

Control of microbial contaminants and disinfection by-products for drinking water in the US: cost and performance

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ABSTRACT: The US Environmental Protection Agency (US EPA) is in the process of developing a sophisticated regulatory strategy in an attempt to balance the risks associated with disinfectants and disinfection by-products (D/DBP) in drinking water. A major aspect of this strategy is the appropriate application of disinfectants and other treatment technologies to minimise the formation of disinfection by-products (DBPs). This paper explores the cost and performance associated with these technological choices. It is clear that the least expensive choice for controlling chlorinated by-products would be to utilise an alternative disinfectant. However, precursor removal by enhanced coagulation and/or the application of granular activated carbon and membrane technology are very effective in controlling DBPs. The removal of precursors can have the effect of simultaneously controlling both chemical and microbiological risks.

INTRODUCTION

The US Environmental Protection Agency (US EPA) is in the process of developing a sophisticated regulatory strategy in an attempt to balance the complex trade-offs in risks associated with controlling disinfectants and disinfection by-products (D/DBP) in drinking water [1]. The Agency is developing three sets of rules: a two-staged D/DBP rule, an interim Enhanced Surface Water Treatment Rule (IESWTR) and an Information Collection Rule (ICR). The IESWTR applies to systems serving 10 000 people or more. A long-term ESWTR (LTESWTR) will be needed for systems serving fewer than 10 000 people. The LTESWTR will be based on the results of additional research and water quality monitoring as they become available. The LTESWTR will also include additional refinements for larger systems.

A key part of the regulatory development is the promulgation of the ICR, which will require drinking water utilities to collect the occurrence and treatment information to evaluate the need for changes in the current Surface Water Treatment Rule (SWTR) and existing microbial treatment practices, and to evaluate the need for future regulation of D/DBPs. The ICR will provide the US EPA with information on the national occurrence in drinking water of chemical by-products that form when disinfectants used for microbial control react with compounds already present in source water and with disease causing micro-organisms. In addition, engineering data on how drinking water utilities currently control chemical and microbial contaminants will be collected. This information will be used to assess the potential health problems created by the presence of DBPs and pathogens in drinking water and to assess the extent and severity of risk and to assist in regulatory and public health decisions.

The D/DBP Rule is being developed in two stages. The Stage 1 D/DBP and IESWTR were proposed in July 1994 with a final promulgation date of November 1998. May 2002 has been established for the final Stage 2 D/DBP and November 2000 for the LTESWTR. Drinking water design information obtained under the ICR, as well as data and information from other sources will be used by the US EPA to develop, analyse, and assess options for proceeding with the Stage 1 D/DBP Rule and IESWTR.

The US EPA first attempted to control disinfection by-products in 1974, when trihalomethane (THM) formation in drinking water was identified as a by-product of chlorination. Based on available toxicologic data, chloroform (one of the THMs) was labelled as a suspect carcinogen. Epidemiological studies also suggested a human risk. Because of these suspected health effects and the potential that a large number of drinking water consumers would be exposed to these by-products, a Total Trihalomethane (TTHM) Regulation was promulgated on 29 November 1979, at a level of 0.10 mg/L. Since that time many other objectional by-products of chlorination have been identified as well.

Section 1401 (1)(D) of the Safe Drinking Water Act, Public Law 93–523, requires that for any regulated contaminant a ‘Treatment Techniques’ document must accompany a Maximum Contaminant Level (MCL) to provide compliance guidance. In order to satisfy this requirement the Water Supply and Water Resources Division (formerly the Drinking Water Research Division) of the US EPA’s Office of Research and Development prepared a comprehensive document entitled ‘Treatment Techniques for Controlling Trihalomethanes in Drinking Water’ which was published in September 1981[2]. The document was subsequently re-published by the American

Water Works Association (AWWA) and was also translated into Japanese.

This paper will review the current status of disinfection practices in the USA, the conditions that cause the formation of disinfection by-products, and discuss the various treatment techniques and associated costs for both controlling disinfection by-products and ensuring microbial safety. Most of the data and information presented in this paper is based on studies conducted in the USA.

THE ROLE OF DISINFECTION IN THE USA

Chlorine has been the most commonly used disinfectant in the USA. In the USA an estimated 220 000 000 people receive disinfected drinking water [1]. Chlorine has been the disinfectant of choice for many utilities, with more than 50% of the systems using surface water and chlorinating before settling and filtration. Many utilities in the USA have explored the use of disinfectants other than chlorine to lower their THM levels below the 0.10 mg/L MCL. Some utilities have considered switching to chloramines as an alternate disinfectant to chlorine. A survey conducted by the American Water Works Association Research Foundation showed that the vast majority of utilities that changed disinfection practices have switched to chloramines [3]. In these cases, chloramines are applied as the final disinfectant. Some utilities are considering the possibility of using ozone as a disinfectant followed by chlorine or chloramines. Ozone is drawing increasing interest, but concern with using ozone includes the need for biostabilisation of the treated water and possible formation of by-products such as aldehydes, ketones, and acids. Chlorine dioxide is an effective disinfectant but there are concerns about its reacting to form the inorganic by-products chlorite and chlorate.

MICROBIOLOGICAL CONTROL

Prior to the discovery that protozoan cysts (*Giardia* and *Cryptosporidium*) were a prime cause of waterborne disease outbreaks, the apparent attainment of adequate disinfection was considered to be relatively simple. Many of the commonly available chemical disinfectants (chlorine, ozone, chlorine dioxide and even chloramines) are successful in reducing coliform bacteria to acceptable levels, which was generally accepted as an indication of safe water. However, it is now known that pathogens can exist even in the presence of high levels of free chlorine. The US EPA has therefore evaluated the common chemical disinfectants for their efficacy in inactivating *Giardia* cysts, viruses and *Cryptosporidium*.

The US EPA has adopted the *CT* concept (concentration in mg/L \times time in minutes) in comparing the biocidal effectiveness of disinfectants. Major considerations are the disinfectant concentration and the time needed to attain inactivation of a certain microbial population exposed under specific conditions. The *CT* concept can be expressed as an empirical equation as shown below [4,5]

$$K = C^n \cdot t \quad (1)$$

where: *C* = disinfectant concentration in mg/L, *n* = coefficient of dilution, *t* = contact time in minutes required for a fixed percentage of inactivation, *K* = constant for a specific micro-organism. *CT* values have been developed for inactivation of various micro-organisms for the major disinfectants. An example of these values is shown in Table 1 [1].

It is evident from Table 1 that ozone shows the highest disinfection efficiency, inactivating 99% of most types of micro-organisms at very low *CT* values. Chloramine shows the lowest efficiency. Chlorine *CT* values for *Cryptosporidium parvum* are

Micro-organism	Free chlorine pH 6–7	Preformed chloramine pH 8–9	Chlorine dioxide pH 6–7	Ozone pH 6–7
<i>E. coli</i>	0.034–0.05	95–180	0.4–0.75	0.02
Polio virus-1	1.1–2.5	768–3740	0.2–6.7	0.1–0.2
Rotavirus	0.01–0.05	3806–6476	0.2–2.1	0.006–0.06
Phage f_2	0.08–0.18	ND	ND	ND
<i>G. lamblia</i> cysts	47–150	2200*	26*	0.5–0.6
<i>G. muris</i> cysts	30–630	1400	7.2–18.5	1.8–2.0
<i>Cryptosporidium parvum</i>	7200†	7200‡	78§	5–10¶

Table 1 Summary of *CT* value ranges for inactivation of various micro-organisms by disinfectants [2,6–9]

Note: All *CT* values are for 99% inactivation at 5 °C except for *Giardia lamblia* and *Cryptosporidium parvum*.

* Values for 99.9% inactivation at pH 6–9.

† 99% inactivation at pH 7 and 25 °C.

‡ 90% inactivation at pH 7 and 25 °C.

§ 90% inactivation at pH 7 and 25 °C.

¶ 99% inactivation at pH 7 and 25 °C.

ND, no data.

high, but ozone is an effective inactivation agent. For these data 'n' has been shown to vary between 0.7 and 1.3, therefore a value of $n = 1$ was chosen for this analysis [6]. In Table 1, performed chloramine were used because it is conservative with respect to *CT* values.

OTHER TREATMENT GOALS

Often, disinfection can also perform other treatment tasks in a drinking water treatment plant, for example: oxidation of metals, taste and odour control, and enhancement of turbidity removal. Probably the greatest need for an oxidant, other than disinfection, is for the precipitation of metals such as iron and manganese. These metals occur in a reduced inorganic state and in metal organic complexes, which are the most difficult forms to remove.

Ozone, the most powerful oxidant, and chlorine dioxide oxidise metals very well. Both are more effective at removing metals than chlorine. Chemical costs can be considerably higher, however, particularly if there is a high oxidant demand.

FORMATION OF DISINFECTION BY-PRODUCTS

Shortly after THMs were identified in chlorinated drinking water, it was recognised that THMs were only one of many halogenated DBPs produced by water chlorination. Compounds such as di- and trichloroacetic acids, haloacetonitriles, haloketones, chloropicrin, cyanogen chloride and chlorohydrate have been identified in chlorinated drinking water. Several of these halogenated DBPs such as dichloroacetic acid are suspected carcinogens and are believed to be more potent carcinogens than any of the THMs. MX[3-chloro-4-(dichloromethyl)-hydroxyl-2(5H)-furanone], a halogenated furanone which has been identified in chlorinated drinking water, has been found to be extremely mutagenic. Some undesirable disinfection by-products may be produced with all disinfectants. Halogenated by-products are, of course, of special inter-

est [10–12]. Bench-scale studies of the chlorination of natural water and humic-acid-spiked water using extraction, capillary column chromatography and mass-spectrometer analytical procedures detected more than 500 disinfection by-products [13]. Many of these were formed at microgram-per-litre concentrations and the majority were not identified.

By-product formation at the bench scale and control at pilot and full scale have been evaluated by examining specific by-products and surrogate parameters such as total organic halogen (TOX). The TOX data suggests the formation of other DBPs, whose total concentrations are likely to equal or exceed those of total trihalomethanes [13]. One bench-scale study showed that the concentrations of THMs increased with time for each pH value. Pilot studies have shown that the percentages of removal of disinfection by-product formation potential from raw Ohio River water to low pH, alum coagulated and filtered effluent were within a range of 60–80%. Bench-scale studies have also shown that bromide heavily influences the nature of the chlorination disinfection by-products formed [14–16].

At a pilot plant located at the Jefferson Parish, Louisiana water utility, the four major disinfectants used in the USA (chlorine, chlorine dioxide, ozone and chloramine) were applied in parallel to clarified and filtered lower Mississippi River water during two studies [8]. One of the surrogates evaluated was total organic halides (TOX). Chlorine produced the highest concentration of TOX, indicating that several other halogenated by-products were formed with the chlorination [8]. Ozone produced the lowest concentration of TOX, with concentrations below the nondisinfected feed to the pilot plant, suggesting that some oxidation occurred as shown in Fig. 1. Average instantaneous TOX concentrations were 25 µg/L, 15 µg/L, 85 µg/L, 117 µg/L and 263 µg/L for the nondisinfected, ozone, chlorine dioxide, chloramine and chlorine streams, respectively. Not all of the organics produced by the disinfectants evaluated at Jefferson Parish were identified. Flame-ionisation detection (FID) and electron-capture detection (ECD) gas-chromatographic profiles gave evidence of the

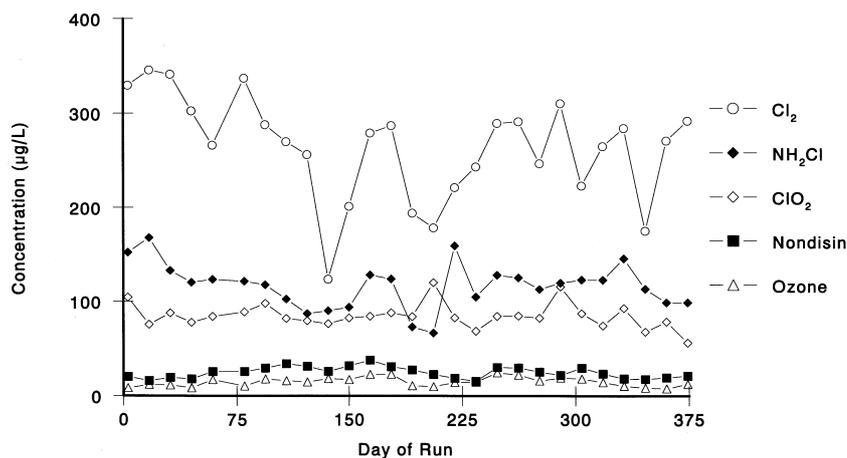


Fig. 1 TOX concentrations after 30 minute contact time

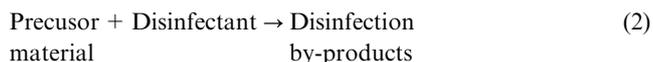
extent of by-product formation for the disinfectants. The number of different products formed and the concentration of products formed by the various disinfection process streams followed the sequence chlorine > chloramine > chlorine dioxide > ozone for these measures.

Although most of the emphasis in the USA has focused on halogenated by-products, to a somewhat lesser degree ozone and other oxidants can also form by-products such as formaldehyde, glyoxal and acetone. In the US EPA's pilot plant in Cincinnati, using Ohio River water, ozonation produced formaldehyde concentrations of $\approx 26 \mu\text{g/L}$ [17]. Concentrations of formaldehyde, acetone and glyoxal subsequently declined through conventional treatment, but increased again due to either clear-well chlorination or chloramination. The loss of formaldehyde, acetone and glyoxal during conventional treatment is assumed to result from biodegradation by heterotrophic plate count (HPC) species, as is evidenced by a decline in formaldehyde concentration and an increase in HPC densities.

The occurrence of disinfection by-products in US drinking water was evaluated at 35 water treatment facilities that had a broad range of source water qualities and treatment processes [18]. Trihalomethanes were the largest class of disinfection by-products detected on a weight basis. Haloacetic acids were the next largest class of compounds found. Formaldehyde and acetaldehyde, by-products of ozonation, were also produced by chlorination. Cyanogen chloride was preferentially produced in chloraminated water. The median, total-trihalomethane quarterly values in this study were comparable to those seen in a survey of 727 utilities by the American Water Works Association Research Foundation [3].

TREATMENT STRATEGIES FOR CONTROLLING DBPS

Disinfection by-products are the result of the interaction of the disinfectant with natural organic matter in water, as shown by eqn 2.



This equation, plus the knowledge that disinfection by-products tend to increase over time indicates that moving the point of disinfection to the end of the treatment process will minimise the time of by-product formation. Numerous experiences have verified the effectiveness of this approach [2]. In addition, most treatment processes will remove the precursor material, thereby minimising by-product formation potential. Other options are the removal of precursor material or natural organic matter before it interacts with the disinfectant, use of a disinfectant that minimises the formation of by-products, or removal of the disinfection by-products once they are formed [19]. It is anticipated that Stage 1 of the D/DBP Rule will require drinking water utilities to achieve a maximum contami-

nant level (MCL) of $80 \mu\text{g/L}$ and that Stage 2 may require an MCL of as low as $40 \mu\text{g/L}$. The IESWTR and the LTESWTR will require total organic carbon (TOC) removal as a measure of precursor removal.

In the following section, the effects, the technology and costs associated with these options for controlling disinfection by-products will be discussed. Since the impact of trihalomethane control is similar to the control of other halogenated by-products, the costs developed for trihalomethane control would be similar to those for the removal of other disinfection by-products.

TREATMENT ALTERNATIVES FOR CONTROLLING DBPS

As can be seen from eqn 2, two alternatives for controlling DBPs are to switch to a disinfectant that minimises by-product formation or to remove the by-product precursor prior to disinfection [19]. The cost and performance of various options for controlling DBPs, as mentioned previously, will be explored in this section [20]. Table 2 contains the common cost assumptions that apply to all the evaluations.

Alternate disinfectants

As mentioned previously, the use of disinfectants other than chlorine is one option for controlling the concentration of halogenated by-products. In a study at Jefferson Parish, LA, lower Mississippi River water was clarified and filtered before being diverted to five parallel streams (Fig. 1). The major objectives of this study were to evaluate: (1) the control of halogenated by-products (2) the microbiological effectiveness of the disinfectants, and (3) potential health effects associated with the use of these disinfectants. Many of the halogenated by-products of interest were analysed for each disinfectant stream [19]. Of special interest was the potential concentration of these by-products when the water was delivered to the customer. This was evaluated by storing samples for a specified time with a disinfectant residual to simulate residence time in the distribution system. It was found that when chlorine was added prior to

Table 2 Common cost assumptions

Items	Value
Capital amortisation	10% over 20 years
Engineering fees	15% of construction
Contractor overhead and profit	12% of construction
ENR construction cost index	5751 (January 1997)
Producers price index	361 (January 1997)
Labour and fringe rate	\$15/hour
Electric power rate	$\$0.024 \times 10^{-6}$ Joules (\$0.086/kwh)
Fuel oil price	\$0.235/L (\$0.889/gallon)

Table 3 Annual alternative disinfectant costs in ¢/thousand m³ (¢/1000 gal)

Unit process	Design flow in thousand m ³ per day* (average flow)			
	0.3789 (0.189)	3.785 (1.89)	37.89 (26.5)	378.9 (264.95)
Chlorine/chlorine	152.2 (40.2)	54.58 (14.4)	8.33 (2.2)	4.54 (1.2)
Chlorine/chloramine	227.5 (60.1)	60.94 (16.1)	10.22 (2.7)	5.30 (1.4)
Ozone/chlorine	454.2 (120)	84.41 (22.3)	27.66 (7.3)	15.90 (4.2)
Ozone/chloramine	518.5 (137)	90.84 (24)	29.14 (7.7)	16.65 (4.4)
Chlorine dioxide/chlorine	571.5 (151)	79.11 (20.9)	21.11 (3.2)	6.06 (1.6)

*To convert from thousand m³ per day to mgd divide by 3.785.

and after sand filtration, an average of 45 µg/L of dichloroacetic acid was detected. If ozone was added prior to sand filtration and the chlorine after sand filtration, the average concentration was reduced to 32 µg/L. If monochloramine was used prior to and after sand filtration, then the average concentration was further reduced to about 8 µg/L. Further reductions were seen for the combination of ozone added before sand filtration and monochloramine after sand filtration (4.6 µg/L average). This trend was seen for other prevalent halogenated by-products such as trichloroacetic acid, bromochloroacetic acid, chloral hydrate and trichloromethane.

Another potential disinfectant that minimises halogenated by-products is chlorine dioxide. At a drinking water utility on the Ohio River, a pilot plant was used to compare chlorine dioxide disinfection with chlorine disinfection [8]. The addition of chlorine dioxide to the raw water with delayed chlorination permitted coagulation/settling/filtration and oxidation to remove trihalomethane precursors, thereby reducing the amount of trihalomethanes formed during the post-treatment chlorination. A comparison of the average trihalomethane concentrations for the two disinfectant modes showed a reduction of ≈ 60% when chlorine dioxide was used. Although chlorine dioxide disinfection can reduce trihalomethane concentrations, control of the metabolites (chlorite and chlorate) is essential before chlorine dioxide can be considered a viable disinfection alternative. Equipment is now available to produce chlorine dioxide that is virtually free of chlorite and chlorate. Studies are being conducted to better affect a reduction of chlorite and chlorine dioxide by a reducing agent [19].

Disinfection costs

For the purpose of this analysis the following assumptions were made: Prechlorine dose = 3 mg/L; postchlorine dose = 1.5 mg/L; preozone dose = 2 mg/L; post chloramine dose (2 mg/L Cl₂ & 0.5 mg/L ammonia); prechlorine dioxide = 1 mg/L. The various disinfectants including capital, operating and maintenance (O&M), and chemical cost for disinfection only are summarised in Table 3. In column 1 of Table 3, the primary disinfectant is listed first.

PRECURSOR REMOVAL BY ENHANCED COAGULATION

Three methods for removing precursor material will be discussed in this section: appropriate coagulation, granular activated carbon and nanofiltration, a newly emerging technology. The performance and cost of each of these technologies will be discussed in that section. Performance is based on Total trihalomethane formation potential (TTHMFP). Some removal is observed when alum was used as a coagulant for turbidity control but when the treatment was modified by adding additional alum and reducing the pH, further precursor removal was noted (Table 4).

Cost of enhanced coagulation

The US EPA has prepared several estimates for treatment optimisation that might lead to enhanced coagulation. Some of these costs are provided in Table 5.

Table 4 Precursor control by coagulation (EPA Pilot Plant) per cent removal of precursor*

TOC		THMFP		TOXFP		TOC		DBPFP†	
A	B	A	B	A	B	C	D	C	D
21	46	28	48	4	56	15	40	56	70

* Ohio River water.

† Based on mean formation potential for several halogenated by-products.

A, alum = 20 mg/L, pH = 7.5; for turbidity control.

B, alum = 89 mg/L, pH = 6.0; for precursor control.

C, alum = 26 mg/L, pH = 7.0; for turbidity control.

D, alum = 40 mg/L, pH = 5.7; for precursor control.

TOC = Total organic carbon.

THMFP = Total trihalomethane formation potential.

TOXFP = Total organic halide formation potential.

DBPFP = Disinfection by-product formation potential.

Table 5 Annual cost for enhanced coagulation in ¢/thousand m³* (¢/1000 gallons) [21]

Unit process	Design flow in thousand m ³ /day* (average flow)						
	18.168 (7.949)	41.635 (18.925)	68.130 (23.308)	98.410 (49.205)	193.035 (102.195)	794.850 (454.200)	1627.580 (1021.950)
Chemical addition	0.713–3.406 (2.7–12.9)	0.290–3.247 (1.1–12.3)	0.158–3.168 (0.6–12.0)	0.106–3.115 (0.4–11.8)	0.079–3.036 (0.3–11.5)	0.026–2.930 (0.1–11.1)	0.008–2.904 (0.03–11.0)
Coagulant improvements	2.059 (7.8)	1.320 (5.0)	1.056 (4.0)	0.950 (3.6)	0.818 (3.1)	0.713 (2.7)	0.686 (2.6)
Rapid Mix	0.733–0.898 (2.7–3.4)	1.716–2.086 (6.5–7.9)	1.795–2.138 (6.8–8.1)	1.742–2.112 (6.6–8.0)	1.002–1.320 (4.1–5.0)	0.317–0.370 (1.2–1.4)	0.158–0.185 (0.6–0.7)
Flocculation improvements	0.845–1.690 (3.2–6.4)	0.607–1.346 (2.3–5.1)	0.554–1.188 (2.1–4.5)	0.528–1.082 (2.0–4.1)	0.317–0.660 (1.2–2.5)	0.079–0.264 (0.3–1.0)	0.079–0.238 (0.3–0.9)
Settling improvements	0.290–0.581 (1.1–2.2)	0.185–0.449 (0.7–1.7)	0.132–0.396 (0.5–1.5)	0.132–0.370 (0.5–1.4)	0.132–0.343 (0.5–1.3)	0.079–0.185 (0.3–0.7)	0.053–0.106 (0.2–0.4)
Filtration improvements	0.079–5.148 (0.3–19.5)	0.079–2.666 (0.3–10.1)	0.079–1.795 (0.3–6.8)	0.079–1.637 (0.3–6.2)	0.079–1.135 (0.3–4.3)	0.053–0.766 (0.2–2.9)	0.026–0.660 (0.1–2.5)
Hydraulic improvements	0.317–0.739 (1.2–2.8)	0.211–0.581 (0.8–2.2)	0.185–0.502 (0.7–1.9)	0.185–0.475 (0.7–1.8)	0.132–0.396 (0.5–1.5)	0.079–0.317 (0.3–1.2)	0.053–0.238 (0.2–0.9)

* To convert from thousand m³ per day to mgd divide by 3.785.

PRECURSOR REMOVAL BY GRANULAR ACTIVATED CARBON (GAC)

GAC is an effective means of removing disinfection by-product precursors from water at a cost that varies widely according to water quality and treatment goals. An example of the effectiveness of GAC for three water utilities is shown in Table 6. Removal is initially good, but diminishes as the time in service increases.

In some cases, the use of GAC for precursor removal would be unreasonable. For example, based on field tests in Miami, FL, in order to remove THMFP in the 15–100 µg/L range it was found that the carbon would require reactivation every 20 days.

Cost of precursor removal using GAC

As mentioned, THM formation is a function of the influent concentration and reactive characteristics of the natural

organic matter in the source water. This cost analysis is based on field-scale data collected from studies in Cincinnati, Ohio, Jefferson Parish, LA, and Manchester, New Hampshire. Influent TOC during the studies ranged from 1.5 to 3.5 mg/L and TOC effluents ranged from 0.6 to 1.6 mg/L. These effluent levels correspond to THMFP effluent values of ≈ 50 µg/L. Because GAC bed life is dependent on influent concentration (C_0) the bed lives were adjusted to reflect the target effluent concentrations (C_c) to be considered. Table 7 contains the assumed bed lives for each of the utilities studied.

The cost calculations are based on the data shown in Table 7 and an assumption of a 20-min empty bed contact time. These target values were used because they are taken from actual studies and are in the range associated with the anticipated regulation. For systems of 0.3785, 3.785 and 37.85 thousand m³

Table 6 Precursor removal by GAC

Utility	Influent THMFP (µg/L)	% Removal	
		Initial	After 90 days
Cincinnati, OH	160	98	63
Manchester, NH	72	85	35
Jefferson Parish, LA	93	83	40

Table 7 Bed life for GAC for removal of THMFP At an influent level of 150 µg/L

	Target effluent THMFP (µg/L)	Bed life (Days)
Cincinnati	100	225
Cincinnati	50	175
Jefferson Parish	100	103
Jefferson Parish	50	63
Manchester	50	80

	Design flow in thousand m ³ /day* (average flow)					
	0.3785 (0.189)	3.785 (1.89)	37.85 (26.495)	94.62 (64.392)	189.25 (132.475)	378.5 (264.95)
Target levels						
$C_e < 100 \mu\text{g/L}$	70.5 (267) to 82.4 (312)	26.4 (100) to 37.2 (141)	15.6 (59) to 19.8 (75)	10.3 (39) to 13.7 (52)	8.4 (32) to 11.4 (43)	7.1 (27) to 10.6 (40)
$C_e < 50 \mu\text{g/L}$	72.9 (276) to 91.9 (348)	25.5 (108) to 45.9 (174)	21.9 (63) to 23.0 (87)	11.1 (42) to 16.4 (62)	9.0 (34) to 13.7 (52)	7.7 (29) to 13.7 (52)

*To convert from thousand m³/day to mgd divide by 3.785.

(0.1, 1 and 10 mgd), pressure contactors were assumed and for systems of 95.00, 190.00 and 3785 thousand m³ (25, 50 and 100 mgd), concrete gravity contactors were assumed. For systems of 0.3785 and 3.785 thousand m³ (0.1 and 10 mgd) replacement of spent carbon with virgin carbon was used in the calculation and for 37.85, 95.00, 190.00 and 378.5 thousand m³ (10, 25, 50 and 100 mgd), systems, on-site multihearth reactivation was assumed. Table 2 contains the cost assumptions used in this analysis. Additional assumptions included a virgin carbon cost of \$2.38 kg (1.08/lb) for 45.360 kg (100 000 lb) and a carbon loss rate of 15% due to handling.

Table 8 summarises the costs for using GAC for removing THM precursor removal based on THMFP to THMFP levels of 100 $\mu\text{g/L}$, respectively.

PRECURSOR REMOVAL BY NANOFILTRATION

Membrane processes are also promising for removing disinfection by-product precursors. Studies in Florida waters have demonstrated that for ground waters, membranes are an excellent treatment alternative. These studies showed that with an average raw water concentration of 455 $\mu\text{g/L}$, trihalomethane-formation-potential (THMFP) average concentrations of 20 $\mu\text{g/L}$ were being produced (95% rejection) in the product water.

For total-organic-halide formation potential (TOXFP) an average raw water concentration of 977 $\mu\text{g/L}$ was reduced to 34 $\mu\text{g/L}$ (96% rejection). Additional studies of specific chlorination by-products at Daytona Beach, Florida showed that with a 4–2–1 pressure vessel array, total disinfection by-products expressed as chloride equivalents show a raw water concentration of 530–715 $\mu\text{g/L}$ with an overall system reduction of 95% to 98% [22].

When membranes are used on surface water, however, extensive pretreatment is usually required. Although rejections are good, the membranes have to be cleaned more often. When a Florida surface water (tributary of the Peace River) was

Table 8 Annual cost for THMFP removal by GAC in ¢/thousand m^3 (¢/1000 gallons)

treated, pretreatment consisted of: (1) alum-coagulated and settled water from the full-scale plant, and (2) pressure sand filtration in the pilot plant, membrane filtration. Under these operating conditions, membrane cleaning was required about every 16 days to avoid a production loss greater than 10%. Raw water THM formation potential averaged 612 $\mu\text{g/L}$ and a product water of 37 $\mu\text{g/L}$ was produced (94% rejection). For an average raw water TOX formation potential of 1965 $\mu\text{g/L}$, the product water was 53 $\mu\text{g/L}$ (97% rejection).

Cost of nanofiltration

In this analysis it is assumed that an 8' \times 40' element removes organics with molecular weights greater than 200 molecular weight units [22]. These organics are primarily separated from product water by sieving (little is removed by diffusion). Based on field experience, greater than 95% of DOC, TOX and DBP are removed. If the concentration in the influent is greater than 150 $\mu\text{g/L}$ of trihalomethane formation potential then 25 $\mu\text{g/L}$ of formation potential is expected in the effluent permeate. For example, the reference design for a 37.85 thousand m³ (10 mgd) nanofiltration system is assumed as raw feed water of 44–287.7 thousand m³ (11–76 mgd) to yield a permeate flow of 37.85 thousand m³ (10 mgd) or 85% recovery. A three-stage membrane configuration is assumed. Two types of systems were considered: groundwater with an average of 732.2 ks/sgm (150 psi), an average flux of 0.6 m/day (15 gal/ft²/day) with 13 membrane skids (12 on-line and one on standby). The assumptions for groundwater and surface water systems are shown in Tables 9 and 10, respectively. The reference design was estimated using an approach described by Suratt [23].

The ground water system is assumed to require no advanced treatment, with a 5- μm cartridge, H₂SO₄ addition for scale control and as an inhibitor. Two types of disposal were assumed: one type of disposal was to surface pond or stream and the other using deep well concentrate disposal. Surface water treatment requires advanced pretreatment to reduce fouling (alum coagulation, solids contact, rapid sand filtration).

Table 9 Nanofiltration assumptions and costs for groundwater treatment for a 37.85 thousand m³ plant*

1. Cost for nanofiltration w/disposal to surface pond or stream	
Construction Cost	
Membrane System, chemical feed, etc. (Water storage assumed to exist already) Disposal pond or stream exists already	\$13 692 480
Concentrate treatment (in-line oxidation) and piping (5000 ft)	\$256 500
Construction Total	\$13 948 980
Amortised @ 10% @ 20 years	\$1639 000/year
O & M Cost	
Nanofilter system	\$2318 060
Concentrate treatment	\$4140
O & M total	\$2359 460
Total system	\$3998 460/year
Unit cost	\$0.289/ thousand m ³ (\$1.095/1000 gal)
2. Costs for nanofiltration using deep well concentrate disposal	
Construction cost	
Membrane system	\$13 692 480
Deep well injection, lagoon backup, piping	\$5790 000
Construction total	\$19 482 480
Amortised @ 10% @ 20 years	\$2289 190/year
O & M Cost	
Nanofilter system	\$2318 060
Concentrate disposal	\$16 600
O & M Total	\$2334 660/year
Total system	\$4623 850
Unit cost	\$0.336/ thousand m ³ (\$1.27/1000 gal)

*To convert from thousand m³ to mgd divide by 3.785.

Table 10 Nanofiltration cost assumptions for surface water treatment for 37.85 thousand m³ plant*

Construction	
Alum coagulation, solids contact, sand	\$6362 050
Nanofiltration + deep well	\$22 358 950
Total Cost	\$28 721 000
Amortised Cost	\$3374 720/year
O & M	
Alum coagulation plant	\$3138 350
Nanofiltration plant	\$2550 530
Total	\$5688 880/year
Total system	\$9063 600/year
Unit cost	\$0.655/thousand m ³ \$2.48/1000 gal

*To convert from thousand m³ to mgd divide by 3.785.

Deep well disposal of concentrate was assumed. Table 11 summarises the costs associated with the use of nanofiltration systems at various treatment capacities, based on estimates using the reference design and a scaling approach described by Eisenburg & Middlebrooks [24]. Figure 2 compares the costs between GAC and nanofiltration for removing THMFP from 150 µg/L to 50 µg/L.

COMPARATIVE ANALYSIS

Making direct comparisons between the various alternatives is difficult. For example, moving the point-of-disinfection (chlorination) would seem to be the lowest cost option. Nanofiltration, although it is the most expensive for precursor removal, has the advantage of removing other contaminants such as total dissolved solids and various inorganics. Therefore, it might be used for achieving other treatment goals, in addition

Table 11 Nanofiltration cost summary in ¢/thousand m³* (¢/1000 gallons)

	Ground water system		Surface water system	
	Permeate capacity in thousand m ³ *	Surface concentrate disposal	Deep well concentrate disposal	Alum coagulation pretreatment with deep well concentrate disposal
0.3785		60.72 (230)	71.54 (271)	136.488 (517)
3.785		39.65 (150)	46.20 (175)	89.760 (340)
8.925		31.15 (118)	36.168 (137)	70.952 (268)
37.85		29.04 (101)	33.528 (127)	65.472 (248)
94.625		27.46 (104)	31.944 (121)	62.304 (236)
189.25		25.08 (95)	29.040 (110)	57.024 (216)
378.50		22.70 (86)	26.400 (100)	51.744 (196)

*To convert from thousand m³ to mgd divide by 3.785.

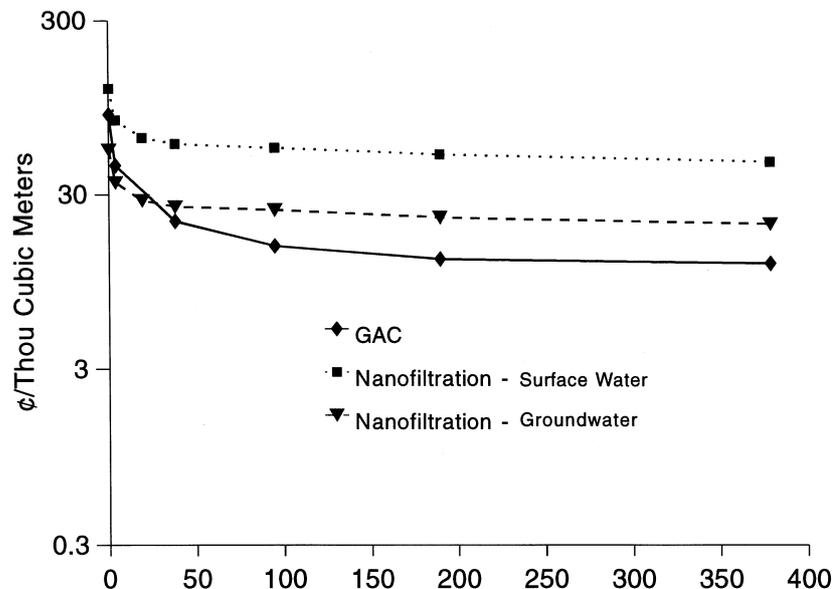


Fig. 2 Cost for removing precursors (150 µg/L to 50 µg/L)

to removing DBP precursors. For example, nanofiltration removed micro-organisms effectively, thus serving as an alternative for chemical disinfection. Although enhanced coagulation was not evaluated for cost it could be very effective if a utility is only slightly out of compliance, however, in addition to increased coagulation costs an additional cost may be associated with sludge handling. Clearly, disinfection is the lowest cost option for controlling disinfection by-products. However, as has been noted, there are also by-products associated with the use of some of the alternatives. For example, chloramination is as good a disinfectant as chlorine, but ozone may enhance the regrowth of some organisms. Retrofitting may be fairly easy with chloraminaton. For example, to switch from chlorine to chloramine may only require the addition of ammonia feed equipment. However, the use of ozone will require the construction of expensive ozone contactors. The use of chlorine dioxide will probably require the use of a reducing agent such as ferrous chloride, which was not included in this costing analysis.

Incremental costs

The technologies discussed would normally be applied incrementally to a utility's existing treatment. In order to illustrate the cost impact that this might incur we have assumed a conventional treatment system and will evaluate the incremental costs associated with disinfection by-products control.

Table 12 summarises the base cost associated with conventional treatment and the incremental costs for disinfection by-products control. The unit processes considered are those that are effective for precursor removal or for alternate disinfectants that will be used to control disinfection by-products.

RISK/RISK TRADEOFF

For many years the primary focus in the EPA's drinking water research programme was on controlling DBPs. It was generally assumed that conventional water treatment, as practised in the USA, would be protective against microbial contamination. However, it has become increasingly apparent that although infectious diseases are largely under control in industrialised countries, outbreaks continue to occur [25]. In the USA, since 1981, 58% of the 345 reported waterborne outbreaks occurred in a water system with inadequate or no disinfection. Recent waterborne outbreaks of cryptosporidiosis in the USA are a reminder that microbial pathogens continue to be a threat for industrialised countries. The largest waterborne outbreak ever recorded in the USA occurred in the spring of 1993 in Milwaukee, Wisconsin.

Contamination of the water supply by *Cryptosporidium* resulted in an estimated 403 000 cases of watery diarrhoea. Morbidity and mortality from waterborne infectious diseases may be lower in industrialised countries, but these types of risks persist and may have severe consequences.

Attempting to balance the risks of drinking water infection against exposure to potentially carcinogenic or toxic compounds requires an adequate quantitative assessment of the competing risks. Such a technique is not available and even if it were, comparing microbial and chemical risks would be difficult. Microbial risks are acute and result in immediate mortality and morbidity. By-product exposures are long-term, and most effects are expected later in life so that their costs are deferred. In developing countries with low life expectancies, a small increase in cancer risk from DBPs may not be considered important. In industrialised countries with longer life expectancies, waterborne disease risks may be small and as a result cancer mortality risks may be perceived as important. It

Item	Design flow in thousands m ³ * (average flow)			
	0.3785 (0.189)	3.785 (1.89)	37.85 (26.495)	378.5 (264.95)
Conventional treatment	136.8 (518)	45.7 (173)	12.1 (46)	8.2 (31)
Conventional treatment and nanofiltration	197.5 (748)	85.3 (323)	38.9 (147)	30.9 (117)
Conventional treatment plus GAC (Ce = 100 mg/L)	195.9 (742) to 207.8 (787)	68.1(258) to 78.9 (299)	27.2 (103) to 31.4 (119)	15.0 (57) to 18.5 (70)
Conventional treatment plus GAC (Ce = 50 mg/L)	198.3 (751) to 217.3 (823)	70.2 (266) to 87.6 (332)	28.2 (107) to 34.6 (131)	15.6 (59) to 21.6 (82)
Conventional treatment plus Chlorine/chloramine	141.2 (535)	45.9 (174)	12.1 (46)	8.2 (31)
Ozone/chlorine	157.1 (595)	47.8 (181)	13.5 (51)	9.0 (34)
Ozone/chloramine	161.6 (612)	48.0 (182)	13.5 (51)	9.0 (34)
Chlorine dioxide chlorine	160.8 (609)	47.0 (178)	12.1 (46)	8.2 (31)
Chlorine dioxide/chloramine	165.3 (626)	47.3 (179)	12.4 (47)	8.2 (31)

*To convert from thousand m³ to mgd divide by 3.785.

is therefore useful to view DBP control strategies in terms of the cost effectiveness of water treatment for preventing microbial risk in comparison to the costs and complexities of the technologies available for controlling DBPs [25]. Therefore, in addition to controlling disinfection by-products, water suppliers must assure that the water they produce is microbiologically safe. This is a major challenge facing the water supply industry.

SUMMARY AND CONCLUSIONS

Regulations to control contaminants in drinking water in the USA are expected to become more and more stringent. Forthcoming disinfection by-product regulations will effect virtually every community water system in the US. There are various ways to control disinfection by-products, one of which is to use an alternative to chlorine to control halogenated by-products. However, when this is done, one has to consider the consequences of using each disinfectant.

More efficient treatment will be required to meet future regulations. In addition, water treatment managers will have to become more knowledgeable about various treatment options that are cost-effective in order for them to meet present and future regulations. Although essentially exempt in the past, small water systems will probably have to comply with future regulations.

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Table 12 Incremental cost for disinfection by-product control in ¢/thousand m³ (£/1000 gallons)

BIBLIOGRAPHY

- Clark RM, Adams JQ, Lykins BW. DBP Control in Drinking Water. Cost and Performances. *J Environ Engng* 1994; **120**(4, July/August): 759–782.
- Symons JM, Stevens AA, Clark RM, Geldreich EE, Love OT Jr, DeMarco J. *Treatment techniques for controlling trihalo-methanes in drinking water*. Drinking Water Research Division, Municipal Environmental Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Cincinnati, OH 45268, EPA 600/2–81–156, 1981.
- McGuire MJ, Meadow RG. AWWARF trihalomethane survey. *JAWWA* 1988; **80**(1): 61–68.
- Chick H. An investigation of the laws of disinfection. *J Hyg* 1908; **8**: 92–158.
- Watson HE. A note on the variation of the rate of disinfection with change in the concentration at the disinfectant. *J Hyg* 1908; **8**: 536–542.
- Lykins BW, Goodrich JA, Hoff JC. Concerns with using chlorine-dioxide disinfection in the USA. *J Water SRT—Aqua* 1990; **39**(6): 376–386.
- Hoff JC. *Inactivation of microbial agents by chemical disinfectants*. US Environmental Protection Agency, EPA/600/286/067, 1986.
- Lykins BW Jr, Koffskey WE, Miller RG. Chemical Products and Toxicologic Effects of Disinfection. *JAWWA* 1986; **78**(11, November): 66–75.
- Korich DG, Mead JR, Madore MS, Sinclair NA, Sterling CR. Effects of ozone, chlorine dioxide, chlorine, and monochloramine on *Cryptosporidium parvum* oocyst viability. *Appl Environ Microbiol* 1990; **56**: 1423–1428.
- Singer PC. Control of disinfection by-products in drinking water. *J Environ Engng* 1994; **120**(4, July/August): 727–744.
- Stevens AA, Miltner RJ, Moore LA, Slocum CJ, Nash HD, Reasoner DJ, Berman D. Detection and control of chlorination

- by-products in drinking water. Proceedings: Conference on Current Research in Drinking Water Treatment, Cincinnati, OH, 24–26 March 1987.
- 12 Bull RJ. Toxicology of disinfectants and disinfection by-products. In: GF Craun, ed. *Safety of Chemical of Microbial Risk*, pp. 239–256. ILSI Press, International Life Sciences Institute, Washington, DC, 1993.
 - 13 Stevens AA, Moore LA, Miltner RJ. Formation and control of non-trihalomethane disinfection by-products. *JAWWA* 1989; **81**(8): 54–60.
 - 14 Pourmoghaddas H, Stevens AA, Kinman RN, Dressman RC, Moore LA, Ireland JA. Effect of bromide ion on formation of HAAs during chlorination. *JAWWA* 1993; **85**(1): 82–87.
 - 15 Minear RA, Bird JC. Trihalomethane: impact of bromide ion concentration on yield, species distribution, rate of formation and influence of other variables. In: Jolley RL, Brungs WA, Cummings RB, eds. *Water Chlorination: Environmental Impact and Health Effects*, Vol. 3, pp. 151–160. Ann Arbor Science Publishers Inc., Ann Arbor, MI, 1980.
 - 16 Cooper WJ, Meyer LM, Bufill CC, Cordal E. Quantitative effects of bromine on the formation and distribution of trihalomethane in groundwater with a high organic content. In: Jolley RL, Bross WA, Cotruvo JA, Cummings RB, Mettice JS, Jacobs VA, eds. *Water Chlorination: Environmental Impact and Health Effects*, Vol. 4, pp. 285–296. Ann Arbor Science Publishers Inc., Ann Arbor, MI, 1983.
 - 17 Miltner RJ. Pilot scale treatment for control of disinfection by-products. In: Clark R, Summers S, eds. *Strategies and Technologies for Meeting SDWA Requirements*, pp. 203–236. Technomics Inc., Lanaster, PA, 1992.
 - 18 Krasner SW, McGuire MJ, Jacangelo JG, Patania NL, Reagan KM, Aieta EM. The occurrence of disinfection by-products in US drinking water. *JAWWA* 1989; **81**(8, August): 41–53.
 - 19 Lykins BW Jr, Clark RM, Westrick JJ. Treatment technologies for meeting US drinking water regulations. Presentation at Joint Conference, Ontario Section AWWA/Ontario Municipal Water Association, Toronto, Ontario, Canada, 6–9 May 1990.
 - 20 Clark RM. Cost considerations. In: Brock McEwen J, ed. *Treatment Process Selection For Particle Removal*, pp. 265–302. American Water Works Association Research Foundation/International Water Supply Association, 1998.
 - 21 US Environmental Protection Agency. *Technology costs for the interim enhanced surface water treatment rule*. Office of Ground Water and Drinking Water, Washington, DC, 1997.
 - 22 Taylor JS, Mulford LA, Barrett WM, Duranceau SJ, Smith DK. *Cost and performance of membranes for organic control in small systems*, US EPA 600/2–89/022, May 1989.
 - 23 Suratt W. Estimating the costs of membrane water treatment plants. Proceedings: AWWA Membrane Processes Conference, Orlando, FL, 10–13 March 1991.
 - 24 Eisenburg T, Middlebrooks E. *Reverse Osmosis Treatment of Drinking Water*. Ann Arbor Science, 1986.
 - 25 Craun GF. Balancing chemical, microbial risks of drinking water disinfection. Prevention of infectious waterborne disease is our primary concern. In: *Water Quality in Latin America. Balancing the Microbial and Chemical Risks in Drinking Water Disinfection*. ILSI Press, Washington, DC, 1996: 183–199.