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CHLORINE

Keith A. Christman
Chlorine Chemistry Council
Arlington, VA, USA

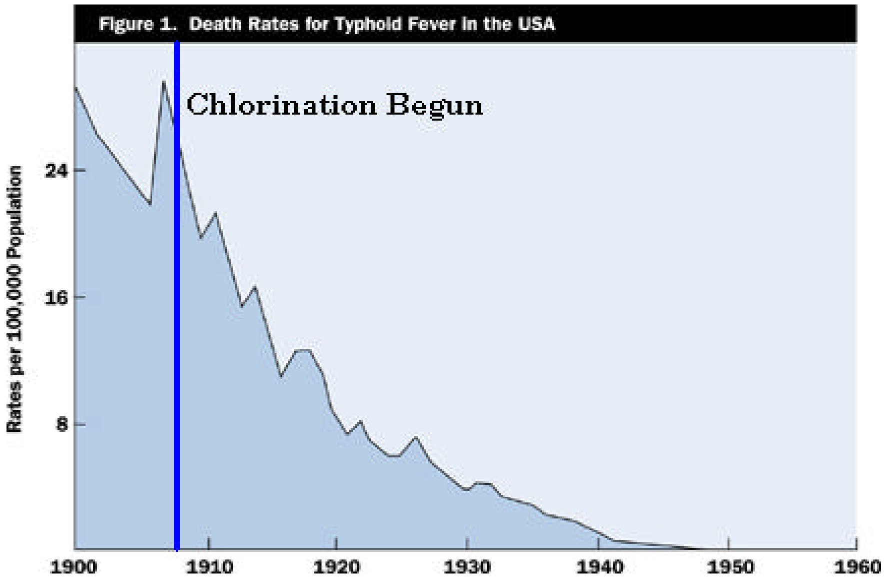
ABSTRACT

Chlorination has played a critical role in protecting drinking water supplies from waterborne infectious diseases for nearly a century. The chlorination of drinking water has been widely recognized as one of the most significant advances in public health protection. Filtration and chlorination have virtually eliminated waterborne diseases such as cholera, typhoid, dysentery and hepatitis A in developed countries. In the United States over 98% of water supply systems that disinfect drinking water use chlorine because of its germicidal potency, economy and efficiency. In addition, chlorine-based disinfectants are the only major disinfectants with the lasting residual properties that prevent microbial regrowth and provide continual protection throughout distribution from the treatment plant to the home. This paper discusses chlorine advantages and disadvantages and updates the reader on current knowledge about disinfection byproducts.

1. History

Chlorination has played a critical role in protecting drinking water supplies from waterborne infectious diseases for 90 years. Filtration and chlorine disinfection of drinking water have been responsible for a large part of the 50 percent increase in life expectancy in developed countries during the 20th century. This fact led *Life* magazine to recently cite drinking water filtration and chlorination as "probably the most significant public health advance of the millennium."

One of the earliest uses of chlorine as a disinfectant was introduced by Dr. Ignaz Semmelweis in 1846. While serving at a Vienna hospital, he determined that child bed fever and other infections were being transmitted among patients by doctors who failed to wash their hands between examinations. He instituted a disinfecting procedure requiring physicians to wash their hands with soap and chlorine water. One of the first known uses of chlorine for water disinfection occurred in 1854 when Dr. John Snow attempted to disinfect the Broad Street Pump water supply in London after an outbreak of cholera. Following a typhoid outbreak in 1897, Sims Woodhead used “bleach solution” as a temporary measure to sterilize potable water distribution mains at Maidstone, Kent (England).



Continuous chlorination of drinking water began in the early years of this century in Great Britain, where its application sharply reduced typhoid deaths. Shortly after this dramatic success, chlorination in the United States began in Jersey City, New Jersey in 1908. Adoption by other cities and towns across the US soon followed and resulted in the virtual elimination of waterborne diseases such as cholera, typhoid, dysentery and hepatitis A. (White, 1986) Before the advent of chlorination for drinking water treatment, typhoid fever killed about 25 out of 100,000 people in the US annually, a death rate approximating that currently associated with automobile accidents.

2. Understanding how chlorine kills pathogens

In 1881, German bacteriologist Robert Koch demonstrated under controlled laboratory conditions that pure cultures of bacteria could be destroyed by hypochlorite (bleach). The bulk of chlorine disinfection research, which was conducted from the 1940s to the 1970s with a focus on bacteria, provided observations as to how chlorine kills the microorganism. The observations that (1) bacterial cells dosed with chlorine release nucleic acids, proteins and potassium and (2) membrane functions such as respiration and active transport are affected more by chlorine than are cytoplasmic processes, directed researchers’ attention to the surface of the bacterial cell. The hypothesis was that the bacterial cell wall, under environmental stress, could interact with chlorine. Chlorine exposure appears to cause physical, chemical, and biochemical alterations to the cell wall, thus destroying the cell’s protective barrier, terminating vital functions, resulting in death of the microorganism. A possible sequence of events during chlorination would be: (1) disruption of the cell wall barrier by reactions of chlorine with target sites at the cell surface, (2) release of vital cellular constituents from the cell, (3) termination of membrane-associated functions, and (4) termination of cellular functions within the cell. During the course of this sequence of events, the microorganism dies, meaning it is no longer capable of growing or causing disease. (Ask the Experts, *Scientific American* Web site, 1998)

2.1 CT values

For effective water treatment, the water supply industry has recognized the need for adequate exposure to the disinfectant and sufficient disinfectant dosage for a certain amount of time. In the 1980s, the two functions were combined with the development of the CT values for various disinfectants.

CT represents the combination of the disinfectant dosage and the length of time water has been exposed to a minimum amount of the disinfectant residual. Mathematically it is represented as

CT = concentration x time
concentration = final disinfectant concentration in mg/l
time = minimum exposure time in minutes

In an assessment of disinfection effectiveness, two types of organisms have been chosen as disinfection surrogates – the protozoan *Giardia* and viruses. CT values established for disinfection of surface waters require treatment plants to achieve a three-log or 99.9% reduction in *Giardia* and a four-log or 99.99% virus reduction. Tables 1 and 2 provide CT data for the various disinfectants. It is important to recognize that the use of chlorine as the disinfectant is only one part of the treatment process. Equally important is the need for improved filtration to remove organisms. A combination of proper disinfection and filtration is most effective in providing safe drinking water. Recent experiments in controlling *Cryptosporidium* also suggest the effectiveness of filtration in the water treatment process.

Table 1. CT Values for 99.9% Reduction of *Giardia Lamblia*

Disinfectant	pH	Temperature °F (°C) 33.8 (1)	41 (5)	50 (10)	59 (15)	68 (20)	77 (25)
Free Chlorine	6	165	116	87	58	44	29
	7	236	165	124	83	62	41
	8	346	243	182	122	91	61
	9	500	353	265	177	132	88
Ozone	6-9	2.9	1.9	1.4	0.95	0.72	0.48
Chlorine Dioxide	6-9	63	26	23	19	15	11
Chloramines	6-9	3800	2200	1850	1500	1100	750

Source: EPA Guidance Manual (1989)

Table 2. CT Values for Inactivation of Virus

Disinfectant	pH (6-9) Inactivation	Temperature °F (°C) 39.9 (0.5)	41 (5)	50 (10)	59 (15)	68 (20)	77 (25)
Free Chlorine	2	6	4	3	2	1	1
	3	9	6	4	3	2	1
	4	12	8	6	4	3	2
Ozone	2	0.9	0.6	0.5	0.3	0.25	0.15
	3	1.4	0.9	0.8	0.5	0.4	0.25
	4	1.8	1.2	1	0.6	0.5	0.3
Chlorine Dioxide	2	8.4	5.6	4.2	2.8	2.1	-
	3	25.6	17.1	12.8	8.6	6.4	-
	4	50.1	33.4	25.1	16.7	12.5	-
Chloramines	2	1243	857	643	428	321	214
	3	2063	1423	1067	712	534	356
	4	2883	1988	1491	994	746	497

Source: EPA Guidance Manual (1989)

3. Chlorine: the disinfectant of choice for drinking water

Chlorine-based chemicals have been the disinfectants of choice for treating drinking water for nearly a century. In fact, some 98% of all systems in the US that treat water employ chlorine-based disinfectants. Facilities use chlorine because it has done its job extremely well, is safe to use when handled properly and is very cost-effective. More than 200 million Americans and Canadians receive chlorine-disinfected drinking water every day.

Table 3. Disinfection practices in the United States

Disinfectant	Percentage*
Chlorine gas	87.0
No ammonia	67.0
Ammonia added	20.0
Chlorine & Hypochlorite	4.5
Chlorine & Chlorine Dioxide	3,0
Chlorine & Chlorine Dioxide & Ammonia Nitrogen	1.5
Hypochlorite	1.5
Chlorine & Hypochlorite & Ammonia Nitrogen	0.75
Chlorine & Chlorine Dioxide & Hypochlorite	0.37
[Subtotal: 98.6% use chlorine-based disinfectants]	
Ozone	0.37
Other	0.75

*percentage of facilities that disinfect

Source: 1989-1990 AWWA Disinfection Committee Survey of Disinfection Practices

While chlorine's most important attributes are its broad-spectrum germicidal potency and persistence in water distribution systems, its ability to efficiently and economically address many other water treatment concerns has also supported its wide use. Chlorine-based compounds are the only major disinfectants exhibiting lasting residual properties. Residual protection guards against microbial regrowth and prevents contamination of the water as it moves from the treatment plant to household taps.

Chlorine's popularity in water disinfection is based on many factors. A study by J. Carrell Morris of the Harvard University School of Medicine identified many of chlorine's benefits in water treatment. (Morris, 1985)

- **Potent germicide.** The demonstrated use of chlorine reduces the level of disease-causing microorganisms in drinking water to almost immeasurable levels.

- **Residual qualities.** Chlorine produces a sustained residual disinfection action "unique among available large-scale water disinfectants". Chlorine's superiority as a residual disinfectant remains true today. The presence of a sustained residual maintains the hygienicity of the finished drinking water from the treatment plant to the consumer's tap.

- **Taste and odor control.** Chlorination of drinking water reduces tastes and odors. Chlorine oxidizes many naturally occurring substances such as foul-smelling algae secretions and odors from decaying vegetation, resulting in nonodorous, better-tasting drinking water.

- **Biological growth control.** Chlorine's powerful germicidal action eliminates slime bacteria, molds and algae. Chlorine controls these nuisance organisms, which typically can grow in reservoirs, on the walls of transmission water mains and in storage tanks.

- **Chemical control.** Chlorine in water treatment destroys hydrogen sulfide and removes ammonia and other nitrogenous compounds that have unpleasant tastes and hinder disinfection.

3.1 Equipment costs

Costs for equipment vary depending upon the amount and type of chemical to be fed, the type of control required, if any, and the needs of the installation. The estimates of equipment costs are listed in Table 4.

Table 4. Equipment costs

Description	Costs
Manual Gas Feeder, Container Mounted	$2,000
Automatic Gas Feeder, Wall Mounted	$4.000
Automatic Gas Feeder, Cabinet Mounted	$6,000
Manual Chemical Feed Pump	$1,000
Automatic Chemical Feed Pump	$3,000
Gas Detector, Wall Mounted	$2,000
Emergency Kit, Type A	$1,500
Emergency Kit, Type B	$2,500

3.2 Operating and maintenance costs

The operating and maintenance costs associated with feeding chlorine and ammonia gases, as well as solutions of hypochlorite and ammonia salts, vary with the type of chemical and size and complexity of the equipment. Plan for annual O&M costs to range from 10 to 20 percent of equipment costs. Equipment manufacturers provide a list of recommended spare parts, which should be kept on hand at a minimum. Most manufacturers will train treatment plant personnel in maintenance and service of their equipment. In addition, some manufacturers provide an exchange program to permit servicing of their equipment at their facilities. This allows operating personnel to send equipment in for repair while a spare or exchanged unit is installed for operation during the time of repair service.

4. Public health protection — a job not complete

Chlorinated drinking water's chief benefit is the protection of public health through the control of waterborne diseases. It plays a paramount role in controlling pathogens in water that cause human illness, as evidenced by the virtual absence of waterborne diseases such as typhoid and cholera in developed countries.

Untreated or inadequately treated drinking water supplies remain the greatest threat to public health, especially in developing countries, where nearly half the population drinks contaminated water. In these countries, diseases such as cholera, typhoid and chronic dysentery are endemic and kill young and old alike. In 1990, over three million children under the age of five died of diarrheal diseases. Unfortunately, the availability of safe drinking water supplies in many areas is practically nonexistent, due to poverty, poor understanding of water contamination, and lack of a treatment and delivery infrastructure. International assistance groups, including the World Health Organization and the Pan American Health Organization (PAHO), have long-standing technical assistance and education programs to improve water supply and sanitation practices. It has been estimated that such improvements - including chlorine disinfection - can prevent 25% of all diarrheal outbreaks and reduce childhood mortality by equal levels. (Craun, 1996)

A recent example of the continuing public health threat from waterborne disease outbreaks occurred here in Peru in 1991, where a major causative factor was the absence or inadequacy of drinking water disinfection. This failure to disinfect was reportedly based in part on concern about US reports of the presence and potential risks of chlorinated disinfection by-products. The result has been a persistent epidemic of cholera, its first appearance in the Americas in this century. The epidemic spread to 19 Latin American countries and was only partially abated through public health interventions supported by PAHO's advice and technical assistance. Nearly a million cases and 10,000 deaths were reported. (Craun, 1996)

These statistics strongly reinforce the concept that water disinfection must be a primary tool in protecting public health worldwide. As noted by the American Academy of Microbiology, "The single, most important requirement that must be emphasized is that disinfection of a public water supply should not be compromised." (Ford and Colwell, 1996)

At the 1992 First International Conference on the Safety of Water Disinfection, a paper by Gunther F. Craun et al. discussed the cost-effectiveness of water treatment for pathogen removal.(Craun, 1994a) An evaluation of five pathogens and treatment costs shows the favorable economic benefits of preventing infectious waterborne diseases. These benefits were determined based on an annual probability of illness and death, assuming no water treatment, and a cost of $3,000 per illness and $500,000 per death. The effectiveness of water treatment in reducing waterborne diseases depends on the quality of the source water and how the treatment system is operated and maintained.

The table below shows positive benefit-cost ratios associated with the installation of chlorination and conventional water treatment to remove and control pathogens in drinking water. The ratios were arrived at by comparing the probability of foregone disease, using the difference between the disease probabilities with no water treatment and those for various levels of water treatment in communities with populations of 10,000, 100,000 and 500,000.

Table 5. Positive benefit-cost ratios -- water treatment & pathogen removal

Population	10,000	100,000	500,000

(a) Treatment costs only			
Good water source			
chlorination alone	50.2	86.2	98.6
conventional treatment plus chlorination	18.4	39.5	53.1
Poor water source			
chlorination alone	37.6	64.6	73.9
conventional treatment plus chlorination	17.5	37.5	53.1
(b) Complete water systems			
Good water source			
chlorination alone	5.0	8.6	9.9
conventional treatment plus chlorination	1.8	4.0	5.3
Poor water source			
chlorination alone	3.8	6.5	7.4
conventional treatment plus chlorination	1.8	3.8	5.3
(c) Worst-case assumptions			
Good water source			
chlorination alone	8.0	13.8	15.8
conventional treatment plus chlorination	2.9	6.3	8.5
Poor water source			
chlorination alone	6.0	10.4	11.8
conventional treatment plus chlorination	2.8	6.0	8.1

Ratio of monetary benefit of disease avoided to cost of drinking water treatment.

The report concluded that "municipal water systems designed to prevent waterborne infectious disease are one of the most effective investments of public funds that society can make. Even conservative estimates under worst-case conditions show benefit-cost ratios of 3:1 for small systems and 8:1 for large systems. Pathogen-free drinking water is a bargain."

Regarding comparison of these benefits with potential cancer risks associated with drinking water disinfection, the group noted that the costs of preventing the relatively small carcinogenic risks may not be warranted in light of many other public health risks that should be reduced.

4.1 Risks of waterborne disease: the old and the new

Waterborne diseases continue to present challenges to public health officials and water suppliers. The presence of disease-causing microorganisms in tap water typically results from poor source water quality, lapses in disinfection and filtration treatment processes, or compromised distribution systems.

In most instances, outbreaks of waterborne diseases occur in water systems with inadequate or no disinfection. However, there are new concerns about emerging pathogens, such as *Cryptosporidium*, that appear even in high-quality water supplies. (Craun et al., 1994b)

Waterborne pathogens that cause disease fall into three general classes - bacteria, viruses and parasitic protozoa, each with various identified species. Bacteria and viruses contaminate both surface and groundwater, whereas parasitic protozoa appear predominantly in surface water. (Tardiff, 1993)

Table 6. Waterborne pathogens

Bacteria	Viruses	Protozoa
Campylobacter	Norwalk-like	*Cryptosporidium parvum*
Escherichia coli	Entero (poliomyelitis, coxsackie,echo, rotavirus)	*Giardia lamblia*
Salmonella (non-typhoid)	Hepatitis A	*Entamoeba histolytica*
Shigella	Rotavirus	
Yersinia		
Vibrio (non-cholera)		
Salmonella (typhoid)		
Vibrio (cholera)		
Legionella		

4.2 Illnesses associated with waterborne pathogens

Bacteria and protozoa generally induce gastrointestinal disorders with a wide range of severity. Bacteria also cause life-threatening diseases such as typhoid and cholera. Viruses cause serious diseases such as aseptic meningitis, encephalitis, poliomyelitis, hepatitis, myocarditis and diabetes. (Payment, 1993) In addition, gastrointestinal disorders may be attributed to unidentified or unspecified microorganisms. In terms of occurrence in the US, protozoan infections are the most common, followed by bacterial infections and then viral infections. (Craun, 1996b)

Table 7. Causes of Waterborne Outbreaks in USA, 1971-92

	Percent of Outbreaks	
Cause of Outbreak	**Community Water Systems**	**Non-Community Water Systems**
Contamination of distribution system	29%	7%
Inadequate disinfection of unfiltered surface water	24%	8%
Inadequate disinfection of groundwater	14%	30%
Untreated groundwater	11%	42%
Inadequate filtration of surface water	11%	1%
Miscellaneous; unknown causes	5%	6%
Inadequate chemical feed	3%	1%
Untreated surface water	2%	5%
Inadequate filtration of groundwater	1%	0
TOTAL	100%	100%

Craun also matched outbreaks with source water and treatment techniques in community water systems. For systems using surface water, source contamination and treatment deficiencies were identified as the major causative agents. Untreated or inadequately treated groundwater was responsible for 10 to 14 percent of all outbreaks from 1971 to 1992. Overall during the period, contaminated, untreated and inadequately treated groundwater was responsible for more outbreaks than contaminated surface water.

5. The disinfection by-products debate

For almost 25 years, drinking water regulatory policy in the United States has focused primarily on mitigating potential health risks associated with chemical contaminants in drinking water supplies. This emphasis on chemical contaminants was caused by a false belief that microbiological threats were largely under control and, to a certain extent, “chemophobia.”

In 1974, US Environmental Protection Agency (EPA) scientists determined that chlorine reacts with certain organic materials during water disinfection to create trihalomethanes (THMs), including chloroform in particular, with lesser amounts of other THMs. Toxicological studies undertaken on chloroform suggested that it was carcinogenic to laboratory animals, although at levels much higher than those found in drinking water. Fears that THMs could be a potential human carcinogen led the EPA to set regulatory limits for these disinfection by-products (DBPs) at 100 parts per billion (ppb) for systems serving more the 10,000 people. In the US, however, there still are no enforceable standards for disinfection by-products in small systems.

In 1994, the EPA proposed stage I of a disinfectants/disinfection by-products rule. This rule would reduce the maximum contaminant level (MCL) for DBPs and extend coverage to small systems. The EPA recommended revisions to this proposed rule in November 1997. These revisions were based on an agreement between members of a Federal Advisory Committee that included representatives from water utilities, the Chlorine Chemistry Council, public health officials, environmentalists and other stakeholder groups. The goal of the new stage I disinfection by-product rule is to reduce levels of DBPs in drinking water without compromising microbial protection. The rule mandates a process called enhanced coagulation to remove DBP precursors. The proposal also sets new MCLs for total THMs at 80 ppb, haloacetic acids at 60 ppb and bromate at 10 ppb. The Federal Advisory Committee was cautious about encouraging the use of alternative disinfectants that would produce other unknown by-products. The Committee also was very cautious about any changes that would encourage utilities to reduce the level of disinfection currently being practiced. There was widespread agreement among members of the group that the risks of microbial pathogens in drinking water must not be allowed to increase. This proposed rule will be finalized in November 1998.

5.1 Chloroform risk less than previously believed

In finalizing the Stage I DBP rule, the EPA has reviewed the science basis for the rule. On March 31, 1998, the EPA published a Notice of Data Availability on Disinfectants and Disinfection By-products. This notice proposed changes to maximum contaminant level goals (MCLG) for DBPs based on new research which recently became available. The EPA sets MCLGs at a level at which no known or anticipated adverse effects on health are expected and which allows for an adequate margin of safety. The most important change in this notice impacting chlorine was the increase in the MCLG for chloroform from 0 to 300 ppb. In proposing this change, the EPA followed the recommendations of an expert panel convened by the International Life Sciences Institute. The expert panel concluded that chloroform was “likely to be a carcinogen above a certain dose range, but unlikely to be carcinogenic below a certain dose.” (ILSI, 1997)

Other groups have also reviewed the data on DBPs and cancer. In 1990, the International Agency for Research on Cancer (IARC) convened an expert workshop to evaluate the possible carcinogenicity of chlorinated drinking water. IARC is an investigative research branch of the World Health Organization, and regularly evaluates the human carcinogenicity of different materials. The IARC working group evaluated every available major scientific analysis of the potential health effects of chlorinated drinking water. They concluded that chlorinated drinking water ***is not a classifiable human carcinogen***. (IARC, 1991)

The National Toxicology Program (NTP) of the US Department of Health and Human Services reached a similar conclusion in 1990. The NTP study examined the carcinogenicity of chlorinated water in laboratory rats and mice. It is important to note that the water used in this study was chlorinated in orders of magnitude above the chlorination levels found in public water supplies. The results of the NTP study reported that there was no evidence of carcinogenic activity in male and female mice or male rats from the consumption of chlorinated water. Equivocal evidence of carcinogenic activity was noted in female rats. (NTP, 1990)

Currently, studies on whether chlorine disinfection by-products cause cancer are not conclusive. In addition to concerns about cancer, new studies have focused on miscarriages and developmental effects of DBPs. A recent study from the California Department of Health Services reported an elevated risk of miscarriage in women who drank tap water with high levels of DBPs. However, when the three communities studied were analyzed separately, this result was statistically significant in only one of the three communities. It is not clear that the miscarriages were in any way causally related to chlorination, and further research is required.

5.2 Comparative risks: microbial versus chemical contaminants

The task for regulators is to maximize public health protection by managing the relative human health risks of microbiological and chemical contaminants in drinking water. Continuing evidence of waterborne disease occurrence suggests that microbial risks should receive a much higher level of attention than DBPs For this reason, The American Academy of Microbiology has recommended that "the health risks posed by microbial pathogens should be placed as the highest priority in water treatment to protect public health". (Ford and Colwell, 1996) Furthermore, EPA staff have noted that the risks of microbial disease from undisinfected drinking water are 100 to 1000 times greater than the risks posed by DBPs. (Regli, 1993)

In a 1993 study submitted to the EPA for the Chlorine Institute during earlier negotiations over the DBP rule, Dr. Robert Tardiff reported results of applying five essential criteria for determining the comparative health risks of microbial and chemical contamination. The five criteria for assessing water-related diseases are: 1) types, 2) incidence, 3) severity, 4) latency, and 5) certainty of occurrence. (Tardiff, 1993)

Dr. Tardiff's report concluded that the risk of microbial disease is much greater than the risk posed by chemicals suspected of causing cancer in humans. Importantly, there are significant differences in the incidence of disease, the amount of time (latency) between exposure and clinical illness, and the certainty that many people will become ill. Compared to chemical risks, microbial risks are much greater (1,000 to 100,000 times), their latency is very much shorter (days vs. decades), and they will almost certainly cause illness in humans.

A 1994 report published by the International Society of Regulatory Toxicology and Pharmacology stated that "the reduction in mortality due to waterborne infectious diseases, attributed largely to chlorination of potable water supplies, appears to outweigh any theoretical cancer risks (which may be as low as 0) posed by the minute quantities of chlorinated organic chemicals reported in drinking waters disinfected with chlorine." (Coulston and Kolbye, 1994)

This view is supported by the American Academy of Microbiology: "It is important to point out that there is no direct and conclusive evidence that disinfection by-products affect human health at concentrations found in drinking water ... Concerns over the toxicology of DBPs should not be allowed to compromise successful disinfection of drinking water, at least without data to support such decisions". (Ford and Colwell, 1996)

Although most research attention has focused on the DBPs of chlorine, other chemical disinfectants also produce by-products when they react with organic matter and other precursors in raw water. Bromate, for example, is mainly a by-product of ozonation of high bromide waters. Bromate is being regulated by the EPA in the stage I rule.

5.3 Control of disinfection by-products

While maintaining adequate disinfection is an absolute necessity, there are some things that can be done to reduce DBP levels without compromising microbial protection. The ability of treatment plants to reduce DBPs depends somewhat on economics. If resources are not available to reduce DBPs, the treatment plant should still continue to adequately disinfect water.

Water suppliers can employ treatment techniques that maximize potable water safety and quality while minimizing the risk of DBP formation. One of the best methods to control DBPs from any disinfection process is to remove organic precursors prior to disinfection. Other conventional methods include changing the point of chlorination, using chloramine in the distribution system and lowering the chlorine feed rate, although this may lead to unacceptable increases in microbial risk. An American Water Works Association (AWWA) Water Quality Committee report identified effective procedures for reducing the formation of trihalomethanes **(**THMs**)**, as follows: (AWWA, 1991)

5.3.1 Organic precursor removal

There are three ways to effectively remove organic precursors:

Coagulation and clarification

Most treatment plants optimize their coagulation process for turbidity (particle) removal. Coagulation processes can, however, be optimized for natural organic matter removal. Precursors are removed when alum or iron salts are used as coagulants for turbidity control. Further precursor removal is usually achieved by reducing the pH prior to or during the addition of these coagulants.

Adsorption

Adsorption processes have been used successfully in some applications for removing disinfection by-product precursor material. Activated carbon can provide adsorption, and significant research has been dedicated to determining the available capacity of activated carbon for dissolved organics and specific micropollutants. Both granular activated carbon and powdered activated carbon perform this function.

Membrane technology

Membranes have been used historically for desalination of brackish waters. The process uses hydraulic pressure to force the liquid through a semi-permeable membrane. This technology has demonstrated excellent removal of THM precursors. The AWWA report states that membrane procedures “actually remove precursors from the finished product (potable water) which makes it a promising alternative for future control of THMs and other disinfection by-products”.

Many of these technologies may be cost prohibitive in developing countries. If that is the case, it cannot be emphasized enough that proper disinfection should be maintained.

5.4 Alternative treatment processes

Alternatives to chlorination have been studied throughout the history of water treatment, and various disinfection methods have been proposed. Some treatment techniques have questionable value in drinking water treatment. Studies by Richard J. Bull, W.P. Heffernan and others indicated that alternative disinfectants also produced a series of by-products. These findings demonstrated that all known methods (with the possible exception of ultraviolet radiation) of drinking water disinfection involve the use of reactive chemicals and, as such, lead to by-product formation. (Bull and Kopfler, 1991)

The water industry has been assessing alternatives to chlorine-based disinfectants. While each alternative has its advantages and disadvantages, all must be assessed on the basis of risks and uncertainties, as well as benefits. This is especially important in light of the limited experience and scientific knowledge associated with these processes. Compared to chlorination, relatively little is known about the potential by-products of alternative disinfectants.

The known advantages and disadvantages associated with chlorine-based and alternative disinfection procedures are described below: (White, 1986)

5.4.1 Chlorine-based disinfectants

<u>Chloramines</u>
This process involves the addition of ammonia and chlorine compounds to a water filtration plant. When properly controlled, the mixture forms chloramines. They are commonly used to maintain a residual in the distribution system following treatment with a stronger disinfectant, such as free chlorine.

Chloramine advantages
- Persistent residual
- Taste and odor minimization
- Lower levels of THM and haloacetic acid (HAA) formation
- Effective disinfection of biofilms in the distribution system

Chloramine disadvantages
- Produces disinfection by-products, including nitrogen-based compounds as well as chloral hydrate which may be regulated as a DBP in the future. There is limited information on the toxicity of chloramine disinfection by-products. In an analysis of the health effects of alternatives, Bull states that “there is little information on which to base an estimate of the health hazard that chloramine poses.” (Bull and Kopfler, 1991)

- Presents problems to individuals on dialysis machines. Chloramine residuals in tap water can pass through membranes in dialysis machines and directly induce oxidant damage to red blood cells.
- Causes eye irritation. Exposure to high levels of chloramine may result in eye irritation.
- Requires increased dosage and contact time (higher CT values, e.g., concentration x time)
- Has questionable values as viral and parasitic germicide
- Can promote growth of algae in reservoirs and an increase in distribution system bacteria due to residual ammonia
- Can produce high levels of HAAs
- Provides weaker oxidation and disinfection capabilities than free chlorine

Chlorine Dioxide (ClO_2)

Chlorine dioxide is generated on-site at water treatment facilities. The popularity of chlorine dioxide as a water disinfectant increased in the 1970's when it was discovered that it did not promote THM formation.

Chlorine dioxide advantages

- Acts as an excellent virucide
- Does not react with ammonia nitrogen to form chlorinated amines
- Does not react with oxidizable material to form THMs; destroys up to 30% of the THM precursors
- Destroys phenols which cause taste and odor problems in potable water supplies
- Forms few chlorinated DBPs such as THMs or HAAs
- Disinfects and oxidizes effectively, including good disinfection of both *Giardia* and *Cryptosporidium*
- Works at low dosage in post-disinfection step with no need of booster stations
- Improves removal of iron and manganese by rapid oxidation and settling of oxidized compounds
- Does not react with bromide to form bromate or brominated by-products

Chlorine dioxide disadvantages

- Decomposes to inorganic by-products. Chlorine dioxide decomposes to chlorite and to a lesser extent chlorate ion.
- Requires on-site generation equipment and handling of chemicals
- Occasionally poses unique odor and taste problems

5.4.2 Alternative Disinfectants

<u>Ozone</u>

Ozone has been used for several decades in Europe for taste and odor control, color removal and disinfection.

Ozone advantages

- Acts as an excellent virucide
- Disinfects and oxidizes very effectively
- Produces no chlorinated THMs, HAAs or other chlorinated by-products
- Enhances turbidity removal under certain conditions
- Inactivates both *Cryptosporidium* and *Giardia*, as well as other known pathogens
- Controls taste and odor

Ozone disadvantages

- Produces disinfection by-products, including:
  - -Aldehydes
  - -Ketones
  - -Carboxylic acids
  - -Brominated THMs including bromoform
  - -Brominated Acetic acids
  - -Bromate
  - -Quinones
  - -Peroxides
- Fosters THM formation when some ozonation by-products combine with secondary disinfection processes. A biologically activated filter will likely be necessary to remove these newly formed precursors.
- Does not provide a persistent residual
- Raises regulatory concerns. Future disinfection by-product regulations may require plants using ozone to install costly precursor removal systems (such as granular activated carbon filtration systems).
- Requires capital investment. Ozone must be produced on-site by costly generation that requires a high level of maintenance and substantial operator training.
- Promotes microbial growth. Ozone readily reacts with more complex organic matter and can break these down to smaller compounds that serve to increase nutrients in water supplies, thus enhancing microbial regrowth in water distribution systems.

<u>Ultraviolet Radiation (UV)</u>

This process involves exposing water to UV radiation, which inactivates various microorganisms. The technique has enjoyed increased application in waste-water treatment but very limited application in potable water treatment.

Ultraviolet radiation advantages
- No chemical storage, handling or feed equipment required
- No identified disinfection by-products

Ultraviolet radiation disadvantages
- No residual action
- High maintenance requirements
- High initial capital costs
- High operating (energy) costs
- Disinfecting action can be compromised by variables such as water clarity, hardness (scaling on the UV tubes), wavelength of the UV radiation, or power failure.

Table 8. Drinking water disinfectants at a glance

Disinfectants	Disinfection Effectiveness	Residual Maintenance	State of Information on By-Product Chemistry	Color Removal	Removal of Common Odors
Chlorine	Good	Good	Adequate	Good	Good
Chloramines	Poor	Good	Limited	Unacceptable	Poor
Chlorine Dioxide	Good	Unacceptable	Adequate	Good	Good
Ozone	Excellent	Unacceptable	Limited	Excellent	Excellent
Ultraviolet Radiation	Fair	Unacceptable	Nil	N/A	N/A

Source: Trussell, R. Rhodes, *Control Strategy 1: Alternative Oxidants and Disinfectants.* 1991.

5.4.3 Unknown factors associated with alternatives

Scientific investigation of risk associated with alternative disinfectants and alternative disinfection by-products is limited. A decision by water facilities to switch from chlorination could be risky because scientists know so little about disinfection by-products from processes other than chlorination.

Dr. Richard Bull noted in his analysis of the health effects of disinfectants and disinfection by-products that “the most irresponsible act would be to jump to unproved alternatives because of perceived risks with present technologies that are just beginning to be understood.” (Bull and Kopfler, 1991)

The EPA acknowledged during the development of disinfectants and disinfection by-products regulations that “we [the EPA] currently do not have a good understanding of the by-products formed from alternate disinfectants and some of their associated health risks”. (US EPA, 1991)

Determining the health risks associated with disinfectants and disinfection by-products requires additional research, especially focused on the major disinfection alternatives. According to William H. Glaze et al. (including Dr. Bull), research is needed to: (1) assess the relative toxicological hazards of the disinfectants and their by-products and (2) develop biologically-based models for the dose-response relationships of these chemicals. (Glaze et al., 1993)

6. The future of chlorine disinfection

The disinfection by-products debate has led some people to think that chlorine’s use in drinking water treatment will diminish. This is highly unlikely. Alternative disinfectants also create by-products. There are other, more appropriate ways to reduce disinfection by-products, such as precursor removal technologies.

Furthermore, chlorine is the disinfectant of choice for drinking water for a number of reasons. Its wide range of benefits cannot be provided by any other single disinfectant. Chlorine-based disinfectants provide the most effective and reliable residual in distribution systems. This residual is an important part of the multi-barrier approach to preventing waterborne disease.

According to the World Health Organization, **disinfection by chlorine is still the best guarantee of microbiologically safe water** (WHO Regional Office for Europe, *Drinking Water Disinfection*). This is unlikely to change in the near future.

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