modifications (i.e., gas chlorination, and hypochlorination). 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. Exhibit 3.8 summarizes the pilot testing cost assumptions used in this document.

Exhibit 3.8 Summary of Piloting Cost Assumptions

Technology	Design Flow (mgd)		
	< 0.1	0.1 to 1	> 1
All chlorination technologies	$0	$0	$0
Chlorine Dioxide	$5,000	$10,000	$50,000
Anodic Oxidation	$5,000	$10,000	$50,000
Ozonation	$5,000	$10,000	$65,000
Nanofiltration	$1,000	$10,000	$60,000

Source: NDWAC recommendation refined based on best professional judgement.

3.4.3 Land

The majority of the technologies discussed in this document will likely fit in existing plant footprints and additional land purchases will not be required. However, several processes (i.e., ozonation, and NF) are not likely to fit in existing footprints and may require systems to purchase additional land.

The amount of land required for the installation or upgrade of a treatment process can vary significantly, and land costs can also vary significantly from region to region depending upon availability.

The NDWAC working group recommended that land costs be included at 2 to 5 percent of total capital costs. However, this recommendation is based on new treatment plant construction which would require an entirely new parcel of land. Land cost were lowered from the NDWAC recommendations because EPA believes, based on best professional judgment, that a majority of ground water systems will have some land available for installation of new technologies. Most systems will have land to accommodate other infrastructure associated with the system (e.g., pumping stations, designated wellhead protection areas, etc.) that may also accommodate new treatment. As a result, land costs are included at percentages ranging from 0.5 to 2 percent depending on the technology. The reason the percentage varies from technology to technology is the relative capital cost of each technology. Percentages were also adjusted based on the estimated building footprint of the technology. That is, if the land cost per acre was considered unreasonable (i.e., significantly higher than $500,000 per acre[3]), the percentage was adjusted accordingly. Exhibit 3.9 summarizes the land cost assumptions used in this document.

Exhibit 3.9 Summary of Land Cost Assumptions as a Percent of Total Capital Cost

Technology	System Size (mgd)		
	< 1	1 - 10	> 10
Ozonation	2%	2%	2%
Nanofiltration	2%	1%	0.5%

Source: NDWAC recommendations refined based on best professional judgement.

3.4.4 Housing, Operator Training, and Public Education

The assumptions behind costing these items (wherever appropriate) are technology-specific and are discussed under the costing for individual technologies (see Section 3.7).

3.5 Example Calculations for Costing Methodologies

This section provides example calculations for the technologies using the approaches described earlier in this chapter. Examples are provided for the Cost Model Approach using each of the three cost models followed by an example using the Cost Build-Up Approach. These numbers and calculations are presented for demonstration purposes only. Descriptions of the calculations used for each of the GWR technologies are provided in Section 3.7.

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[3] Based on best professional judgement, the upper end of land costs in the US is in the vicinity of $500,000 per acre. Anything beyond that value is considered high. This is consistent with the Technology and Cost document for the Stage 2 DBPR/LT2ESWTR. (USEPA, 2003).

3.5.1 Example Calculations for the Cost Model Approach using W/W Model

The following sample calculation describes how costs were derived using the W/W Model. Cost estimates using the Cost Model Approach entail the application of NDWAC and TDP-recommended cost factors. The steps outlined below incorporate those recommendations.

Example Technology - Chlorine Gas (applied chlorine dose of 4 mg/L using 150 lb. Cylinders) for a plant with a design flow capacity of 2 mgd

1. The total "raw" capital cost model output for installing a chlorine gas unit to a treatment process with a design flow capacity of 2 mgd and a chlorine dose of 4 mg/L is $20,928

2. Total process cost (excluding housing) = cost of equipment (from above) + labor + pipes & valves + electrical & instrumentation + concrete + steel (all from the raw model output)
   = $27,827

3. The modified capital cost can then be calculated using the total cost factor described in Section 3.3 (i.e., 2.0) = result from step 2 × total cost factor
   = $27,827 × 2.0
   = $55,654

4. Housing cost (from raw model output) = $10,546

5. Permitting costs = included in the cost factor for chlorine based processes (see Section 3.4.1)

6. Piloting costs = $0 for chlorine (see Section 3.4.2).

7. Land, operator training, and public education costs are assumed to be zero (see Section 3.4)

8. Total capital costs (modified) = (step 3) + (step 4) + (step 5) + (step 6) + (step 7)
   = $55,654 + $10,546 + $0 + $0 + $0
   = **$66,200** (2003 dollars)

9. Annual O&M cost based on direct model output = **$18,431** (2003 dollars)

3.5.2 Example Calculations for the Cost Model Approach using Water Model

Example Technology - Gas Chlorination (applied dose of 4 mg/L) for a plant with a design flow capacity of 0.36 mgd

1. The total "raw" capital cost model output for installing a gas chlorination unit (including housing) to a treatment process with a design flow capacity of 0.36 mgd and a dose of 1 mg/L is $30,154

2. The model calculated the fraction of process cost to be 39.62 percent (from the “raw” output). This number was derived from a sample model run for the applicable technology presented in the Water Model documentation. The “raw” electronic model output does not provide a very detailed breakout of the total capital cost. However, the breakout of process, construction, and engineering costs are provided in the model documentation for a given sample run. The assumption is that the breakout percentages for process, construction, and engineering costs are independent of the process and operating parameters and can therefore be applied to any run for that particular technology.

3. Total process cost = “raw” model output from step 1 × process cost factor derived in step 2.
   = $30,154 × 39.62% = $11,947.

4. The modified capital cost can then be calculated using the total cost factor in Section 3.3 (i.e., 2.5) = result from step 3 × total cost factor
   = $11,947 × 2.5
   = $29,868

5. Housing costs are not added separately as in the case of the W/W Model because the Water Model assumes that additional housing for the facility being costed is not required.

6. Permitting costs for gas chlorination are assumed to be incorporated by the capital cost factor, and are not added separately (see Section 3.4.1)

7. Land, piloting, operator training, and public education costs are assumed to be zero (see Section 3.4).

8. Hence, total capital costs (modified) = (step 4) + (step 5) + (step 6) + (step 7)
   = $29,868 + $0 + $0 +$0
   = **$29,868** (2003 dollars)

9. Annual O&M cost based on direct model output = **$6,554** (2003 dollars)

3.5.3 Example Calculations for the Cost Model Approach (VSS Model)

Example Technology - Hypochlorination (applied dose of 4 mg/L) for a plant with a design flow capacity of 0.091 mgd

1. The capital cost equation for disinfection using hypochlorite is CAP = 4.7 (where CAP = capital cost in 1,000s of dollars at a 1993 price level).

2. To escalate to 2003 dollars, multiply the equation generated capital cost by the ratio of the ENR average Building Cost index for 2003 to the average 1993 index value. $ 4,700 × 1.23 (see Section 3.2.3) = $5,793.

3. Based on the model results, the fraction of process cost is 61.93 percent. This number was derived from a sample model run for the applicable technology, presented in the VSS Model documentation. The “raw” electronic model output does not provide a very detailed breakout of the total capital cost. However, the breakout of process, construction, and engineering costs are provided in the model documentation for a given “sample” run. The assumption here is that the breakout percentages for process, construction, and engineering costs are independent of the process and operating parameters and can therefore be applied to any run for that particular technology. Total process cost is $5,793 × 61.93% = $3,588.

4. The modified capital cost can then be calculated using the total cost factor presented in section 3.3 (i.e., 2.5) = result from step 3 × total cost factor
= $3,588 × 2.5
= $8,970

5. Permitting costs for chlorination technologies are assumed to be incorporated by the capital cost factor and are thus not added separately.

6. Land, piloting, operator training, and public education costs are assumed to be zero (see Section 3.4). Housing costs are estimated within the VSS Model (see Section 3.2.3).

7. Hence, total modified capital costs = (step 4) + (step 5) + (step 6)
= $8,970 + $0 + $0
= **$8,970** (2003 dollars)

8. Annual O&M costs are not based on the VSS Model. Instead, they were developed using BPJ. Hence they are not discussed here.

3.5.4 Example Calculations for the Cost Build-Up Approach

Example Technology - ozonation for a plant with a design flow capacity of 0.091 mgd

1. Develop process cost using manufacturers’ estimates. In this case:
Process costs = cost of ozone generator + cost of pipes and valves + cost of instrumentation and controls + cost of pumping equipment + cost of ozone contactor + cost of off-gas destruction + cost of ozone quench
= $122,149 (vendor estimate)

2. Compute Direct capital cost.
Direct capital cost = (Process cost from step 1) × (the appropriate capital cost factor).
= $122,149 × 2.5 (see Section 3.3.1)
= $305,371

3. Compute Indirect capital cost.
Indirect capital cost = “Additional” cost items such as land, permitting, piloting/treatability testing, operator training, housing, public education, etc. (see Section 3.4 for details), to which cost factors are NOT applied.
Indirect capital cost = operator training cost + piloting + housing + land + permitting
= $924 + $5,000 + $5,866 + $2,443 + $3,664
= $17,897

4. Compute Total Capital cost.

Total Capital cost = Direct capital cost + Indirect capital cost
= $305,371 + $17897
= **$323,268**

5. Estimate Annual O&M costs.

Annual O&M costs = annual cost for chemicals + parts + monitoring + labor + electricity; where:

- Chemicals costs = annual chemical usage based on the applied dose for a given average flow × unit cost of chemical based on vendor estimates = $36

- Material costs are based on vendor estimates = $946

- Labor costs = estimated labor hours based on discussions with vendors or best professional judgement × unit labor cost of $24.74/hr
 = $43,832

- Electricity costs = estimated total kWh based on discussions with vendors or simple computations based on equipment ratings × unit electricity cost of $0.076/kWh
 = $306

C Process monitoring = $10,400

Annual O&M Costs = **$55,520**
(i.e., 17 percent of total capital cost)

3.6 Costs for Storage tanks Including Finished Water Pumping

3.6.1 Introduction

In addition to the capital and O&M costs for installation of the disinfection technologies, ground water systems may also require storage tanks to provide sufficient contact time for disinfection. Systems which have disinfection but do not achieve the required inactivation may also be able to increase their inactivation by adding additional storage. This section provides the capital costs and cost equations for the storage tanks associated with chlorination (gas chlorination, hypochlorination, and anodic oxidation), and chlorine dioxide systems. Costs are for storage tanks that provide the contact time needed for 4-log inactivation of viruses at 15°C and a pH between 6 and 9. The document titled *The Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems using Surface Water Sources* (AWWA, 1991b) provided the appropriate CT values for the disinfectants.

3.6.2 Storage tanks

EPA considered "at-grade" baffled steel tanks for required capacities less than 100,000 gallons. For capacities greater than or equal to 100,000 gallons, "at-grade" baffled prestressed concrete tanks were assumed. The unit costs for these tanks were obtained from R.S. Means (2001). EPA assumed the use of baffled storage tanks to provide an actual contact time of 1.5 times the theoretical detention time in accordance with the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Resources* (AWWA, 1991b). Based on best professional judgement, an additional cost adjustment factor of 15 percent was applied to the R.S. Means costs to account for engineering, piping, fittings and other appurtenances. O&M costs are assumed to be part of a PWS's overall preventive maintenance plan and are expected to be negligible. These include yearly inspection by the operator and the painting of both the interior and exterior once every 10 years (USEPA , 1993b).

3.6.3 Finished Water Pumping

Ground water systems that require a storage tank for additional contact time for disinfection also require a high lift pump after the tank. The system replaces the existing pumps with pumps that pump water from the well to the distribution system and then restages the existing pumps with in-plant pumping for a lower head.

The W/W Model estimates the costs of finished water pumping and assumes the design flow for these costs. The model applies to design flow rates ranging from 1 to 200 mgd. It linearly extrapolates the cost curve for design flows less than 1 mgd, all the way down to zero flow (where cost is zero). The finished water requirements may be greater than the average daily flow depending on the layout of the distribution system and the plant storage capacities. Pumps are vertical turbines driven by 1,800 revolutions per minute (rpm), constant speed, drip proof, high thrust vertical motors. EPA assumed a total dynamic head (TDH) of 300 ft for these pumps. Costs also include a standby pump with a capacity equal to the largest pump provided, all electrical equipment and instrumentation, and valving and manifolding within the pumping station. The capital cost does not include wet well or housing. This model assumes a 90 percent motor efficiency and an 85 percent pump efficiency.

3.6.4 Cost Estimates

Exhibits 3.9 and 3.10 present the estimated costs for modifying ground water systems to achieve the required 4-log inactivation of viruses. These exhibits present two different disinfection technologies. Exhibit 3.9 present costs for adding a storage tank for chlorine gas and hypochlorination, the most commonly used disinfection technologies. They are also applicable to systems using anodic oxidation. Exhibit 3.10 presents the costs for operating an "at-grade" storage tank for chlorine dioxide contact.

As indicated in Exhibit 3.9, estimates for storage tank costs for chlorinating systems are not available for design flows greater than 76 mgd. Similarly, as indicated in Exhibit 3.10, estimates for storage tank costs for chlorine dioxide are not available for design flows greater than 22 mgd. This is because R.S. Means provides cost estimates for storage tanks up to a capacity of 500,000 gallons.

The capital costs for each system size are presented in Exhibits 3.10 and 3.11. Exhibits A.1 and A.2 of Appendix A present the linear regression cost coefficients A and B (described below) for all pertinent flow ranges. Costs were assumed to vary linearly with flow between any two adjacent flow points.

Cost ($) = A + [B × Flow (in kgpd)], where:
A = Y-axis intercept of the linear regression for that flow range
B = Slope of the linear regression for that flow range

The data shown in Exhibits A.1 and A.2 of Appendix A serve as inputs to the GWR EA Cost Model.

Exhibit 3.10 Estimated Costs for At-Grade Tanks for Chlorine Contact (Residual of 2 mg/L) - Costs in 2003$

Design Flow (mgd)	CT (mg-min/L)	C (mg/L)	T (min)	Tank Volume (gal)	Clearwell and Apurtenance Cost	Finished Water Pumping Costs	At-grade Clearwell and Pumping Costs	Basis for Clearwell Cost
					A	B	C = A + B	
0.007	4	2	2	6.5	$372.42	$415.39	$787.81	Steel tank (R.S. Means, 2001)
0.022	4	2	2	20.4	$402.16	$1,305.05	$1,707.22	Steel tank (R.S. Means, 2001)
0.037	4	2	2	34.3	$431.90	$2,194.72	$2,626.63	Steel tank (R.S. Means, 2001)
0.091	4	2	2	84.3	$538.97	$5,396.91	$5,935.88	Steel tank (R.S. Means, 2001)
0.18	4	2	2	166.7	$715.43	$10,674.98	$11,390.41	Steel tank (R.S. Means, 2001)
0.27	4	2	2	250.0	$893.87	$16,012.99	$16,906.86	Steel tank (R.S. Means, 2001)
0.36	4	2	2	333.3	$1,072.32	$21,351.00	$22,423.31	Steel tank (R.S. Means, 2001)
0.68	4	2	2	629.6	$1,706.78	$40,329.54	$42,036.32	Steel tank (R.S. Means, 2001)
1	4	2	2	925.9	$2,341.24	$59,308.09	$61,649.33	Steel tank (R.S. Means, 2001)
1.2	4	2	2	1,111.1	$2,737.78	$90,947.62	$93,685.40	Steel tank (R.S. Means, 2001)
2	4	2	2	1,851.9	$4,323.94	$217,505.71	$221,829.65	Steel tank (R.S. Means, 2001)
3.5	4	2	2	3,240.7	$7,297.99	$326,957.60	$334,255.58	Steel tank (R.S. Means, 2001)
7	4	2	2	6,481.5	$12,108.24	$536,716.69	$548,824.93	Steel tank (R.S. Means, 2001)
17	4	2	2	15,740.7	$20,350.74	$1,039,131.05	$1,059,481.79	Steel tank (R.S. Means, 2001)
22	4	2	2	20,370.4	$24,999.99	$1,286,088.80	$1,311,088.79	Steel tank (R.S. Means, 2001)
76	4	2	2	70,370.4	$75,211.94	$3,488,387.75	$3,563,599.70	Steel tank (R.S. Means, 2001)
210	4	2	2	194,444.4	$128,755.21	$8,953,351.98	$9,082,107.19	Pre-stressed concrete tank (R.S. Means, 2001)
430	4	2	2	398,148	N/A	Beyond Model Range	N/A	Pre-stressed concrete tank (R.S. Means, 2001)
520	4	2	2	481,481	N/A	Beyond Model Range	N/A	Pre-stressed concrete tank (R.S. Means, 2001)

1. N/A = Not Applicable
2. O&M costs are assumed to be part of a PWS's overall preventive maintenance plan and are expected to be negligible.

Exhibit 3.11 Estimated Costs for At-Grade Tanks for Chlorine Dioxide Contact (Residual of 0.625 mg/L) - Costs in 2003$

Design Flow (mgd)	CT (mg-min/L)	C (mg/L)	T (min)	Tank Volume (gal)	Clearwell and Apurtenance Cost	Finished Water Pumping Costs	At-grade Clearwell and Pumping Costs	Basis for Clearwell Cost
					A	B	C = A + B	
0.007	16.7	0.625	26.72	86.6	$543.97	$415.39	$959.35	Steel tank (R.S. Means, 2001)
0.022	16.7	0.625	26.72	272.1	$941.30	$1,305.05	$2,246.35	Steel tank (R.S. Means, 2001)
0.037	16.7	0.625	26.72	457.7	$1,338.63	$2,194.72	$3,533.35	Steel tank (R.S. Means, 2001)
0.091	16.7	0.625	26.72	1,125.7	$2,769.03	$5,396.91	$8,165.94	Steel tank (R.S. Means, 2001)
0.18	16.7	0.625	26.72	2,226.7	$5,126.54	$10,674.98	$15,801.52	Steel tank (R.S. Means, 2001)
0.27	16.7	0.625	26.72	3,340.0	$7,510.53	$16,012.99	$23,523.52	Steel tank (R.S. Means, 2001)
0.36	16.7	0.625	26.72	4,453.3	$9,894.53	$21,351.00	$31,245.53	Steel tank (R.S. Means, 2001)
0.68	16.7	0.625	26.72	8,411.9	$13,467.43	$40,329.54	$53,796.98	Steel tank (R.S. Means, 2001)
1	16.7	0.625	26.72	12,370.4	$16,966.08	$59,308.09	$76,274.17	Steel tank (R.S. Means, 2001)
1.2	16.7	0.625	26.72	14,844.4	$19,450.64	$90,947.62	$110,398.26	Steel tank (R.S. Means, 2001)
2	16.7	0.625	26.72	24,740.7	$29,388.89	$217,505.71	$246,894.60	Steel tank (R.S. Means, 2001)
3.5	16.7	0.625	26.72	43,296.3	$48,023.10	$326,957.60	$374,980.70	Steel tank (R.S. Means, 2001)
7	16.7	0.625	26.72	86,592.6	$91,502.93	$536,716.69	$628,219.62	Steel tank (R.S. Means, 2001)
17	16.7	0.625	26.72	210,296.3	$134,469.20	$1,039,131.05	$1,173,600.25	Steel tank (R.S. Means, 2001)
22	16.7	0.625	26.72	272,148.1	$156,764.42	$1,286,088.80	$1,442,853.22	Steel tank (R.S. Means, 2001)
76	16.7	0.625	26.72	940,148.1	$397,552.38	$3,488,387.75	$3,885,940.13	Steel tank (R.S. Means, 2001)
210	16.7	0.625	26.72	2,597,777.8	$995,065.11	$8,953,351.98	$9,948,417.09	Pre-stressed concrete tank (R.S. Means, 2001)
430	16.7	0.625	26.72	N/A	N/A	Beyond Model Range	N/A	Pre-stressed concrete tank (R.S. Means, 2001)
520	16.7	0.625	26.72	N/A	N/A	Beyond Model Range	N/A	Pre-stressed concrete tank (R.S. Means, 2001)

1. N/A = Not Applicable
2. O&M costs are assumed to be part of a PWS's overall preventive maintenance plan and are expected to be negligible.

3.7 Costing for Applicable Technologies

This section discusses the methodology for developing cost estimates for the following ground water treatment systems:

- Gas Chlorination
- Hypochlorination
- Temporary Hypochlorination
- Chlorine Dioxide
- Anodic Oxidation
- Ozonation
- Nanofiltration (NF)

3.7.1 Gas Chlorination Systems

3.7.1.1 Medium-to-Large Systems Costs: W/W Model

EPA used the W/W Model to estimate costs for systems with design flows equal to or greater than 1 mgd for a chlorine dose of 4 mg/L. Based on the AWWA disinfection survey (AWWA 1998), the average chlorine dose for community water system (CWS) plants expected to achieve a 4-log inactivation of viruses was found to be 4 mg/L. Costs were also developed for systems that would require additional storage capacity for contact time, besides chlorine addition. The details pertaining to additional storage costs are presented in Section 3.6.

Capital Costs - The W/W Model assumes that systems use the following two kinds of storage and feed systems to deliver chlorine:

- For systems with feed rates between 10 and 100 lbs/day, costs are developed assuming a chlorine gas feed system using 150-lb gas cylinders.
- For systems with feed rates between 100 and 2,000 lbs/day, costs are developed assuming a feed system using 1-ton gas cylinders.
- For systems with feed rates between 2,000 and 10,000 lbs/day, costs are developed assuming a feed system with on site-storage with bulk rail delivery.

However, for the range of flows and chlorine gas dose costed, the feed rates were always less than 2,000 lbs/day. Therefore, the details of the on-site storage with bulk rail delivery option are not discussed here.

Construction costs for a 10 to 100 lbs/day system include:

- Chlorinator
- Stand-by chlorinator
- Booster pump
- Injector
- Piping manifold system
- Booster pump piping and valving
- Housing for the chlorinator equipment
- Cylinder scales

Construction costs for a 100 to 2,000 lbs/day feed system include the following items in addition to those discussed under 10 to 100 lbs/day systems:

- Electrically operated monorail trolley hoist
- Cylinder scales

- Residual analyzer with flow proportioning controls (system > 1,000 lbs/day)

- Storage room for the gas cylinders with 30-day storage capacity

The model outputs were modified using the recommended methodology in Section 3.3. Additional costs for housing, permitting, and piloting were added to arrive at the total capital costs (see Section 3.5 for sample calculations). Because chlorination is fairly standardized and easy to operate, EPA believes that minimal training will be required and the vendor will supply the necessary training at minimal costs. To the degree that more rigorous training will be required, additional costs will be incurred.

O&M Costs - System O&M costs include the following:

- Process energy

- Building energy

- Equipment maintenance

- Labor

- Chemicals

EPA estimated the process energy cost using booster pump size and electrical hoists. The building energy costs for both the chlorinator room and cylinder storage room include lighting, heating, and ventilation. The model bases the building energy cost on 102.6 kilowatt-hour per square foot per year (kWh/ft^2/yr) including lighting, heating, and ventilation. Where appropriate, labor hours cover loading and unloading cylinders from delivery trucks, periodic changeover of gas cylinders, and daily checking of system operation and the chlorine residual. A cost of $296.80/ton for 1-ton cylinders and $636/ton for 150-lb cylinders serves as the basis for the annual chemical cost.

3.7.1.2 Small-to-Medium Systems Costs: Water Model

EPA used the Water Model to estimate costs for systems with design flows less than 1 mgd. Based on the AWWA disinfection survey (AWWA, 1998), the average chlorine dose for community water system plants expected to achieve a 4-log inactivation of viruses was found to be 4 mg/L. Costs were also developed for systems that would require additional storage capacity besides chlorine addition. The details pertaining to the cost estimates for storage tanks are presented in Section 3.6. The model is applicable for chlorine loading rates in the range 1-80 lbs/day.

Capital Costs - The gas feed chlorination system used as a basis of design in the Water Model consists of a typical side stream chemical feed system using 150-lb cylinders for chlorine gas delivery and storage. The construction costs estimated by the Water Model include the following:

- Chlorine manifold piping

- Chlorinator

- Side stream booster pump

- Venturi gas injector

The Water Model includes two feed systems, one using an applicable chlorine feed range of 1 to 40 lbs/day and the second with a feed range of 40 to 80 lbs/day. Systems with chlorine usage rates less than 40 lbs/day use a single two-cylinder scale. The scale measures the amount of chlorine remaining in the cylinders. Systems with a chlorine usage rate between 40 and 80 lbs/day use two parallel gas feed systems, each with two 150 lb cylinders and an automatic switch-over. The model includes the cost of piping and valves between the booster pump and injector system and between the chlorinator and injector. Construction costs include a 10 feet (ft) by 10 ft by 10 ft building with a 30 air changes/hour ventilation system, louvers, automatic damper, chlorine leak detector, and protective respiratory apparatus.

The model outputs were modified using the recommended methodology in Section 3.3. Additional costs for housing, permitting, and piloting were added to arrive at the total capital costs (see Section 3.5 for sample calculations). Because chlorination is fairly standardized and easy to operate, EPA believes that minimal training will be required and the vendor will supply the necessary training at minimal costs. To the degree that more rigorous training will be required, additional costs will be incurred.

O&M Costs - System O&M costs include the following:

- Process energy

- Building energy

- Equipment maintenance

- Labor

- Chemicals

The model estimates the process energy cost based on a booster pump sized to pump against a pressure of 150 pounds per square inch (psi) with a capacity varying between 5.5 to 10.5 gallons per minute (gpm). The model bases the building energy cost on 102.6 kilowatt-hour per square foot per year (kWh/ft^2/yr) including lighting, heating, and ventilation. The model estimated equipment maintenance at approximately 5 percent of equipment capital cost per year. Labor averages one-half hour per day to cover periodic changeover of gas cylinders and daily checking of system operation and the chlorine residual. A cost of $636/ton for chlorine in 150-lb cylinders serves as the basis for the annual chemical cost.

3.7.1.3 Very Small Systems Costs: VSS Model

The VSS document does not provide equations for chlorine gas feed technology.

3.7.1.4 Gas Chlorination - Cost Summary and Equations

Exhibit 3.12 presents the total capital and O&M costs for each system size (with and without storage options). Exhibit A.1 of Appendix A presents the linear regression cost coefficients A and B (described below) for all pertinent flow ranges for estimated capital and O&M costs. Since cost floor estimates are not readily available, the lowest calculated costs are assumed to be the cost floor for this technology. Costs were assumed to vary linearly with flow between any two adjacent flow points.

Cost ($) = A + [B × Flow (in kgpd)], where:
A = Y-axis intercept of the linear regression for that flow range
B = Slope of the linear regression for that flow range

The data shown in Exhibit A.3 of Appendix A serve as inputs to the Ground Water Rule economic assessment cost model.

Exhibit 3.12 Estimated Costs for Gas Chlorination Systems (*continued on next page)*

Design Flow (mgd)	Average Daily Flow (mgd)	Total Capital Cost ($)	Annual O&M Cost ($)	Model Used
Chlorine gas (4.0 mg/L) with no storage				
< 0.007	< 0.0015	$29,868	$6,182	Cost floor[1]
0.007	0.0015	$29,868	$6,182	WM Process 23
0.022	0.0054	$29,868	$6,198	WM Process 23
0.037	0.0095	$29,868	$6,213	WM Process 23
0.091	0.025	$29,868	$6,267	WM Process 23
0.18	0.054	$29,868	$6,365	WM Process 23
0.27	0.084	$29,868	$6,466	WM Process 23
0.36	0.11	$29,868	$6,554	WM Process 23
0.68	0.23	$29,868	$6,961	WM Process 23
1	0.35	$56,898	$16,542	W/W Process 50
1.2	0.41	$58,757	$16,812	W/W Process 50
2	0.77	$66,200	$18,431	W/W Process 50
3.5	1.4	$80,157	$21,287	W/W Process 50
7	3	$112,725	$22,338	W/W Process 50
17	7.8	$207,757	$34,104	W/W Process 50
22	11	$259,231	$41,973	W/W Process 50
76	38	$583,551	$117,190	W/W Process 50
210	120	-	-	Flow beyond model range
430	270	-	-	Flow beyond model range
520	350	-	-	Flow beyond model range
Chlorine gas (4.0 mg/L) with storage[2]				
< 0.007	< 0.0015	$30,655	$6,182	Cost Floor[1]
0.007	0.0015	$30,655	$6,182	WM Process 23
0.022	0.0054	$31,575	$6,198	WM Process 23
0.037	0.0095	$32,494	$6,213	WM Process 23
0.091	0.025	$35,803	$6,267	WM Process 23
0.18	0.054	$41,258	$6,365	WM Process 23
0.27	0.084	$46,774	$6,466	WM Process 23

Design Flow (mgd)	Average Daily Flow (mgd)	Total Capital Cost ($)	Annual O&M Cost ($)	Model Used
0.36	0.11	$52,291	$6,554	WM Process 23
0.68	0.23	$71,904	$6,961	WM Process 23
1	0.35	$118,547	$16,542	W/W Process 50
1.2	0.41	$152,442	$16,812	W/W Process 50
2	0.77	$288,030	$18,431	W/W Process 50
3.5	1.4	$414,413	$21,287	W/W Process 50
7	3	$661,550	$22,338	W/W Process 50
17	7.8	$1,267,239	$34,104	W/W Process 50
22	11	$1,570,320	$41,973	W/W Process 50
76	38	$4,147,151	$117,190	W/W Process 50
210	120	-	-	Flow beyond model range
430	270	-	-	Flow beyond model range
520	350	-	-	Flow beyond model range

[1] Since cost floor estimates are not readily available, the lowest calculated costs are assumed to be the minimum costs for this technology. A cost floor refers to the minimum cost incurred by any system, howsoever small, in implementing a technology. It is driven by the minimum size of the individual components that make a unit process or the minimum lot size of equipments and fittings. For example, commercially available pumps can't be smaller than a particular size.

[2] See Exhibit 3.9 for storage costs.

3.7.2 Hypochlorination Systems (with and without additional storage)

Based on the AWWA disinfection survey (AWWA, 1998), the average chlorine dose for community water system plants expected to achieve a 4-log inactivation of viruses was found to be 4 mg/L. This section discusses the assumptions made to develop cost estimates for hypochlorination systems, using the cost models. Costs were also developed for systems that would require additional storage capacity besides chlorine addition. Costs were also not included for training as it is assumed water treatment operators are familiar with chlorination. The details pertaining to the cost estimates for additional storage are presented in Section 3.7.

3.7.2.1 Medium-to-Large Systems Costs: W/W Model

The W/W Model was used to estimate hypochlorination costs for systems with design flows greater than or equal to 1 mgd. The model can estimate costs up to a design flow of 200 mgd.

3.7.2.2 Small-to-Medium Systems Costs: Water Model

The hypochlorination systems used as a basis of design in the Water Model are capable of feeding 0.1 to 100 lbs/day of either sodium or calcium hypochlorite solution. Using the equipment listed, systems may feed an equivalent of 0.01 to 1,000 lbs/day of available chlorine, depending upon hypochlorite solution strength and metering pump output.

Capital Costs - The construction costs estimated by the Water Model include the following:

- Solution preparation tank with mixer
- Strainer at the solution tank discharge
- Diaphragm metering pump

The system includes an electrical interlock to ensure that the system feeds hypochlorite solution only when water is flowing. Operators manually set the metering pump discharge rate, therefore, the system requires a constant water flow rate. EPA assumed the system uses PVC piping and valves. Construction costs include a 10 ft by 10 ft by 10 ft building with an emergency shower.

The model outputs were modified using the recommended methodology in Section 3.3. Additional costs for housing, permitting, and piloting were added to arrive at the total capital costs (see Section 3.5 for sample calculations). Because chlorination is fairly standardized and easy to operate, EPA believes that minimal training will be required and the vendor would supply any needed training at minimal costs. To the degree that more rigorous training will be required, additional costs will be incurred.

O&M Costs - System O&M costs include the following:

- Process energy
- Building energy
- Equipment maintenance materials
- Labor
- Chemicals

EPA estimated the process energy cost based on a diaphragm meter pump used continuously and a periodically used mixer on the hypochlorite solution tank. The costs of equipment maintenance materials include periodic maintenance of the metering pump. EPA assumed an average of one-half hour per day spent on labor to cover the periodic preparation of the hypochlorite solution, and the daily checking of system operation and chlorine residual. A cost of $1,192.50/ton for 12.5 percent sodium hypochlorite solution (about 1 pound of chlorine per gallon) formed the basis for the annual chemical cost estimates.

3.7.2.3 Very Small Systems Costs: VSS Model

Capital Costs - To estimate capital costs, EPA used the relevant VSS Model equations for design flows between 0.030 mgd and 0.1 mgd for a hypochlorite feed system. The VSS Model estimated the capital costs for these systems (excluding permitting costs) at $4,700. The model outputs were modified using the recommended methodology in section 3.3. Additional costs for housing, permitting, and piloting were added to arrive at the total capital costs (see section 3.5 for sample calculations). The total capital costs (in 2003 dollars) are presented in Exhibit 3.12. Because chlorination is fairly standardized and easy to operate, EPA assumed that the vendor would supply the needed training at minimal costs. To the degree that more rigorous training will be required, additional costs will be incurred.

O&M Costs - The VSS O&M equation generated unrealistically high O&M costs relative to the Water Model O&M outputs for the higher flow rates. Therefore, EPA developed O&M cost estimates using engineering costing procedures for average flows less than and equal to 0.025 mgd. They were based on the following assumptions based on best professional judgement:

- Part replacement cost was estimated based on vendor quotes for parts anticipated to fail or be consumed (tube or diaphragm for chemical metering pumps, reagents for on-line chlorine analyzer).
- Electricity costs were estimated based on metering pumps power requirements.
- Labor costs reflect the labor hours required for routine maintenance. Maintenance labor hours were assumed to be 4 hours per month.
- Labor and chemical costs used for developing these costs are listed in Exhibits 3.3 and 3.5, respectively.

3.7.2.4 Hypochlorination - Cost Summary and Equations

Total capital and O&M costs (in 2003 dollars) for each system size are presented in Exhibit 3.13. Exhibit A.4 of Appendix A presents the linear regression cost coefficients A and B (described below) for all pertinent flow ranges. Since cost floor estimates are not readily available, the lowest calculated costs are assumed to be the cost floor for this technology. Costs were assumed to vary linearly with flow between any two adjacent flow points. Because there is a discontinuity in the costs where the cost models changed, the highest cost for the Water Model was extended into the region of the W/W Model which predicted lower costs than the Water Model. This gives a conservative estimate for the area where the models disagree.

Cost ($) = A + [B × Flow (in kgpd)], where:
A = Y-axis intercept of the linear regression for that flow range
B = Slope of the linear regression for that flow range

The data shown in Exhibit A.4 of Appendix A serve as inputs to the GWR EA Cost Model.

3.7.2.5 Additional Cost Model Inputs for Gas Chlorination and Hypochlorination

The GWR EA Cost Model generates costs for systems that currently disinfect but do not achieve 4-log inactivation of viruses. Based on the AWWA disinfection survey data (AWWA, 1998) the average chlorine dose of the CWS plants in this category was found to be 2.5 mg/L. Therefore costs are also developed for gas chlorination and hypochlorination systems (specifically, hypochlorination for systems serving populations less than 10,000 and gas chlorination for the rest) increasing the chlorine dose from 2.5 mg/L to 4 mg/L. This is consistent with the assumption that a dose of 4 mg/L will achieve 4-log inactivation of viruses.

The increase in O&M costs (in 2003 dollars) for each system size are presented in Exhibit 3.13. Exhibit A.5 of Appendix A presents the linear regression cost coefficients A and B (described below) for all pertinent flow ranges. The use of different models causes a discontinuity in costs with a sharp spike and then a dip. The costs for the 0.0095 mgd flow was extended over the next two flows to smooth out the curves and remove the unrealistic spike.

Increase in Cost ($) = A + [B × Flow (in kgpd)], where:
A = Y-axis intercept of the linear regression for that flow range
B = Slope of the linear regression for that flow range

Exhibit 3.13 Estimated Costs for Hypochlorination Systems

Design Flow (mgd)	Average Daily Flow (mgd)	Total Capital Cost ($)	Annual O&M Cost ($)	Model Used
Hypochlorite (4 mg/L) without storage				
< 0.007	< 0.0015	$8,970	$1,468	Floor for capital cost[1], O&M cost[2]
0.007	0.0015	$8,970	$1,468	Floor for capital cost[1], O&M cost[2]
0.022	0.0054	$8,970	$1,665	Floor for capital cost[1], O&M cost[2]
0.037	0.0095	$8,970	$1,871	VSS for capital cost, O&M cost[2]
0.091	0.025	$8,970	$2,650	VSS for capital cost, O&M cost[2]
0.18	0.054	$24,402	$6,414	WM Process 25
0.27	0.084	$24,402	$6,602	WM Process 25
0.36	0.11	$24,402	$6,765	WM Process 25
0.68	0.23	$24,402	$7,519	WM Process 25
1	0.35	$69,897	$4,660 [3]	W/W Process 49
1.2	0.41	$72,604	$5,157	W/W Process 49
2	0.77	$81,006	$7,975	W/W Process 49
3.5	1.4	$88,812	$12,768	W/W Process 49
7	3	$103,095	$24,652	W/W Process 49
17	7.8	$137,972	$59,887	W/W Process 49
22	11	$152,455	$83,394	W/W Process 49
76	38	$297,421	$281,401	W/W Process 49
210	120	-	-	Beyond model range[4]
430	270	-	-	Beyond model range[4]
520	350	-	-	Beyond model range[4]
Hypochlorite (4.0 mg/L) with storage[5]				
< 0.007	< 0.0015	$9,757	$1,468	Floor for capital cost[1], O&M cost[2]
0.007	0.0015	$9,757	$1,468	Floor for capital cost[1], O&M cost[2]
0.022	0.0054	$10,677	$1,665	Floor for capital cost[1], O&M cost[2]
0.037	0.0095	$11,596	$1,871	VSS for capital cost, O&M cost[2]
0.091	0.025	$14,906	$2,650	VSS for capital cost, O&M cost[2]
0.18	0.054	$35,793	$6,414	WM Process 25
0.27	0.084	$41,309	$6,602	WM Process 25
0.36	0.11	$46,826	$6,765	WM Process 25
0.68	0.23	$66,439	$7,519	WM Process 25
1	0.35	$131,546	$4,660 [3]	W/W Process 49
1.2	0.41	$166,289	$5,157	W/W Process 49
2	0.77	$302,836	$7,975	W/W Process 49

[1] Since cost floor estimates are not readily available, the lowest calculated costs are assumed to be the minimum costs for this technology.

[2] O&M costs are based on engineering costing procedures using assumptions based on best professional judgement.

[3] A drop in O&M costs is due to the use of a different cost model (i.e., the W/W Model)

[4] Chlorine use rate outside range of costing models.

[5] See Exhibit 3.10 for storage costs.

Exhibit 3.14 Estimated *Additional* O&M Costs For Hypochlorite/ Gas Chlorination Systems When Increasing Chlorine Dose From 2.5 mg/L to 4 mg/L

Average Daily Flow (mgd)	Annual O&M Cost Increase	Comment
< 0.0015	$28	Hypochlorite
0.0015	$28	Hypochlorite
0.0054	$102	Hypochlorite
0.0095	$179	Hypochlorite
0.025	$471	Hypochlorite
0.054	$127	Hypochlorite
0.084	$197	Hypochlorite
0.11	$259	Hypochlorite
0.23	$542	Hypochlorite
0.35	$1,100	Hypochlorite
0.41	$1,256	Hypochlorite
0.77	$2,252	Hypochlorite
1.4	$2,370	Chlorine gas
3	$5,107	Chlorine gas
7.8	$7,184	Chlorine gas
11	$10,137	Chlorine gas
38	$39,395	Chlorine gas
120	-	Beyond model range
270	-	Beyond model range
350	-	Beyond model range

1. Hypochlorination costs for average flows # 0.025 mgd are based on best professional judgement.
2. Hypochlorination costs for 0.025 mgd < average flow < 0.35 mgd are based on the Water Model, Process 25.
3. Hypochlorination costs for 0.35 mgd # average flow # 0.77 mgd are based on the W/WModel, Process 49.
4. Gas chlorination costs for 0.77 mgd < average flow # 38 mgd are based on the W/W Model, Process 50.

3.7.3 Temporary Hypochlorination

Systems are assumed to install a portable hypochlorination system at the well site. A temporary hypochlorination system is assumed to consist of a chemical storage tank, a chemical feed pump, chemical feed tubing, and a housing. The main differences between this option and the permanent hypochlorination discussed above are the temporary nature of the facilities. Housing costs here are for a small temporary shelter only large enough to house the equipment rather than a lighted building. Doses and duration of treatment also differ.

The system was designed assuming a 12.5 percent solution of hypochlorite. The pump was sized using the system design flow. The tank was sized assuming that it could hold sufficient hypochlorite solution to provide the average flow rate with a dose of 2 mg/L of hypochlorite for one week. Exhibit 3.15 displays the assumptions for required pumping rates and tank volumes.

Exhibit 3.15 Temporary Hypochlorination Pumping Rates and Tank Volumes

Design Flow (mgd)	Average Flow (mgd)	Dose (mg/L)	Hypochlorite Solution Strength (%)	Hypochlorite needed (gal/hr)	Tank Size (gal)
A	B	C	D	E = A*C/28.752*D	F = 5.843*B*C/D
0.007	0.0015	2	12.5%	0.0	0.1
0.022	0.0054	2	12.5%	0.0	0.5
0.037	0.0095	2	12.5%	0.0	0.9
0.091	0.025	2	12.5%	0.1	2.3
0.18	0.054	2	12.5%	0.1	5.0
0.27	0.084	2	12.5%	0.2	7.9
0.36	0.11	2	12.5%	0.2	10.3
0.68	0.23	2	12.5%	0.4	21.5
1	0.35	2	12.5%	0.6	32.7
1.2	0.41	2	12.5%	0.7	38.3
2	0.77	2	12.5%	1.1	72.0
3.5	1.4	2	12.5%	1.9	130.9
7	3	2	12.5%	3.9	280.5
17	7.8	2	12.5%	9.5	729.2
22	11	2	12.5%	12.2	1028.4
76	38	2	12.5%	42.3	3552.6
210	120	2	12.5%	116.9	11218.7

Costs were taken from the 2003 Cole Parmer catalog. The pumps used were single head chemical-feed diaphragm pumps. A 115 VAC, 60 Hz pump with 3/8 inch tubing was assumed. For flows greater than 10 gal/hr high volume pumps were assumed. A service kit including an extra diaphragm, valve, spring, and O-rings were included in the price for each pump. Costs were also included for 60 ft. of PTFE tubing. Exhibit 3.16 shows the costs for pumps with given design flow rates.

Exhibit 3.16 Pump Costs (2003$)

Pump Size (gal/hr)	Cost ($)
Up to 10.5	513.50
> 10.5 and < 16.5	668.50
> 16.5 and < 32.5	673.50

Source: 2003 Cole Parmer Catalog

If the required flow was greater than 32.5 gal/hr multiple pumps were assumed.

The tanks assumed were XLPE corrosion resistant horizontal leg tanks. Exhibit 3.17 Shows the costs of the chemical storage tanks. Tanks are available in up to 300 gallon sizes. If more than 300 gallons of storage is required, multiple tanks were assumed.

Exhibit 3.17 Tank Costs (2003$)

Tank Size (gallons)	Cost ($)
55	328.00
110	408.00
200	585.00
300	660.00

Source: 2003 Cole Parmer Catalog

Housing costs were based on the size of the storage tank plus an additional foot clearance. Costs were calculated using the 1999 RS means cost of $35.15 per square foot. The cost was converted to 2003 dollars by using the BCI index. Exhibit 3.18 Displays the total capital costs of the temporary hypochlorination system. An extra 25 percent of the total capital costs of the equipment was added to account for installation and an extra 20 percent was added to account for valving and instrumentation.

Exhibit 3.18 Capital Costs for Temporary Hypochlorination

Design Flow (mgd)	Average Flow (mgd)	Capital Cost ($)
0.007	0.0015	$1,874
0.022	0.0054	$1,874
0.037	0.0095	$1,874
0.091	0.025	$1,874
0.18	0.054	$1,874
0.27	0.084	$1,874
0.36	0.11	$1,874
0.68	0.23	$1,874
1	0.35	$1,874
1.2	0.41	$1,874
2	0.77	$1,990
3.5	1.4	$2,246
7	3	$2,355
17	7.8	$15,822
22	11	$19,483
76	38	$24,830

Chemical and pumping electricity costs were assumed to be the same as for a hypochlorination system as listed in above. Labor costs were considered to be for 15 minutes a day for an operator to check the pump, measure the residual, and refill the storage tank as necessary for systems with a flow of 1 mgd or less and 30 minutes a day for larger systems. A labor rate of $27.01 was used. Exhibit 3.19 shows the operating and maintenance costs for the system.

Exhibit 3.19 Operating and Maintenance Costs

Design Flow (mgd)	Average Flow (mgd)	Chemical & Electricity Costs ($)	Labor ($)	Total O&M ($)
0.007	0.0015	$172	$2,465	$2,636
0.022	0.0054	$172	$2,465	$2,636
0.037	0.0095	$369	$2,465	$2,833
0.091	0.025	$575	$2,465	$3,039
0.18	0.054	$1,354	$2,465	$3,818
0.27	0.084	$1,485	$2,465	$3,949
0.36	0.11	$1,673	$2,465	$4,137
0.68	0.23	$1,836	$2,465	$4,300
1	0.35	$2,590	$2,465	$5,054
1.2	0.41	$228	$4,929	$5,157
2	0.77	$3,046	$4,929	$7,975
3.5	1.4	$7,839	$4,929	$12,768
7	3	$19,723	$4,929	$24,652
17	7.8	$54,958	$4,929	$59,887
22	11	$78,465	$4,929	$83,394
76	38	$276,472	$4,929	$281,401

3.7.4 Chlorine Dioxide Systems (with and without additional storage)

Costs were estimated based on the cost models and vendor information and are presented for both systems that would require additional storage capacity and those that will not require additional storage. The details pertaining to the cost estimates for systems requiring additional storage for added contact time are presented in Section 3.6.

3.7.4.1 Chlorine Dioxide Dose

Chlorine dioxide costs were evaluated at an applied dose of 1.25 mg/L. This is a conservative maximum dose for compliance with the chlorite maximum contaminant level (MCL) of 1 mg/L, assuming 70 percent conversion of chlorine dioxide to chlorite and allowing for impurities in chlorine dioxide generation. An average chlorine dioxide residual of 0.625 mg/L (i.e., half the applied dose) was assumed for sizing the storage tanks.

3.7.4.2 Capital Cost Assumptions

Feed Equipment (for systems with design flows > 2 mgd)

Feed equipment costs for systems with design capacities greater than 2 mgd were estimated using the W/W Costs 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 systems with design capacities less than or equal to 2 mgd, feed equipment was classified as an O&M cost item instead of a capital cost item. The rationale behind this assumption and the corresponding costing assumptions are outlined in Section 3.7.4.3.

Instrumentation & Controls (I&C), and Pipe & Valves (P&V)

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 are based on quantity takeoffs from actual designs, information from actual plant construction projects, and equipment supplier quotes.

Capital Cost Multipliers

The feed equipment, I&C, and P&V capital cost items were calculated as a subtotal representing process costs. The process cost subtotal was then multiplied by a capital cost factor (2.5 for systems < 1 mgd or 2.0 for systems $ 1 mgd); the capital cost factors are intended to account for items not included in the process costs.

Permitting

Significant process improvements or new treatment will likely require coordination with the appropriate regulatory agency. As such, permitting costs are included at 3 percent of the process cost. As discussed in the earlier sections, minimum and maximum permitting costs were assumed to be $2,500 and $500,000, respectively (NDWAC and TDP recommendations).

Pilot/Bench Testing

The necessity for pilot or bench-scale testing was assumed to ensure that chlorine dioxide use would be compatible with any existing treatment and/or the water quality conditions. The level of testing required was estimated based on system size. Costs for testing were included as shown below (see Exhibit 3.8):

- For systems less than 0.1 mgd: $5,000
- For systems from 0.1 to 1 mgd: $10,000
- For systems greater than 1.0 mgd: $50,000

Chlorine Dioxide System Housing

Housing costs are assumed to be $51.10 per sq. ft. This is based on the R.S. Means (2000) estimate of the median cost of a factory type building, updated to year 2003 dollars using the BCI. The footprint area for housing was calculated using the W/W Model. These are shown in Exhibit 3.20.

3.7.4.3 O&M Cost Assumptions

O&M costs for all systems were estimated using the W/W Cost Model. The sections below address specifics of the line O&M costs.

Feed Equipment (for systems with design flows #2 mgd)

This is a capital cost item for systems with design flows greater than 2 mgd. However, based on vendor information, it is believed that for design capacities less than or equal to 2 mgd, utilities can lease the equipment more economically than constructing their own system. Thus vendor quotes of equipment leasing costs were applied for these systems (i.e., those with design flows # 2 mgd) and classified as an O&M cost line item instead of a capital cost line item.

Chemical Usage

Chlorine dioxide costs were evaluated at an applied dose of 1.25 mg/L. The unit costs for sodium chlorite and chlorine gas (i.e., the reactants for generating chlorine dioxide) are presented in Exhibit 3.5.

Footprint area, Electricity and Labor

The footprint area, electricity usage, and labor hours were calculated using the W/W Cost Model. Exhibit 3.15 presents the values calculated by the model.

Exhibit 3.20 W/W Cost Model Footprint Area, Electricity Usage and Required Labor

Design Capacity (mgd)	Footprint Area for Housing (ft^2)	Electricity Usage/Year (KWh)	O&M Labor/Year (hours)
0.091	109	3,437	421
0.18	109	3,437	454
0.27	109	3,437	475
0.36	109	3,437	482
0.68	109	3,437	500
1	109	3,437	517
1.2	114	3,443	526
2	129	3,457	577
3.5	157	3,504	619
7	225	3,638	667
17	357	3,917	816
22	412	4,163	897
76	1,009	7,241	1,356
210	2,192	15,165	2,548
430	4,048	24,749	3,835
520	4,765	29,766	4,521

Source: Based on the W/W Model.

3.7.4.4 Chlorine Dioxide - Cost Summary and Equations

Total capital and O&M costs (in 2003 dollars) for each system size are presented in Exhibit 3.21. Exhibit A.6 of Appendix A presents the linear regression cost coefficients A and B (described below) for all pertinent flow ranges. Cost estimates for design flows < 0.091 mgd are not presented since chlorine dioxide is not a feasible technology for the very small systems (i.e., systems serving populations < 100). Costs were assumed to vary linearly with flow between any two adjacent flow points.

Cost ($) = A + [B × Flow (in kgpd)], where:
A = Y-axis intercept of the linear regression for that flow range
B = Slope of the linear regression for that flow range

The data shown in Exhibit A.6 of Appendix A serve as inputs to the GWR EA Cost Model.

Exhibit 3.21 Estimated Costs for Chlorine Dioxide Systems *(continued on next page)*

Design Flow (MGD)	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1	1.2
Average Flow (MGD)	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35	0.41
Capital Cost Summary										
Total Capital Cost	Data Not Used			$32,661	$38,604	$39,406	$40,300	$43,239	$40,269	$80,831
Subtotal Indirect Capital Costs				$13,061	$18,061	$18,061	$18,061	$18,061	$18,061	$58,344
Piloting				$5,000	$10,000	$10,000	$10,000	$10,000	$10,000	$50,000
Permitting				$2,500	$2,500	$2,500	$2,500	$2,500	$2,500	$2,500
Land										
Operator Training										
Housing				$5,561	$5,561	$5,561	$5,561	$5,561	$5,561	$5,844
Housing SF				109	109	109	109	109	109	114
Other Indirect Costs										
Capital Cost Multiplier				$19,600	$20,543	$21,344	$22,239	$25,177	$22,208	$22,487
Subtotal Process Cost				$7,840	$8,217	$8,538	$8,895	$10,071	$11,104	$11,243
Pipes and Valves				$1,701	$1,900	$2,073	$2,265	$2,898	$ 3,454	$ 3,462
Instrumentation and controls				$6,139	$6,317	$6,465	$6,630	$7,173	$ 7,650	$ 7,781
Pumping										
Chlorine Dioxide Generator										
Storage Tanks										
Process Monitoring Equipment										
Feed Equipment										
Other Process Cost #2										
Annual O&M Cost Summary										
Total Annual O&M Cost	Data Not Used			$14,787	$15,953	$17,006	$17,289	$18,112	$18,881	$19,673
Feed Equipment				$2,373	$2,373	$2,373	$2,373	$2,373	$2,373	$2,373
Chemicals				$30	$61	$97	$121	$266	$ 399	$ 471
Part Replacement										
Performance monitoring										
Materials				$1,708	$2,026	$2,239	$2,320	$2,542	$ 2,748	$ 2,866
Electricity				$ 261	$ 261	$ 261	$ 261	$ 261	$ 261	$ 262
Electricity Use (KWH)				3,437	3,437	3,437	3,437	3,437	3,437	3,443
Labor $				$10,416	$11,232	$12,037	$12,214	$12,670	$ 13,101	$ 13,702

See Exhibit 3.11 for storage costs.

Exhibit 3.21 Estimated Costs for Chlorine Dioxide Systems (*continued*)

Design Flow (MGD)	2	3.5	7	17	22	76	210	430	520
Average Flow (MGD)	0.77	1.4	3	7.8	11	38	120	270	350
Capital Cost Summary									
Total Capital Cost	$82,332	$191,425	$211,957	$268,990	$297,453	$605,595	$902,161	$1,254,689	$1,379,227
Subtotal Indirect Capital Costs	$59,099	$60,514	$64,004	$71,191	$74,389	$109,008	$172,932	$271,584	$309,533
Piloting	$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	$2,967	$3,346	$7,449	$10,938	$14,747	$16,045
Land									
Operator Training									
Housing	$6,599	$8,014	$11,504	$18,224	$21,043	$51,559	$111,993	$206,838	$243,487
Housing SF	129	157	225	357	412	1,009	2,192	4,048	4,765
Other Indirect Costs									
Capital Cost Multiplier	$23,233	$130,911	$147,954	$197,799	$223,065	$496,587	$729,229	$983,105	$1,069,694
Subtotal Process Cost	$11,617	$65,456	$73,977	$98,899	$111,532	$248,293	$364,614	$491,553	$534,847
Pipes and Valves	$ 3,484	$ 3,526	$ 3,627	$ 4,968	$ 5,824	$ 15,084	$ 22,541	$ 30,324	$ 32,976
Instrumentation and controls	$ 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
Other Process Cost #2									
Annual O&M Cost Summary									
Total Annual O&M Cost	$22,048	$22,001	$28,867	$40,191	$47,010	$94,126	$230,088	$446,533	$561,934
Feed Equipment	$2,373								
Chemicals	$ 883	$ 1,658	$ 3,425	$ 8,941	$ 12,699	$ 43,724	$ 138,128	$ 310,813	$ 402,894
Part Replacement									
Performance monitoring									
Materials	$ 3,499	$ 3,952	$ 4,315	$ 5,444	$ 5,954	$ 7,463	$ 11,157	$ 13,957	$ 15,451
Electricity	$ 263	$ 266	$ 276	$ 298	$ 316	$ 550	$ 1,153	$ 1,881	$ 2,262
Electricity Use (KWH)	3,457	3,504	3,638	3,917	4,163	7,241	15,165	24,749	29,766
Labor $	$ 15,031	$ 16,125	$ 20,850	$ 25,508	$ 28,040	$ 42,389	$ 79,650	$ 119,882	$ 141,326

3.7.5 Anodic Oxidation Systems

In order to estimate costs for anodic oxidation systems, EPA estimated the costs for onsite generation of hypochlorite, a process that is similar to the anodic oxidation process. This section discusses the assumptions and the unit process used to estimate costs for anodic oxidation. Costs were also presented for systems that would require additional storage capacity besides disinfectant addition. The details pertaining to the cost estimates for storage tanks are presented in Section 3.6.

3.7.5.1 Medium-to-Large Systems Costs: W/W Model

EPA used the W/W Cost Model to estimate costs for all design flow categories. The W/W Cost Model based the cost estimates on two types of generation equipment: open-cell and membrane systems. EPA based the costs on the open-cell technology for systems with a chlorine-producing capacity up to 2,500 lbs/day and membrane technology for systems producing more than 2,500 lbs of chlorine per day.

Open-cell systems include an electrolysis cell with an anode and a cathode. Membrane systems include an electrolysis cell with a membrane separating the anode and the cathode. EPA assumed that for every 1 mg/L of sodium hypochlorite generated 2.2 mg/L of sodium chloride was required (i.e., for a 4 mg/L dose of sodium hypochlorite 8.8 mg/l of sodium chloride was required).

Capital Costs - The construction costs include the following:

- Electrolysis cells
- Power rectifier
- Salt storage tank
- Brine dissolver
- Brine storage tank
- Water softener
- Brine transfer and metering pumps
- Oxidants solution transfer and metering pumps
- Oxidants solution storage tank
- Piping and valves
- Flowmeters
- Electrical control equipment
- Housing

For systems producing more than 500 lbs/day of chlorine, the storage tank and brine dissolver are located outside. These estimates include a brine purification system for systems producing more than 2,000 lbs/day of chlorine. The model outputs were modified using the recommended methodology in Section 3.3. Additional costs for housing, permitting, and piloting were added to arrive at the total capital costs (see Section 3.5 for sample calculations).

O&M Costs - System O&M costs include the following:

- Process energy
- Equipment maintenance
- Materials
- Chemicals

The process energy requirements vary from 2.0 to 4.7 kilowatt hour per pound (kWh/lb) of chlorine equivalent. The membrane cell consumes less energy than the open-cell system. Maintenance requirements include the replacement of the electrode every two years, while material costs include the salt consumption.

3.7.5.2 Small-to-Medium Systems Costs: Water Model

There are no cost curves or processes available for anodic oxidation systems in the Water Model.

3.7.5.3 Very Small Systems Costs: VSS Model

The VSS document does not provide equations for anodic oxidation systems.

3.7.5.4 Anodic Oxidation - Cost Summary and Equations

Total capital and O&M costs (in 2003 dollars) for each system size are presented in Exhibit 3.22. Exhibit A.7 of Appendix A presents the linear cost coefficients A and B (described below) for all pertinent flow ranges. Since cost floor estimates are not readily available, the lowest calculated costs are assumed to be the cost floor for this technology. Costs were assumed to vary linearly with flow between any two adjacent flow points.

Cost ($) = A + [B × Flow (in kgpd)], where:
A = Y-axis intercept of the linear regression for that flow range
B = Slope of the linear regression for that flow range

The data shown in Exhibit A.7 of Appendix A serve as inputs to the GWR EA Cost Model.

3.7.5.5 Additional Cost Model Inputs for Chlorine-based Technologies

The GWR EA Cost Model requires the following input pertaining to the chlorine-based technologies (i.e., gas chlorination, hypochlorination, chlorine dioxide and anodic oxidation), in addition to their unit costs (i.e., capital and O&M costs for the various flows):

Disinfection monitoring costs: This involves measuring the disinfectant residual to ascertain the effectiveness of the disinfection unit process. The disinfection monitoring costs are presented in Exhibit 3.23. The costs are separated into two size categories: (1) for systems serving a population less than or equal to 3,300, and (2) for systems serving a population greater than 3,300.

Systems serving < 3,300: For systems serving fewer than 3,300 people no capital costs are incurred. Annual O&M cost components include the following

- Labor costs
- Chlorine test kits, each lasting a 100 days. Each system thus incurs the cost of 3.65 kits per annum.

Systems serving $3,300: For systems serving 3,300 people or more both capital and O&M costs are incurred. Capital cost components include the following:

- Chlorine Analyzer (Hach CL 17)
- Power cord
- Chart Recorder (Honeywell 10" round)
- Installation cost

O&M cost components include the following:

- Labor costs
- Maintenance kit
- Monthly reagents
- Charts
- Recorder

Exhibit 3.22 Estimated Costs for Anodic Oxidation Systems

Design Flow (mgd)	Average Flow (mgd)	Total Capital Cost (no storage) ($)	Total Capital Cost (with storage[1]) ($)	Annual O&M Cost ($)	Model Used
< 0.007	< 0.0015	$39,396	$40,184	$2,908	Cost floor
0.007	0.0015	$39,396	$40,184	$2,908	W/W Process 54
0.022	0.0054	$52,218	$53,925	$2,914	W/W Process 54
0.037	0.0095	$60,313	$62,940	$5,028	W/W Process 54
0.091	0.025	$78,932	$84,868	$6,715	W/W Process 54
0.18	0.054	$100,475	$111,865	$8,596	W/W Process 54
0.27	0.084	$111,761	$128,668	$9,929	W/W Process 54
0.36	0.11	$123,015	$145,438	$10,888	W/W Process 54
0.68	0.23	$163,065	$205,102	$13,533	W/W Process 54
1	0.35	$219,436	$281,085	$15,831	W/W Process 54
1.2	0.41	$254,667	$348,353	$16,952	W/W Process 54
2	0.77	$374,031	$595,861	$23,064	W/W Process 54
3.5	1.4	$575,457	$909,713	$29,552	W/W Process 54
7	3	$904,296	$1,453,121	$46,031	W/W Process 54
17	7.8	$1,632,569	$2,692,051	$89,120	W/W Process 54
22	11	$1,836,363	$3,147,452	$117,433	W/W Process 54
76	38	$3,293,387	$6,856,987	$354,875	W/W Process 54
210	120	-	-	-	Flow beyond model range
430	270	-	-	-	Flow beyond model range
520	350	-	-	-	Flow beyond model range

[1] See Exhibit 3.10 for storage costs.

Exhibit 3.23 Estimated Costs for Disinfection Monitoring *(continued on next page)*

SYSTEMS SERVING # 3,300

Component	Frequency (Per Year)	Hours (Per Day)	Unit Cost	Total Cost
Monitoring labor[1] 25 - 100	365	0.5	$21.44/hr	$3,912.80
Monitoring labor[1] 101 - 500	365	0.5	$23.09/hr	$4,213.93
Monitoring labor[1] 501 - 3,300	365	0.5	$24.74/hr	$4,515.05
Chlorine test kits[2]	3.65	N/A	$35.50	$129.58
Total Cost (25 - 100) = $4,042.38 **Total Cost (101 - 500) = $4,343.51** **Total Cost (501 - 3,300) = $4,644.63**				

[1] 30 minutes of monitoring time per day for 365 days per year, (Source: best professional judgement).

[2] Source: Products for Analysis, Hach Co. catalogue (1998). Model 2231-02 (Updated to 2003$).

Exhibit 3.23 Estimated Costs for Disinfection Monitoring *(continued)*

SYSTEMS SERVING > 3,300

Component	Frequency (Per Year)/Initial nos.	Hours/day	Unit cost	Total cost
Capital Costs				
Chlorine analyzer[1]	1	N/A	$2,251	$2,251
Power cord[1]	1	N/A	$9	$9
Chart recorder[1]	1	N/A	$630	$630
Installation[2] (3,301 - 10,000)	1	N/A	$203	$203
Installation[2] (10,001 - 100,000)	1	N/A	$208	$208
Installation[2] (>100,000)	1	N/A	$250	$250
Total Capital Cost (3,301 - 10,000) = $3,094 Total Capital Cost (10,001 - 100,000) = $3,100 Total Capital Cost (>100,000) = $3,141				
Annual O&M Costs				
Labor (3,301 - 10,000)	80hr./yr.[3]	--	$25.34/hr	$2,027
Labor (10,001 - 100,000)	80hr./yr.[3]	--	$26.05/hr	$2,084
Labor (>100,000)	80hr./yr.[3]	--	$31.26	$2,501
Maintenance kit[1]	1	N/A	$147	$147
Monthly reagents[1]	12	N/A	$19	$226
Charts[1]	1	N/A	$16	$16
Recorder pens[1]	1	N/A	$54	$54
Total O&M Cost (3,301 - 10,000) = $2,470 **Total O&M Cost (10,001-100,000) = $2,527** **Total O&M Cost (>100,000) = $2,944**				

[1] Source: Products for Analysis, Hach Co. catalogue (1998).
[2] Source: Labor Costs for National Drinking Water Rules (USEPA, 2003).
[3] EPA estimate based on best professional judgement.
Detail may not add due to independent rounding.

3.7.6 Ozonation Systems

3.7.6.1 Ozone Dose

Capital costs were estimated based on an ozone dose of 4.5 mg/L (for details see USEPA, 2003). The corresponding average ozone dose for day to day operations was assumed to be 2.43 mg/L, and was used to determine O&M costs.

3.7.6.2 Capital Cost Assumptions

The capital cost for ozone can be broken down into two distinct categories: process costs and indirect capital costs. Process costs include in-plant pumping, ozone generation system, ozone contactor, off-gas destruction facilities, effluent ozone quench, chemical storage, stainless steel piping, valves, ductwork, and electrical and instrumentation (E&I). Indirect costs applied for the ozone system include housing, operator training, land, permitting, and piloting.

Process costs were estimated and added together resulting in a total process cost at each flow rate. This value was then multiplied by the appropriate capital cost multiplier (either 2.0 or 2.5) resulting in a value that represents constructed process facilities. To this result the indirect costs were added, resulting in a total capital cost for all elements associated with implementing ozone treatment at an existing treatment plant.

Process Costs

In-plant Pumping

In-plant pumping costs include costs for a concrete wet-well, vertical turbine pumps, piping, and valving (P&V), manifolding, and all E&I associated with the in-plant pumping only. P&V and E&I were included within the in-plant pumping line item costs because common construction practices will apply. No corrosion resistant materials (e.g., stainless steel) were assumed to be required. Other details are provided below:

- A vertical turbine pump vendor provided the range of flow rates and TDH requirements. 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 given in the section “Ozone Contactor Costs”.

- P&V and E&I were estimated as a percentage of the manufactured equipment (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 vendor-provided process monitoring equipment necessary to verify generation rates and dosing. These costs were developed through contacting suppliers of ozone generation equipment. Vendors were contacted and given the required oxygen generation rates (lbs/day). They responded with quotes for all the above components.

The costs also include the ozone dissolution system (a venturi-type injector). 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 the actual ozone generation requirement is estimated as:

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

The feed gas delivery system include the liquid oxygen (LOX) storage tank for systems where LOX use is applicable (> 100 lbs/day). For the smaller systems, the costs include all equipment necessary to generate oxygen onsite using pressure swing absorption (PSA). PSA requires feed gas equipment such as an air compressor, air chiller, and air dryer.

Ozone Contactor Costs

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 (i.e., railings, hatches, pipe supports, additions, etc.). 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. With a given tank volume estimate unit costs measured in terms of $/cubic yard of concrete were applied. The unit costs used for concrete approved for drinking water use are the following:

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

These unit costs are based on best professional judgement where each of the above unit costs is 1.5 times a base cost for only the concrete work in many locations in the United States. That is, to perform only the concrete work (no excavation, backfill, misc. fittings, coatings, etc.) values of $350, $450, and $550 per cubic yard are commonly used as unit costs 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. The costs were then updated to 2003 dollars by using the BCI index. Concrete costs are quite variable across the United States. The 2001 Means Heavy Construction Cost Data reference gives a range between $56/cubic yard and $90/cubic yard for 5000 psi ready-mix concrete for Cincinnati, OH and San Francisco, CA, respectively. The unit costs used capture representative costs at many locations. Using these unit costs and the tankage design assumptions, cost vs. contactor volume relations were developed for both concrete baffled (> 1 mgd) and non-concrete baffled tanks. Specific “geometric” design criteria applicable for the ozone contact chamber costs are summarized below:

- wall thickness = 18in, bottom slab and cover thickness = 12in
- length-to-width ratio = 2.5
- water depth inside the chamber ranges from 5 to 20 feet

- design volume = 1.2 × required volume (for freeboard and odor control)

- concrete baffle thickness = 8in (Note: stainless steel baffles for systems with design flows < 1 mgd and concrete baffles for systems with design flows Š1 mgd)

Off-Gas Destruction

Off-gas destruction cost includes the catalytic destruction unit and the blower to maintain negative pressure over the contactors. Ductwork for conveying the off-gas from the contactors to the unit is not included in this line item cost. E&I around the unit is not included in this line item. These items are accounted for separately (see *Stainless Steel Piping (Including Valves and Duct Work* and *Electrical and Instrumentation))*.

Effluent Ozone Quench

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, such as corrosion of equipment, the residual ozone must be quenched (destroyed) prior to the next unit process. The ozone quenching is 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.

- 10 percent of design transferred dose ends up as residual (requiring peroxide quench).

- Peroxide storage facilities must allow for 30 days of storage without new deliveries.

Effluent ozone quench includes the cost of the hydrogen peroxide storage tank(s), peroxide feed pumps, and an effluent residual ozone sensor (liquid stream unit) and associated analyzer. These costs were based on calls to vendors; some package delivery systems were costed as well as the individual components to build a complete system. Costs do not include P&V necessary to convey peroxide to the injection location. They do not include E&I beyond the purchase of the ozone analyzer. These items are accounted for separately (see *Stainless Steel Piping (Including Valves and Duct Work* and *Electrical and Instrumentation (E&I)* on page 3-44). The following three quenching systems based on dosing requirements were costed.

- Very small quenching systems (i.e., 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 out by a chemical supplier (O&M cost only). The system cost is the sum of the individual components as quoted by vendors.

- Small quenching systems (i.e., systems dosing between 100 and 1,000 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 (i.e., systems dosing in excess of 1,000 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 larger peroxide tanks at the larger dose and quench requirements. The concrete was assumed to be 12"-thick reinforced concrete with an “on-grade” slab 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 is 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 in 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 separate process cost line item. This line item captures the cost of electrical and instrumentation equipment (cabling, motor control centers, Programmable Logic Controls (PLCs), additional ozone analyzers, flow meters communications cable, software, standby power, etc.) beyond that provided with the ozone generation system or the effluent quench system. This addition includes instrumentation to ensure that housing around the ozone generator is monitored for ambient ozone levels. Alarm systems are typically part of a monitoring program. Costs for these items also 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. EPA used 20 percent of all the components of the process not solely the generation equipment to represent the electrical and instrumentation costs.

Indirect Costs

Indirect costs assumed for the ozone system include housing, operator training, land, permitting, and piloting.

Housing

These costs are based on the estimated footprint of the ozone generation equipment (minimum 100 ft^2), multiplied by an average housing cost of \$51.1/ft^2 based on RS Means (2000) factory building estimates updated to year 2003 dollars using the BCI.

Operator training

This is assumed to be a capital cost for systems with flows less than 1 mgd. Forty hours of training is assumed at the technical labor rate. For systems greater than 1 mgd, training is assumed to occur on the job.

Piloting and Permitting

Exhibit 3.7 shows the piloting assumptions for ozone. 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 vendor's facility (ozone generation system vendor). The cost for larger systems is 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 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 as it is not likely to be necessary for a small test application. 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. For further discussion of unintended consequences and related potential increases in health risks see Section 5.2.5.9 of the GWR EA. Permitting costs were added based on the assumptions outlined in section 3.3.

pH adjustment

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 feed system and chemical costs to reduce the pH using sulfuric acid and raising the pH using caustic (after ozonation). Capital costs for pH reduction are 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 are applied separately and it is included as a line item under "indirect costs".

3.7.6.3 O&M Cost Assumptions

O&M costs include LOX, quenching agent, part replacement, performance monitoring, electricity, and labor costs. Exhibit 3.24 details the O&M assumptions.

Exhibit 3.24 Ozonation O&M Cost Assumptions

Cost Item	Basis
LOX (where used)	\$80/ton for LOX
Quench	Chemical suppliers contacted for chemical costs.
Part Replacement	Vendor provided estimates as a percentage of ozone equipment costs.
Electricity	Pumps and ozone generation. \$0.076/kWh, 11.3 kWh/lb ozone for smaller systems (<100 lbs/day), includes generator, destruction unit, and PSA. 5.2 kWh/lb ozone for LOX systems, includes generator and destruction unit.
BDOC Monitoring	1 sample/week/reactor for biological dissolved organic carbon, \$100/sample.
pH reduction (when used)	Assuming 50th percentile alkalinity (78 mg/L as $CaCO_3$) 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: Vendor estimates, best professional judgement, and the ICR database, as applicable.

The labor costs are a function of the cost category and the assumptions on the level of effort for each system, presented below:

- 3 hr/day for monitoring, plus 4 hr/month maintenance (< 100 mgd design flow)
- 6 hr/day for monitoring, plus 8 hr/month maintenance (\$ 100 mgd design flow)

3.7.6.4 Ozonation - Cost Summary and Equations

Total capital and O&M costs (in 2003 dollars) for each system size are presented in Exhibit 3.25. Exhibit A.8 of Appendix A presents the linear regression cost coefficients A and B (described below) for all pertinent flow ranges. Cost estimates for design flows < 0.091 mgd are not presented since ozonation is not a feasible technology for the very small systems (i.e., systems serving populations < 100). Costs were assumed to vary linearly with flow between any two adjacent flow points.

Cost (\$) = A + [B × Flow (in kgpd)], where,
A = Y-axis intercept of the linear regression for that flow range
B = Slope of the linear regression for that flow range

The data shown in Exhibit A.8 of Appendix A serve as inputs to the GWR EA Cost Model.

Exhibit 3.25 Estimated Costs for Ozonation Systems *(continued on next page)*

Design Flow (mgd)	0.091	0.18	0.27	0.36	0.68	1	1.2
Average Flow (mgd)	0.025	0.054	0.084	0.11	0.23	0.35	0.41
Unit Capital Cost Summary							
Total Unit Capital Cost (no pH adj.)	**$323,268**	**$383,356**	**$439,266**	**$493,875**	**$676,432**	**$805,095**	**$902,872**
Indirect Capital Costs (no pH adj.)	$17,897	$23,977	$25,138	$26,209	$29,788	$88,774	$91,158
Total Unit Capital Cost (with pH adj.)	**$346,000**	**$426,480**	**$483,965**	**$540,149**	**$728,305**	**$862,567**	**$963,844**
Indirect Capital Costs (with pH adj.)	$40,628	$67,101	$69,837	$72,482	$81,661	$146,246	$152,130
Piloting	$5,000	$10,000	$10,000	$10,000	$10,000	$65,000	$65,000
Permitting	$3,664	$4,313	$4,970	$5,612	$7,760	$10,745	$12,176
Land	$2,443	$2,875	$3,313	$3,741	$5,173	$7,163	$8,117
Operator Training	$924	$924	$990	$990	$990	$0	$0
Housing	$5,866	$5,866	$5,866	$5,866	$5,866	$5,866	$5,866
pH adjustment (if used)	22,732	43,124	44,699	46,274	51,873	57,472	60,971
Capital Cost Multiplier	$305,371	$359,379	$414,128	$467,667	$646,644	$716,322	$811,714
Subtotal Process Cost	$122,149	$143,752	$165,651	$187,067	$258,657	$358,161	$405,857
Stainless pipes, valves, ductwork	$15,954	$19,483	$23,061	$26,556	$38,593	$54,321	$61,756
Ozone process E&I	$12,763	$15,586	$18,449	$21,245	$30,875	$43,457	$49,405
Off Gas Destruction	$6,528	$7,712	$8,910	$10,108	$14,366	$18,625	$21,287
Effluent Ozone Quench	$4,908	$4,955	$5,003	$5,051	$5,221	$5,391	$5,497
Ozone Contactor	$8,164	$13,027	$17,982	$22,603	$37,476	$67,114	$76,058
Ozone Generation System	$44,215	$52,238	$60,351	$68,463	$97,309	$126,155	$144,184
In plant pumping	$29,617	$30,750	$31,895	$33,040	$34,817	$43,097	$47,671
Chemical Storage	$0	$0	$0	$0	$0	$0	$0
Annual O&M Summary							
Total Annual O&M Cost (no pH adjust.)	**$55,520**	**$55,884**	**$59,391**	**$59,737**	**$61,152**	**$62,566**	**$63,350**
Total Annual O&M Cost (with pH adjust)	**$56,513**	**$58,029**	**$62,728**	**$64,107**	**$70,289**	**$76,470**	**$79,638**
Chemicals O2	$0	$0	$0	$0	$0	$0	$0
Chemicals H2O2	$36	$79	$123	$161	$336	$511	$598
Part Replacement	$946	$1,118	$1,292	$1,465	$2,082	$2,700	$3,086
Performance monitoring	$10,400	$10,400	$10,400	$10,400	$10,400	$10,400	$10,400
Electricity	$306	$456	$611	$746	$1,368	$1,990	$2,301
Labor	$43,832	$43,832	$46,966	$46,966	$46,966	$46,966	$46,966
pH adjustment (when used)	993	2,145	3,337	4,370	9,137	13,904	16,287

Technology is not feasible for systems with design flows less than 0.091 mgd.

adj. = adjustment.

Exhibit 3.25 Estimated Costs for Ozonation Systems *(continued)*

Design Flow (mgd)	2	3.5	7	17	22	76	210	430	520
Average Flow (mgd)	0.77	1.4	3	7.8	11	38	120	270	350

Unit Capital Cost Summary

Total Unit Capital Cost (no pH adj.)	**$1,227,534**	**$1,597,111**	**$2,360,888**	**$3,957,086**	**$4,559,473**	**$12,674,233**	**$26,570,288**	**$45,364,301**	**$53,714,159**
Indirect Capital Costs (no pH adj.)	$105,167	$123,040	$162,340	$280,413	$330,542	$911,177	$2,199,804	$3,876,427	$4,423,346
Total Unit Capital Cost (with pH adj.)	**$1,302,503**	**$1,698,325**	**$2,523,342**	**$4,294,510**	**$4,984,382**	**$14,043,980**	**$30,284,633**	**$52,927,986**	**$62,852,574**
Indirect Capital Costs (with pH adj.)	$180,136	$224,254	$324,794	$617,837	$755,451	$2,280,924	$5,914,149	$11,440,112	$13,561,761
Piloting	$65,000	$65,000	$65,000	$65,000	$65,000	$65,000	$65,000	$65,000	$65,000
Permitting	$16,836	$22,111	$32,978	$55,150	$63,434	$176,446	$365,557	$500,000	$500,000
Land	$11,224	$14,741	$21,985	$36,767	$42,289	$117,631	$243,705	$414,879	$492,908
Operator Training	$0	$0	$0	$0	$0	$0	$0	$0	$0
Housing	$12,107	$21,188	$42,376	$123,496	$159,819	$552,101	$1,525,542	$2,896,548	$3,365,438
pH adjustment (if used)	74,969	101,215	162,454	337,424	424,909	1,369,747	3,714,345	7,563,685	9,138,415
Capital Cost Multiplier	$1,122,367	$1,474,071	$2,198,548	$3,676,673	$4,228,931	$11,763,056	$24,370,484	$41,487,874	$49,290,813
Subtotal Process Cost	$561,184	$737,035	$1,099,274	$1,838,337	$2,114,466	$5,881,528	$12,185,242	$20,743,937	$24,645,407
Stainless pipes, valves, ductwork	$85,853	$111,868	$167,219	$280,370	$322,289	$811,823	$1,542,432	$2,433,201	$2,866,603
Ozone process E&I	$68,682	$89,494	$133,775	$224,296	$257,831	$649,458	$1,233,946	$1,946,560	$2,293,283
Off Gas Destruction	$29,525	$36,307	$52,132	$82,171	$91,729	$251,298	$425,249	$594,031	$686,415
Effluent Ozone Quench	$5,922	$6,719	$8,578	$13,889	$16,545	$72,638	$121,238	$201,029	$233,670
Ozone Contactor	$107,982	$158,526	$255,057	$468,843	$559,567	$1,221,228	$2,742,878	$4,914,161	$5,896,994
Ozone Generation System	$199,982	$245,920	$353,108	$556,575	$621,315	$1,702,128	$2,880,363	$4,023,582	$4,649,334
In plant pumping	$63,238	$86,184	$126,461	$206,601	$238,274	$1,151,745	$3,182,452	$6,516,449	$7,880,357
Chemical Storage	$0	$2,018	$2,944	$5,592	$6,915	$21,211	$56,684	$114,924	$138,750

Annual O&M Summary

Total Annual O&M Cost (no pH adjust.)	**$67,621**	**$77,719**	**$95,346**	**$145,700**	**$177,752**	**$464,832**	**$1,377,320**	**$2,871,997**	**$3,662,456**
Total Annual O&M Cost (with pH adjust)	**$98,210**	**$133,334**	**$214,522**	**$455,559**	**$614,733**	**$1,974,401**	**$6,144,381**	**$13,597,884**	**$17,566,383**
Chemicals O2	$0	$4,557	$9,764	$25,387	$35,802	$123,681	$390,570	$878,783	$1,139,163
Chemicals H2O2	$1,124	$1,605	$3,439	$8,943	$12,611	$43,567	$137,580	$309,554	$401,274
Part Replacement	$4,280	$5,263	$7,557	$11,911	$13,296	$36,426	$61,640	$86,105	$99,496
Performance monitoring	$10,400	$10,400	$10,400	$10,400	$10,400	$15,600	$31,200	$52,000	$62,400
Electricity	$4,166	$7,431	$15,722	$40,596	$57,179	$197,096	$622,028	$1,399,343	$1,813,911
Labor	$47,652	$48,463	$48,463	$48,463	$48,463	$48,463	$134,302	$146,212	$146,212
pH adjustment (when used)	30,589	55,616	119,177	309,859	436,981	1,509,569	4,767,061	10,725,886	13,903,927

adj. = adjustment.

3.7.7 Nanofiltration (NF)

3.7.7.1 General Assumptions

NF is an advanced treatment process that typically requires higher levels of pre- and post-treatment than traditional water treatment processes. The costs provided assume that the NF system is used on a system already generating water of desired quality for NF or that the ground water is of good enough quality to not require pretreatment. These costs do not include any additional post-treatments that may be necessary because of site-specific water quality. Costs are developed assuming a feed water temperature of 10°C. It should be noted that the cost of a NF system can vary with the design temperature, and that the assumption is conservative.

The cost estimates assume 100 percent of the flow is treated by the NF membranes (i.e., no blending). Recovery is 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 as a result of this type of operation. The costs associated with these losses are not included in the estimates provided because the costs of water can be highly variable from region to region and may also include complex legal issues.

3.7.7.2 Capital Cost Assumptions

Capital costs are estimated based on vendor quotes, cost estimating guides (RS Means, 2001), cost models, and best professional judgement. The spent brine is assumed to be directly discharged to a sewer. The methodology used for estimating capital costs is discussed in this section.

Membrane System Costs

NF equipment costs were obtained from vendors. The NF equipment cost included costs for the following items:

- Membrane skid with filter housings
- NF membrane elements (initial batch)
- Cartridge prefiltration
- 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 3.26. The NF skids are equipped with all necessary instrumentation and controls and pipes and valves and therefore these costs are included as part of the NF equipment cost.

Exhibit 3.26 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 prefiltration	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: Best professional judgement (USEPA, 2005).

Online Process Monitoring Equipment

Costs for process monitoring included provision of online meters for each NF train/skid. The meters can be used for integrity testing. The NF train/skid is assumed to have up to a 2 mgd capacity. Process monitoring equipment include online conductivity/pH meter ($2,500 for meter and probe) and turbidimeter ($2,500 for meter and probe). For systems less than 2 mgd capacity, one conductivity/pH meter and one turbidimeter is assumed. For systems greater than 2 mgd, the number of meters is based on the number trains/skids.

Brine Discharge Pipeline

It is assumed systems will build a brine discharge pipeline either to the ocean, an existing brine interceptor pipeline, or to a sanitary sewer. Costs for brine discharge include laying a pipeline of 500 ft. This pipeline is made of PVC or reinforced concrete and assumed to have diameters varying from 2 to 24 inches depending on the quantity of water to be discharged. Costs for the pipeline are obtained from *Small Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993a) and *Water System Byproducts Treatment and Disposal Cost Document* (DPRA, 1993b).

Capital Cost Multipliers

The previously discussed capital costs (e.g., NF equipment, process monitoring equipment and brine pipeline) are totaled to arrive at the subtotal process cost. The subtotal process cost is then multiplied with an appropriate multiplier to obtain the capital costs. Capital cost multipliers of 1.67 and 2.0 are used for small (< 2 mgd) and large ($ 2 mgd) systems, respectively. Unlike other treatment processes, membrane systems are typically supplied by the equipment vendor as package, skid-mounted units; therefore, smaller capital cost multipliers are used.

Permitting

Incorporating NF treatment will require coordination with the appropriate regulatory agencies. To account for this, permitting costs are included at 3 percent of the process cost. A minimum permitting fee of $2,500 and a maximum of $500,000 is assumed (NDWAC and TDP recommendation).

Pilot Testing

It is assumed that pilot- or bench-scale tests are necessary to ensure compatibility of membrane materials with process chemicals (e.g., preoxidants), as well as determine critical design parameters, such as design flux and cleaning frequency. Bench-scale flat sheet tests are 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 is assumed for systems between 0.1 and 1 mgd. For systems greater than 1 mgd, a three month pilot test costing $60,000 is 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 3.27 summarizes the membrane housing cost assumptions used for NF costs. Typical NF plant footprints between 900 to 1,100 ft^2 per mgd of design flow is assumed. For small systems, a minimum housing area of 100 ft^2 is assumed. Housing costs are assumed to be $51.10 per sq. ft. This is based on the R.S. Means (2000) estimate of the median cost of a factory type building, updated to year 2003 dollars using the BCI.

Exhibit 3.27 Summary of NF Housing Cost Assumptions

System Size (mgd)	Housing Area [1]	Housing[2] Cost ($/ft^2)
< 10 MGD	1,100 ft^2 per MGD	$51.1
$ 10 MGD	900 ft^2 per MGD	$51.1

[1] A minimum housing area of 100 ft^2 is also assumed for very small systems.

[2] Source: R.S. Means (2000) median cost for a factory type building updated to 2003 dollars using the BCI.

Land

The NDWAC cost working group recommended a factor of 2 to 5 percent of capital cost for land. Previous technology cost efforts adopted land costs at a factor of 5 percent for systems less than 1 mgd and 2 percent for systems greater than 1 mgd. However, the previous cases assumed new plant construction with no land currently available, as opposed to the case in this document where some land at the well site is already owned by the system. Using a 2-5 percent factor for land resulted in unrealistic per acreage costs for land acquisition ($/acre). Therefore, the land cost factors are adjusted as shown in Exhibit 3.28.

Exhibit 3.28 NF Land Cost Assumptions

System Size (mgd)	Land Cost (% of Capital Cost)[1]
< 1	2%
1 - < 10	1%
$ 10	0.5%

[1] Capital Cost = Total Process Cost × Capital Cost Multiplier.
Source: USEPA, 2005.

Operator Training

The NDWAC cost working group also recommended inclusion of operator training. The operator training costs are based on the number of hours required per system size to train an operator. Based upon system size, this training could last a few hours or a few days. Exhibit 3.29 summarizes the operator training cost assumptions used.

Exhibit 3.29 NF Operator Training Cost Assumptions

System Size (MGD)	Training Cost ($)
< 0.5	included in membrane system price
0.5 - < 1	$1,000
1 - < 10	$3,000
10 - < 100	$10,000
$ 100	$25,000

Source: USEPA, 2005.

Indirect Capital Costs

Costs for permitting, piloting, membrane housing, land and operator training are calculated and are referred to as indirect capital costs for the purposes of this document. Indirect capital costs are added to the direct capital costs to obtain total capital costs.

3.7.7.3 O&M Cost Assumptions

NF O&M costs are estimated using current plant operational data, industry guidelines, and cost models. This section discusses the assumptions regarding O&M estimates presented in this document.

Clean-in-Place (CIP) Chemicals

NF systems require periodic (typically quarterly or semi-annually) chemical cleaning to remove biological/particulate foulants and scalants. Membrane cleaning is performed using manufacturer-recommended cleaning agents. Because of the variability in cleaning practices, a standard rule-of-thumb of $0.01 per 1,000 gallons of water produced is assumed for all system sizes to account for cleaning chemical costs. Thus, cleaning chemical costs can be estimated by the following equation.

Cleaning Chemicals ($/yr) = 0.01 × Average Flow produced (mgd) × 1000 × 365

A minimum cost of $50/year is assumed for cleaning chemicals, this accounts for the cost of purchasing a 15-gallon pail of cleaning chemical.

Acid/Anti-Scalant Chemicals

Acid and anti-scalant addition may be necessary to reduce the fouling and scaling of NF membranes. The dosages of acid and anti-scalant needed is a function of the feed water quality. As a rule-of-thumb, a cost of $0.04 per 1,000 gallons of water produced is assumed for average flows less than 0.35 mgd and $0.03 per 1,000 gallons is assumed for average flows greater than or equal to 0.35 mgd. This cost difference represents economies achieved by bulk purchases. Therefore, acid and anti-scalant chemical costs can be estimated by the following equations.

For average flows < 0.35 mgd
Acid and Anti-Scalant Chemicals ($/yr) = 0.04 × Average Flow produced (mgd) × 1000 × 365

For average flows $ 0.35 mgd
Acid and Anti-Scalant Chemicals ($/yr) = 0.03 × Average Flow produced (mgd) × 1000 × 365

A minimum cost of $50 is assumed for acid/anti-scalants to account for purchasing these chemicals in small quantities of 5 gallons.

NF Membrane Replacement

NF membranes are assumed to have a life of 5 years. Therefore, the annual cost for NF membrane replacement is assumed to be 20 percent of the NF membrane purchase cost.

NF Membrane Replacement ($/yr) = 0.20 × NF Membrane Element Process Cost

Cartridge Filter Replacement

Cartridge filters collect particulate matter and prevent them from depositing on to the NF membranes. These cartridge filters have to be replaced more frequently for turbid waters and less frequently for clean waters. Costs for cartridge filter replacement are 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 greater than or equal to 0.35 mgd. Therefore, cartridge filter replacement costs can be estimated by the following equations.

For average flows < 0.35 mgd
Cartridge Filter Replacement Cost ($/yr) = 0.002 × Average Flow produced (mgd) × 1000 × 365

For average flows $ 0.35 mgd
Cartridge Filter Replacement Cost ($/yr) = 0.02 × Average Flow produced (mgd) × 1000 × 365

Repair, Maintenance and Replacement

NF systems require periodic maintenance and repair. The O&M cost for repair, maintenance, and purchase of replacement parts is typically about $0.01 per 1,000 gallons produced (Bergman, 1996). A minimum cost of $100 per year is assumed for repair and replacement for small systems. The cost equation for repair, maintenance, and replacement is shown below.

$$\text{Repair, Maintenance \& Replacement Cost (\$/yr)} = 0.01 * \text{Average Flow produced (mgd)} \times 1000 \times 365$$

Performance Monitoring

In addition to online conductivity, pH and turbidity monitoring (included in capital cost estimates), the costs for periodic heterotrophic plate count (HPC) bacterial monitoring are included in the O&M estimates. HPC is monitored to detect biological activity on the finished water side of the membrane. Field HPC tests cost approximately $1 per test, and require 1 hour of labor. The frequency of HPC testing is assumed to be one test per membrane skid per week. The NF skid size of 2 mgd is 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 are assumed to be 1.2 kWh/1,000 gallons and 0.6 kWh/1,000 gallons produced, respectively. Unit power cost of $0.076 per kWh is used to estimate the power cost. The equation for power cost is given below.

$$\text{Power Cost (\$/yr)} = 1.8 \text{ x } 0.076 \text{ x Average Flow produced (mgd) x } 1{,}000 \text{ x } 365$$

Labor

Technical labor estimates include operation and maintenance of the membrane systems, including labor associated with periodic data logging, repair of process equipment, sampling, and testing. No additional managerial labor is assumed. A summary of labor hour assumptions is provided in Exhibit 3.30.

Exhibit 3.30 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

Source: USEPA, 2005.

POTW Surcharge

A fee of $0.00183 per 1000 gallons discharged to the sanitary sewer was assumed. This rate is based upon data provided in the DPRA reports (1993a and 1993b). The discharge volume is based on an average system recovery of 85 percent; therefore, the waste volume is 0.15 × average daily flow treated. The surcharge for brine discharge can be calculated using the equation below.

Surcharge for Brine Discharge ($/yr) = 0.00183 × 0.15 × Average Flow produced (mgd) × 1000 × 365

Costs for concentrate handling include:

- Direct discharge of 15 percent of the feed flow to a sewer/storm/sanitary interceptor or ocean outfall, located 500 feet or less from the NF plant (at 85 percent recovery, 15 percent would be the brine stream).

- Assuming that the brine stream has adequate residual pressure, no additional pumping is necessary.

3.7.7.4 Nanofiltration - Cost Summary and Equations

Total capital and O&M costs for each system size are presented in Exhibit 3.31. Exhibit A.9 of Appendix A presents the linear regression cost coefficients A and B (described below) for all pertinent flow ranges. Costs were assumed to vary linearly with flow between any two adjacent flow points.

Cost ($) = A + [B × Flow (in kgpd)], where:
A = Y-axis intercept of the linear regression for that flow range
B = Slope of the linear regression for that flow range

The data shown in Exhibit A.9 of Appendix A serve as inputs to the GWR EA Cost Model.

Exhibit 3.31 Estimated Costs for Nanofiltration Systems *(continued)*

Design Flow, mgd	0.007	0.022	0.037	0.091	0.18	0.27	0.36	0.68	1	1.2
Average Flow, mgd	0.0015	0.0054	0.0095	0.025	0.054	0.084	0.11	0.23	0.35	0.41
Unit Capital Cost Summary										
Total Unit Capital Cost	**$52,107**	**$69,454**	**$86,801**	**$156,293**	**$223,250**	**$316,569**	**$357,931**	**$664,969**	**$914,766**	**$1,083,344**
Indirect Capital Costs	$9,461	$9,801	$10,141	$11,606	$27,544	$35,829	$43,177	$71,730	$140,830	$156,348
Piloting	$1,000	$1,000	$1,000	$1,000	$10,000	$10,000	$10,000	$10,000	$60,000	$60,000
Permitting	$2,500	$2,500	$2,500	$2,599	$3,516	$5,043	$5,654	$10,657	$13,903	$16,653
Land	$853	$1,193	$1,533	$2,894	$3,914	$5,615	$6,295	$11,865	$7,739	$9,270
Operator Training	$0	$0	$0	$0	$0	$0	$1,000	$1,000	$3,000	$3,000
Housing	$5,108	$5,108	$5,108	$5,113	$10,114	$15,171	$20,228	$38,208	$56,188	$67,426
Capital Cost After Multiplier	$42,646	$59,653	$76,660	$144,687	$195,707	$280,740	$314,754	$593,239	$773,935	$926,996
Subtotal Process Cost	$25,537	$35,720	$45,904	$86,639	$117,190	$168,108	$188,475	$355,233	$463,434	$555,087
Subtotal NF Equipment Cost	$20,677	$31,016	$41,355	$82,710	$113,726	$165,420	$186,097	$355,394	$465,244	$558,292
Pipes and Valves	$2,068	$3,102	$4,135	$8,271	$11,373	$16,542	$18,610	$35,539	$46,524	$55,829
Instrumentation and Controls	$4,135	$6,203	$8,271	$16,542	$22,745	$33,084	$37,219	$71,079	$93,049	$111,658
Cartridge Prefiltration	$1,654	$2,481	$3,308	$6,617	$9,098	$13,234	$14,888	$28,432	$37,219	$44,663
Acid and Anti-Scalent Feed Systems	$620	$930	$1,241	$2,481	$3,412	$4,963	$5,583	$10,662	$13,957	$16,749
System Feed Pumps	$2,585	$3,877	$5,169	$10,339	$14,216	$20,677	$23,262	$44,424	$58,155	$69,787
Nanofilter Membrane Elements	$4,135	$6,203	$8,271	$16,542	$22,745	$33,084	$37,219	$71,079	$93,049	$111,658
Membrane Skid with Filter Housing	$4,135	$6,203	$8,271	$16,542	$22,745	$33,084	$37,219	$71,079	$93,049	$111,658
Clean-In-Place (CIP) System	$1,034	$1,551	$2,068	$4,135	$5,686	$8,271	$9,305	$17,770	$23,262	$27,915
Online Conductivity/pH and Turbidity Meters	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169	$5,169
Brine Discharge Pump (Not Included)	$258	$388	$517	$1,034	$1,422	$2,068	$2,326	$4,442	$5,816	$6,979
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**	**$126,572**
Acid, Anti-Scalant, Caustic Chemicals	$50	$79	$139	$365	$788	$1,226	$1,606	$3,358	$3,832	$4,489
Clean-in-Place Chemicals	$50	$50	$50	$91	$197	$307	$401	$839	$1,277	$1,496
NF Membrane Replacement	$827	$1,241	$1,654	$3,308	$4,549	$6,617	$7,444	$14,216	$18,610	$22,332
Cartridge Filter Replacement	$30	$30	$30	$30	$39	$61	$80	$168	$2,555	$2,993
Repair, Maintenance and Replacement	$100	$100	$100	$100	$197	$307	$401	$839	$1,277	$1,496
Process Monitoring (HPCs)	$1,167	$1,167	$1,167	$1,253	$1,253	$1,338	$1,338	$1,338	$1,338	$1,338
Power	$75	$270	$474	$1,248	$2,696	$4,194	$5,493	$11,484	$17,476	$20,472
Labor	$4,460	$4,460	$4,460	$4,803	$14,408	$15,438	$15,438	$15,438	$30,876	$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	$41,079

Land costs drop from a design flow of 0.68 mgd to 1 mgd due to a decrease in the land cost multiplier as we shift from one flow range to the next (i.e., from 2% of capital cost for < 1 mgd to 1% of capital cost for 1 - < 10 mgd, see Exhibit 3.20).

Exhibit 3.31 Estimated Costs for Nanofiltration Systems *(continued on next page)*

Design Flow, mgd	2	3.5	7	17	22	76	210	430	520
Average Flow, mgd	0.77	1.4	3	7.8	11	38	120	270	350

Unit Capital Cost Summary

Total Unit Capital Cost	**$2,023,265**	**$3,412,330**	**$6,761,659**	**$15,488,708**	**$19,905,140**	**$57,703,935**	**$130,061,681**	**$266,180,394**	**$319,911,447**
Indirect Capital Costs	$220,447	$336,553	$610,105	$1,138,529	$1,450,479	$4,345,668	$10,835,264	$21,576,007	$25,960,227
Piloting	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000	$60,000
Permitting	$27,042	$46,137	$92,273	$215,253	$276,820	$500,000	$500,000	$500,000	$500,000
Land	$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	$10,000	$10,000	$25,000	$25,000	$25,000	$25,000
Housing	$112,376	$196,658	$393,317	$781,525	$1,011,385	$3,493,876	$9,654,132	$19,767,985	$23,905,470
Capital Cost After Multiplier	$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	$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
Subtotal NF Equipment Cost	$904,640	$1,550,812	$3,101,624	$7,237,122	$9,304,871	$26,880,739	$59,964,726	$123,031,075	$147,844,065
Pipes and Valves	$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	$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	$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	$27,139	$46,524	$93,049	$217,114	$279,146	$806,422	$1,798,942	$3,690,932	$4,435,322
System Feed Pumps	$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	$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	$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	$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	$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)	$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	**$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	$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	$2,810	$5,110	$10,949	$28,468	$40,147	$138,691	$437,972	$985,437	$1,277,418
NF Membrane Replacement	$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	$5,621	$10,219	$21,899	$56,936	$80,295	$277,382	$875,944	$1,970,874	$2,554,836
Repair, Maintenance and Replacement	$2,810	$5,110	$10,949	$28,468	$40,147	$138,691	$437,972	$985,437	$1,277,418
Process Monitoring (HPCs)	$2,739	$2,813	$5,626	$12,659	$16,879	$54,857	$149,100	$362,344	$437,833
Power	$38,448	$69,905	$149,796	$389,470	$549,252	$1,897,416	$5,991,840	$13,481,640	$17,476,200
Labor	$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)	$77,148	$140,270	$300,578	$781,502	$1,102,118	$3,807,315	$12,023,100	$27,051,975	$35,067,375

3.8 Summary

Exhibit 3.32 shows a summary of all the costs derived in this chapter. The exhibit displays the costs in terms of system size. The costs presented in this chapter are derived based on flow. The costs in Exhibit 3.32 were derived using the coefficients displayed in Appendix A of this document and multiplying those coefficients times the average flow for a given size category. The flows per size category are listed in Exhibit 4.6 of the GWR EA.

Exhibit 3.32 Estimated Unit Costs of Treatment Corrective Actions for Source Water Contamination

Corrective Action	System Size (Population Served)								
	<100	101-500	501-1,000	1,001-3,300	3,301-10,000	10,001-50,000	50,001-100,000	100,001-1 Million	> 1 Million
Systems Adding Treatment									
Chlorine gas feed capital cost	$ 29,868	$ 29,868	$ 29,868	$ 29,868	$ 29,868	$ 58,781	$ 65,006	$ 96,958	$ 337,511
Chlorine gas feed annual O&M cost	$ 6,192	$ 6,227	$ 6,307	$ 6,456	$ 6,857	$ 16,951	$ 18,197	$ 21,854	$ 61,772
Chlorine gas feed & storage capital cost	$ 31,216	$ 33,354	$ 37,960	$ 46,039	$ 66,058	$ 152,883	$ 266,275	$ 541,906	$ 2,192,279
Chlorine gas feed & storage annual O&M cost	$ 6,192	$ 6,227	$ 6,307	$ 6,456	$ 6,857	$ 16,951	$ 18,197	$ 21,854	$ 61,772
Hypochlorite feed capital cost	$ 8,970	$ 8,970	$ 15,072	$ 24,402	$ 24,402	$ 72,631	$ 79,658	$ 96,180	$ 187,445
Hypochlorite annual O&M cost	$ 1,585	$ 2,076	$ 4,180	$ 6,582	$ 7,326	$ 7,558	$ 7,909	$ 19,177	$ 135,513
Hypochlorite feed & storage capital cost	$ 10,318	$ 12,456	$ 23,164	$ 40,573	$ 60,593	$ 166,733	$ 280,927	$ 541,128	$ 2,042,213
Hypochlorite & storage annual O&M cost	$ 1,585	$ 2,076	$ 4,180	$ 6,582	$ 7,326	$ 7,558	$ 7,909	$ 19,177	$ 135,513
Chlorine Dioxide System capital cost	N/A	N/A	$ 35,011	$ 39,299	$ 42,363	$ 80,836	$ 82,091	$ 202,017	$ 371,828
Chlorine Dioxide annual O&M cost	N/A	N/A	$ 15,261	$ 16,897	$ 17,901	$ 19,878	$ 21,705	$ 25,983	$ 59,412
Chlorine Dioxide System & storage capital cost	N/A	N/A	$ 46,196	$ 61,792	$ 89,439	$ 191,678	$ 307,085	$ -	$ -
Chlorine Dioxide & storage annual O&M cost	N/A	N/A	$ 16,251	$ 17,720	$ 18,733	$ 20,392	$ 22,257	$ -	$ -
Anodic Oxidant capital cost	$ 47,219	$ 65,151	$ 87,450	$ 110,256	$ 151,129	$ 255,055	$ 354,880	$ 745,098	$ 2,188,039
Anodic Oxidant annual O&M cost	$ 2,911	$ 5,471	$ 7,480	$ 9,791	$ 12,855	$ 17,479	$ 22,181	$ 38,439	$ 179,932
Anodic Oxidant & storage capital cost	$ 48,568	$ 68,637	$ 95,543	$ 126,427	$ 187,320	$ 349,157	$ 556,149	$ 1,190,046	$ 4,042,807
Anodic Oxidant & storage annual O&M cost	$ 2,911	$ 5,471	$ 7,480	$ 9,791	$ 12,855	$ 17,479	$ 22,181	$ 38,439	$ 179,932
Ozonation capital cost	N/A	N/A	$ 347,027	$ 431,809	$ 622,023	$ 903,927	$ 1,175,442	$ 1,991,127	$ 6,518,099
Ozonation annual O&M cost	N/A	N/A	$ 55,668	$ 59,028	$ 60,789	$ 63,718	$ 67,004	$ 87,225	$ 253,317
Nanofiltration capital cost	$ 62,691	$ 104,856	$ 182,768	$ 304,122	$ 573,460	$ 1,086,398	$ 1,872,457	$ 5,140,179	$ 29,028,479
Nanofiltration annual O&M cost	$ 7,520	$ 10,253	$ 20,140	$ 37,037	$ 63,670	$ 133,397	$ 194,361	$ 541,543	$ 3,873,384
Systems upgrading from less than 4-log to 4-log or greater									
Add storage capital cost	$ 1,349	$ 3,486	$ 8,093	$ 16,171	$ 36,191	$ 94,102	$ 201,269	$ 444,947	$ 1,854,768
Increase dose - hypochlorination annual O&M cost	$ 72	$ 179	$ 179	$ 195	$ 470	NA	NA	NA	NA
Increase dose - chlorine gas annual O&M cost	NA	NA	NA	NA	NA	$ 1,342	$ 2,108	$ 3,846	$ 17,838

Source: derived from Appendix A of this document and Exhibit 4.6 of the GWR EA

4. Introduction to Best Management Practices

4.1 Introduction to Best Management Practices

This chapter provides information about ten different best management practices (BMPs) that may prevent, eliminate, or reduce contamination to a water system. BMPs differ from treatment technologies in that they don't inactivate or physically remove viruses in the water. Instead, the purpose of a BMP is to protect the water source, well, or distribution system from contamination. Two categories of BMPs are discussed in this chapter: system assessment and corrective actions.

System assessment BMPs help determine if systems require source water monitoring or corrective action to address fecal contamination problems or significant deficiencies. This chapter provides a background discussion and description of ten different BMPs, as well as a discussion of the implementation issues and the advantages, disadvantages, and limitations associated with each BMP. The BMPs discussed in this chapter are the following:

System Assessment

- Sanitary survey (Section 4.2.1)
- Hydrogeologic sensitivity assessment (Section 4.2.2)

Corrective Actions

Significant Deficiency Corrective Actions

- Replacing well seal (Section 4.3.1.1)
- Rehabilitation of an existing well (Section 4.3.1.2)

Source Water Corrective Actions

- Eliminating known sources of contamination (Section 4.3.2.1)
- Rehabilitation of an existing well (Section 4.3.2.2)
- Purchasing water from another utility (Section 4.3.2.3)
- Installation of new wells (Section 4.3.2.4)

Additional Corrective Actions[1]

- Storage tank cover replacement or repair (Section 4.3.3.1)
- Cross-connection control/backflow prevention program (Section 4.3.3.2)
- Installation of security measures (Section 4.3.3.3)

In addition, for systems that employ nontreatment corrective actions, the GWR EA Cost Model assumes interim disinfection will be installed until the nontreatment corrective action begins. Information on interim disinfection is provided in Section 2.2.4.

4.2 System Assessment BMPs

The system assessment BMPs are measures intended to identify conditions that might lead to microbial contamination of drinking water and to identify the corrective actions that may prevent or minimize this contamination. These system assessment BMPs include sanitary surveys and hydrogeologic sensitivity assessments.

4.2.1 Sanitary Survey

4.2.1.1 Background and Description

A sanitary survey is an onsite review of the water source, facilities, equipment, operation and maintenance of a public water system for the purpose of evaluating the adequacy of such source, facilities, equipment, operation and maintenance for producing and distributing safe drinking water (40 CFR 141.2). Sanitary surveys allow a PWS to identify existing or potential sources of contamination. Qualified persons from the Primacy agency or an independent third party perform sanitary surveys. They should be trained and able to identify sanitary risks that may adversely affect the ability of a ground water system to produce a safe, reliable, and adequate quality of potable water to the consumer (NETA, 2000).

4.2.1.2 Implementation Issues

The sanitary survey involves three phases: preparation, on-site inspection, and follow-up activities.

Preparation

Before conducting or scheduling the on-site portion of a sanitary survey, the inspector must review past sanitary survey reports, compliance records, water system plans, previous sampling results, operating reports, and engineering studies. This pre-survey review provides an opportunity to examine previous sampling and measurement results and allows the inspector to properly format the survey and ensure that it addresses all issues. The inspector should also ensure that enough time is included to evaluate whether the field equipment is in good repair. The water system operator must be contacted beforehand to explain the purpose of the survey, schedule the survey, and discuss anything that needs to occur before the inspector goes on-site.

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[1] Note, these additional corrective actions are included here for reference only. They are not used in the GWR EA and are not included in the GWR compliance forecast.

On-site Inspection

There are eight essential elements involved in conducting an on-site sanitary survey. The on-site sanitary survey includes visiting the water supply source and source facilities, pump stations, the treatment plant, storage facilities, distribution system, and sampling locations. The eight essential elements of a thorough sanitary survey include an evaluation of the following:

- Source (protection, physical components, and condition)
- Treatment
- Distribution system
- Finished water storage
- Pumps/pump facilities and controls
- Monitoring/reporting/data verification
- Water system management/operations
- Operator compliance with State requirements

Source (Protection, Physical Components, and Condition) - The source for a PWS is the first of the multiple barriers to preventing waterborne disease. Objectives include evaluating the reliability and quality of the source during the sanitary survey using available information and assessing the potential for contamination from activities within the watershed, as well as from the physical components and condition of the source facility.

To accomplish these objectives, the inspector needs to review available information such as watershed control plans, source water assessment and protection plans, and/or wellhead protection plans where they exist for a system. In the field, the inspector should discuss the water supply source with the operator(s) and verify the information received from plans with field observations.

Treatment - In general, systems use different types of treatment units for different objectives. The sanitary survey inspector will evaluate all water treatment processes at the water system, including the design, operation, maintenance, and management of the water treatment plant to identify existing or potential sanitary risks. The inspector should evaluate the treatment facilities and processes to determine their ability to meet regulatory requirements and to provide an adequate supply of safe drinking water at all times, including periods of high demand and poor source water quality. A sanitary survey of a treatment facility should do the following:

- Analyze all the distinct parts of the treatment process, including coagulation/flocculation, sedimentation, filtration, disinfection, chemical feed systems, hydraulics, controls, safety features and wastewater management, where applicable.
- Review source water quality data that may impact the treatment process, such as turbidity, pH, alkalinity, and water temperature.

- Identify features that may pose a sanitary risk, such as cross-connections in the plant.

- Review the criteria, procedures, and documentation used to comply with regulatory requirements - adequate disinfection based on study of CT values (discussed in Chapter 2), the turbidity of individual filters, the turbidity of the finished water, profiles of post-backwash turbidity, etc. where applicable.

The inspector will need to review the design criteria, plant records, and compliance strategies in addition to performing the actual inspection of the facility.

Distribution Systems - The water distribution system is the final link between the water source and the consumer. The distribution system delivers drinking water produced at the water treatment facility to the water system's customers. A typical water distribution system comprises miles of water pipes constructed in a network which includes numerous valves, fire hydrants, pumps, storage tanks, meters, and other appurtenances.

Water distribution systems consist of three elements: treated water storage facilities (e.g., ground storage tanks, elevated storage tanks, standpipes, hydropneumatic tanks), pumping facilities (e.g., booster pumps, piping, control, pump building), and the distribution lines (e.g., pipes, valves, fire hydrants, meters). These components must be integrated in order to function as a comprehensive system that can meet various schedules of demand. The water distribution system needs a thorough inspection to determine whether the distribution system can provide a safe, reliable, and adequate supply of drinking water to the customers. The objectives of surveying the water distribution system are to do the following:

- Determine the potential for degradation of the water quality in the distribution system

- Determine the reliability, quality, capacity, and vulnerability of the distribution system

- Ensure that the sampling and monitoring plan(s) for the system conform with the requirements and adequately assess the quality of the water in the distribution system

To meet these objectives, the inspector will need to review the system configuration and condition, design and construction criteria, system operation and maintenance records, and sampling and monitoring plan(s) in addition to the actual inspection of the system.

Finished Water Storage - A survey of the storage facilities is critical to ensuring the availability of safe water, and the adequacy of construction and maintenance of the facilities. Finished or treated water storage facilities provide the following benefits to the operation of a public water system:

- Allow treatment facilities to operate at or near uniform rates, even though the demands of the system may greatly fluctuate

- Supply the peak and emergency needs of the system

- Maintain an adequate pressure in the system

- Provide extended contact or detention time for disinfection

- Serve as reservoirs for the blending and mixing of the water from different sources that may have varying water qualities

The objectives of surveying the finished water storage facilities are to do the following:

- Review the design and major components of storage to determine reliability, adequacy, capacity, and vulnerability
- Evaluate the operation and maintenance and safety practices to determine that storage facilities are reliable
- Recognize any sanitary risks attributable to storage facilities (UFTREEO Center, 1998)

To accomplish these objectives, the inspector needs to review the information available from the State’s files for the system’s finished water storage facilities. In the field, the inspector should perform an inspection to verify the information and adequately assess facility conditions. The inspector may need to climb storage tanks as part of the inspection (particularly if the water system uses elevated tanks and standpipes). Since this can pose safety hazards, the inspector needs training in appropriate safety procedures. In some cases, the results of a recent inspection by a qualified tank contractor may provide the inspector with sufficient information without climbing the tank.

***Pumps/Pump Facilities and Controls* -** Pumps and pump facilities are essential components of all water systems. In addition to transporting water through the system, pump applications include chemical feed systems, sludge removal, air compression, and sampling (UFTREEO Center, 1998). Normally, there are several types of pumps used for an application. However, there are usually only one or two types of pumps that will be the best fit for intended use. The objectives of surveying the pumps/pump facilities and controls are to do the following:

- Review the design uses, and major components of water supply pumps
- Evaluate the operation and maintenance as well as safety practices to determine that water supply pumping facilities are reliable
- Recognize any sanitary risks attributable to water supply pumping facilities (UFTREEO Center, 1998)

***Monitoring/Reporting/Data Verification* -** For the water industry quality control consists of monitoring the product (drinking water) from the source to the tap, with in-house as well as outside laboratory testing for confirmation, as well as audits of existing data. A monitoring plan or program provides the operator with data to assist in identifying potential problems and adjusting treatment processes accordingly. It is important that all water systems create a water quality monitoring plan and document monitoring results. Federal regulatory requirements, dictate the minimum scope of a water quality monitoring plan. Primacy agencies may have more stringent requirements. The objectives of surveying the water quality monitoring/reporting/data verification are to do the following:

- Review the water quality monitoring plan of the PWS for conformance with regulatory requirements
- Verify that the PWS is following the water quality monitoring plan by checking test results
- Verify that all in-house testing as well as equipment and reagents used conform to accepted test procedures and quality

- Verify the data submitted to the regulatory agency

- Evaluate the procedures an operator follows to identify any problems with the process and determine the changes needed to correct the problem

Water System Management/Operation - Management and staff need to work together to create an environment allowing facilities to meet the goal of providing the best possible quality of drinking water to the consumer. The objectives of surveying the water management/operation are to do the following:

- Review the water quality goals and evaluate any plan(s) (e.g. capital improvement plans) the system has to accomplish the stated goals

- Identify and evaluate the basic information on the system, management, staffing, operations, and maintenance

- Review and evaluate the plan(s) for safety, emergency situations, maintenance, and security to maintain system reliability

- Evaluate the system's revenue and budget and asset management for drinking water to establish the long-term viability of meeting water quality goals (UFTREEO Center, 1998)

Operator Compliance with Primacy Agency Requirements - A system operator plays a critical role in the reliable delivery of safe drinking water. Operator compliance with Primacy Agency requirements includes Primacy agency-specific operation and maintenance requirements, training and certification requirements, and overall competency with on-site observations of system performance.

Follow-up Activities - One of the most important components of the sanitary survey involves the State writing the sanitary survey report after the on-site inspection is completed. The report should be completed and presented in a timely manner and it should include the date of the survey, personnel present during the survey, the findings of the survey, recommended or required improvements, and the deadlines for completion. The report may assist in the planning of daily operations and long-term projects.

PWSs with uncorrected significant deficiencies found during the sanitary survey must consult with the primacy agency within 30 days or receiving written notice of the significant deficiency. Systems must provide corrective actions, or be in compliance with State approved corrective action plan and schedule (including State specified interim measures) within 120 days after the State notifies the system of the significant deficiencies. Once the system receives State approval, the system must abide by the State approved plan and schedule. The State agency should monitor progress towards correcting the deficiencies to ensure that corrective actions are suitable and that the system corrects any sanitary problems. Moreover, the State or Primacy Agency should determine whether the system needs to conduct another sanitary survey before the next scheduled survey.

4.2.1.3 Advantages and Limitations

Some advantages of conducting sanitary surveys are as follows:

- Identification of potential sources of contamination

- Identification of potential problems with production, distribution, or treatment systems

- Evaluation of the system operations by an the Primacy agency or approved contractor reduces bias in the evaluation

- Provide information and assistance

- Keep systems informed

The quantity and quality of the data available may limit the scope of the sanitary survey. The survey in and of itself does not mitigate problems; rather, it identifies problems, and the utility must then implement proper solutions to protect public health.

4.2.2 Hydrogeologic Sensitivity Assessment (HSA)

4.2.2.1 Background and Description

Hydrogeologic sensitivity to fecal contamination is not solely a function of the demonstrated presence or absence of contaminant sources. Rather, the characteristics of the aquifer and overlying geologic materials provide the basis of the sensitivity of a ground water source. Hydrogeologic sensitivity also refers to the relative ease with which a contaminant applied on or near the surface can migrate to the aquifer of interest. Hydrogeologic sensitivity depends on the hydrogeologic characteristics of the area. For instance, karst, fractured rock, and gravel aquifers can be susceptible to microbial contamination due to the large water-bearing openings found in these formations. A sensitivity assessment is recommended in the Ground Water Rule. An assessment of a well’s vulnerability may include an evaluation of monitoring data as well as hydrogeology. HSAs also may include information collected for a Source Water Assessment Program (SWAP).

4.2.2.2 Implementation Issues

HSAs are determined using hydrogeologic data from the surrounding area. The first step in an HSA is to identify the aquifer from which the ground water system is drawing its water, where multiple aquifers are present. This requires accurate well construction records that provide the depth of the well, a record of the geologic strata encountered during the drilling, and an indication of the type and depth of well casing, grouting, and well screen installed. The second step in assessing the sensitivity of a system is to characterize the hydrogeology of the source aquifer (i.e., if the aquifer is in a karst, gravel, or fractured bedrock). The next step is to determine if the aquifer has a hydrogeologic barrier that would prevent the vertical movement of microbial contaminants from the surface into the aquifer. A confining layer, an example of a hydrogeologic barrier, is a layer of impermeable material such as clay, that is sufficiently thick and uniformly distributed to protect the underlying aquifer. The final step involves making a determination of the sensitivity of the well based upon the available information and to document this finding in an assessment report.

4.2.2.3 Advantages and Limitations

HSAs are beneficial because they can easily identify high-risk aquifers. However, as with sanitary surveys, an HSA alone does not protect water quality. Additional monitoring, and in some cases, implementation of corrective actions helps protect public water supplies in sensitive settings.

4.3 Corrective Action BMPs

The purpose of corrective action BMPs is to eliminate sources of microbial contamination that may develop within drinking water supply wells, within storage tanks, within distribution systems, and with septic tank usage. The sanitary survey or source water monitoring will help identify the problem and suggest the corrective action necessary. Corrective action BMPs costed for deficiencies identified during a sanitary survey include: rehabilitating a well and replacing a well seal. Corrective action BMPs which were costed for deficiencies identified during source water monitoring include eliminating known sources of contamination, rehabilitating existing wells, purchasing water from another water system, and installing new wells. Additional corrective actions which were not costed for the GWR EA but are included for scoping the range of BMPs used include replacing or repairing a storage tank cover, implementing a cross-connection control program, or installing security measures. The BMPs listed here are not exhaustive but represent the range of BMPs available.

4.3.1 Significant Deficiency Correction Actions

4.3.1.1 Replacing a Well Seal

Background and Description

Contamination may enter a well through a leaking well seal. For example, runoff from nearby agricultural fields can contaminate a well by entering through a leaking well seal. A well seal can leak because of improper installation or deterioration due to age or corrosive conditions. Replacing the well seal can correct a deficiency that could otherwise allow contamination from a nearby source to enter the well.

Implementation Issues

If seal failure was caused by something other than age, care should be taken to ensure that the conditions are improved so that failure does not occur again. Care should be taken in the installation of the seal and materials should be chosen that are resistant to the conditions surrounding the well.

Advantages and Limitations

Replacing the well seal is a simple and relatively inexpensive way to reduce contamination, if the source is a leaking seal. It does not eliminate the source of contamination, however, and contamination can re-occur if the seal fails again.

4.3.1.2 Rehabilitation of Existing Wells

Background and Description

Old or poorly constructed wells can lead to contamination. Rehabilitating a well can often correct the problems which lead to the contamination. Systems that rehabilitate existing wells do so to ensure the integrity of the casing, screen, seal and pump and to prevent well contamination. The need for well rehabilitation may result from poor design of the original well, the age of the existing well, or damage to some well components. If a system must rehabilitate a well, it may need to repair or replace the well screen, well casing, well seal, and/or the well pump.

The well casing should extend above ground, and the system should grade the ground surface at the well site to drain surface water away from the well. If a system decides to replace the casing, it should select the casing in accordance with applicable State or local criteria, codes, and regulations or adopt other national criteria such as AWWA Standards (1997b) or the Ten States Standards (1997) if no local regulations exist.

Implementation Issues

The parties responsible for public water supply well installation can take an active role in protecting the public from ground water contamination by constructing safe wells and by properly abandoning old wells. Proper design and rehabilitation of well screens, casings, seals, and pumps may require additional training of inspectors, engineers and contractors.

Advantages and Limitations

Proper rehabilitation of wells will greatly reduce the potential for well contamination by repairing potential leaks in screens, casings, or seals. Rehabilitation of existing wells will also enhance yields and water quality as well as contribute to extending the useful life of the well.

4.3.2 Source Water Corrective Actions

4.3.2.1 Eliminating Known Sources of Contamination

Background and Description

If the sanitary survey or source water monitoring is able to identify the sources of contamination or significant deficiency, the PWS must provide corrective action. Potential sources of contamination include the following:

- Septic tanks or cesspools
- Concentrated animal feeding operations
- Unlined or leaky sewage lagoons
- Secondary sewage treatment plant effluent used to recharge ground water or irrigate crop land
- Land application of raw or primary treated sewage or sewage sludge
- Ruptured, leaking sewage collection lines
- Improperly abandoned wells

Implementation Issues

It may be difficult to determine with certainty that a given source of contamination is responsible for contaminating a well. The Primacy Agency may also require interim corrective actions to protect the consumer from fecal contamination while the source of contaminant is being eliminated.

Once the system eliminates known sources of contamination, there will be a period of time over which a well may continue to be contaminated. This will vary based upon the extent of contamination, the time-of-travel to the well, and longevity of the contamination.

Advantages and Limitations

This corrective action is advantageous because it eliminates the known source of contamination which may also act as a source for future contamination. This corrective action may be limited, however, since it may require State or Federal intervention depending on the source(s) of contamination and negotiations with the responsible party(ies). That is, the contamination source may not be under the direct, immediate control of the affected PWS. It may also be difficult to identify a specific source of contamination.

4.3.2.2 Rehabilitating a Well

The need to rehabilitate a well may be identified by either sanitary survey or source water monitoring. The issues brought up in either case are the same. See section 4.3.1.2 for a discussion of well rehabilitation.

4.3.2.3 Purchasing Water from Another Utility

Background and Description

A water utility with fecally contaminated source water or a significant deficiency may decide to purchase water from another utility if the costs of eliminating the contamination or treating the ground water are prohibitively expensive. The system may purchase water in whole or for part of the system.

Implementation Issues

There are a number of issues that will impact a system's ability to purchase water, including the proximity of a system to another system with the capacity available to sell water to the system. Systems will need to construct a transmission main from the water seller to their distribution system and may need to install booster pumps or pressure reducer valves to insure the system maintains a pressure plane. In some cases, additional disinfection may be necessary.

Advantages and Limitations

A drinking water utility may achieve greater efficiency by combining with another utility. Small systems, however, may find themselves limited by using another utility's water and no longer in control of the quality of their product.

4.3.2.4 Installation of New Wells

Background and Description

When a PWS becomes fecally contaminated or certain significant deficiencies cannot be corrected, and other corrective actions are not feasible nor effective, a new well may be necessary. Systems site, design, and construct new wells in accordance with current applicable State and local criteria, codes, or regulations. Systems choose well sites to ensure the avoidance of potential contamination from known pollutant sources or contaminated aquifers, and systems construct wells so that surface pollutants cannot reach the aquifer (Driscoll, 1986). Systems should ensure the new well is not vulnerable to the source of contamination that affected the original well.

Some of the parameters to consider when determining the site location, well construction methods, and disinfection procedures, may include the following (Lehr et al., 1980):

- Character of the local hydrogeology, such as: the slope of the ground surface, nature of the soil and underlying material, thickness of the water-bearing formation, depth to the water table, and slope of the water table
- Location, boring logs, and construction details of all operating or abandoned local wells
- Extent of recharge area likely to contribute water to the supply
- Nature, distance, and direction to local sources of pollution
- Possibility of surface drainage or flood water entering the supply
- Methods used for protecting the supply against local sources of pollution
- Well construction considerations (depth of the well, the casing diameter, wall thickness, screen diameter and material, construction, the formation seal material, depth of placement, annular thickness, and method of replacement)
- Surface protection of the well, including presence of sanitary well seal, height that casing projects above ground, pumphouse floor, or flood level; protection of well from erosion and animals, and pumphouse construction
- Pump capacity and pumping level
- Disinfection equipment, supervision, and test kits

In general, systems should locate a well on the highest ground whenever practical, and upgradient from nearby or potential sources of pollution, such as sewage drainage fields, farm feed lots, or land application of manure. The well casing should extend above ground, and the system should grade the ground surface at the well site to drain surface water away from the well.

Construction of the well should utilize natural sanitary protection afforded by the geologic and ground water conditions. Similarly, systems should design the well to avoid both natural and man-made contamination and select casing and construct wells in accordance with applicable State or local criteria/codes/regulations, or other criteria such as AWWA Standards (1997b) or the Ten States Standards (1997) when no local regulations exist.

Implementation Issues

The parties responsible for public water supply well installation and siting can take an active role in protecting the public from ground water contamination by properly constructing wells and making sure that systems properly abandon old wells. Proper siting, design, and construction of wells will require additional education of inspectors, engineers, well drillers, and contractors. System operators must know the benefits of proper siting and construction in order to allocate sufficient resources to implement this practice.

Advantages and Limitations

Use of a new well as opposed to correcting problems at an old well can be a more simple, less costly option. New wells may, however, be subject to the same contamination sources as existing wells, so unless care is taken in siting construction of the new well, the original contamination problem could appear in the new well. The time or costs to construct a new well may also serve as a limitation as well as its proximity to other well(s) used by the PWS. Interim measures may need to be put in place until the new well is installed.

4.3.3 Additional Corrective Actions

These corrective actions are examples of BMPs systems may use to address a significant deficiency or fecal contamination. They may be identified by a sanitary survey or source water monitoring. These corrective actions are included for comparison to the previous corrective actions which were used in the GWR EA.

4.3.3.1 Storage Tank Cover Replacement or Repair

Background and Description

The sanitary survey may locate defects in the storage tank cover. Any damage to the storage tank cover allows the potential for contamination of the finished water by birds, rodents, or other disease vectors and can allow unauthorized human access.

Implementation Issues

Replacement or repair of a storage tank cover may require taking the tank out of service and interruptions in water service. A system may need to clean and disinfect a repaired tank prior to returning the tank to service. Interim measures may need to be undertaken until the storage tank cover is repaired or replaced.

Advantages and Limitations

Replacing or repairing the storage tank cover will prevent any threats of future contamination as it eliminates a pathway for contamination; however, this corrective action may not immediately address existing contamination in the source water, unless the tank is drained and disinfected.

4.3.3.2 Cross-Connection Control and Backflow Prevention Program

Background and Description

Implementing a Cross-Connection Control and Backflow Prevention (CCCBFP) Program, including the installation of backflow prevention assemblies and devices, can prevent the flow of non-potable substances into the distribution system. When implementing the CCCBFP Program, the drinking water system should adhere to applicable State and/or local criteria, codes, and/or regulations. Some codes or regulations may include documenting installation procedures and the periodic testing of backflow prevention assemblies.

CCCBFP can prevent the introduction of non-potable substances into the public water supply due to backsiphonage or backpressure. Some common elements of a CCCBFP Program include:

- Installation of backflow prevention assemblies or devices at all high hazard service connections.

- Elimination of cross-connections.

- Ensuring the inspection and testing of all backflow prevention assemblies or devices either by the system or the hired contractor.

- Providing administrative authority to implement the program.

- Training and certification of personnel to maintain and administer the program and test backflow prevention assemblies.

- Implementation of proper record keeping and reporting procedures.

- Education and notification of the public.

There are numerous potential cross-connection and backflow hazards. The degree of protection from a cross-connection and backflow hazard should be commensurate with the degree of hazard. There are five types of backflow prevention devices commonly used: air-gaps, double check valves, reduced-pressure principle assemblies, atmospheric-vacuum breakers, and pressure-vacuum breakers (USEPA, 1989b).

To locate, eliminate, and prevent cross-connections and backflow, the program may identify who has authority to enforce the codes and regulations covering hazard identification, and installation, testing, and maintenance of backflow prevention assemblies or devices.

The legal basis for adoption of a CCCBFP Program ordinance varies by State. Water systems should consult on this matter with the State Primacy Agency when developing a program (Salvato, 1982).

Implementation Issues

There are several issues involved in the process of developing and implementing a CCCBFP Program. Both water suppliers and water users (utility customers) have a clearly implied responsibility to protect the safety of water in the public distribution system and on their premises. The CCCBFP Program should clearly define and establish responsibilities for each aspect of installation, maintenance, testing, and inspection of control devices as well as enforcement of the plan (Salvato, 1982).

A building's piping system may require protection in accordance with the requirements of the local drinking water, health, plumbing, or construction authority. The water distribution systems of some premises served by PWSs, such as hotels, hospitals, and industrial plants, can be quite complex. Contaminated backflow from these premises may result from backpressure or backsiphonage where cross-connections are established between appliances and equipment containing non-potable substances and the potable water supply. CCCBFP Programs usually require the installation of backflow prevention devices or assemblies at water service connections where potentially hazardous conditions exist (AWWA, 1990b; EPA, 1989b). AWWA Manual M14 (1990b) lists potential CCCBFP Program elements, and backflow prevention devices and assemblies to use in those cases where local authorities do not regulate these controls.

Advantages and Limitations

CCCBFP reduce the potential for the introduction of pathogenic microbes and toxic chemicals in the distribution system. Additional advantages of an effective CCCBFP Program include eliminating transient contamination events resulting from pressure fluctuations that may otherwise go undetected and minimizing the introduction of corrosive materials. Potential disadvantages may also exist, such as the potential for jurisdictional problems where overlaps exist.

4.3.3.3 Installation of Security Measures

Background and Description

Systems may need to install security measures in circumstances where the sanitary survey or on-site inspection reveals vandalism or security breaches. Measures that a water system may take to correct security breaches include installing a fence or locking buildings to restrict access to the system. In addition, alarms and cameras may be used to detect security breaches.

Implementation Issues

Water systems should prioritize their security measures and concentrate on the most vulnerable parts of the system, such as unstaffed facilities (e.g., finished water storage tanks). An important implementation issue is the extent of the water system that needs to be secured. This would depend on how widely spread the system/facility is, the number and complexity of the treatment trains, the extent of the watershed, the distance of the treatment plant from the influent wells, accessibility of the distribution system to the public, etc. Possible security measures include locked fence enclosures and employing a full time, on-site security staff.

Advantages and Limitations

Installing security measures can increase the public’s confidence in the protection of their drinking water and indeed can afford substantial protection against vandalism that might result in contamination of the water. However, security measures are not always foolproof or absolute in combating vandalism or security breaches.

5. Costs for Best Management Practices

This chapter describes the costs incurred for the best management practices (BMPs) identified and discussed in Chapter 4. Because in some ways BMPs are a reasonable and sound way to minimize the need for installing some more expensive corrective actions, public water systems (PWSs) practice one form or another of BMPs regardless of rules and regulations. EPA does not expect systems with existing disinfection treatment to abandon that practice in favor of fully implementing BMPs.

Costs of the BMPs provided in this chapter are intended to be used as estimates. Where appropriate, the costs of these BMPs presented are per unit of number of wells in a system. This chapter includes costs on the following BMPs:

System Assessment

- Sanitary survey (Section 5.2.1)
- Hydrogeologic sensitivity assessment (Section 5.2.2)

Corrective Actions

Significant Deficiency Corrective Actions (Section 5.3.1)

- Replacing well seal (Section 5.3.1.1)
- Rehabilitation of existing wells (Section 5.3.1.2)

Source Water Corrective Actions (Section 5.3.2)

- Eliminating known sources of contamination (Section 5.3.2.1)
- Rehabilitation of existing wells (Section 5.3.2.2)
- Purchasing water from another utility (Section 5.3.2.3)
- Installation of new wells (Section 5.3.2.4)

Additional Corrective Actions[1] (Section 5.3.3)

- Storage tank cover replacement or repair (Section 5.3.3.1)
- Cross-connection control/backflow prevention program (Section 5.3.3.2)
- Installation of security measures (Section 5.3.3.3)

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[1] Note, these additional corrective actions are included here for reference only. They are not used in the GWR EA and are not included in the GWR compliance forecast.

In addition, for systems that employ nontreatment corrective actions, the GWR EA Cost Model assumes interim disinfection will be installed until the nontreatment corrective action begins. Cost information on interim disinfection is provided in Chapter 3, Section 3.7.3.

5.1 Introduction

The estimated costs for carrying out each of the various system assessment and corrective action BMPs that were described in Chapter 4 are based upon specific components of each BMP. Those components are identified and discussed in the sections that follow. Costs for all of the BMPs are highly dependent upon labor and on the number of wells at a particular ground water system implementing a BMP.

To remain consistent with the unit costs estimates presented in Chapter 3, the corrective actions cost estimates have been updated to 2003 dollars by applying the appropriate Building Cost Index (BCI) (i.e., [BCI Avg 2003 ÷ BCI Avg. 1998] = 3693 ÷ 3391 = 1.089) (www.enr.com).

Exhibit 5.1 presents a summary of the labor rates for various types of personnel who carry out aspects of one or more of the BMP components. These rates include overhead as well as individual wages. The R.S. Means (1998) labor costs were updated to 2003 dollars using the Employment Cost Index (ECI) available from the website “http:\\www.bls.gov”. Exhibit 5.1b includes labor costs for system operators.

Exhibit 5.2 provides a summary of the number of wells per system in the various population categories.

Exhibit 5.1a State Labor Rate Components of BMPs

Cost Element	Unit Cost	2003 Dollars	Source
Staff Hydrogeologist	Hour	$ 27.10	R.S. Means[1]
Field Engineer	Hour	$ 37.34	R.S. Means[1]

[1] R.S. Means 1998 costs updated to 2003 dollars using ECI.

Exhibit 5.1b PWS Operator Labor Rate Components of BMPs

Size of PWS	Unit Cost	2003 Dollars	Source
25 - 100	Hour	$ 21.44	Labor Costs for National Drinking Water Rules (USEPA 2003)
101 - 500	Hour	$ 23.09	Labor Costs for National Drinking Water Rules (USEPA, 2003)
500 - 3,300	Hour	$ 24.74	Labor Costs for National Drinking Water Rules (USEPA, 2003)
3,301 - 10,000	Hour	$ 25.34	Labor Costs for National Drinking Water Rules (USEPA, 2003)
10,001 - 100,000	Hour	$ 26.05	Labor Costs for National Drinking Water Rules (USEPA, 2003)
> 100,000	Hour	$ 31.26	Labor Costs for National Drinking Water Rules (USEPA, 2003)

Source: GWR EA, Ex 6.1

Exhibit 5.2 Average Number of Wells per Community Water System

Population Served	Number of Wells per System
100 or fewer	1.5
101-500	2.0
501-1,000	2.3
1,001-3,300	3.1
3,301-10,000	4.6
10,001-50,000	9.8
50,001-100,000	16.1
Greater than 100,000	49.9

Source: USEPA, 2001.

5.2 System Assessment

5.2.1 Sanitary Survey

States or designated agents perform sanitary surveys, however, systems will incur costs to accompany State inspectors during a review of the treatment plant and the distribution system, as well as to prepare for the sanitary survey, and to review and discuss the sanitary survey report. The State labor costs for a Sanitarian are assumed to be equivalent to that of a Field Engineer (at $37.34 per hour, in 2003 dollars). Exhibits 5.3a and 5.3b indicate the sanitary survey components and State labor costs for a sanitary survey. The level of effort for systems that have treatment installed is greater than systems with no treatment. Therefore separate costs are calculated for systems with and without treatment. Sanitary surveys will increase either in scope or frequency under the GWR for some systems. Some systems will incur the full cost for conducting additional sanitary surveys beyond their current requirements. Other systems will only need to add additional elements to their existing sanitary surveys. It is assumed that the additional effort will be half of the effort required to perform a full sanitary survey and that 10 percent of systems will only be required to perform an incremental survey. This leads to a unit cost for incremental surveys which is 0.05 times the cost for a full survey.

Hours are included for the engineer to review the plant and distribution system, to enter the data, write, document and review the report. All burden estimates are based on consultations with EPA, State, and Industry professionals with significant experience conducting sanitary surveys on ground water systems.

The costs outlined in Exhibits 5.4a and 5.4b indicate the system costs for a sanitary survey. As discussed in Section 4.2.1, the system should prepare and organize data for the survey. EPA assumes that the system operator would accompany the engineer to the well and review the report. Costs are based on the unit labor cost of a plant operator. As with the States costs, both unit costs for full surveys and weighted unit costs for incremental survey are provided.

Exhibit 5.3a Estimated State Costs for a Sanitary Survey for Systems with Treatment (2003$)

System Size (Population Served)	Labor Cost (per hour)	Review/ Inspect Wells	Review/ Inspect Treatment	Review/ Inspect Distribution System	Report Documentation/ File Review	Report Development	Data Entry	Report Review and Discussion w/ PWS	Travel	Total Unit Burden (hours)	Unit Cost (Full Survey)	Weighted Unit Cost (Incremental Survey)
	A	B	C	D	E	F	G	H	I	J=sum(B-I)	K=A*J	L=0.05*K
Community Water Systems (CWSs)												
<100	$ 37.34	1.1	0.8	1.2	2.3	5.7	0.8	1.1	1.8	14.8	$ 551	$ 28
101-500	$ 37.34	1.2	0.8	1.2	2.3	5.8	0.8	1.1	1.8	14.9	$ 557	$ 28
501-1,000	$ 37.34	1.5	1.1	1.7	2.6	7.4	0.8	1.2	1.8	18.0	$ 671	$ 34
1,001-3,300	$ 37.34	2.2	1.3	2.9	3.4	8.8	1.2	1.4	1.8	22.8	$ 851	$ 43
3,301-10K	$ 37.34	2.7	1.6	3.6	3.7	9.6	1.3	1.8	1.8	25.9	$ 967	$ 48
10,001-50K	$ 37.34	3.7	2.0	4.3	5.3	10.1	1.4	1.9	1.8	30.3	$ 1,132	$ 57
50,001-100K	$ 37.34	9.0	3.0	12.0	12.0	12.0	2.0	3.0	1.8	54.8	$ 2,044	$ 102
100,000-1M	$ 37.34	15.0	8.0	24.0	18.0	18.0	3.0	3.0	1.8	90.8	$ 3,389	$ 169
>1,000,000	$ 37.34	24.0	10.0	36.0	18.0	18.0	4.0	4.0	1.8	115.8	$ 3,389	$ 169
Nontransient Noncommunity Water Systems (NTNCWSs)												
<100	$ 37.34	1.0	0.8	1.0	1.9	5.1	1.0	1.3	1.8	13.8	$ 515	$ 26
101-500	$ 37.34	1.0	0.8	1.1	2.0	5.3	1.0	1.3	1.8	14.2	$ 531	$ 27
501-1,000	$ 37.34	1.1	0.9	1.3	2.1	6.5	0.8	1.2	1.8	15.6	$ 583	$ 29
1,001-3,300	$ 37.34	1.1	1.1	1.2	2.1	6.2	0.8	1.3	1.8	15.6	$ 581	$ 29
3,301-10K	$ 37.34	1.5	1.5	1.7	2.2	6.7	0.8	1.5	1.8	17.6	$ 657	$ 33
10,001-50K	$ 37.34	1.3	0.8	1.8	2.5	5.0	0.8	1.3	1.8	15.0	$ 560	$ 28
50,001-100K	$ 37.34	1.5	0.8	2.3	2.5	5.0	0.8	1.3	1.8	15.8	$ 588	$ 29
100,000-1M	$ 37.34	8.0	1.0	10.0	8.0	10.0	1.0	1.5	1.8	41.3	$ 1,540	$ 77
>1,000,000	NA	NA	NA	NA	NA	NA	NA	NA	1.8	NA	NA	NA
Transient Noncommunity Water Systems (TNCWSs)												
<100	$ 37.34	0.7	0.6	0.6	1.5	5.1	0.8	0.9	1.8	11.9	$ 443	$ 22
101-500	$ 37.34	0.7	0.6	0.6	1.5	5.3	0.8	0.9	1.8	12.1	$ 452	$ 23
501-1,000	$ 37.34	1.0	0.8	1.0	1.8	5.8	0.8	0.9	1.8	13.9	$ 518	$ 26
1,001-3,300	$ 37.34	0.9	1.0	0.9	1.7	4.7	0.8	1.1	1.8	12.9	$ 480	$ 24
3,301-10K	$ 37.34	1.2	1.3	1.2	1.5	5.2	0.8	1.2	1.8	14.1	$ 526	$ 26
10,001-50K	$ 37.34	0.8	0.5	1.3	1.3	3.8	0.8	0.8	1.8	10.8	$ 401	$ 20
50,001-100K	$ 37.34	1.3	0.5	1.3	1.3	3.8	0.8	0.8	1.8	11.3	$ 420	$ 21
100,000-1M	$ 37.34	8.0	1.0	10.0	3.0	8.0	0.5	1.0	1.8	33.3	$ 1,242	$ 62
>1,000,000	NA	NA	NA	NA	NA	NA	NA	NA	1.8	NA	NA	NA

Notes: Weighted unit costs equal 5% of the unit costs. This factor accounts for 50% effort for an incremental survey and 10% of systems that do not already comply with rule requirements (see text discussion).

Exhibit 5.3b Estimated State Costs for a Sanitary Survey for Systems without Treatment (2003$)

System Size (Population Served)	Labor Cost (per hour)	Review/ Inspect Wells	Review/ Inspect Distribution System	Report Documentation/ File Review	Report Development	Data Entry	Report Review and Discussion w/ PWS	Travel	Total Unit Burden (hours)	Unit Cost (Full Survey)	Weighted Unit Cost (Incremental Survey)
	A	B	C	D	E	F	G	H	I=sum(B-H)	J=A*I	K=0.05*J
Community Water Systems (CWSs)											
<100	$ 37.34	1.1	1.2	2.3	5.7	0.8	1.1	1.8	13.9	$ 521	$ 26
101-500	$ 37.34	1.2	1.2	2.3	5.8	0.8	1.1	1.8	14.1	$ 526	$ 26
501-1,000	$ 37.34	1.5	1.7	2.6	7.4	0.8	1.2	1.8	16.9	$ 631	$ 32
1,001-3,300	$ 37.34	2.2	2.9	3.4	8.8	1.2	1.4	1.8	21.5	$ 803	$ 40
3,301-10K	$ 37.34	2.7	3.6	3.7	9.6	1.3	1.8	1.8	24.3	$ 909	$ 45
10,001-50K	$ 37.34	3.7	4.3	5.3	10.1	1.4	1.9	1.8	28.3	$ 1,058	$ 53
50,001-100K	$ 37.34	9.0	12.0	12.0	12.0	2.0	3.0	1.8	51.8	$ 1,932	$ 97
100,000-1M	$ 37.34	15.0	24.0	18.0	18.0	3.0	3.0	1.8	82.8	$ 3,090	$ 155
>1,000,000	$ 37.34	24.0	36.0	18.0	18.0	4.0	4.0	1.8	105.8	$ 3,090	$ 155
Nontransient Noncommunity Water Systems (NTNCWSs)											
<100	$ 37.34	1.0	1.0	1.9	5.1	1.0	1.3	1.8	13.0	$ 487	$ 24
101-500	$ 37.34	1.0	1.1	2.0	5.3	1.0	1.3	1.8	13.5	$ 503	$ 25
501-1,000	$ 37.34	1.1	1.3	2.1	6.5	0.8	1.2	1.8	14.8	$ 551	$ 28
1,001-3,300	$ 37.34	1.1	1.2	2.1	6.2	0.8	1.3	1.8	14.5	$ 540	$ 27
3,301-10K	$ 37.34	1.5	1.7	2.2	6.7	0.8	1.5	1.8	16.1	$ 601	$ 30
10,001-50K	$ 37.34	1.3	1.8	2.5	5.0	0.8	1.3	1.8	14.3	$ 532	$ 27
50,001-100K	$ 37.34	1.5	2.3	2.5	5.0	0.8	1.3	1.8	15.0	$ 560	$ 28
100,000-1M	$ 37.34	8.0	10.0	8.0	10.0	1.0	1.5	1.8	40.3	$ 1,503	$ 75
>1,000,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Transient Noncommunity Water Systems (TNCWSs)											
<100	$ 37.34	0.7	0.6	1.5	5.1	0.8	0.9	1.8	11.3	$ 421	$ 21
101-500	$ 37.34	0.7	0.6	1.5	5.3	0.8	0.9	1.8	11.5	$ 431	$ 22
501-1,000	$ 37.34	1.0	1.0	1.8	5.8	0.8	0.9	1.8	13.0	$ 487	$ 24
1,001-3,300	$ 37.34	0.9	0.9	1.7	4.7	0.8	1.1	1.8	11.9	$ 443	$ 22
3,301-10K	$ 37.34	1.2	1.2	1.5	5.2	0.8	1.2	1.8	12.8	$ 476	$ 24
10,001-50K	$ 37.34	0.8	1.3	1.3	3.8	0.8	0.8	1.8	10.3	$ 383	$ 19
50,001-100K	$ 37.34	1.3	1.3	1.3	3.8	0.8	0.8	1.8	10.8	$ 401	$ 20
100,000-1M	$ 37.34	8.0	10.0	3.0	8.0	0.5	1.0	1.8	32.3	$ 1,204	$ 60
>1,000,000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Notes: Weighted unit costs equal 5% of the unit costs. This factor accounts for 50% effort for an incremental survey and 10% of systems that do not already comply with rule requirements (see text discussion).

Exhibit 5.4a Estimated System Costs for Performing a Sanitary Survey for Systems with Treatment (2003$)

System Size (Population Served)	Labor Cost (per hour)	Review/ Inspect Wells	Review/ Inspect Treatment	Review/ Inspect Distribution System	Report Review and Discussion w/ State	Total Unit Burden (hours)	Unit Cost (Full Survey)	Weighted Unit Cost (Incremental Survey)
	A	B	C	D	E	F=sum(B-E)	G=A*F	H=0.05*G
Community Water Systems (CWSs)								
<100	$ 21.44	1.1	0.8	1.2	1.1	4.3	$ 92	$ 5
101-500	$ 23.09	1.2	0.8	1.2	1.1	4.3	$ 99	$ 5
501-1,000	$ 24.74	1.5	1.1	1.7	1.2	5.4	$ 135	$ 7
1,001-3,300	$ 24.74	2.2	1.3	2.9	1.4	7.7	$ 191	$ 10
3,301-10K	$ 30.51	2.7	1.6	3.6	1.8	9.6	$ 291	$ 15
10,001-50K	$ 31.08	3.7	2.0	4.3	1.9	11.8	$ 368	$ 18
50,001-100K	$ 31.08	9.0	3.0	12.0	3.0	27.0	$ 839	$ 42
100,000-1M	$ 35.25	15.0	8.0	24.0	3.0	50.0	$ 1,762	$ 88
>1,000,000	$ 35.25	24.0	10.0	36.0	4.0	74.0	$ 1,762	$ 88
Nontransient Noncommunity Water Systems (NTNCWSs)								
<100	$ 21.44	1.0	0.8	1.0	1.3	4.0	$ 87	$ 4
101-500	$ 23.09	1.0	0.8	1.1	1.3	4.2	$ 96	$ 5
501-1,000	$ 24.74	1.1	0.9	1.3	1.2	4.5	$ 110	$ 6
1,001-3,300	$ 24.74	1.1	1.1	1.2	1.3	4.7	$ 116	$ 6
3,301-10K	$ 30.51	1.5	1.5	1.7	1.5	6.2	$ 188	$ 9
10,001-50K	$ 31.08	1.3	0.8	1.8	1.3	5.0	$ 155	$ 8
50,001-100K	$ 31.08	1.5	0.8	2.3	1.3	5.8	$ 179	$ 9
100,000-1M	$ 35.25	8.0	1.0	10.0	1.5	20.5	$ 723	$ 36
>1,000,000	$ 35.25	NA	NA	NA	NA	NA	NA	NA
Transient Noncommunity Water Systems (TNCWSs)								
<100	$ 21.44	0.7	0.6	0.6	0.9	2.7	$ 59	$ 3
101-500	$ 23.09	0.7	0.6	0.6	0.9	2.7	$ 63	$ 3
501-1,000	$ 24.74	1.0	0.8	1.0	0.9	3.7	$ 92	$ 5
1,001-3,300	$ 24.74	0.9	1.0	0.9	1.1	3.9	$ 96	$ 5
3,301-10K	$ 30.51	1.2	1.3	1.2	1.2	4.8	$ 147	$ 7
10,001-50K	$ 31.08	0.8	0.5	1.3	0.8	3.3	$ 101	$ 5
50,001-100K	$ 31.08	1.3	0.5	1.3	0.8	3.8	$ 117	$ 6
100,000-1M	$ 35.25	8.0	1.0	10.0	1.0	20.0	$ 705	$ 35
>1,000,000	$ 35.25	NA	NA	NA	NA	NA	NA	NA

Notes: Weighted unit costs equal 5% of the unit costs. This factor accounts for 50% effort for an incremental survey and 10% of systems that do not already comply with rule requirements (see text discussion).

Exhibit 5.4b Estimated System Costs for Performing a Sanitary Survey for Systems without Treatment (2003$)

System Size (Population Served)	Labor Cost (per hour)	Review/ Inspect Wells	Review/ Inspect Distribution System	Report Review and Discussion w/ State	Total Unit Burden (hours)	Unit Cost (Full Survey)	Weighted Unit Cost (Incremental Survey)
	A	B	C	D	E=sum(B-D)	F=A*E	G=0.05*F
Community Water Systems (CWSs)							
<100	$ 21.44	1.1	1.2	1.1	3.5	$ 75	$ 4
101-500	$ 23.09	1.2	1.2	1.1	3.5	$ 81	$ 4
501-1,000	$ 24.74	1.5	1.7	1.2	4.4	$ 108	$ 5
1,001-3,300	$ 24.74	2.2	2.9	1.4	6.4	$ 159	$ 8
3,301-10K	$ 30.51	2.7	3.6	1.8	8.0	$ 243	$ 12
10,001-50K	$ 31.08	3.7	4.3	1.9	9.8	$ 305	$ 15
50,001-100K	$ 31.08	9.0	12.0	3.0	24.0	$ 746	$ 37
100,000-1M	$ 35.25	15.0	24.0	3.0	42.0	$ 1,480	$ 74
>1,000,000	$ 35.25	24.0	36.0	4.0	64.0	$ 1,480	$ 74
Nontransient Noncommunity Water Systems (NTNCWSs)							
<100	$ 21.44	1.0	1.0	1.3	3.3	$ 70	$ 4
101-500	$ 23.09	1.0	1.1	1.3	3.4	$ 79	$ 4
501-1,000	$ 24.74	1.1	1.3	1.2	3.6	$ 89	$ 4
1,001-3,300	$ 24.74	1.1	1.2	1.3	3.6	$ 89	$ 4
3,301-10K	$ 30.51	1.5	1.7	1.5	4.7	$ 142	$ 7
10,001-50K	$ 31.08	1.3	1.8	1.3	4.3	$ 132	$ 7
50,001-100K	$ 31.08	1.5	2.3	1.3	5.0	$ 155	$ 8
100,000-1M	$ 35.25	8.0	10.0	1.5	19.5	$ 687	$ 34
>1,000,000	$ 35.25	NA	NA	NA	NA	NA	NA
Transient Noncommunity Water Systems (TNCWSs)							
<100	$ 21.44	0.7	0.6	0.9	2.2	$ 46	$ 2
101-500	$ 23.09	0.7	0.6	0.9	2.2	$ 50	$ 2
501-1,000	$ 24.74	1.0	1.0	0.9	2.9	$ 72	$ 4
1,001-3,300	$ 24.74	0.9	0.9	1.1	2.9	$ 72	$ 4
3,301-10K	$ 30.51	1.2	1.2	1.2	3.5	$ 107	$ 5
10,001-50K	$ 31.08	0.8	1.3	0.8	2.8	$ 85	$ 4
50,001-100K	$ 31.08	1.3	1.3	0.8	3.3	$ 101	$ 5
100,000-1M	$ 35.25	8.0	10.0	1.0	19.0	$ 670	$ 33
>1,000,000	$ 35.25	NA	NA	NA	NA	NA	NA

Notes:

Weighted unit costs equal 5% of the unit costs. This factor accounts for 50% effort for an incremental survey and 10% of systems that do not already comply with rule requirements (see text discussion).

5.2.2 Hydrogeologic Sensitivity Assessment (HSA)

Similar to the sanitary survey, it is assumed that HSAs are conducted primarily by the Primacy agency with assistance from the systems. The assistance provided by the systems is expected to be small and negligible in terms of cost. The HSA is a voluntary approach recommended by EPA but not required by the GWR. Costs calculated here are not used to calculate rule costs but shown for demonstrative purposes. Exhibit 5.5 presents the cost components for a State inspector to perform a HSA. The costs assume 2 hours of labor per well. The labor rate for the hydrogeologist is $27.10 per hour (in 2003 dollars). The cost per entry point is then determined by dividing by the number of entry points. In some cases where an entry point is determined to be sensitive, States will also make barrier determinations. The number of hours for a barrier determination are assumed to equal those to perform the HSA.

Exhibit 5.5 Estimated State Costs of a Hydrogeologic Sensitivity Assessment (2003$)

System Size (Population Served)	HSAs						
	Labor Cost (per hour)	HSA Labor per Well	Wells per System	Conduct HSA (hours/ system)	Entry Points per System	Conduct HSA (hours/ entry point)	Unit Cost
	A	B	C	D = B*C	E	F = D/E	G = A*F
Community Water Systems (CWSs)							
<100	$ 27.10	2	1.5	3.0	1.3	2.3	$ 63
101-500	$ 27.10	2	2.0	4.0	1.6	2.5	$ 68
501-1,000	$ 27.10	2	2.3	4.6	2.0	2.3	$ 62
1,001-3,300	$ 27.10	2	3.1	6.2	2.4	2.6	$ 70
3,301-10K	$ 27.10	2	4.6	9.2	3.2	2.9	$ 78
10,001-50K	$ 27.10	2	9.8	19.6	5.6	3.5	$ 95
50,001-100K	$ 27.10	2	16.1	32.2	11.3	2.8	$ 77
100,001-1 Million	$ 27.10	2	49.9	99.8	12.4	8.0	$ 218
> 1 Million	$ 27.10	2	49.9	99.8	11.4	8.8	$ 237
Total							
Nontransient Noncommunity Water Systems (NTNCWSs)							
<100	$ 27.10				1.0	2.3	$ 63
101-500	$ 27.10				1.0	2.5	$ 68
501-1,000	$ 27.10				1.0	2.3	$ 62
1,001-3,300	$ 27.10				1.0	2.6	$ 70
3,301-10K	$ 27.10				1.0	2.9	$ 78
10,001-50K	$ 27.10				1.0	3.5	$ 95
50,001-100K	$ 27.10				1.0	2.8	$ 77
100,001-1 Million	$ 27.10				1.0	8.0	$ 218
> 1 Million	NA				NA	NA	NA
Total							
Transient Noncommunity Water Systems (TNCWSs)							
<100	$ 27.10				1.0	2.3	$ 63
101-500	$ 27.10				1.0	2.5	$ 68
501-1,000	$ 27.10				1.0	2.3	$ 62
1,001-3,300	$ 27.10				1.0	2.6	$ 70
3,301-10K	$ 27.10				1.0	2.9	$ 78
10,001-50K	$ 27.10				1.0	3.5	$ 95
50,001-100K	$ 27.10				1.0	2.8	$ 77
100,001-1 Million	$ 27.10				1.0	8.0	$ 218
> 1 Million	NA				NA	NA	NA
Total							
All Total							

Notes: Detail may not add to totals due to independent rounding.

NA Not applicable (no NCWSs of this size category).

Sources: (A) Labor rates for staff hydrogeologist from Exhibit 5.1

(B) Labor for conducting assessment includes time for travel, records review, wellhead inspection, and report preparation.

(C) Wells per system from US EPA Drinking Water Baseline Handbook (2001).

(E) Entry points per system derived from 1995 CWSS.

Labor hours per entry point for NTNCWSs and TNCWSs based on EPA estimate of hours per entry point for CWSs.

5.3 Corrective Actions

This section provides estimates of costs for the corrective action BMPs that systems may undertake. A summary of the costs and assumptions used to determine costs accompanies each action. The total cost estimates include capital costs (construction costs), and where applicable, operation and maintenance (O&M) costs. Costs depend largely on site-specific conditions and may vary depending on the individual components employed and the specific population category.

5.3.1 Significant Deficiency Corrective Actions

5.3.1.1 Replacing a Well Seal

The total cost for a replacing a well seal including parts and installation is $3,300 for a 6-inch diameter well according to 1998 RS Means. Updating these costs to 2003 dollars gives $3,627.

5.3.1.2 Rehabilitation of Existing Wells

The cost components for rehabilitating an existing well include replacing the well screen, well casing, well surface seal, testing the well pump, and well disinfection. Exhibit 5.6 presents the estimated cost to rehabilitate a 6-inch diameter community water system (CWS) well. The estimated individual cost components are material, labor, and equipment costs include replacing the well screen, steel well casing, surface seal, testing the well pump, and well disinfection. The casing was assumed to be 100 feet in length. The estimated total cost for rehabilitating a community well is $11,986 (in 2003 dollars). In addition to the items costed out in Exhibit 5.6, the well pump may also require replacement as part of the rehabilitation efforts. Exhibit 5.7 presents the cost for removing the old pump, and purchasing and installing a new pump.

Exhibit 5.6 Estimated Costs for Rehabilitating Community Water System Wells (2003$)

Cost Component	Total, Including Overhead and Profit[1]
Well Screen[2]	$2,100
Steel Well Casing[3]	$1,200
Surface Seal[4]	$3,300
Well Test Pump, Install & Remove[5]	$3,400
Well Disinfection[6]	$700
Permitting costs[7]	$300
Total (1998$)[8]	$11,000
Total (2003$)	**$11,986**

[1] Costs include rental of equipment as well as operating costs for equipment under normal use. The operating costs include parts and labor for routine servicing and repairs. Total cost includes overhead and profit as reported by R.S. Means (1997a) rounded to the nearest $100.

[2] The well screen is assumed to be stainless steel and 20-feet in length and 6-inch diameter.

[3] Well casing applied to 100 feet of the well. Casing is assumed to be steel and weigh 8.75 pounds per foot.

[4] The surface seal is a one-time cost.

[5] Well test pump, install, and remove is a one-time cost.

[6] Well disinfection is a one-time cost.

[7] Permitting costs based on 3 percent of capital.

[8] Source: R.S. Means, 1998.

Exhibit 5.7 Estimated Costs for the Installation of a Booster Pump (2003$)

Cost Component	Number	Population Size Category							
		<100	101–500	501–1,000	1,001–3,300	3,301–10,000	10,001–50,000	50,001–100,000	>100,000
Centrifugal Pump[1]	1	$3,575	$4,675	$5,700	$5,875	$7,625	$9,500	$12,800	$14,200
90 Degree Elbows (steel flanged)	2	$360	$360	$424	$660	$660	$660	$890	$1,670
Tees (Steel, Flanged)	2	$400	$532	$660	$1,150	$1,150	$1,150	$1,290	$2,500
Gate valves (Steel, flanged)	2	$680	$810	$1,320	$1,756	$1,756	$1,812	$3,350	$5,450
Subtotal		$5,015	$6,377	$8,104	$9,441	$11,191	$13,122	$18,330	$23,820
Design[2]		$802	$1,020	$1,297	$1,511	$1,791	$2,100	$2,933	$3,811
Permitting[3]		$150	$191	$243	$283	$336	$394	$550	$715
Total Cost[4,5] (1998$)		$6,000	$7,600	$9,600	$11,200	$13,300	$15,600	$21,800	$28,300
Total Cost[4] (2003$)		**$6,510**	**$8,266**	**$10,436**	**$12,193**	**$14,156**	**$16,636**	**$23,766**	**$30,792**

[1] Horizontal 1-stage split casing pump.

[2] Design costs based on 16 percent of capital.

[3] Permitting costs based on 3 percent of capital.

[4] Estimate rounds cost to nearest $100.

[5] Source: R.S. Means, 1998.

5.3.2 Source Water Corrective Actions

5.3.2.1 Eliminating Known Sources of Contamination

There are many possible actions that a system could take to eliminate a source of contamination. EPA has estimated the costs associated with eliminating a known source of contamination by assuming that the system must remove and replace a septic system or cesspool. Exhibit 5.8 presents costs associated with the remediation to relocate a 2,500 gallon septic tank and leach field to eliminate the source of contamination. The capital costs itemized in Exhibit 5.8 include materials and labor. EPA developed excavation costs by assuming the installation of a new septic tank 500 feet from the old tank site. Total estimated costs for the drainage of the old septic tank and installation of a new tank are $16,533 (in 2003 dollars).

Exhibit 5.8 Estimated Costs for Elimination of Known Sources of Contamination - Drainage of the Old Septic Tank and Installation of a New Septic Tank (2003$)

Item	Units	Number	Unit Cost, Including O&P	Estimate[1]
Survey and siting new septic tank (4 hrs)[2]	hourly	4	$18.03	$100
Excavate (170 C.Y.) ½ C.Y. backhoe (1 day)[2]	daily	1	$1,000.40	$1,000
Installation 500' of 6" vitrified clay piping	L.F.	500	$7.35	$3,700
Excavate for new septic tank (16 C.Y.) 3/4 C.Y. backhoe[2]	daily	1	$1,111.75	$1,100
Septic tank purchase and installation (2500 gal)	each	1	$1,225.00	$1,200
Fittings, 6" PVC Tees	each	5	$102.00	$500
Empty old tank and dispose of contents	tank	1	$177.00	$200
Backfill old tank using existing stockpile and front-end loader[2]	daily	1	$800.90	$800
Compaction in 12" layers air tamp[1]	daily	1	$1,516.30	$1,500
Leaching field excavation 30 C.Y. ½ C.Y. backhoe (1 day)[2]	daily	1	$911.10	$900
Installation of 190' of 6" perforated PVC	L.F.	190	$6.90	$1,300
Concrete leaching distribution box installation 4'x4'x4'	each	1	$258.00	$300
Gravel fill to 1' depth in 3 trenches (7 C.Y.)	C.Y.	7	$17.80	$100
Trench backfill common earth and compaction (14 C.Y.)[2]	C.Y.	14	$3.99	$100
			Subtotal Capital Cost	$12,800
			Design cost[3]	$2,000
			Permitting cost[4]	$400
			Total (1998$)	$15,200
			Total (2003$)	**$16,533**

O&P - Overhead and Profit
LF - Linear foot
CY - Cubic yard

[1] Estimate rounded to nearest $100.
[2] Best professional judgement for the number and specification of the relevant items
[3] Design cost based on 16 percent of capital.
[4] Permitting costs based on 3 percent of capital.

Source: R.S. Means, 1998.

5.3.2.2 Rehabilitation of Existing Wells

The costs for rehabilitating a well discovered through source water monitoring is the same as discussed in Section 5.3.1.2.

5.3.2.3 Purchasing Water from Another Utility

Exhibit 5.9 presents the cost components for purchasing water, which includes installing the infrastructure for delivering water to the system, as well as piping, construction, permitting, and design. EPA used a distance of 1.5 miles from the new connection to the system for estimating costs. Total capital costs increase with increasing population size category and increasing pipe diameter. The overall cost will vary, however, depending on the price of water and the quantity of water purchased to supplement the system’s demand.

Exhibit 5.9 General Costs Associated with a System Purchasing Water (2003$)

	Population Size Category							
	<100	**101–500**	**501–1,000**	**1,001–3,300**	**3,301–10,000**	**10,001–50,000**	**50,001-100,000**	**>100,000**
Capital Costs								
Pipe Diameter (inches)	4	4	6	6	8	8	10	12
Piping Unit Cost/LF	$13.95	$13.95	$16	$16	$19.55	$19.55	$28.5	$31.5
Construction[1]	$132,600	$132,600	$152,100	$152,100	$185,800	$185,800	$270,900	$299,400
Permitting[2]	$4,000	$4,000	$4,600	$4,600	$5,600	$5,600	$8,100	$9,000
Design[2]	$21,200	$21,200	$24,300	$24,300	$29,700	$29,700	$43,300	$47,900
Capital Costs (1998$)	$157,800	$157,800	$181,000	$181,000	$221,100	$221,100	$322,300	$356,300
Capital Costs (2003$)	**$173,180**	**$173,180**	**$198,599**	**$198,599**	**$242,618**	**$242,618**	**$353,697**	**$390,999**
Operation and Maintenance Costs								
Unit cost of H_2O per kgal[3] (1998$)	$1.60	$1.60	$1.17	$1.63	$2.21	$1.50	$1.57	$1.06
Unit cost of H_2O per kgal[3]	$1.76	$1.76	$1.28	$1.78	$2.43	$1.64	$1.64	$1.17
Total Avg Annual Expense	$6,350	$22,430	$77,110	$167,190	$517,110	$1,925,940	$7,674,550	$23,060,500
Total Avg Annual Expense	$6,923	$24,386	$83,904	$181,963	$562,836	$2,096,248	$8,084,200	$24,291,400
Percent Operating Expense	95%	93%	88%	87%	88%	88%	85%	84%
Percent of Operating Avoided[4]	31%	30%	30%	24%	22%	21%	19%	21%
Expense Avoided[4] (1998$)	$1,883	$6,245	$20,396	$34,948	$99,827	$350,660	$1,261,905	$4,099,281
Expense Avoided[4] (2003$)	$2,050	$6,797	$22,200	$38,039	$108,667	$381,676	$1,373,520	$4,461,862
Avg. Daily Production (MGD)	0.01	0.03	0.10	0.31	0.94	3.68	11.78	50.19
Avoided cost per kgal (1998$)	$0.57	$0.52	$0.59	$0.31	$0.29	$0.26	$0.29	$0.22
Avoided cost per kgal (2003$)	$0.62	$0.57	$0.64	$0.34	$0.32	$0.28	$0.32	$0.24
Net cost per kgal (1998$)	$1.03	$1.08	$0.58	$1.32	$1.92	$1.24	$1.28	$0.84
Net cost per kgal (2003$)	**$1.12**	**$1.18**	**$0.63**	**$1.44**	**$2.09**	**$1.35**	**$1.39**	**$0.91**

[1] Construction cost based on the installation of 1.5 miles of piping; ductile iron piping; plus 20 percent for fittings, excavation, and other expenses; rounded to the nearest $100.

[2] Design cost based on 16 percent of capital; permitting cost based on 3 percent of capital.

[3] Unit cost based on the mean wholesale per 1,000 gal sold.

[4] Avoided cost is the estimated cost the system would incur if it continued to produce its own water. The estimate is based upon the mean expenses for energy, chemicals and supplies in primarily ground water systems divided by their average annual production of water.

Sources: R.S. Means, 1998; USEPA, 1997a

5.3.2.4 Installation of New Wells

The cost to develop new ground water source wells for potable water supply depends on the capacity and demand requirements of the new wells and the drilling environment. The key parameters include well depth and diameter, the length of surface casing, water depth, and the size of the pump and developing the wells, acquiring and placing new submersible pumps, conducting pump tests, well disinfection, sealing the surface of the wells, testing the wells for water quantity and quality, well permitting, added piping, and building well houses.

Community water systems requiring a larger capacity well will have higher installation and development costs. Assuming that the new well is 250-feet deep and 6-inches in diameter, EPA estimates the cost, rounded to the nearest $100, to be $30,200 (in 2003 dollars). This estimate includes costs for materials, labor, equipment (including some O&M expenses), overhead, profit, and permitting.

Exhibit 5.10 identifies each cost component and the materials, labor, and equipment costs associated with each component of the new well.

Exhibit 5.10 Estimated New Well Costs for Community Water Systems (2003$)

Cost Component	Total Including Overhead and Profit[1,2]
Well Drilling[3]	$7,100
Well Screen[4]	$2,100
Steel Well Casing[5]	$1,200
Develop Well[6]	$1,600
Pump Test[7]	$400
Surface Seal[8]	$3,300
Well Disinfection[9]	$700
25-hp Pump[10]	$5,500
Well House[11]	$5,000
Permitting costs[12]	$800
Total (1998$)	**$27,700**
Total (2003$)	**$30,172**

[1] Equipment costs include not only rental, but also operating costs for equipment under normal use. The operating costs include parts and labor for routine servicing and repairs.

[2] Total cost includes overhead and profit as reported by R.S. Means (1997a) rounded to the nearest $100.

[3] The well is 250-feet deep and 6-inches in diameter.

[4] The well screen assembly is stainless steel and 20-feet in length and 6 inches in diameter.

[5] Well casing applied to 100-feet of the well. Casing assumed to be steel and weigh 8.75 pounds per foot.

[6] The cost for developing the well is a one-time cost estimated to take 3 hours to complete.

[7] The cost for conducting a 1-hour pump test is a one-time cost.

[8] The surface seal is a one-time cost.

[9] Well disinfection is a one-time cost.

[10] The pump is a 25-hp submersible pump.

[11] The well house price is equivalent to a prefab residential 2-car garage.

[12] Permitting costs based on 3 percent of capital.

Source: R.S. Means, 1998

5.3.3 Additional Corrective Actions

5.3.3.1 Storage Tank Cover Replacement or Repair

Aging water storage tanks with damaged tank covers may be a source of contamination. Exhibit 5.11 presents estimated costs for repairing water storage tank covers according to population size category. These cost estimates assume a 20 percent value of the total cost for installing a new tank. Total repair estimates include capital, and overhead and profit (O&P) costs. Storage tank size increases with population size category. EPA used a tank size 1,000,000 gallons for estimating costs for systems serving populations greater than 10,000 persons.

Exhibit 5.11 Estimated Costs for the Repair of Storage Tank Cover (2003$)

Cost Component [1]	**Population Size Category**							
	<100	**101–500**	**501–1,000**	**1,001–3,300**	**3,301–10,000**	**10,001–50,000**	**50,001–100,000**	**>100,000**
Tank Size (gal) & Style	10,000 surface	30,000 surface	100,000 elevated	250,000 elevated	750,000 elevated	1,000,000 elevated	1,000,000 elevated	1,000,000 elevated
New Tank Construction Cost[3,4] (1998$)	$13,500	$30,200	$225,000	$310,000	$690,000	$797,000	$797,000	$797,000
New Tank Construction Cost (2003$)[3]	**$14,673**	**$32,859**	**$244,891**	**$337,371**	**$751,000**	**$867,452**	**$867,452**	**$867,452**
Repair Estimate[1,2,3] (1998$)	$2,700	$6,040	$45,000	$62,000	$138,000	$159,400	$159,400	$159,400
Repair Estimate[1,2,3] (2003$)	**$2,893**	**$6,613**	**$48,978**	**$67,474**	**$150,241**	**$173,490**	**$173,490**	**$173,490**

[1] Estimate is for tank cover repair only and does not require design or permitting costs.

[2] Total tank cover repair estimate is calculated based on 20% cost of the total cost for constructing a new tank.

[3] Estimate rounds cost to nearest $100.

[4] Source: R.S. Means, 1998.

5.3.3.2 Cross-Connection Control and Backflow Prevention Program

The cost components of a cross-connection control and backflow prevention program can be broadly classified as:

- Cost of Backflow Prevention Assemblies and Devices
- Cost of Program Administration: This can be further classified as: program organization, system survey, record keeping costs, and enforcement.

The cost of program administration is usually more significant for small systems (i.e., typically systems serving populations less than or equal to 10,000). However, for large systems, the costs of the backflow devices and assemblies costs are usually more significant than the program administration costs. This section provides the costs of installing a backflow prevention device and describes the items included under program administration.

Backflow Prevention Assemblies and Devices

Exhibit 5.12 presents the costs of installing a backflow prevention assembly (i.e., a reduced pressure flanged iron assembly). This is the usually the most expensive assembly and is used in situations of highest hazard when backpressure and backsiphonage are both possible (www.usc.edu/dept/fccchr).

Systems should install above-grade housing with drainage and heat to protect the equipment from freezing where systems cannot install valves indoors. Installation costs do not include costs for this housing, or costs for engineering/construction. Maintenance of these assemblies includes a minimum of annual testing and inspection. In addition, the frequency for performance monitoring and internal inspections (dismantling, cleaning, and repairs) should occur based on local water quality conditions, the probability of contamination due to potential backflow, and manufacturers' recommendations for the specific backflow prevention assembly.

Backflow prevention equipment installation and maintenance is generally the consumer's responsibility. However, depending on how a system implements the cross-connection control and backflow prevention program, the customer and the utility can share costs for the equipment and equipment installation, inspection, testing, and maintenance. The utility, on the other hand, is primarily responsible for the administration of cross-connection control and backflow prevention and the inspection, review, and approval of all backflow prevention assemblies and devices.

Exhibit 5.12 Estimated Costs for a Backflow Prevention Assembly (2003$)

	Population Size Category							
Cost Component [1,2,3]	**<100**	**101–500**	**501–1,000**	**1,001–3,300**	**3,301–10,000**	**10,001–50,000**	**50,001–100,000**	**>100,000**
Reduced Pressure, Flanged	2.5 inch	2.5 inch	2.5 inch	3 inch	3 inch	4 inch	6 inch	6 inch
Total - incl. O&P (1998$)	$2,100	$2,100	$2,100	$2,200	$2,200	$3,000	$4,700	$4,700
Total- incl. O&P (2003$)	**$2,273**	**$2,273**	**$2,273**	**$2,377**	**$2,377**	**$3,307**	**$5,166**	**$5,166**

[1] Estimates assume larger systems will on average have larger connections on which to install backflow prevention assemblies.

[2] Estimates assume assemblies are reduced pressure principle, flanged iron devices, and includes valves and installation.

[3] Does not include design or permit costs.

Source: R.S. Means, 1998 (includes O&P, rounded to nearest $100).

Program Administration

The administration of a CCCBPP is typically the responsibility of the utility. Costs for program administration depend on the system size (population served and area covered), system demographics (number of industrial, residential, and institutional customers), available staffing resources, maintenance and record keeping, and specific code and regulatory requirements. Another factor in the administrative costs in some cases is overcoming political resistance. The *Cross-Connection Control Manual* provides additional guidance on program administration (USEPA, 1989c). Program administration will require availability of technical and administrative staff. If sufficient staff is available, appropriate division of program oversight duties may apply. Otherwise, these tasks may require additional staff or temporary help. In some cases, program administration is contracted out. The Program Administration costs can be classified under three headings:

Program Organization: It involves establishing the legal foundation for the plan, establishing responsibilities and chain of command, conducting employee and consumer education programs, implementing required codes and regulations for enforcing the program, monitoring the progress of the program, etc.

System Survey: It involves surveying the system for potential cross-connections and identifying and prioritizing hazardous connections.

Record Keeping: It involves updating and maintaining records that are pertinent to the implementation of the CCCBPP.

Exhibit 5.13 summarizes the activities included under each of the three components of Program Administration.

Exhibit 5.13 Cost Components of Program Administration for a Cross-Connection Control and Backflow Prevention Program

Cost Component	Specific Items Included
Program Organization	Consulting with relevant local and State administrations Establishing responsibilities and authorities for required program activities (inspections, maintenance, reporting, etc.) Notifying and educating employees and consumers of program and implications Developing and implementing a local ordinance Program Enforcement by the utility
System Survey	Recording number and sites of connections Identifying potential hazardous connections Prioritizing hazardous connections Developing inspection schedules and records
Record keeping	Inspection records Installation, repair, and maintenance of records Customer correspondence records Ordinance development records Assembly test records

In addition to the other items presented in this section, a successful cross connection control program will require development of testing and enforcement programs to ensure proper operation and compliance. Such programs represent additional costs that are not included here.

5.3.3.3 Installation of Security Measures

Exhibit 5.14 presents the cost components for installing fencing, a gate with a lock, and flood lights for 0.5 and 1-acre lots based on the need for a 0.5-acre of security fencing for systems serving populations of 3,300 or fewer, and on the need for 1-acre of security fencing for systems serving populations greater than 3,300. EPA estimates the cost for installing security measures on a 0.5-acre lot to be $9,920, and for a 1-acre lot to be $13,640 (in 2003 dollars).

Exhibit 5.14 Estimated Costs for Installation of Security Measures (2003$)

Item	Population Served	
	≤3,300[1]	>3,300[2]
Chainlinked fence with 3 strands barbed wire, 2" post @ 10' O.C., set in concrete, 6' H (9 ga.wire, galv. steel)	$8,200	$11,600
Gate for 6' high fence, 1-5/8" frame, 3' wide, galv. steel	$250	$250
Flood lights-35 watt low pressure sodium wall mounted (2)	$600	$600
Lock	$10	$10
Total (1998$)	**$9,100**	**$12,500**
Total (2003$)	**$9,920**	**$13,640**

Total cost includes overhead and profit, rounded to the nearest $100.

[1] Security measures assumed for a 0.5-acre lot (600 L.F.).

[2] Security measures assumed for a 1-acre lot (850 L.F.).

Source: R.S. Means, 1998.

5.4 Summary

Exhibit 5.15 summarizes the costs derived in this chapter. The summary table includes those BMPs which were used in the EA for the GWR.

Exhibit 5.15 Estimated Unit Costs of Non-Treatment Corrective Actions for Source Water Contamination (2003$)

Corrective Action	Size Category (Population Served)								
	<100	101-500	501-1,000	1,001-3,300	3,301-10,000	10,001-50,000	50,001-100,000	100,001-1 Million	>1 Million
Nontreatment Corrective Actions									
Rehabilitate an Existing Well	$11,986	$11,986	$11,986	$11,986	$11,986	$11,986	$11,986	$11,986	$11,986
Drill a New Well	$30,172	$30,172	$30,172	$30,172	$30,172	$30,172	$30,172	$30,172	$30,172
Purchase Water									
Capital	$173,180	$173,180	$198,599	$198,599	$242,618	$242,618	$353,697	$390,999	$390,999
O&M ($ per kgal)	$1.12	$1.18	$0.63	$1.44	$2.09	$1.35	$1.39	$0.91	$0.91
Eliminate Source of Contamination	$16,533	$16,533	$16,533	$16,533	$16,533	$16,533	$16,533	$16,533	$16,533

Source: Sections 5.1 through 5.2

Appendix A

Linear Regression Coefficients for Unit Costs

Exhibit A-1 Cost Equation Coefficient Inputs for At-grade Tanks for Chlorine Contact

(Residual 2 mg/L)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.	
	A	B
<=7	787.81	0.00
7-<=22	358.75	61.29
22-<=37	358.75	61.29
37-<=91	359.18	61.28
91-<=180	358.77	61.29
180-<=270	357.51	61.29
270-<=360	357.51	61.29
360-<=680	358.67	61.29
680-<=1000	358.67	61.29
1000-<=1200	-98,530.98	160.18
1200-<=2000	-98,530.98	160.18
2000-<=3500	71,928.42	74.95
3500-<=7000	119,686.24	61.31
7000-<=17000	191,365.13	51.07
17000-<=22000	204,017.97	50.32
22000-<=76000	393,399.16	41.71

Exhibit A-2 Cost Equation Coefficient Inputs for At-grade Tanks for Chlorine Dioxide Contact

(Residual 0.625 mg/L)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.	
	A	B
91-<=180	358.77	85.79
180-<=270	357.51	85.80
270-<=360	357.51	85.80
360-<=680	5875.14	70.47
680-<=1000	6032.93	70.24
1000-<=1200	-94346.26	170.62
1200-<=2000	-94346.26	170.62
2000-<=3500	76113.14	85.39
3500-<=7000	121741.77	72.35
7000-<=17000	246453.18	54.54
17000-<=22000	258140.16	53.85

Exhibit A-3 Cost Equation Coefficient Inputs for Gas Chlorination (Dose 4 mg/L)

(No Storage)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
<=7	29,867.54	0.00	<= 1.5	6,182.00	0.00
7-<=22	29,867.54	0.00	1.5-<=5.4	6,175.85	4.10
22-<=37	29,867.54	0.00	5.4-<=9.5	6,178.24	3.66
37-<=91	29,867.54	0.00	9.5-<=25	6,179.90	3.48
91-<=180	29,867.54	0.00	25-<=54	6,182.52	3.38
180-<=270	29,867.54	0.00	54-<=84	6,183.20	3.37
270-<=360	29,867.54	0.00	84-<=110	6,181.69	3.38
360-<=680	29,867.54	0.00	110-<=230	6,180.92	3.39
680-<=1000	-27,572.19	84.47	230-<=350	-11,402.58	79.84
1000-<=1200	47,603.00	9.30	350-<=410	14,967.00	4.50
1200-<=2000	47,592.50	9.30	410-<=770	14,968.14	4.50
2000-<=3500	47,590.67	9.30	770-<=1400	14,940.33	4.53
3500-<=7000	47,589.00	9.31	1400-<=3000	20,367.38	0.66
7000-<=17000	46,202.60	9.50	3000-<=7800	14,984.25	2.45
17000-<=22000	32,745.40	10.29	7800-<=11000	14,923.31	2.46
22000-<=76000	127,100.63	6.01	11000-<=38000	11,329.04	2.79

(With Storage)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
<=7	30,655.35	0.00	<= 1.5	6,182.00	0.00
7-<=22	30,226.29	61.29	1.5-<=5.4	6,175.85	4.10
22-<=37	30,226.29	61.29	5.4-<=9.5	6,178.24	3.66
37-<=91	30,226.72	61.28	9.5-<=25	6,179.90	3.48
91-<=180	30,226.31	61.29	25-<=54	6,182.52	3.38
180-<=270	30,225.05	61.29	54-<=84	6,183.20	3.37
270-<=360	30,225.05	61.29	84-<=110	6,181.69	3.38
360-<=680	30,226.21	61.29	110-<=230	6,180.92	3.39
680-<=1000	-27,213.51	145.76	230-<=350	-11,402.58	79.84
1000-<=1200	-50,927.98	169.48	350-<=410	14,967.00	4.50
1200-<=2000	-50,938.48	169.48	410-<=770	14,968.14	4.50
2000-<=3500	119,519.08	84.26	770-<=1400	14,940.33	4.53
3500-<=7000	167,275.24	70.61	1400-<=3000	20,367.38	0.66
7000-<=17000	237,567.73	60.57	3000-<=7800	14,984.25	2.45
17000-<=22000	236,763.37	60.62	7800-<=11000	14,923.31	2.46
22000-<=76000	520,499.79	47.72	11000-<=38000	11,329.04	2.79

Exhibit A-4 Cost Equation Coefficient Inputs for Hypochlorination (Dose 4 mg/L)

(No Storage)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
<=7	8,969.67	0.00	<= 1.5	1,468.31	0.00
7-<=22	8,969.67	0.00	1.5-<=5.4	1,392.80	50.34
22-<=37	8,969.67	0.00	5.4-<=9.5	1,392.45	50.40
37-<=91	8,969.67	0.00	9.5-<=25	1,393.78	50.26
91-<=180	-6,809.78	173.40	25-<=54	-593.79	129.77
180-<=270	24,402.32	0.00	54-<=84	6,075.16	6.27
270-<=360	24,402.32	0.00	84-<=110	6,074.27	6.28
360-<=680	24,402.32	0.00	110-<=230	6,073.54	6.29
680-<=1000	-72,273.88	142.17	230-<=350	7,519.86	0.00
1000-<=1200	56,362.00	13.54	350-<=410	7,519.00	0.00
1200-<=2000	60,001.00	10.50	410-<=770	6,999.67	1.27
2000-<=3500	70,598.00	5.20	770-<=1400	2,116.89	7.61
3500-<=7000	74,529.00	4.08	1400-<=3000	2,369.50	7.43
7000-<=17000	78,681.10	3.49	3000-<=7800	2,630.13	7.34
17000-<=22000	88,729.80	2.90	7800-<=11000	2,588.69	7.35
22000-<=76000	93,394.78	2.68	11000-<=38000	2,724.48	7.33

(With Storage)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
<=7	9,757.48	0.00	<= 1.5	1,468.31	0.00
7-<=22	9,328.42	61.29	1.5-<=5.4	1,392.80	50.34
22-<=37	9,328.42	61.29	5.4-<=9.5	1,392.45	50.40
37-<=91	9,328.85	61.28	9.5-<=25	1,393.78	50.26
91-<=180	-6,451.02	234.69	25-<=54	-593.79	129.77
180-<=270	24,759.83	61.29	54-<=84	6,075.16	6.27
270-<=360	24,759.83	61.29	84-<=110	6,074.27	6.28
360-<=680	24,760.99	61.29	110-<=230	6,073.54	6.29
680-<=1000	-71,915.20	203.46	230-<=350	7,519.86	0.00
1000-<=1200	-42,168.98	173.72	350-<=410	7,519.00	0.00
1200-<=2000	-38,529.98	170.68	410-<=770	6,999.67	1.27

Exhibit A-5 Cost Equation Coefficient Inputs for Difference in Chlorine (gas/hypochlorination)

O&M Costs from a Dose of 2.5 mg/L to 4 mg/L

Average Flow range (kgpd-kgpd)	**O&M Cost difference Regression Coeff.**	
	A	B
<= 1.5	27.90	0.00
1.5-<=5.4	-0.72	19.08
5.4-<=9.5	1.59	18.65
9.5-<=25	178.61	0.02
25-<=54	179.00	0.00
54-<=84	145.95	0.61
84-<=110	-2.94	2.38
110-<=230	-0.17	2.36
230-<=350	-526.10	4.65
350-<=410	190.00	2.60
410-<=770	121.67	2.77
770-<=1400	2,107.78	0.19
1400-<=3000	-24.88	1.71
3000-<=7800	3,808.88	0.43
7800-<=11000	-13.94	0.92
11000-<=38000	-1,782.93	1.08

Exhibit A-6 Cost Equation Coefficient Inputs for Chlorine Dioxide (Dose 1.25 mg/L)

(No Storage)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
91-<=180	26,584.02	66.78	25-<=54	13,782.58	40.19
180-<=270	37,001.90	8.90	54-<=84	14,056.30	35.12
270-<=360	36,722.75	9.94	84-<=110	16,093.91	10.86
360-<=680	36,993.82	9.18	110-<=230	16,534.07	6.86
680-<=1000	43,238.21	0.00	230-<=350	16,636.30	6.41
1000-<=1200	-144,720.88	187.96	350-<=410	14,261.63	13.20
1200-<=2000	78,579.32	1.88	410-<=770	16,969.05	6.60
2000-<=3500	-63,125.11	72.73	770-<=1400	21,363.74	0.89
3500-<=7000	170,892.66	5.87	1400-<=3000	17,131.46	3.91
7000-<=17000	172,034.60	5.70	3000-<=7800	21,789.44	2.36
17000-<=22000	172,213.83	5.69	7800-<=11000	23,570.13	2.13
22000-<=76000	171,914.01	5.71	11000-<=38000	27,814.09	1.75
76000-<=210000	437,393.28	2.21	38000-<=120000	31,119.03	1.66
210000-<=430000	565,655.87	1.60	120000-<=270000	56,932.02	1.44
430000-<=520000	659,676.23	1.38	270000-<=350000	57,055.82	1.44

(With Storage)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
91-<=180	26,942.79	152.57	25-<=54	14,677.60	42.78
180-<=270	37,359.41	94.70	54-<=84	15,518.24	27.21
270-<=360	37,080.26	95.74	84-<=110	16,853.91	11.31
360-<=680	42,868.96	79.66	110-<=230	17,316.11	7.11
680-<=1000	49,271.14	70.24	230-<=350	17,421.56	6.65
1000-<=1200	-239,067.14	358.58	350-<=410	17,220.51	7.23
1200-<=2000	-15,766.93	172.50	410-<=770	17,422.93	6.73
2000-<=3500	12,988.03	158.12	770-<=1400	22,607.49	0.00
3500-<=7000	292,634.43	78.22	1400-<=3000	19,606.03	2.14
7000-<=17000	418,487.78	60.24	3000-<=7800	19,356.21	2.23
17000-<=22000	430,353.98	59.54	7800-<=11000	20,947.43	2.02

Exhibit A-7 Cost Equation Coefficient Inputs for Anodic Oxidation (Dose 4 mg/L)

(No storage)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
<=7	39,396.48	0.00	<= 1.5	2,907.70	0.00
7-<=22	33,413.28	854.74	1.5-<=5.4	2,905.31	1.59
22-<=37	40,343.67	539.72	5.4-<=9.5	129.44	515.64
37-<=91	47,556.05	344.80	9.5-<=25	3,993.82	108.86
91-<=180	56,906.20	242.05	25-<=54	5,094.19	64.85
180-<=270	77,901.22	125.41	54-<=84	6,196.68	44.43
270-<=360	78,000.42	125.04	84-<=110	6,830.96	36.88
360-<=680	77,958.05	125.16	110-<=230	8,463.04	22.04
680-<=1000	43,278.31	176.16	230-<=350	9,128.48	19.15
1000-<=1200	43,279.60	176.16	350-<=410	9,291.23	18.69
1200-<=2000	75,620.74	149.21	410-<=770	9,991.43	16.98
2000-<=3500	105,464.05	134.28	770-<=1400	15,134.34	10.30
3500-<=7000	246,617.80	93.95	1400-<=3000	15,133.14	10.30
7000-<=17000	394,504.98	72.83	3000-<=7800	19,100.99	8.98
17000-<=22000	939,670.31	40.76	7800-<=11000	20,105.94	8.85
22000-<=76000	1,242,761.05	26.98	11000-<=38000	20,697.38	8.79

(With Storage)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
<=7	40,184.29	0.00	<= 1.5	2,907.70	0.00
7-<=22	33,772.03	916.04	1.5-<=5.4	2,905.31	1.59
22-<=37	40,702.42	601.02	5.4-<=9.5	129.44	515.64
37-<=91	47,915.23	406.08	9.5-<=25	3,993.82	108.86
91-<=180	57,264.97	303.33	25-<=54	5,094.19	64.85
180-<=270	78,258.73	186.70	54-<=84	6,196.68	44.43
270-<=360	78,357.93	186.33	84-<=110	6,830.96	36.88
360-<=680	78,316.73	186.45	110-<=230	8,463.04	22.04
680-<=1000	43,636.99	237.45	230-<=350	9,128.48	19.15
1000-<=1200	-55,251.38	336.34	350-<=410	9,291.23	18.69
1200-<=2000	-22,910.25	309.39	410-<=770	9,991.43	16.98
2000-<=3500	177,392.46	209.23	770-<=1400	15,134.34	10.30
3500-<=7000	366,304.03	155.26	1400-<=3000	15,133.14	10.30
7000-<=17000	585,870.11	123.89	3000-<=7800	19,100.99	8.98
17000-<=22000	1,143,688.28	91.08	7800-<=11000	20,105.94	8.85
22000-<=76000	1,636,160.22	68.70	11000-<=38000	20,697.38	8.79

Exhibit A-8 Cost Equation Coefficient Inputs for Ozonation

(No pH adjustment)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
91-<=180	261,830.35	675.14	25-<=54	55,205.76	12.56
180-<=270	271,534.78	621.23	54-<=84	49,571.30	116.90
270-<=360	275,438.44	606.77	84-<=110	58,272.41	13.32
360-<=680	288,498.99	570.49	110-<=230	58,441.08	11.79
680-<=1000	403,021.23	402.07	230-<=350	58,441.08	11.79
1000-<=1200	316,210.63	488.88	350-<=410	57,990.96	13.07
1200-<=2000	415,879.99	405.83	410-<=770	58,486.38	11.86
2000-<=3500	734,764.83	246.38	770-<=1400	55,279.62	16.03
3500-<=7000	833,333.71	218.22	1400-<=3000	62,294.73	11.02
7000-<=17000	1,243,548.46	159.62	3000-<=7800	63,874.29	10.49
17000-<=22000	1,908,971.15	120.48	7800-<=11000	67,572.90	10.02
22000-<=76000	1,253,459.60	150.27	11000-<=38000	60,793.68	10.63
76000-<=210000	4,792,888.54	103.70	38000-<=120000	41,971.65	11.13
210000-<=430000	8,630,547.65	85.43	120000-<=270000	181,578.13	9.96
430000-<=520000	5,470,535.57	92.78	270000-<=350000	204,198.02	9.88

(With pH adjustment)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
91-<=180	263,710.67	904.27	25-<=54	55,205.76	52.29
180-<=270	311,509.78	638.72	54-<=84	49,571.30	156.63
270-<=360	315,413.44	624.27	84-<=110	58,272.41	53.04
360-<=680	328,473.99	587.99	110-<=230	58,441.08	51.51
680-<=1000	442,996.23	419.57	230-<=350	58,441.08	51.51
1000-<=1200	356,185.63	506.38	350-<=410	57,990.96	52.80
1200-<=2000	455,854.99	423.32	410-<=770	58,486.38	51.59
2000-<=3500	774,739.83	263.88	770-<=1400	55,279.62	55.75
3500-<=7000	873,308.71	235.72	1400-<=3000	62,294.73	50.74
7000-<=17000	1,283,523.46	177.12	3000-<=7800	63,874.29	50.22
17000-<=22000	1,948,946.15	137.97	7800-<=11000	67,572.90	49.74
22000-<=76000	1,293,434.60	167.77	11000-<=38000	60,793.68	50.36
76000-<=210000	4,832,863.54	121.20	38000-<=120000	41,971.65	50.85
210000-<=430000	8,670,522.65	102.92	120000-<=270000	181,578.13	49.69
430000-<=520000	5,510,510.57	110.27	270000-<=350000	204,198.02	49.61

Exhibit A-9 Cost Equation Coefficient Inputs for Nanofiltration

Design Flow range (kgpd-kgpd)	**Total Capital Costs Regression Coeff.**		**Average Flow range (kgpd-kgpd)**	**O&M Costs Regression Coeff.**	
	A	B		A	B
<=7	52,107.22	0.00	<= 1.5	6,908.69	0.00
7-<=22	44,012.03	1,156.46	1.5-<=5.4	6,513.35	263.56
22-<=37	44,012.03	1,156.46	5.4-<=9.5	6,502.37	265.59
37-<=91	39,186.26	1,286.88	9.5-<=25	6,158.52	301.78
91-<=180	87,830.12	752.34	25-<=54	51.91	546.05
180-<=270	36,612.96	1,036.87	54-<=84	14,480.22	278.86
270-<=360	192,484.23	459.57	84-<=110	20,720.87	204.56
360-<=680	12,513.50	959.49	110-<=230	18,012.58	229.19
680-<=1000	134,149.45	780.62	230-<=350	-8,977.50	346.53
1000-<=1200	71,874.26	842.89	350-<=410	29,112.38	237.71
1200-<=2000	-326,538.15	1,174.90	410-<=770	36,319.37	220.13
2000-<=3500	171,179.90	926.04	770-<=1400	37,785.44	218.22
3500-<=7000	63,000.00	956.95	1400-<=3000	21,651.71	229.75
7000-<=17000	652,725.04	872.70	3000-<=7800	42,227.27	222.89
17000-<=22000	472,838.89	883.29	7800-<=11000	198,620.98	202.84
22000-<=76000	4,505,630.65	699.98	11000-<=38000	195,547.90	203.12
76000-<=210000	16,665,213.20	539.98	38000-<=120000	531,298.29	194.28
210000-<=430000	130,182.12	618.72	120000-<=270000	541,027.91	194.20
430000-<=520000	9,465,362.32	597.01	270000-<=350000	1,939,143.53	189.02

Exhibit A-10 Cost Equation Coefficient Inputs for Temporary Hypochlorination (Dose 4 mg/L) (No Storage)

Design Flow range (kgpd-kgpd)	Total Capital Costs Regression Coeff.		Average Flow range (kgpd-kgpd)	O&M Costs Regression Coeff.	
	A	B		A	B
<=7	1,873.73	0.00	<= 1.5	2,636.18	0.00
7-<=22	1,873.73	0.00	1.5-<=5.4	2,636.18	0.00
22-<=37	1,873.73	0.00	5.4-<=9.5	2,376.72	48.05
37-<=91	1,873.73	0.00	9.5-<=25	2,706.92	13.29
91-<=180	1,873.73	0.00	25-<=54	2,367.63	26.86
180-<=270	1,873.73	0.00	54-<=84	3,582.10	4.37
270-<=360	1,873.73	0.00	84-<=110	3,341.95	7.23
360-<=680	1,873.73	0.00	110-<=230	3,987.92	1.36
680-<=1000	1,873.73	0.00	230-<=350	2,855.17	6.28
1000-<=1200	1,873.73	0.00	350-<=410	4,455.47	1.71
1200-<=2000	1,699.73	0.15	410-<=770	1,947.61	7.83
2000-<=3500	1,647.53	0.17	770-<=1400	2,116.89	7.61
3500-<=7000	2,137.63	0.03	1400-<=3000	2,369.50	7.43
7000-<=17000	-7,071.52	1.35	3000-<=7800	2,630.13	7.34
17000-<=22000	3,373.51	0.73	7800-<=11000	2,588.69	7.35
22000-<=76000	17,304.65	0.10	11000-<=38000	2,724.48	7.33