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TECHNOLOGIES AND COSTS FOR CONTROL OF DISINFECTION BY-PRODUCTS

EXECUTIVE SUMMARY

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TECHNOLOGIES AND COSTS FOR CONTROL OF DISINFECTION BY-PRODUCTS

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BACKGROUND

The 1986 Amendments to the Safe Drinking Water Act (SDWA) require the United States Environmental Protection Agency (EPA) to set maximum contaminant level goals (MCLGs) for many contaminants found in drinking water. These MCLGs must provide an adequate margin of safety from contaminant concentrations that are known or anticipated to induce adverse effects on human health. For each contaminant, EPA must establish a maximum contaminant level (MCL) that is as close to the MCLG as is feasible with the use of best available technology (BAT). Although the BAT identified for each contaminant must be an economically feasible and proven technology under field conditions, systems are not required to install BAT for purposes of meeting a corresponding MCL.

EPA is currently in the process of establishing MCLs and/or treatment techniques for disinfectants and disinfection by-products (D/DBPs). The D/DBPs in current regulatory focus include:

- Trihalomethanes (THMs), including each of the four individual species (chloroform, bromodichloromethane, dibromochloromethane, and bromoform);
- Haloacetic acids (HAAs), including dichloro- and trichloroacetic acid;
- Chloral hydrate;
- Bromate;
- Chlorine;
- Chloramines; and
- Chlorine dioxide, chlorite and chlorate.

Total trihalomethanes (TTHMs) is the only contaminant currently regulated; the MCL for TTHMs is 100 μg/L. This MCL applies to the sum of the four chlorinated and/or brominated THMs (chloroform, bromodichloromethane, dibromochloromethane, and bromoform).

The purpose of this document is to characterize the feasibility of treatment for DBP control and to estimate costs for treatment alternatives that can then be used by utilities to meet national regulations. Treatment criteria were developed through the use of a Water Treatment Plant (WTP) simulation model for parameters critical to disinfection and DBP control.

The WTP simulation model was developed for EPA as a part of this effort and predicts DBP formation based on source water quality and operational parameters for unit treatment processes. The model predicts the removal of DBP precursors through treatment processes, and DBP formation upon chlorination. Processes for DBP precursor removal that can be simulated include coagulation, GAC adsorption, and membranes; precipitative softening is being developed at this time. The WTP simulation model can only predict the formation of THMs and HAAs at this time; predictions for bromate and bromoform production following ozonation are being developed. Limited verification has been performed on the WTP model predictions.

The design criteria established through modelling were used to develop treatment costs for DBP control. These costs are used by EPA to determine national costs for various potential DBP regulatory scenarios.

DBP PROPERTIES AND TREATMENT ALTERNATIVES

This document includes a description of the chemical structures and physical/chemical characteristics of those disinfectants and DBPs that are being considered by USEPA for possible regulation. DBP formation depends on many factors including the type(s) of disinfectants, disinfectant dosages, and water quality characteristics such as pH and concentration of natural occurring organic material (NOM).

Research has identified the following generic treatment alternatives for control of D/DBPs:

- Removal of NOM prior to disinfection;
- Use of alternative oxidants or disinfectants that do not create DBPs at levels considered adverse to human health; and
- Removal of DBPs after they are formed.

Because of the uncertainty relative to the occurrence and health risk for DBPs from alternative oxidants and disinfectants, the first alternative listed above is considered the most desirable for reducing the D/DBPs being considered for regulation.

Further, several studies using a variety of waters throughout the country have demonstrated that although the use of alternative disinfectants may decrease some DBPs, other DBPs can be increased through the reaction of the alternative disinfectant with precursors present in the raw water. Therefore, the impacts of treatment process modifications and water quality characteristics on DBPs must be viewed in light of potential risk trade-offs. The risk trade-off becomes especially difficult since little is known about the health effects of many D/DBPs.

A major concern in the water industry is how to provide adequate disinfection to inactivate microorganisms while, at the same time, minimize DBP formation. In addition, it is important to control known DBPs without increasing risks from, as yet, undefined DBPs. This document discusses the following technologies available for D/DBP control:

- Coagulation/filtration;
- Precipitative softening;
- Adsorption processes;
- Oxidation processes;
- Air stripping;
- Membrane processes;
- Reduction processes; and
- Biological processes.

REMOVAL OF DBP PRECURSORS

NOM is a generic term for naturally occurring organic material that contains precursors which react with disinfectants to form DBPs. NOM consists of humic substances, amino acids, sugars, aliphatic acids, aromatic acids and a large number of other organic molecules. NOM has been shown to bind with metals and synthetic organic chemicals

(SOCs), thereby allowing these contaminants to proceed through treatment processes not designed for NOM removal. These conditions can contribute to the following:

- Increased disinfectant demand, requiring higher disinfectant dosages.
- Increased substrate for microorganism growth in distribution systems.
- Competition with SOCs for activated carbon adsorption sites; and
- Higher coagulant dosages.

Because the characteristics of NOM are widely varied on a chemical and physical basis, surrogate parameters must be used to measure NOM levels. Commonly used surrogates to measure NOM or DBP precursor concentrations include:

- THM formation potential (THMFP);
- Total and dissolved organic carbon (TOC and DOC); and
- Ultraviolet absorbance at a wavelength of 254 nm (UV-254).

These surrogates may be used to screen raw water sources for DBP precursor content and to determine the performance of unit processes for the removal of DBP precursors. The following processes were evaluated as technologies for NOM (DBP precursor) removal:

- Coagulation/filtration and precipitative softening;
- Adsorption processes such as granular activated carbon (GAC), powdered activated carbon (PAC) and resin adsorbents;
- Oxidation processes such as ozone and chlorine dioxide;
- Membrane processes; and
- Biological degradation.

Based on the evaluations in this document, the following processes are considered most effective for NOM removal:

- Coagulation/filtration, particularly at low pH and high coagulant dosages;
- GAC adsorption; and
- Membrane processes.

ALTERNATIVE DISINFECTANTS

In addition to treatment technologies to remove NOM, alternative disinfectants were evaluated for D/DBP control. Any disinfection alternative implemented at a treatment plant should:

- Provide adequate disinfection to control pathogens at the treatment plant and in the distribution system;
- Limit the formation of regulated DBPs to concentrations lower than the MCL;
- Limit the formation of unregulated DBPs to concentrations lower than those of potential concern; and
- Achieve adequate color removal, iron oxidation and taste and odor control.

The most prevalent disinfectants for primary disinfection (pathogen inactivation) in the United States include chlorine (Cl_2), chlorine dioxide (ClO_2) and ozone (O_3). Secondary disinfection is provided by maintaining a disinfectant residual throughout the distribution system; candidate secondary disinfectants in the United States include Cl_2, chloramines (NH_2Cl), and ClO_2.

To achieve both primary and secondary disinfection, utilities may use a combination of disinfectants. Primary and secondary disinfectant combinations that are capable of meeting the Surface Water Treatment Rule (SWTR) are summarized in Table ES-1.

TABLE ES-1

PRIMARY AND SECONDARY DISINFECTION ALTERNATIVES

Primary Disinfectant	Secondary Disinfectant
Chlorine	Chlorine
Chlorine	Chloramines
Ozone	Chlorine
Ozone	Chloramines
Chlorine Dioxide	Chlorine
Chlorine Dioxide	Chloramines
Chlorine Dioxide	Chlorine Dioxide

Although the SWTR does not specify primary disinfection credit for the ozone/hydrogen peroxide process, the process can be used as a primary disinfectant if the utility can demonstrate that adequate levels of primary disinfection are maintained. It also should be noted that primary disinfection credit can be achieved with chloramines. Few utilities, however, are expected to continue to use chloramines in this capacity because of the relatively poor disinfecting capacity and large CT values (the product of disinfectant concentration in mg/L and disinfection contact time in minutes) required by the SWTR. Because ozone does not maintain a residual in the distribution system over time, another disinfectant must be applied to achieve secondary disinfection. The presence of a disinfectant residual continues the formation of DBPs in the distribution system, the extent of which depends on the type of disinfectant and treated water characteristics.

In the United States, the combination of disinfectants most commonly used are chlorine/chlorine and chlorine/chloramine for primary/secondary disinfection. In waters with high THMFP, some utilities have used chloramines throughout the treatment plant. With the promulgation of the SWTR, however, these utilities are evaluating whether this practice can be continued, given the large CT values required for disinfection credit using chloramines as a primary disinfectant.

Other utilities, particularly in the southeast, midwest and Texas, have pursued the use of chlorine dioxide as a primary disinfectant. Utilities typically have used chlorine or chloramines as a secondary disinfectant when chlorine dioxide is used as a primary disinfectant.

Finally, ozone is increasing in popularity as a primary disinfectant in the United States. Although chlorine dioxide is used as a residual disinfectant when ozone is applied in parts of Germany and Switzerland, free chlorine and more commonly chloramines are typically used as secondary disinfectants in the United States.

Each of these disinfectant combinations produce DBPs. Therefore, the use of alternative disinfectants requires considerable care. A modified disinfection scheme may decrease the formation of some DBPs while increasing the presence of others. As previously indicated, the rate and extent of DBP formation is strongly related to the type, concentrations and characteristics of the NOM present, the type of disinfectant, the locations of disinfectant application, residence time in the system and other water quality characteristics, such as pH, temperature, and bromide concentration.

REMOVAL OF DBPs AFTER FORMATION

Removing DBPs before the finished water enters the distribution system is the remaining DBP control strategy discussed in this document. The strategy for removing DBPs after their formation is limited by the following factors:

- The amount of DBPs formed in the treatment plant relative to the amount formed in the distribution system; and
- Costs for the required treatment.

The following technologies may be applicable for removing various DBPs:

- GAC adsorption;
- PAC adsorption;
- Air stripping;
- Conventional treatment;

- Oxidation;
- Membranes;
- Reducing agents; and
- Biological treatment.

For this approach to be feasible from a process standpoint, a significant proportion of the DBPs must be formed before the water leaves the treatment plant. In addition, the application of a given technology may be specific to only a small portion of the DBPs formed, and therefore, is relatively costly compared to removing precursors for a wide range of DBPs.

DEVELOPMENT OF DESIGN CRITERIA AND UPGRADE COSTS

The overall approach for the development of design criteria and upgrade costs for selected DBP control alternatives assumes that there are five basic types of treatment practiced in the United States at the present time:

- Surface Waters
    - Coagulation/filtration systems
    - Precipitative softening systems
    - Unfiltered systems (including those that will be required to filter under the SWTR)
- Ground Waters
    - Unfiltered systems
    - Precipitative softening systems

For the analysis presented in this document, only the surface water, coagulation/filtration category was evaluated. This category was analyzed first because: 1) surface water systems are generally more sensitive to DBP formation than ground waters, and 2) this category represents the largest population served.

As stated previously in this section, the three basic alternatives for control of D/DBPs are:

- Removal of NOM prior to disinfection;
- Use of alternative disinfectants; and
- Removal of DBPs after formation.

Design criteria and upgrade costs were developed for specific treatment schemes employing the first two control alternatives. Costs for removal of DBPs after formation were not developed because it is almost always more cost efficient to remove the precursors before they are formed.

Based on overall effectiveness, expected economic feasibility and practical full-scale experience, the most promising and effective processes for the removal of NOM are:

- Increasing the coagulant dosage (only for coagulation/filtration systems);
- Installing GAC adsorption; and
- Installing membrane filtration.

For the use of alternate disinfectants, only two primary disinfectants are considered; Cl_2 and O_3. The most applicable secondary disinfection alternatives for the control of DBPs are Cl_2 and NH_2Cl. Therefore, the disinfection alternatives in Table ES-2 were considered in this evaluation.

TABLE ES-2

DISINFECTION ALTERNATIVES EVALUATED

Primary Disinfectant	Secondary Disinfectant
Chlorine	Chlorine
Chlorine	Chloramine
Ozone	Chloramine

Chlorine dioxide is not considered as a primary disinfectant in this analysis because equations were not available for predicting chlorine dioxide decay and formation of the inorganic by-products chlorite and chlorate. Although chlorine dioxide is not evaluated in this document, upgrade costs for chlorine dioxide disinfection are provided in another document; Technologies and Costs for Ground Water Disinfection.

Treatment plants may require one, or a combination of, the control alternatives listed above in order to meet future D/DBP standards. A summary of D/DBP control alternatives and combination of alternatives for which design criteria and upgrade costs were generated is provided in Table ES-3.

TABLE ES-3

SUMMARY OF DBP CONTROL ALTERNATIVES EVALUATED

NOM Removal Process	Disinfection Strategy		
	Cl_2/Cl_2	Cl_2/NH_2Cl	O_3/NH_2Cl
Original Treatment Process Train	X(1)	X	X
Increase Coagulant Dosage	X	X	X
Install GAC Adsorption	X	X	X
Install Membranes	X	X	NE(2)

Notes:
(1)Base plant process with Cl_2/Cl_2 disinfection.
(2)NE - Not evaluated.

Upgrade costs for each D/DBP control alternative are designed to represent the costs for an existing plant to improve treatment to meet potential D/DBP standards. Upgrade costs were generated by calculating the difference in total cost between a completely new treatment plant <u>without</u> D/DBP control and a completely new treatment plant <u>with</u> D/DBP control. The treatment plant without D/DBP control, also referred to as the "base plant", is assumed to be a facility which utilizes a Cl_2/Cl_2 disinfection strategy and which currently meets the requirements of the SWTR.

To estimate upgrade costs for any D/DBP control alternative, design criteria must first be developed. For this analysis, design criteria were developed using the WTP simulation model and accepted engineering practices. The WTP model simulates NOM removal, DBP formation, and disinfectant levels in a water treatment plant and its distribution system. Using this model, water quality-related design parameters such as chemical dosages, contact basin size and sludge production were predicted. Other design criteria common to all alternatives, such as clarifier overflow rates and filtration loading rates, were developed based on accepted engineering practice.

Raw water quality plays a significant role in determining design criteria for a given treatment plant. As a result, design criteria for treatment parameters such as chemical dosages, contact basin size and solids production were developed for a wide range of water qualities which were assumed to be representative of the treatment category under consideration (surface water treatment plants using coagulation and filtration). The median values generated in this analysis were used as design criteria for each control alternative.

Through the development of design criteria and upgrade costs for the control alternatives listed in Table ES-3, it was found that the upgrade costs for different *combinations* of alternatives was nearly equal to the *sum* of the individual costs for each upgrade. For example, the cost for installing GAC adsorption and switching to chloramines was nearly equal to the sum of individual upgrade cost for adding GAC and the upgrade cost for switching to chloramines. As a result, this document provides costs for the following NOM removal and alternate disinfection processes:

- Using monochloramine (as opposed to free chlorine) as a secondary disinfectant;
- Increasing coagulant dosage to improve NOM removal;
- Using ozone as a primary disinfectant and monochloramine as a secondary disinfectant;
- Installing post-filter GAC adsorption; and
- Installing membrane filtration.

A summary of the key design criteria and assumptions used to develop upgrade costs are presented in Table ES-4.

TABLE ES-4

DESIGN CRITERIA AND KEY ASSUMPTIONS

Control Alternative	Design Criteria and Key Assumptions
Using Chloramines	▪ 4:1 chlorine residual to ammonia ratio. ▪ 0.8 mg/L ammonia dose.
Increase Coagulant Dose	▪ Alum as coagulant. ▪ Increase dosage to 50 mg/L from 10 mg/L. ▪ Lagoons used for dewatering. ▪ Land for additional lagoons available on site.
Using Ozone/Chloramines	▪ 5 mg/L ozone dose. ▪ Ozone generation system and contact chamber sized for design flow. ▪ 4:1 chlorine residual to ammonia ratio. ▪ 0.8 mg/L ammonia dose.
Install GAC Adsorption	▪ EBCTs of 15 and 30 minutes. ▪ 180-day regeneration frequency. ▪ Replacement of GAC for Flow Categories 1 to 6(1). ▪ On-site GAC regeneration for Flow Categories 7 to 12(1).
Install Membranes	▪ Nanofiltration assumed. ▪ Sized for design flow. ▪ Molecular weight cutoff = 200. ▪ Recovery rate = 85 percent. ▪ Operating pressure = 80 psi.

Note:

(1)See Table ES-5 for Flow Category description.

As shown in Table ES-4, design criteria and upgrade costs for membrane filtration were based on nanofiltration. Nanofiltration is capable of achieving significant removals of NOM as well as providing excellent disinfection. Ultrafiltration is also a membrane process capable of providing DBP and disinfection control. Although ultrafiltration is very effective in removing pathogens and costs less than nanofiltration, it typically does not remove as much NOM as nanofiltration. Systems may be able to use a combination of ultrafiltration for pathogen removal and chloramines for reduced DBP formation when used as a secondary disinfectant. A potential problem with this approach, however, includes failure of the membrane, allowing pathogens to enter the distribution system without necessary removal or inactivation (chloramines do not provide an adequate backup primary disinfection capability in the event of catastrophic membrane failure).

Upgrade cost estimates were prepared for each control alternative for water supply systems of several sizes, based on USEPA's 12 flow categories. These categories were divided into two groups; small systems having design flow of less than 1 mgd and large systems having design flow greater than 1 mgd. The median population served, average flow and design capacity for each flow category is presented in Table ES-5.

TABLE ES-5

USEPA FLOW CATEGORIES

USEPA Flow Categories	Median Population Served	Average Flow (mgd)	Design Capacity (mgd)
Small Systems - Design Flow < 1 mgd			
1	57	0.0056	0.024
2	225	0.024	0.087
3	750	0.086	0.27
4	1,910	0.23	0.65
Large Systems - Design Flow > 1 mgd			
5	5,500	0.70	1.8
6	15,000	2.1	4.8
7	35,000	5.0	11
8	60,000	8.8	18
9	88,000	13	26
10	175,000	27	51
11	730,000	120	210
12	1,550,000	270	430

For these systems, the cost presented in this document apply separately to each treatment facility within a given water system. For example, some large systems have treatment facilities at multiple locations. The total costs for such a system can be obtained by adding together the costs for each individual treatment facility.

Estimated costs were developed using the WATER model for small systems and the WATERCO$T model for large systems. Where necessary, these computer models were supplemented with costs from GAC cost models and vendor costs. Estimated total upgrade costs consist of operation and maintenance (O&M) and annual debt service on the capital cost (i.e., 10 percent interest, 20-year design life). The cost basis is June 1991. Some cost indices have increased insignificantly between June 1991 and September 1992; others have decreased.

Upgrade costs are shown graphically in Figures ES-1 and ES-2. Figure ES-1 shows upgrade costs for NOM removal strategies (i.e., increasing coagulant dosage, installing GAC and installing membrane filtration). Although ultrafiltration was not evaluated in the document, upgrade costs (capital and O&M) may be 10 to 20 percent less than nanofiltration. Figure ES-2 shows upgrade costs for alternate disinfection strategies (i.e., Cl_2/NH_2Cl and O_3/NH_2Cl).

Each upgrade cost represents the cost to install and operate the given control alternative; no consideration is given in this document to the costs for retrofitting the existing plant. Retrofit costs can increase the upgrade cost from 10 to greater than 100 percent depending on site-specific factors such as unknown interferences, extra piping, site constraints, hydraulics and the requirement to maintain the existing plant in operation. The type of control technology also affects retrofit costs. For example, retrofit costs would most likely be greater for GAC alternatives compared to the addition of an ammonia feed system. Therefore, it is recognized that costs for individual utilities may vary depending upon unique site constraints and design criteria.

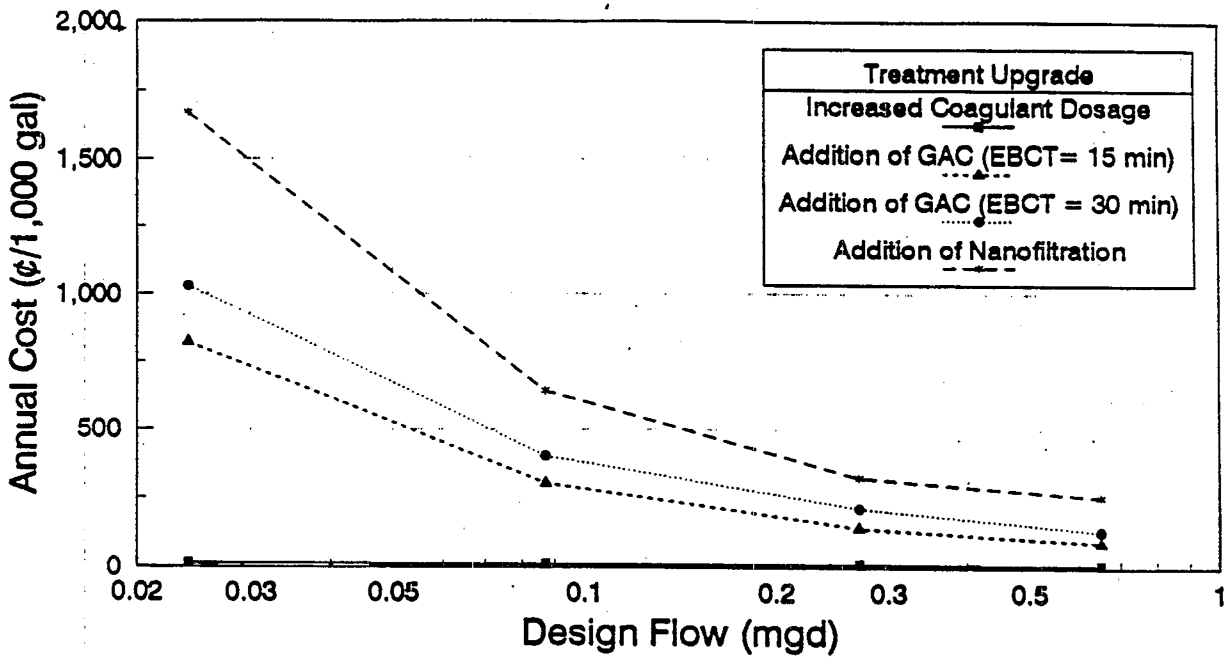
It must also be recognized that upgrade costs for the control alternatives presented in this document are developed based on specific design criteria and assumptions. As a result of some of these assumptions, upgrade costs were found to be independent of selected DBP limits. For example, the cost for a system installing GAC adsorption with a 15 minute empty-bed contact time and a regeneration frequency of 180 days will be the same whether a particular system is attempting to meet a TTHM goal of 100 $\mu g/L$ or 25 $\mu g/L$, because the criteria are specified. The ability of such a treatment plant to meet selected D/DBP goals using GAC adsorption depends, to a large degree, upon raw water quality. Although a wide variety of raw water quality was considered during the development of design criteria for plants in this treatment category (surface water systems using coagulation and filtration), it is not the purpose of this document to evaluate the ability of a particular treatment plant to meet a DBP limit using a given treatment technology. Rather, this document presents the estimated costs for each control alternative based on the specified design criteria.

A more detailed description of the selection of design criteria and costs can be found in the document entitled "Technologies and Costs for the Control of Disinfection By-Products." The upgrade costs presented in this document are used as the basis to generate national costs for compliance with different disinfection/disinfection by-product goals.

FIGURE ES-1

UPGRADE COSTS FOR IMPROVED NOM REMOVAL

SMALL SYSTEMS



LARGE SYSTEMS

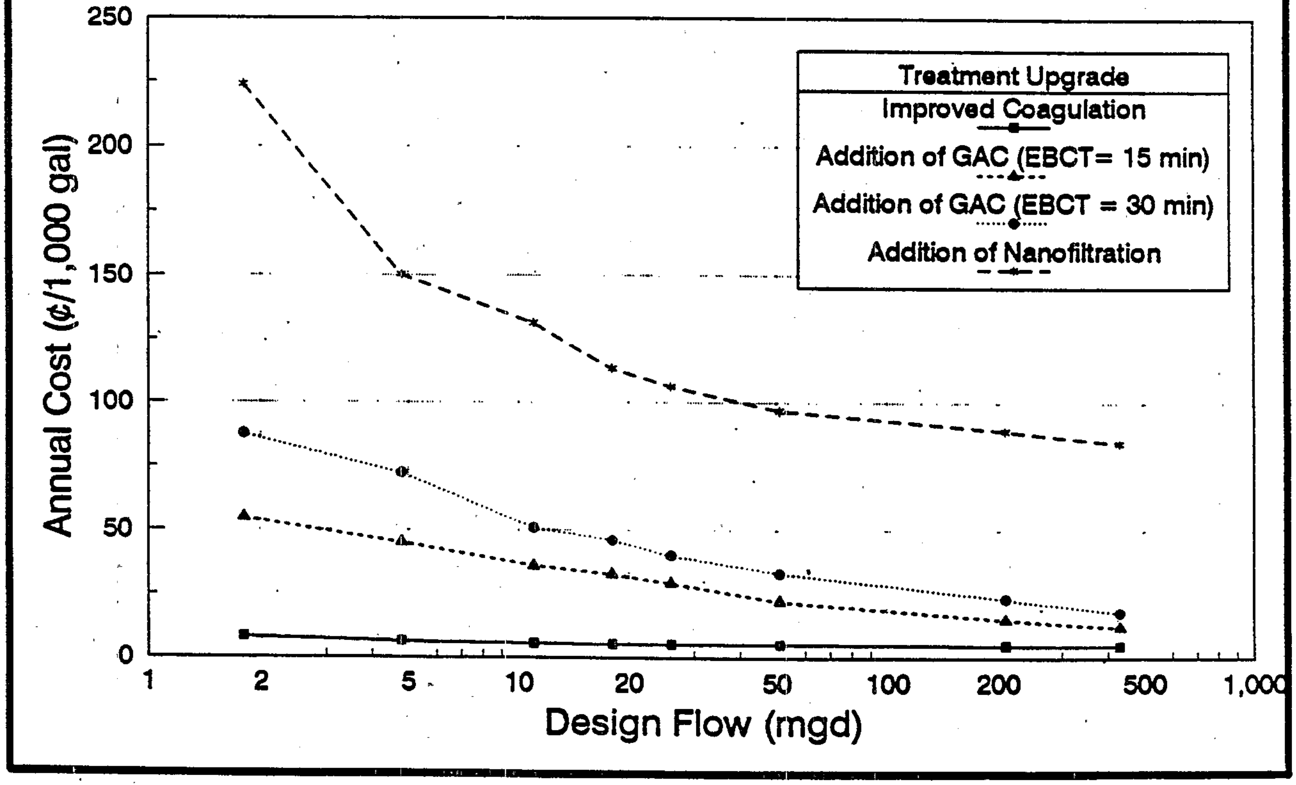
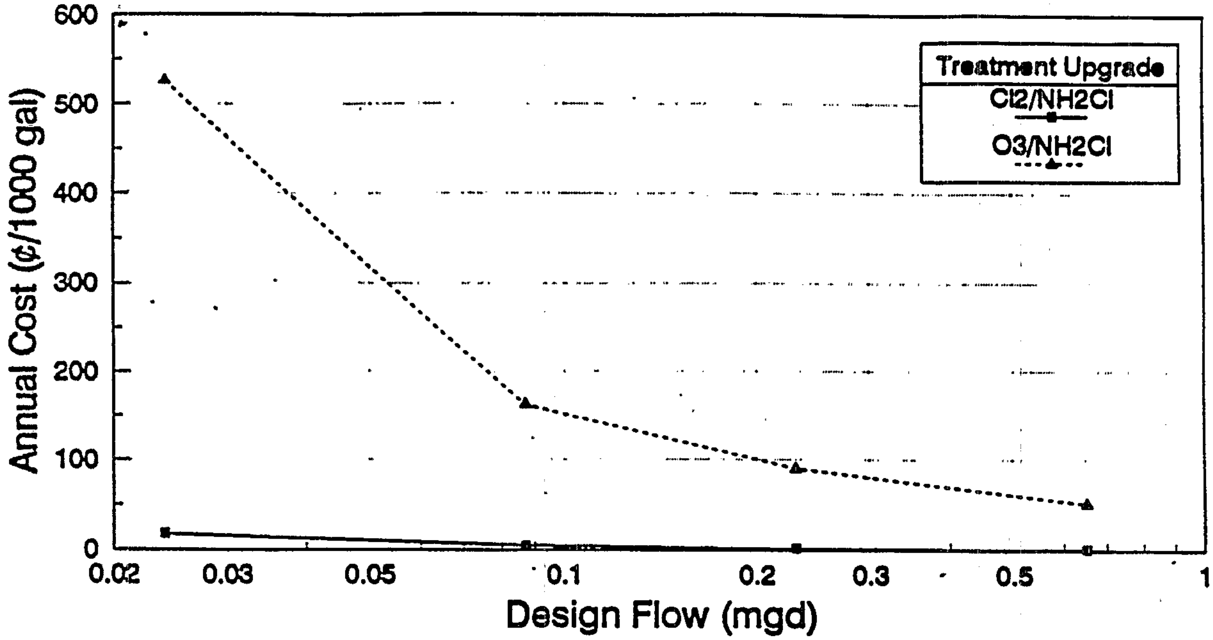


FIGURE ES-2

UPGRADE COSTS FOR ALTERNATE DISINFECTION

SMALL SYSTEMS



LARGE SYSTEMS