Environmental Microbiology

7 Disinfection

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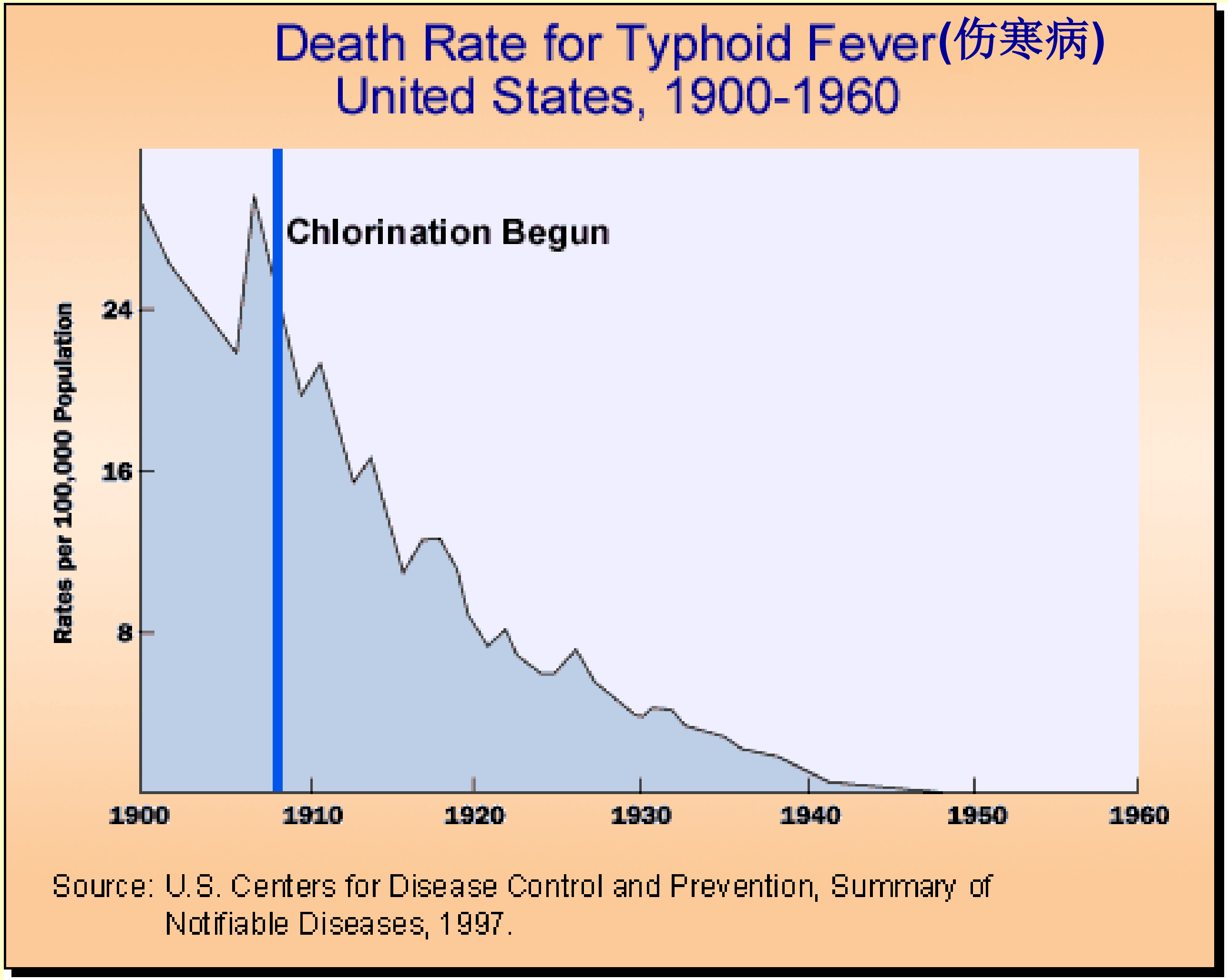
Introduction

Safe practice of chlorination of drinking water has improved human lives for most of the last century – Chlorine is a potent disinfectant and it leaves residue that protects the water quality in the distribution network. In the past people object the taste and odor of chlorinated water



Recent Development

- The “problem” of **disinfection Byproducts(DBP):**
  - Since 1970s the discovery of the DPBs,trihalo-methanes (THMs) and other halogenated organics, has put the continuous use of chlorine and the related products in the field of drinking water disinfection into question due to their potential cancer causing property.

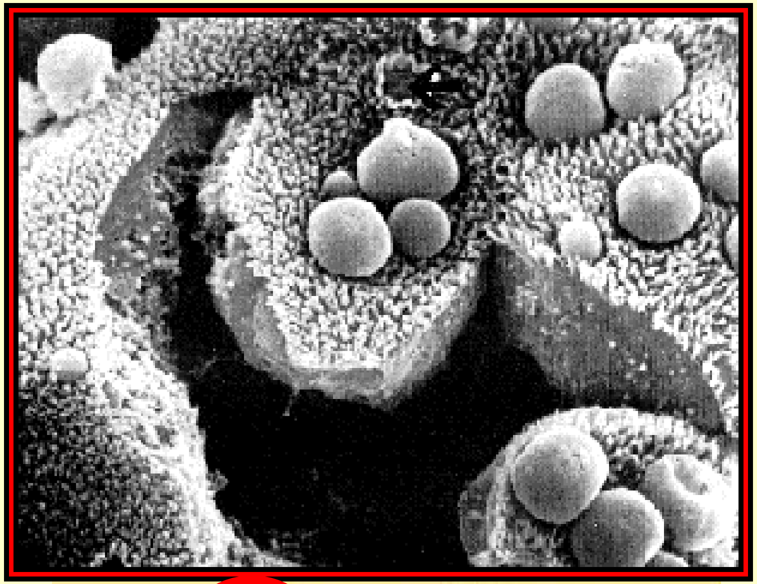
- The problem of **newly discovered pathogens:**
  - In late 1990s, several protozoan species have caused massive outbreaks of waterborne illness. These organisms are somewhat chlorine resistant.

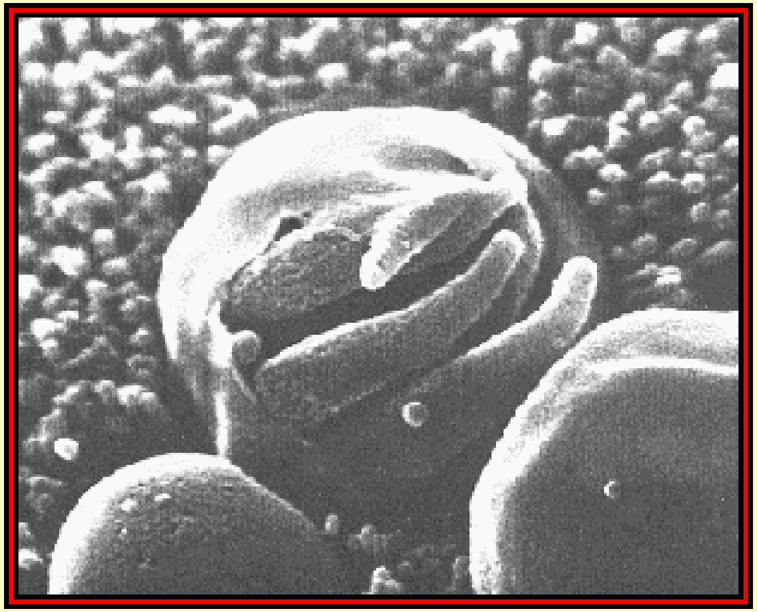
Reported outbreaks, their causes, the numbers of cases of associated illness reported, and the types of water systems (1991 – 2000)

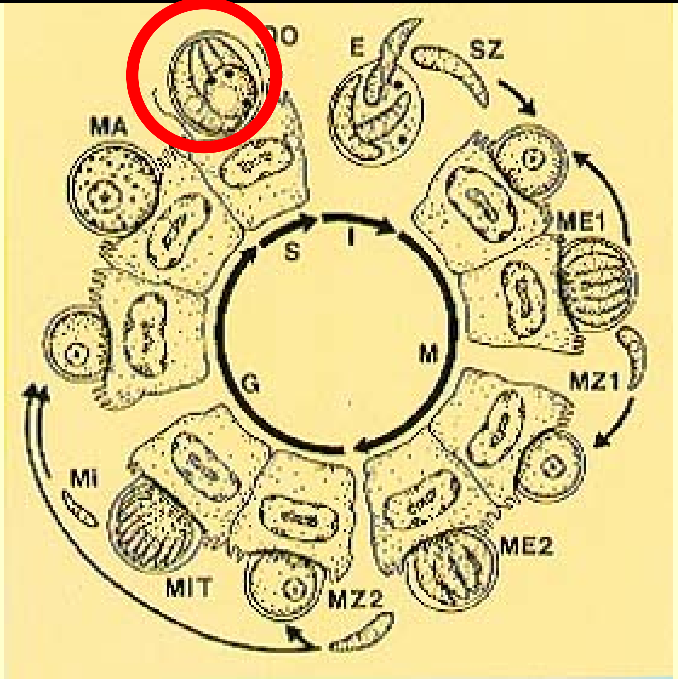
Etiological Agent	Community Water Systems 2		Noncommunity Water Systems 3		Individual Water Systems 4		All Systems	
	Outbreaks	Cases	Outbreaks	Cases	Outbreaks	Cases	Outbreaks	Cases
Giardia	11	2,073	5	167	6	16	22	2,256
Cryptosporidium*	7	407,642	2	578	2	39	11	408,259
Campylobacter jejuni	1	172	3	66	1	102	5	340
Salmonellae,nontyphoid	2	749	0	0	1	84	3	833
E. coli	3	208	3	39	3	12	9	259
E. coli O157:H7/C. jeuni	0	0	1	781	0	0	1	781
Shigella	1	83	5	484	2	38	8	605
Plesiomonas shigelloides	0	0	1	60	0	0	1	60
Non-01 V. cholerae	1	11	0	0	0	0	1	11
Hepatitis A virus	0	0	1	46	1	10	2	56
Norwalk-like viruses	1	594	4	1,806	0	0	3	2,400
Small, round-structured virus	1	148	1	70	0	0	2	218
Chemical	18	522	0	0	7	9	25	531
Undetermined	11	10,162	38	4,837	11	238	60	15,237
Total	57	422,364	64	8,934	34	548	155	431,846

1 Data in Table 1-1 are compiled from CDC Morbidity and Mortality Weekly Report Surveillance Summaries for 1991-1992, 1993-1994, 1995-1996, 1997-1998 and 1999-2000. Figures include adjustments to numbers of outbreaks and illness cases originally reported, based on more recent CDC data.
2 Community water systems are those that serve communities of an average of at least 25 year-round residents and have at least 15 service connections.
3 Non-community water systems are those that serve an average of at least 25 residents and have at least 15 service connections and are used at least 60 days per year.
4 Individual water systems are those serving less than 25 residents and have less than 15 service connections.
* There were 403,000 cases of illness reported in Milwaukee in 1993.

隐孢子虫 *Cryptosporidium parvum*

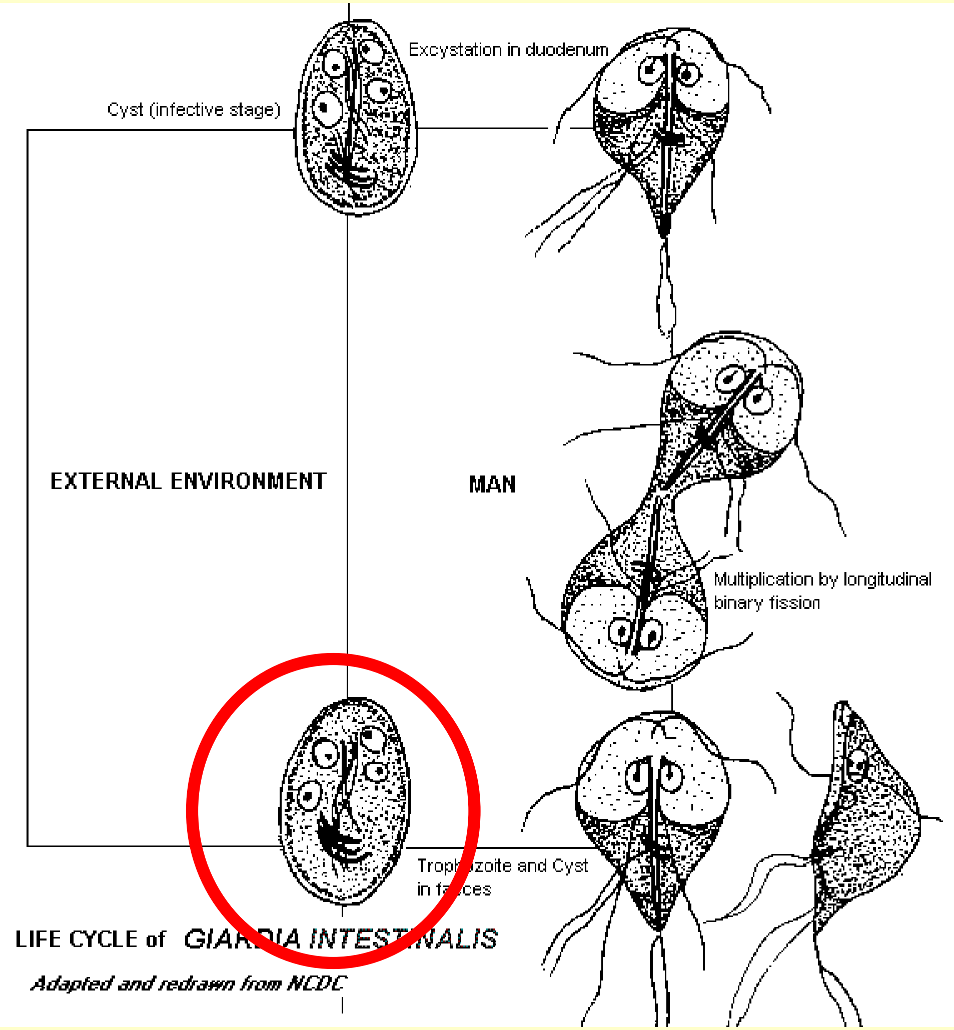


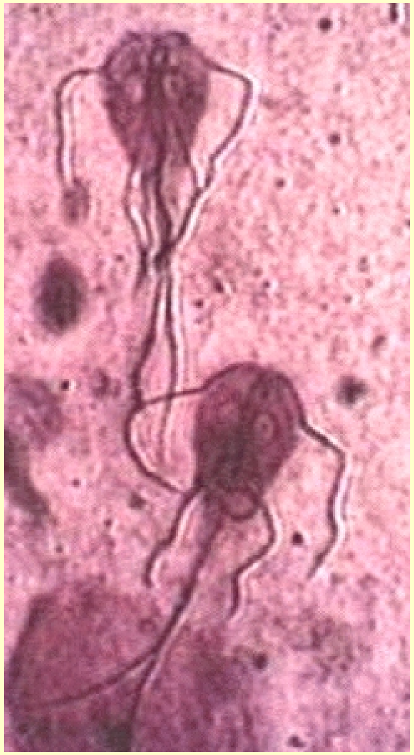


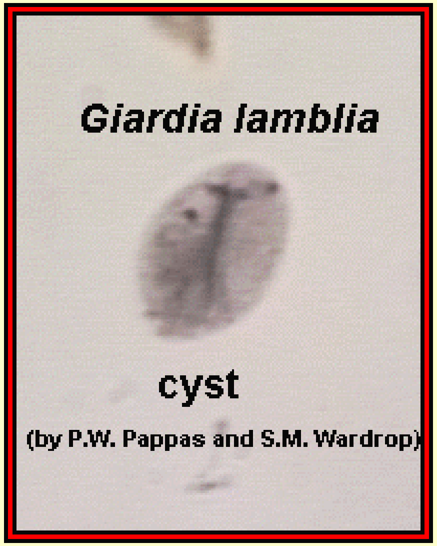


Life cycle of *Cryptosporidium parvum*. Abbreviations: (E) Excystation (either as thick-walled oocyst from environment or via thin-walled oocyst excysting in situ), resulting in release of 4 sporozoites through suture in wall; (G) Gamogony; (I) Infective phase; (M) Merogony; (ME1) Type I meront containing 8 merozoites; (ME2) Type II meront containing 4 merozoites; (MA) Macrogamete, containing wall forming bodies; (Mi) Microgamete; (MiT) Microgametocyte with 16 non-flagellated microgametes; (MZ1) Type I merozoite; (MZ2) Type II merozoite; (OO) oocyst; (S) Sporogony; (SZ) sporozoite. See 1986, J Protozool 33: 98-108.

Giardia Lamblia 贾第虫







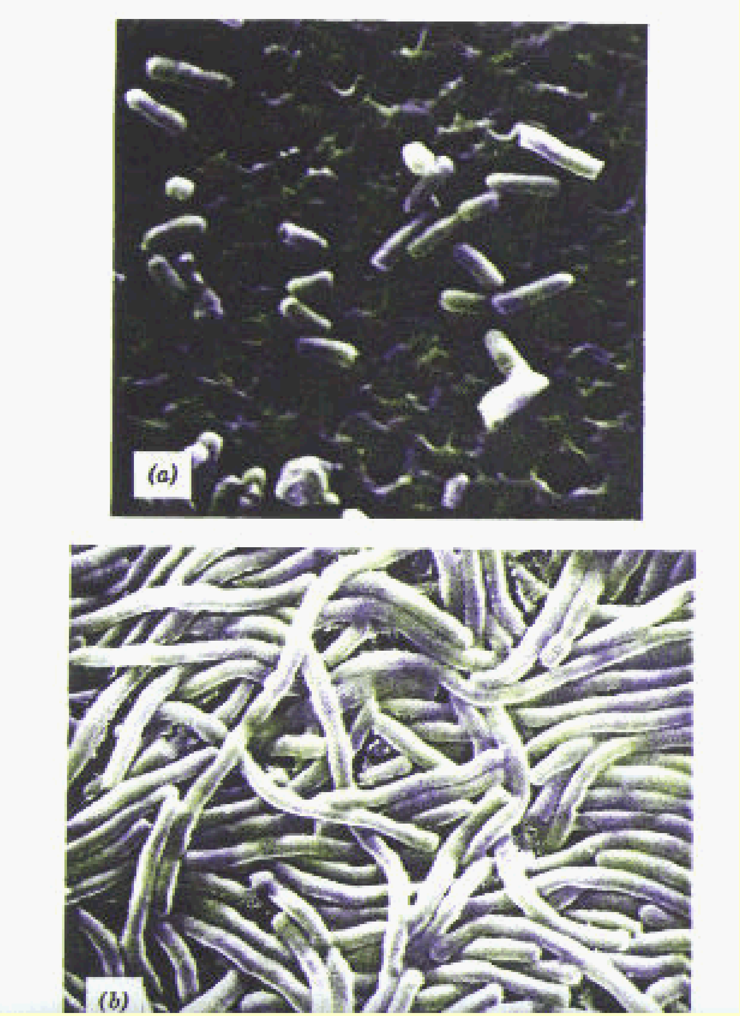


Figure 4. Normal and elongated *E. coli*: (a) scanning electron microphotograph of normal *E. coli* (Gram-negative rods); (b) scanning electron microphotograph of *E. coli* grown in medium containing a few parts per million of *cis*-diamminedichloroplatinum(II). Same magnification in both pictures. The platinum drug has inhibited cell division, but not growth, leading to long filaments. *(Courtesy of D. Beck)* Reprinted with permission.

Disinfectants used in the US, 2000

Disinfectant	Large Systems (>10,000 persons)	Small Systems Using Groundwater (<10,000 persons)	Small Systems Using Surface Water (<10,000 persons)
Elemental Chlorine	84%	61%	82%
Sodium Hypochlorite	20%	34%	17%
Calcium Hypochlorite	<1%	-	9%
Chloramines	29%	-	2%
Ozone	6%	-	-
UV	-	-	-
Chlorine Dioxide	8%	-	6%

Source: American Water Works Association 2000.
Note: The totals may be greater than 100 percent because some systems use more than one type of disinfectant.

Standards for indicator microorganism

TABLE 23.8 U.S. Federal and State Standards for Microorganisms

Authority	Standards
U.S. EPA	
Safe Drinking Water Act	0 coliforms/100 ml
Clean Water Act	
Wastewater discharges	200 fecal coliforms/100 ml
Sewage sludge	<1000 fecal coliforms/4 g <3 *Salmonella*/4 g <1 enteric virus/4 g <1 helminth oval/4 g
California	
Wastewater reclamation for irrigation	≤2.2 MPN/100 ml coliforms
Food and Drug Administration	
Shellfish growing areas[a]	14 MPN/100 ml fecal coliforms

[a] FDA, 2005.

TABLE 23.9 Drinking Water Criteria of the European Union

Tap water	
Escherichia coli	0/100 ml
Fecal streptococci	0/100 ml
Sulfite-reducing clostridia	0/20 ml
Bottled water	
Escherichia coli	0/250 ml
Fecal streptococci	0/250 ml
Sulfite-reducing clostridia	0/50 ml
Pseudomonas aeruginosa	0/250 ml

From European Union, 1995.

TABLE 23.10 Guidelines for Recreational Water Quality Standards

Country or agency	Regime (samples/time)	Criteria or standard[a]
U.S. EPA	5/30 days	200 fecal coliforms/100 ml $<$10% to exceed 400/ml Freshwater[b] 33 enterococci/100 ml 126 E. *coli*/100 ml Marine waters[b] 35 enterococci/100 ml
European Economic Community	2/30 days[c]	500 coliforms/100 ml 100 fecal coliforms/100 ml 100 fecal streptococci/100 ml 0 *Salmonella*/liter 0 enteroviruses/10 liters
Ontario, Canada	10/30 days	$\leq$1000 coliforms/100 ml $\leq$100 fecal coliforms/100 ml

From Saliba, 1993; U.S. EPA, 1986.

[a] *All bacterial numbers in geometric means.*

[b] *Proposed, 1986.*

[c] *Coliforms and fecal coliforms only.*

表 1　基本控制项目最高允许排放浓度（日均值）　　单位　mg/L

序号	基本控制项目		一级标准		二级标准	三级标准
			A 标准	B 标准		
1	化学需氧量（COD）		50	60	100	120①
2	生化需氧量（BOD_5）		10	20	30	60①
3	悬浮物（SS）		10	20	30	50
4	动植物油		1	3	5	20
5	石油类		1	3	5	15
6	阴离子表面活性剂		0.5	1	2	5
7	总氮　（以 N 计）		15	20	-	-
8	氨氮（以 N 计）②		5（8）	8（15）	25（30）	-
9	总磷（以 P 计）	2005 年 12 月 31 日前建设的	1	1.5	3	5
		2006 年 1 月 1 日起建设的	0.5	1	3	5
10	色度（稀释倍数）		30	30	40	50
11	pH		6-9			
12	粪大肠菌群数（个/L）		10^3	10^4	10^4	-

Chlorination Chemistry

Chlorine gas hydrolyzes rapidly in water to form hypochlorous acid (HOCl). The following equation presents the hydrolysis reaction:

$$Cl_{2(g)} + H_2O \Rightarrow HOCl + H^+ Cl^- \qquad \textit{Equation 1}$$

Note that the addition of chlorine gas to water reduces the pH of the water due to the production of hydrogen ion.

Hypochlorous acid is a weak acid (pK_a of about 7.5), meaning it dissociates slightly into hydrogen and hypochlorite ions as noted in Equation 2:

$$HOCl \Leftrightarrow H^+ + O\,Cl^- \qquad \textit{Equation 2}$$

Between a pH of 6.5 and 8.5 this dissociation is incomplete and both HOCl and OCl^- species are present to some extent (White, 1992). Below a pH of 6.5, no dissociation of HOCl occurs, while above a pH of 8.5, complete dissociation to OCl^- occurs. As the germicidal effects of HOCl is much higher than that of OCl^-, chlorination at a lower pH is preferred.

The reaction between sodium hypochlorite and water is shown in the following reaction:

$$NaOCl + H_2O \Rightarrow HOCl + Na^+ + OH^- \qquad \textit{Equation 3}$$

Equation 3 shows that the application of sodium hypochlorite to water produces hypochlorous acid, similar to chlorine gas hydrolysis (Equation 1). However, unlike chlorine hydrolysis, the addition of sodium hypochlorite to water yields a hydroxyl ion that will increase the pH of the water. In addition, excess sodium hydroxide is used to manufacture sodium hypochlorite, which will further increase the pH of the water.

Calcium Hypochlorite. Calcium hypochlorite is formed from the precipitate that results from dissolving chlorine gas in a solution of calcium oxide (lime) and sodium hydroxide. Granular calcium hypochlorite commercially available typically contains 65 percent available chlorine. This means that 1.5 pounds of calcium hypochlorite contains the equivalent of one pound of chlorine. The reaction between calcium hypochlorite and water is shown in the following reaction:

$$Ca(OCl)_2 + 2H_2O \Rightarrow 2HOCl + Ca^{++} + 2OH^- \qquad \textit{Equation 4}$$

Equation 4 shows that the application of calcium hypochlorite to water also produces hypochlorous acid, similar to chlorine gas hydrolysis (Equation 1). Similar to sodium hypochlorite solution, the addition of calcium hypochlorite to water yields hydroxyl ions that will increase the pH of the water.

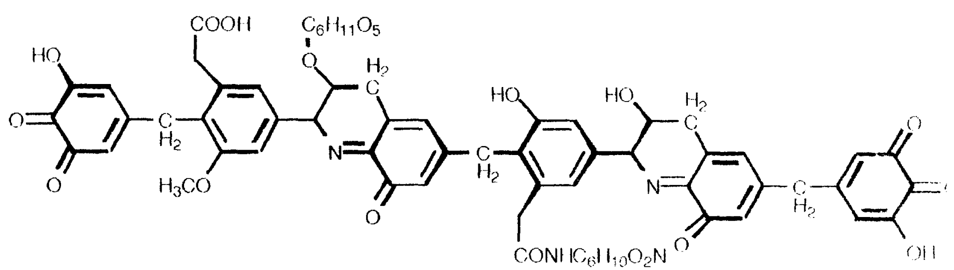
Table 2-20. Typical Chlorine Dosages at Water Treatment Plants

Chlorine Compound	Range of Doses
Calcium hypochlorite	0.5–5 mg/L
Sodium hypochlorite	0.2–2 mg/L
Chlorine gas	1–16 mg/L

Source: SAIC, 1998, as adapted from EPA's review of public water systems' Initial Sampling Plans which were required by EPA's Information Collection Rule (ICR)

Chlorine reacts with natural organic matters (NOMs) in water (typical in clean drinking water at 1 to 3 mg/l TOC)

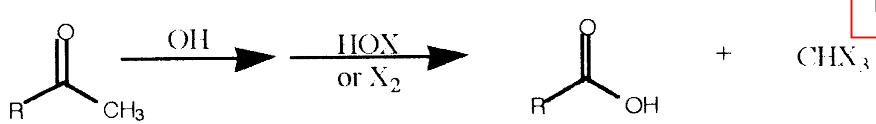
Humic acid model proposed by Dragunov (Jug). **(腐殖酸)**



+ Cl_2

THMs formation:
In the range of 10s to 100s ppb depends on TOC, Cl_2, time, PH, And others

Haloform Reaction:



Named DBPs

Chlorination DBP Class	Individual DBPs	Chemical Formula
Trihalomethanes, THM_4		
	Chloroform	$CHCl_3$
	Bromodicloromethane	$CHCl_2Br$
	Dibromochloromethane	$CHClBr_2$
	Bromoform	$CHBr_3$
Haloacetic Acids, HAA_5		
	Monochloroacetic acid	$CH_2Cl\ COOH$
	Dichloroacetic acid	$CHCl_2\ COOH$
	Trichloroacetic acid	$CCl_3\ COOH$
	Bromodichloro acid	$CHBrCl\ COOH$
	Bromodichloroacetic acid	$CBrCl_2\ COOH$

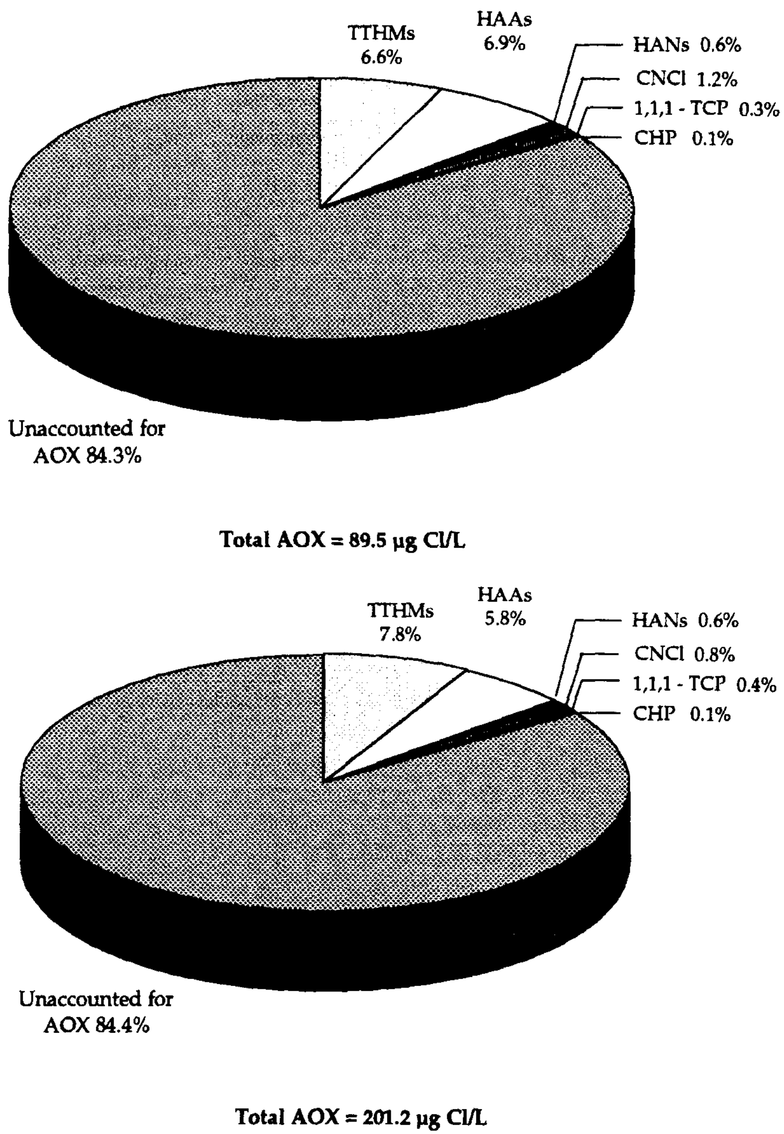


Figure 12 Average contribution of known DBPs to finished water AOX for phase II pilot runs 1 to 2 (spring runoff—low color conditions). a (Top): pilot train 1 - HR-Cl_2 scenario; b (bottom): pilot train 2 - LR-Cl_2 scenario.

Ways to reduce Chlorine DBPs

- **Removal the DBP Precursors (NOM):**
  - Enhanced coagulation
  - Ultrafiltration Membrane
  - Using anionic IOX resins (MIEX)
  - Ozone oxidation followed by biological treatment
  - Carbon adsorption
- **Alternative Disinfection Processes:**
  - Ozone
  - Chlorine Dioxide
  - Chloramines
  - UV Light

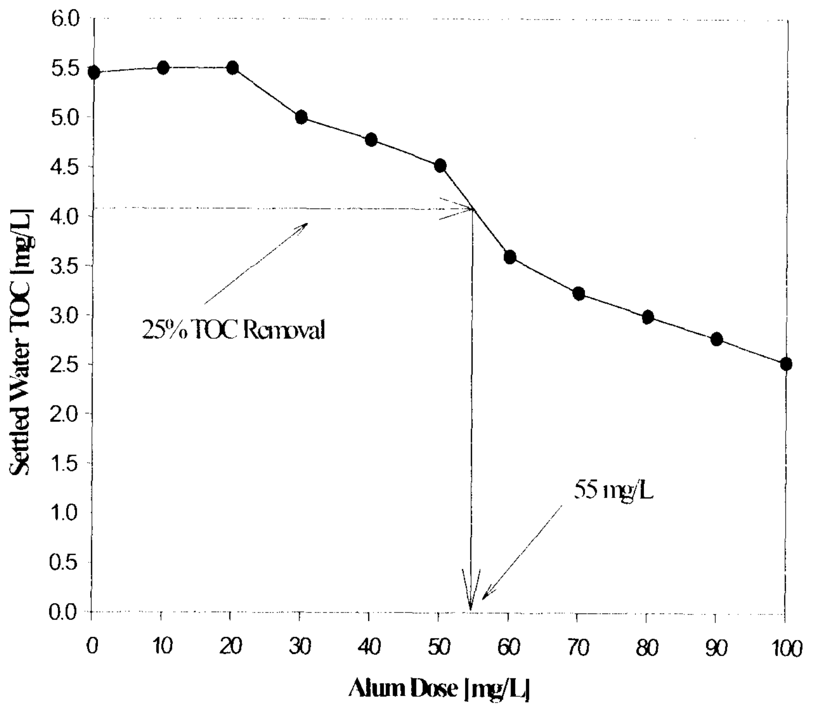
Enhanced Coagulation

The addition of coagulants can adsorb some NOMs

- Both Ferric and Alum will remove some TOC
- Low pH value will enhance the removal
- Higher dosage will also enhance the removal

Example Adjusting the full-scale dose to meet Step 1 requirement

Settled Water TOC vs. Coagulant Dose



Ozone

It is a powerful oxidant and disinfectant

Ozone has to be generated on site and transferred into wat

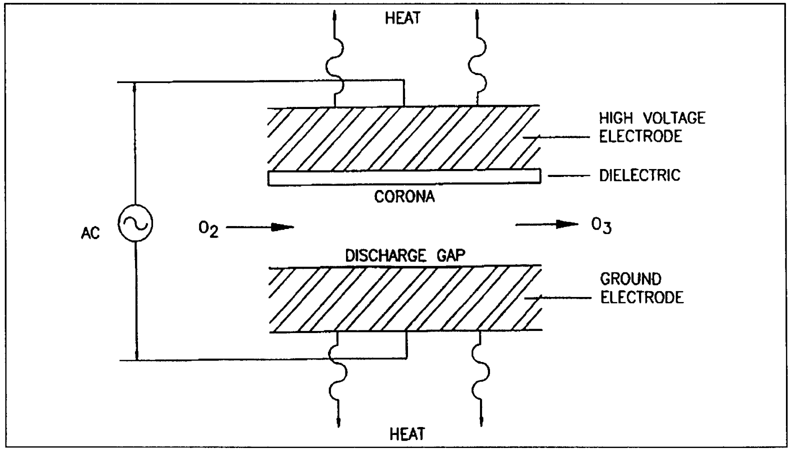
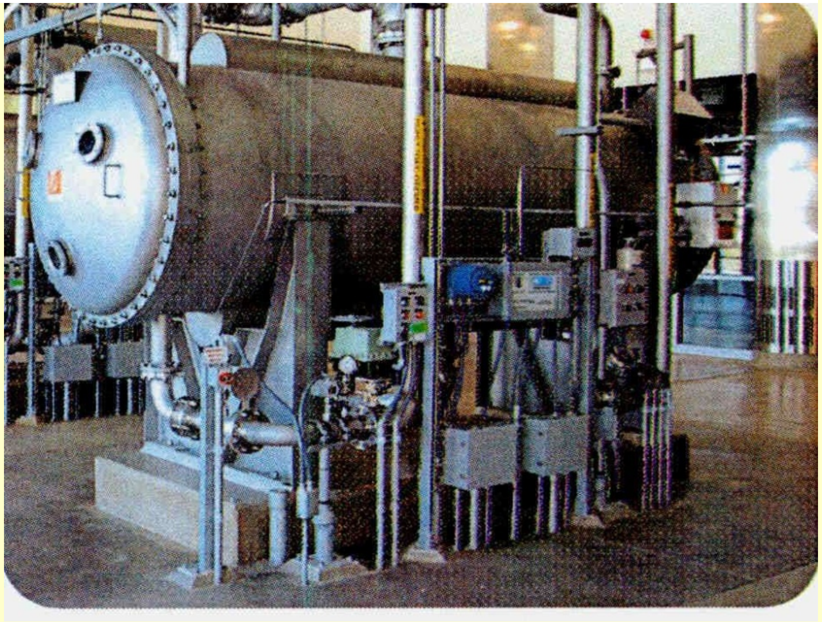


Figure 3-3. Basic Ozone Generator



$$3O_2 + \text{Energy} \longrightarrow 2\,O_3$$

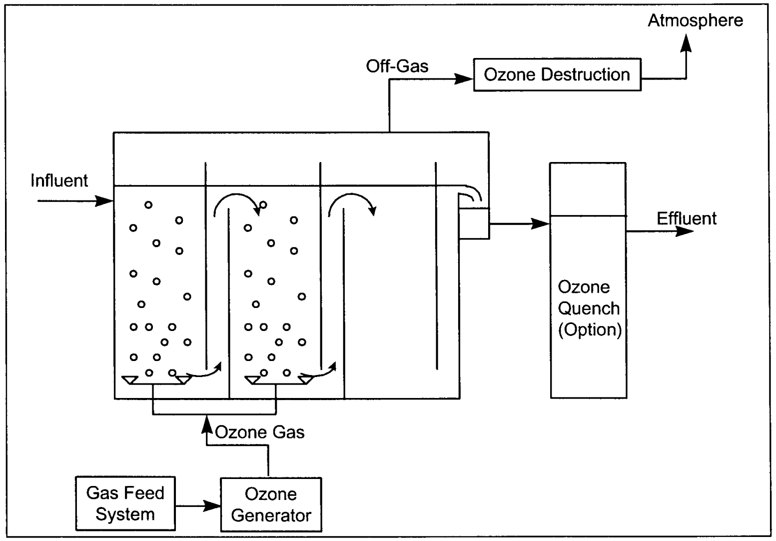
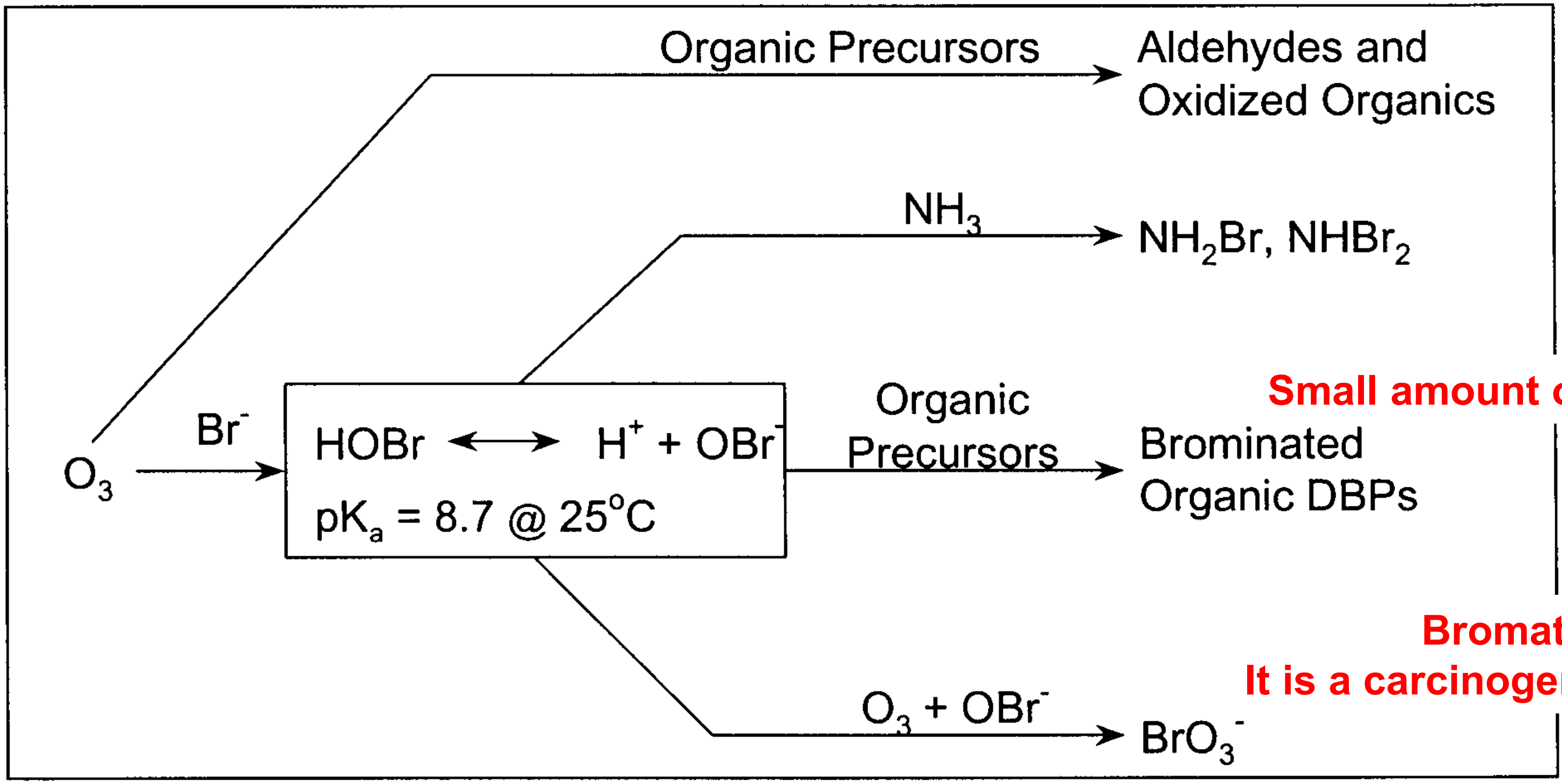


Figure 3-4. Simplified Ozone System Schematic

Ozone is one of the most potent disinfectants.
But it is difficult to produce and dispense.
And it will not leave any residue

Ozone will also form DBPs:

The organics are more biodegradable



Small amount of Br-CHs

Bromate

It is a carcinogen <10 ppb

Figure 3-11. Principal Reactions Producing Ozone Byproducts

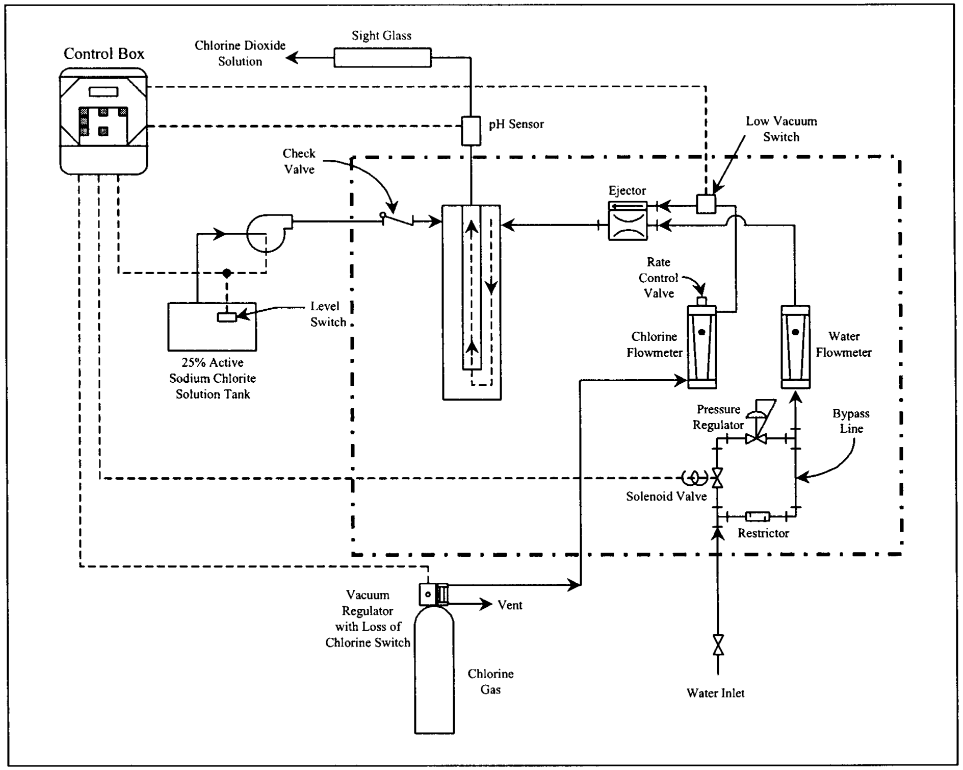
Chlorine Dioxide

Chlorine Dioxide Generation – On-site generation with Reaction between Sodium Chlorite and Chlorine

$$2NaClO_2 + Cl_{2(g)} = 2ClO_{2(g)} + 2NaCl$$

$$2NaClO_2 + HOCl = 2ClO_{2(g)} + NaCl + NaOH$$

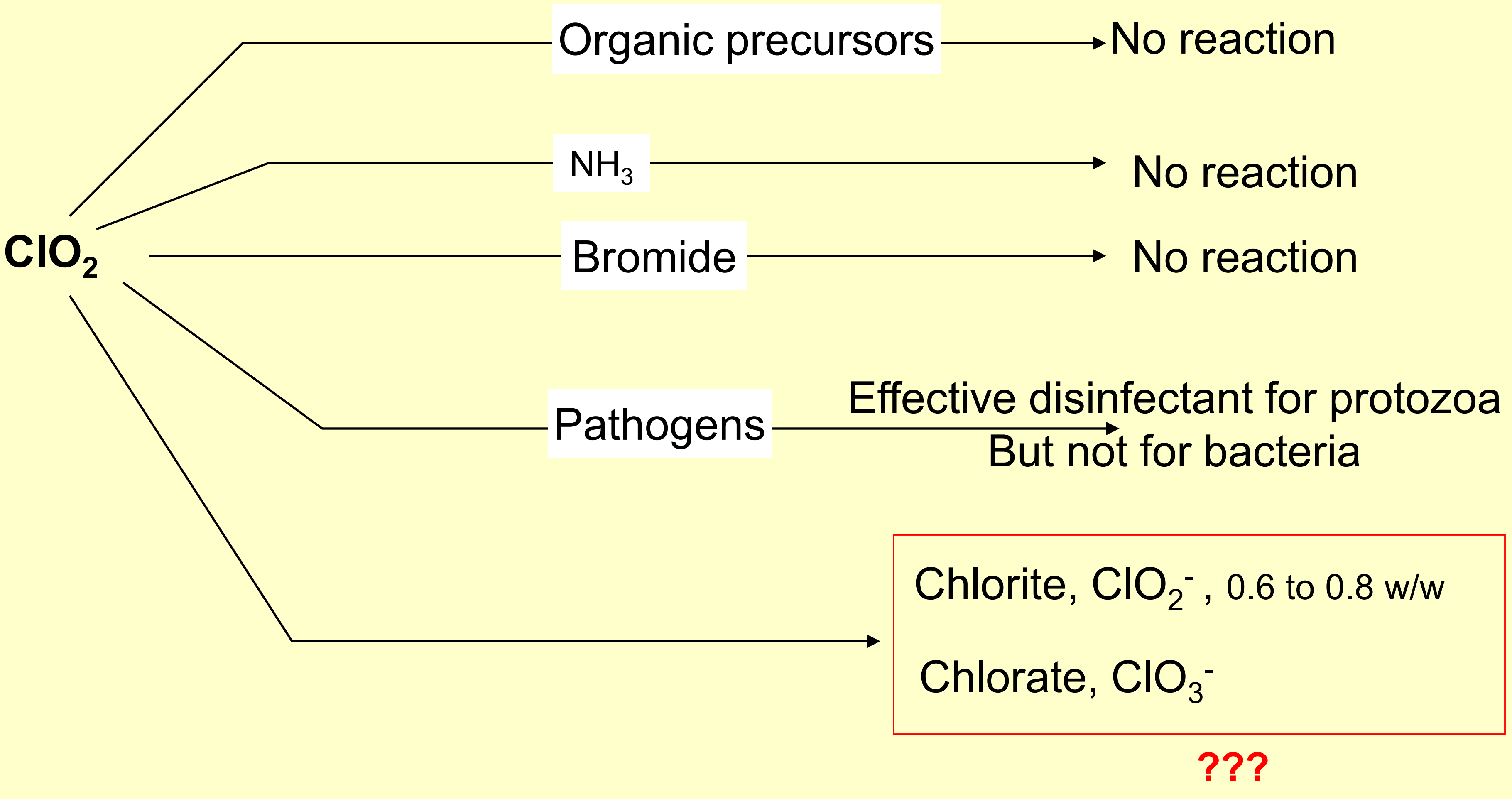
$$5NaClO_2 + 4HCl = 4ClO_{2(g)} + 5NaCl + 2H_2O$$



Source: Demers and Renner, 1992.

Figure 4-1. Conventional Chlorine Dioxide Generator When Using Chlorine-Chlorite Method

Chlorine Dioxide Chemistry in Water



Chloramines

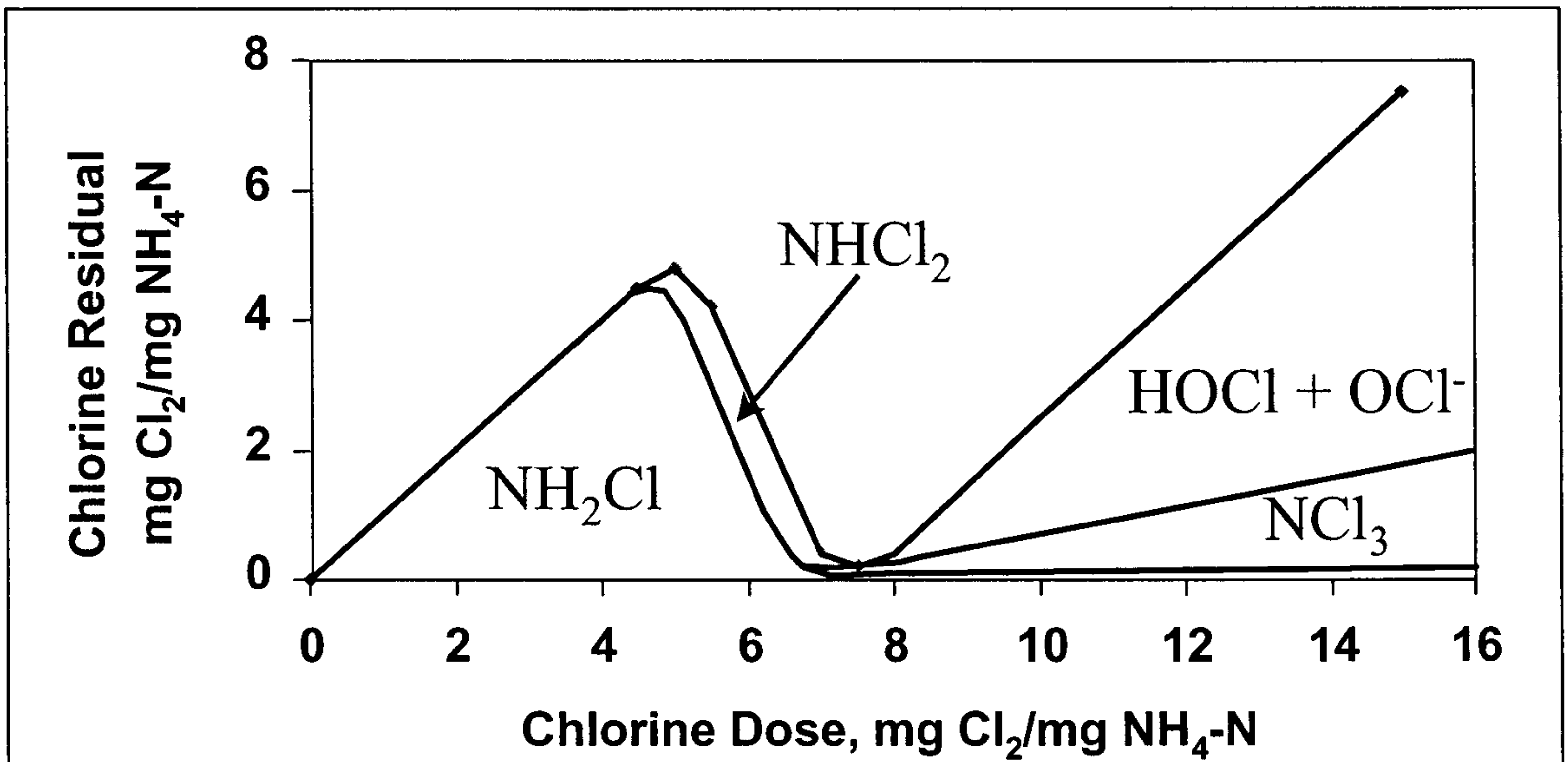
Chloramines are not strong disinfectants
But it is stable in the distribution pipe network
So, it is used as 2^{nd} disinfectant

Chloramines are formed by react Ammonia(aq) with Chlorine

$$NH_3(aq) + HOCl \rightleftarrows NH_2Cl + H_2O$$

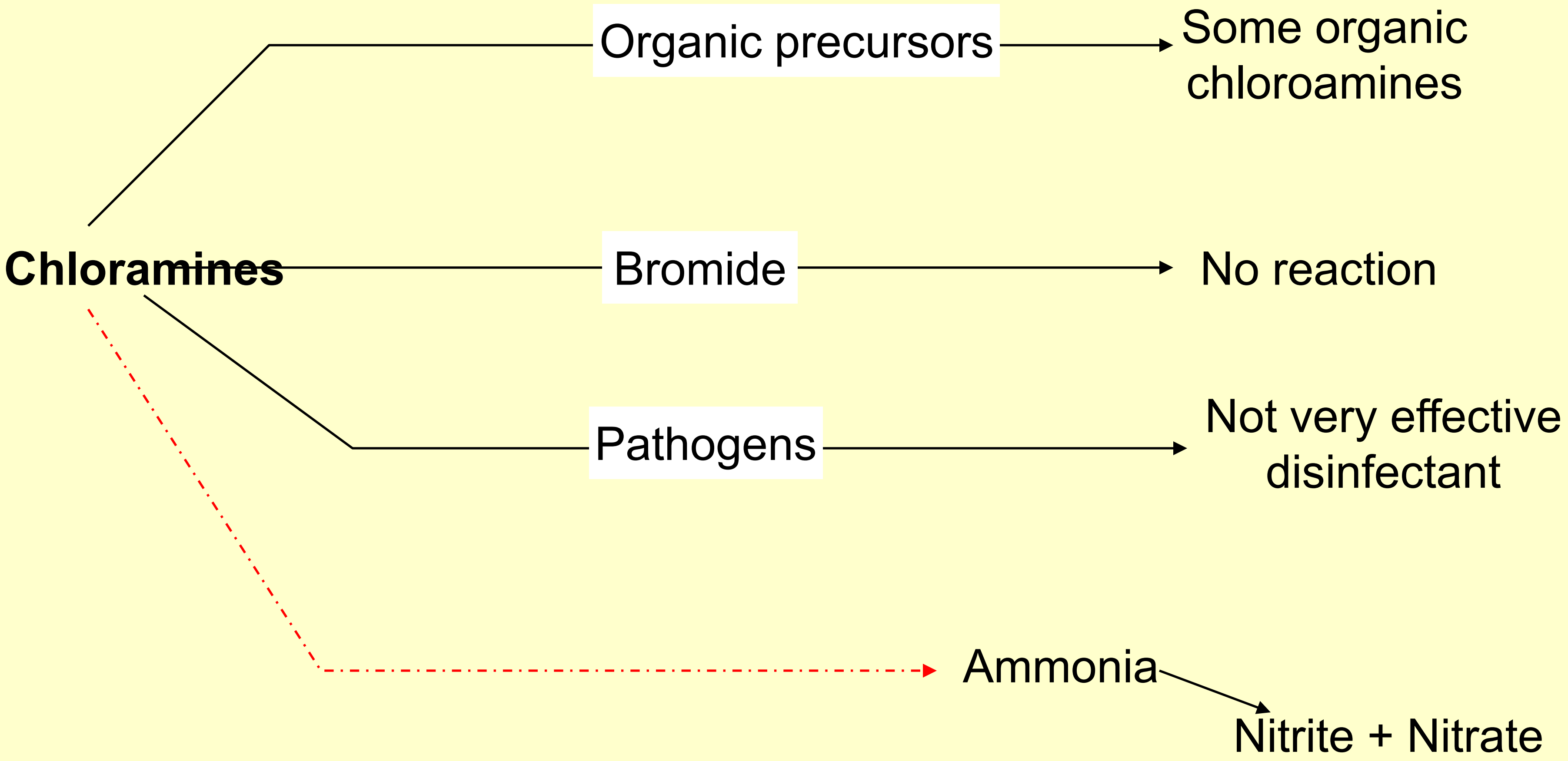
$$NH_2Cl + HOCl \rightleftarrows NHCl_2 + H_2O$$

$$NHCl_2 + HOCl \rightleftarrows NCl_3 + H_2O$$



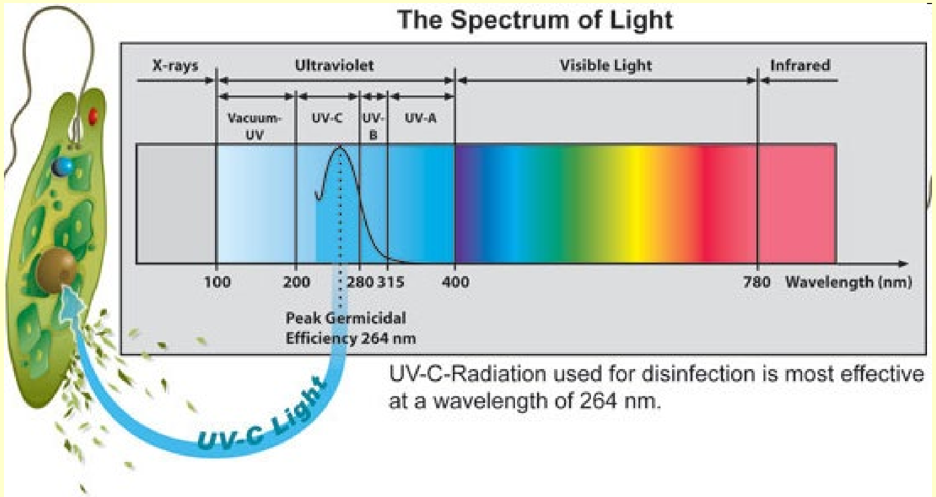
Theoretical Breakpoint Curve

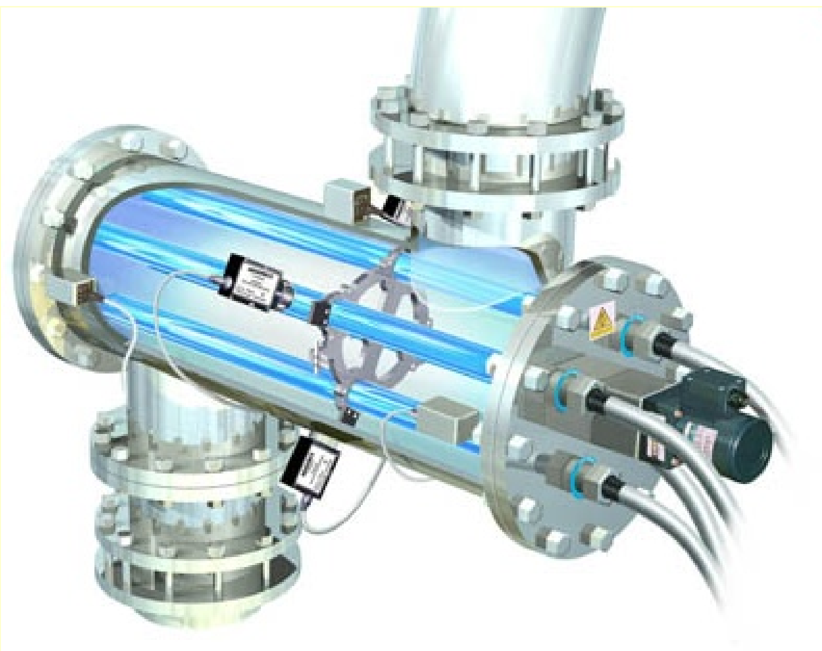
Chloramines Chemistry in Water



Ultraviolet Light

UV light does not produce any toxic residue
But it does not leave residual disinfectant to protect clean water in the distribution network and suspended solids in water can shield bacteria from receiving dosage.


The Spectrum of Light
X-rays
Ultraviolet
Visible Light
Infrared
Vacuum-UV
UV-C
UV-B
UV-A
100
200
280
315
400
780
Wavelength (nm)
Peak Germicidal Efficiency 264 nm
UV-C-Radiation used for disinfection is most effective at a wavelength of 264 nm.
UV-C Light



Current US EPA Regulation Concerning Disinfections

Table 1-3. Primary Drinking Water Regulations Related to Disinfection Byproducts

Compound	MCLG (mg/L)	MCL (mg/L)	Potential Health Effects	Sources of Drinking Water Contamination
Bromate	Zero[3]	0.010[4]	Cancer	Ozonation byproduct
Bromodichloromethane	Zero[3]	see TTHMs	Cancer, liver, kidney, and reproductive effects	Drinking water chlorination and chloramination byproduct
Bromoform	Zero[3]	see TTHMs	Cancer, nervous system, liver and kidney effects	Drinking water ozonation, chloramination, and chlorination byproduct
Chlorite	0.8[3]	1.0[4]	Hemolytic anemia	Chlorine dioxide disinfection byproduct
Chloroform	Zero[3]	see TTHMs	Cancer, liver, kidney, reproductive effects	Drinking water chlorination and chloramination byproduct
Dibromochloromethane	0.06[3]	see TTHMs	Nervous system, liver, kidney, reproductive effects	Drinking water chlorination and chloramination byproduct
Dichloroacetic Acid	Zero[3]	See HAA5	Cancer and other effects	Drinking water chlorination and chloramination byproduct
Haloacetic Acids[1] (HAA5)	N/A	0.060[4]	Cancer and other effects	Drinking water chlorination and chloramination byproduct
Trichloroacetic Acid	0.3[3]	See HAA5	Possibly cancer and reproductive effects	Drinking water chlorination and chloramination byproduct
Total Trihalomethanes[2] (TTHMs)	N/A	0.08[4]	Cancer and other effects	Drinking water chlorination and chloramination byproduct

Source: 63 *FR* 69390 (12/16/98)

[1] HAA5 is the sum of the concentrations of mono-, di-, and trichloroacetic acids and mono-and dibromoacetic acids.

[2] Total Trihalomethanes are the sum of the concentrations of bromodichloromethane, dibromochloromethane, bromoform, and chloroform.

[3] Finalized on December 16, 1998 (63 FR 69390) as established in 40 CFR §141.53.

[4] Finalized on December 16, 1998 (63 FR 69390) as established in 40 CFR §141.64

Table 1-2. Primary Drinking Water Regulations Related to Microbiological Contaminants

Compound	MCLG (mg/L)	MCL (mg/L)	Potential Health Effects	Sources of Drinking Water Contamination
Giardia lamblia	Zero	TT[1]	Gastroenteric disease	Human and animal fecal waste
Legionella	Zero	TT	Legionnaire's disease	Common bacteria in natural waters; can proliferate in water heating systems
Heterotrophic Plate Count	N/A	TT	Indicates water quality, effectiveness of treatment	
Total Coliform	Zero	< 5.0%[2]	Indicates potential presence of gastroenteric pathogens	Human and animal fecal waste
Turbidity	N/A	TT	Indicates water treatment failure and pathogens in drinking water	Particles from storm runoff, discharges into source water, and erosion
Viruses	Zero	TT	Gastroenteric disease	Human and animal fecal waste

Source: AWWA Internet, 1997.

[1] TT = Treatment technique requirement in lieu of MCL as established in 40 CFR §141.70.

[2] No more than 5.0 percent positive if >40 samples/month. No more than 1 positive if <40 samples/month [40 CFR §141.63(a)].

Table 1-4. Primary Drinking Water Regulations Related to Residual Disinfectants

Disinfectant	MRDLG[3] (mg/L)	MRDL[4] (mg/L)
Chlorine[1]	4 (as Cl_2)	4.0 (as Cl_2)
Chloramine[2]	4 (as Cl_2)	4.0 (as Cl_2)
Chlorine Dioxide	0.8 (as ClO_2)	0.8 (as ClO_2)

[1] Measured as free chlorine
[2] Measured as total chlorine
[3] Finalized on December 16, 1998 (63 *FR* 69390) as established in 40 CFR §141.54.
[4] Finalized on December 16, 1998 (63 *FR* 69390) as established in 40 CFR §141.65

Table 1-5. Log Removal/Inactivation through Filtration and Disinfection Required Under the SWTR

Process	*Giardia* cysts	Virus
Total log removal/inactivation Required	***3.0***	***4.0***
Conventional sedimentation/filtration credit	2.5	2.0
Disinfection inactivation required	0.5	2.0
Direct filtration credit	2.0	1.0
Disinfection inactivation required	1.0	3.0
Slow sand filtration credit	2.0	2.0
Disinfection inactivation required	1.0	2.0
Diatomaceous earth credit	2.0	1.0
Disinfection inactivation required	1.0	3.0
No Filtration	0.0	0.0
Disinfection inactivation required	3.0	4.0

Source: AWWA, 1991.

Note: Some instances may require higher than 3 and 4 log removal. Also, some states may reduce removal filtration process.

Disinfection Kinetics

Disinfection Kinetics Chick-Watson theory:

$$\frac{dN}{dt} = -K\,N \quad = -k'C^{n}\,N$$

Where n = 1

$$= -k'C\,N$$

$$N = N_0\, e^{-k'\boxed{C\,t}}$$

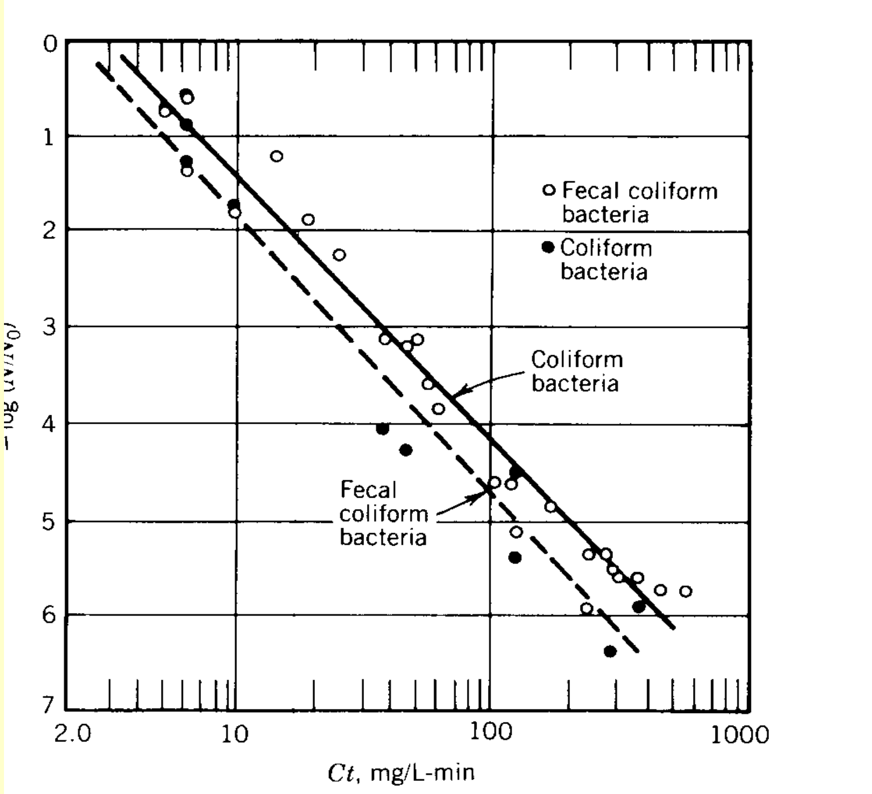
Where:

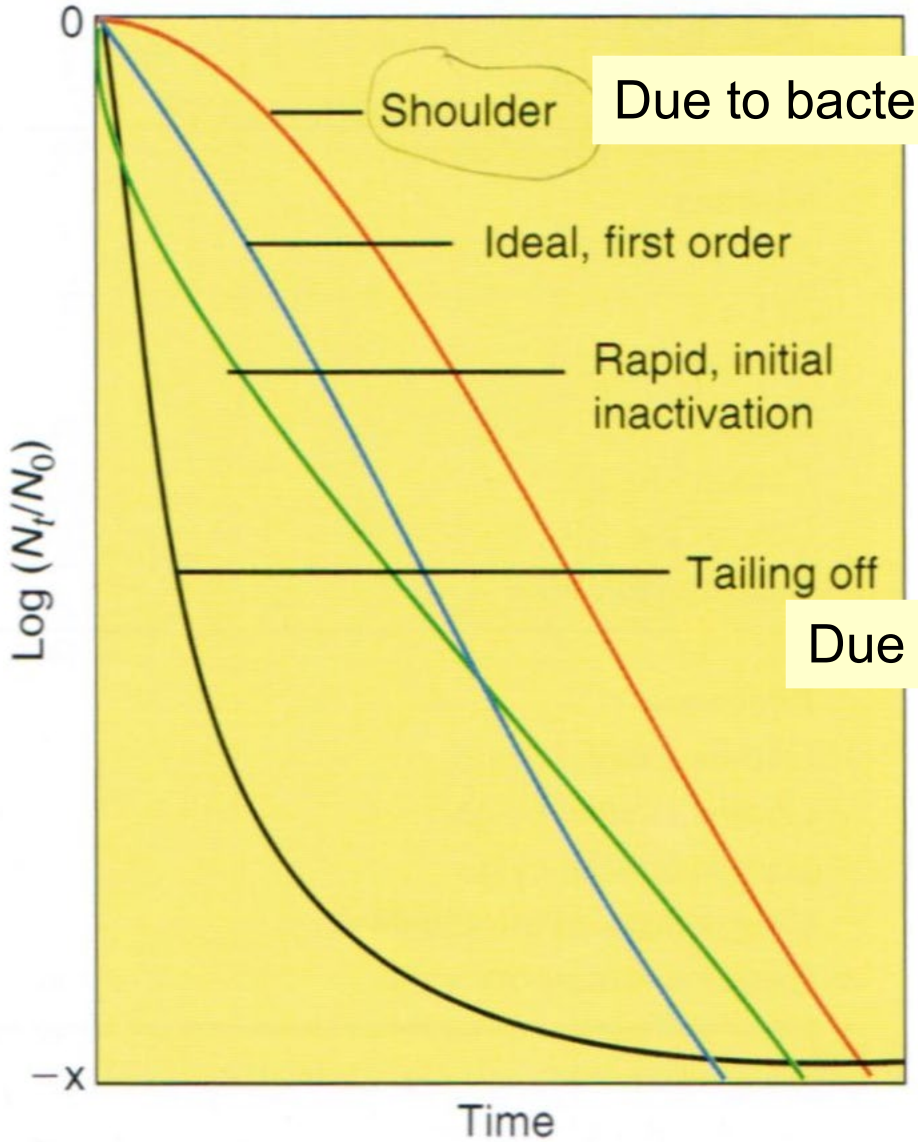
N : numbers of organisms

k' : Kinetic coeffiicient

C : Disinfectants conc.

t : Contact time





Due to bacteria clump together

Due to resistant subculture

FIGURE 26.3 Types of inactivation curves observed for microorganisms.

The Measured C · t Values for Various Disinfectants against Different Pathogens

Table 1

Microorganism	Disinfectant: Free Chlorine pH 6 to 7	Preformed Chloramine pH 8 to 9	Chlorine Dioxide pH 6 to 7	Ozone pH 6 to 7
Escherichia Coli	0.034 - 0.05	95 - 180	0.4 - 0.75	0.02
Polio 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
Giardia lamblia cysts	47 > 150	2200(a)	26(a)	0.5 - 0.6
Giardia muris cysts	30 - 630	1400.00	7.2 - 18.5	1.8 - 2.0
Cryptosporidium parvum	7200(b)	7200(c)	78(c)	5 - 10(b)

(a) Values for 99% inactivation at pH 6-9.
(b) 99% inactivation at pH 7 and 25^{o}C
(c) 90% inactivation at pH 7 and 25^{o}C

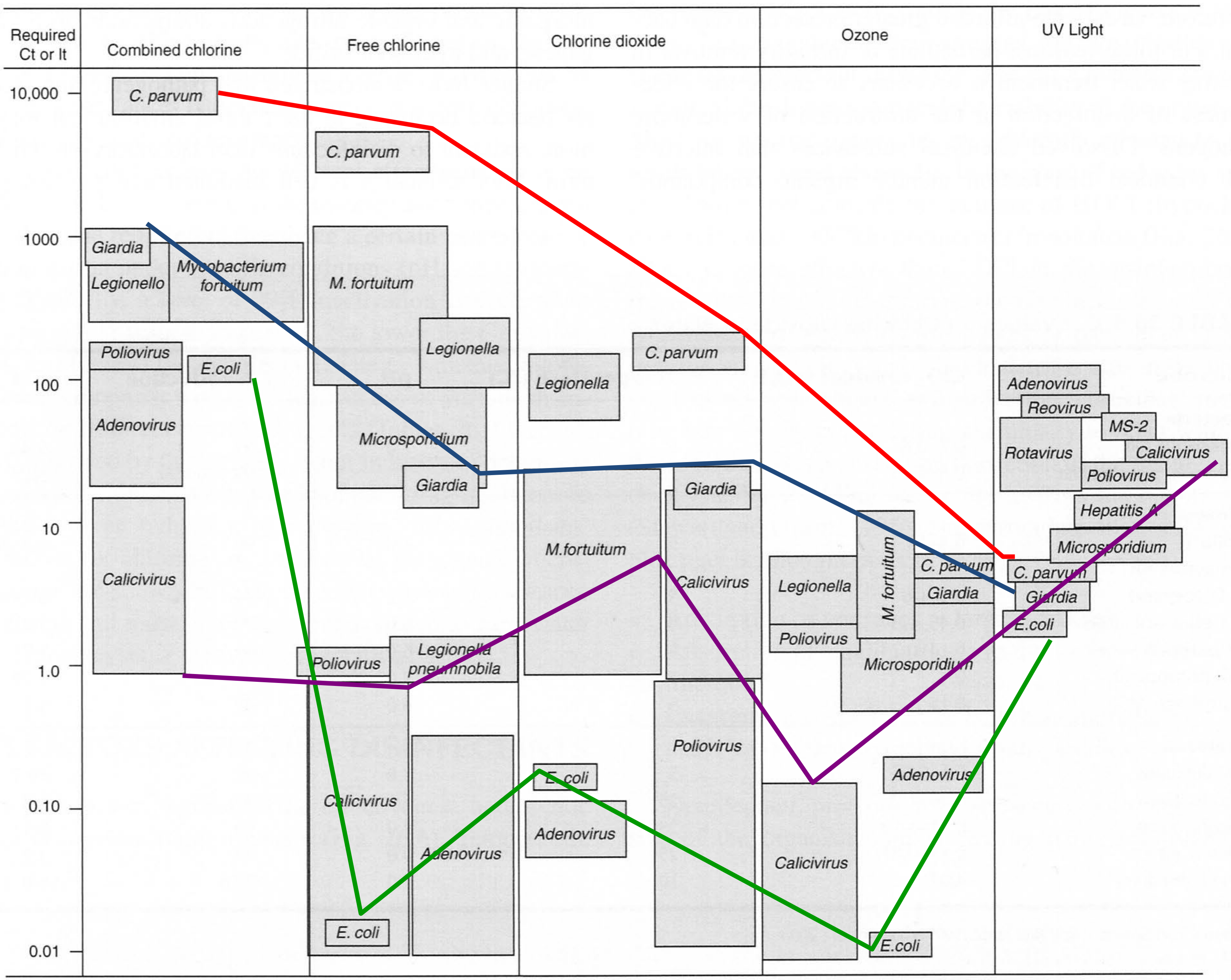
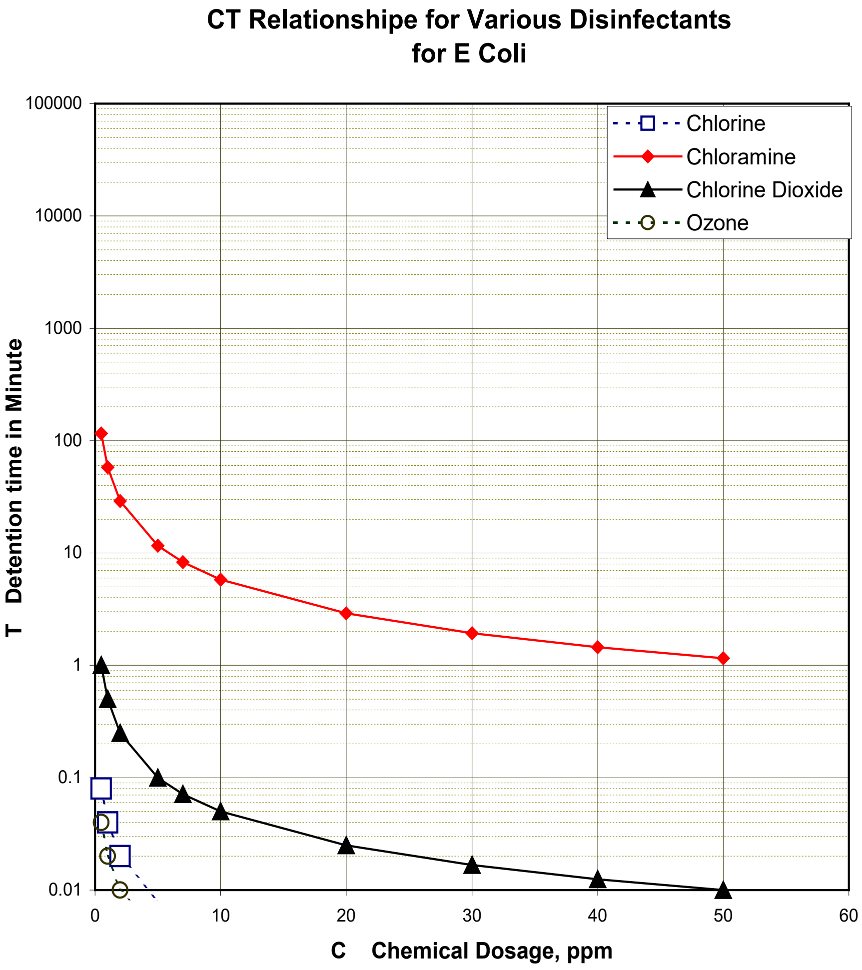
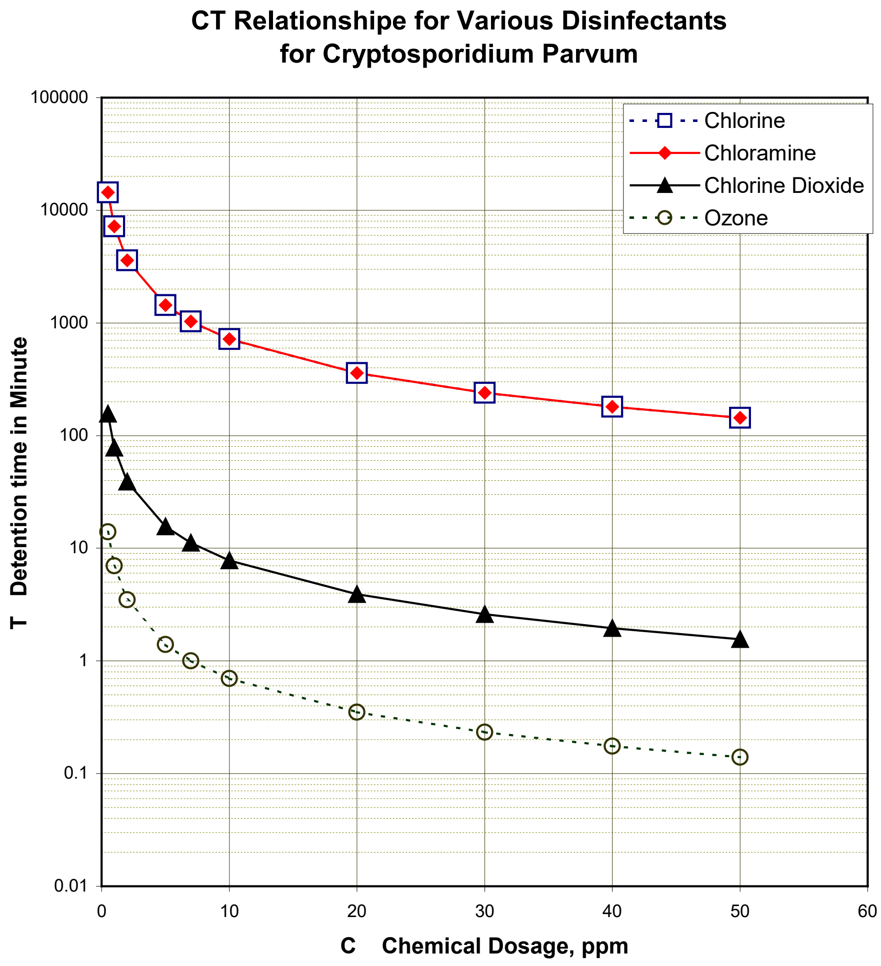


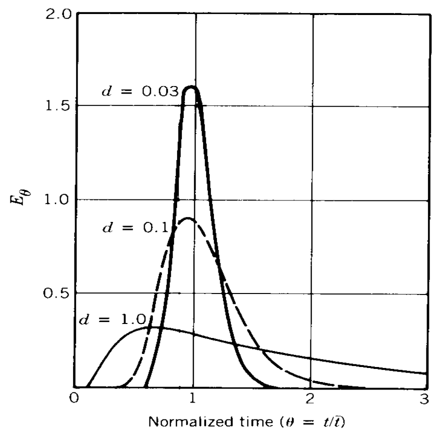
FIGURE 26.4 Overview of disinfection requirements for 99% inactivation of microorganisms. Adapted from Jacangelo *et al.*, 1997. Ct = concentration of disinfectant x time. It = (uW s/cm^2) (time).

The C • t = Constant Relationship

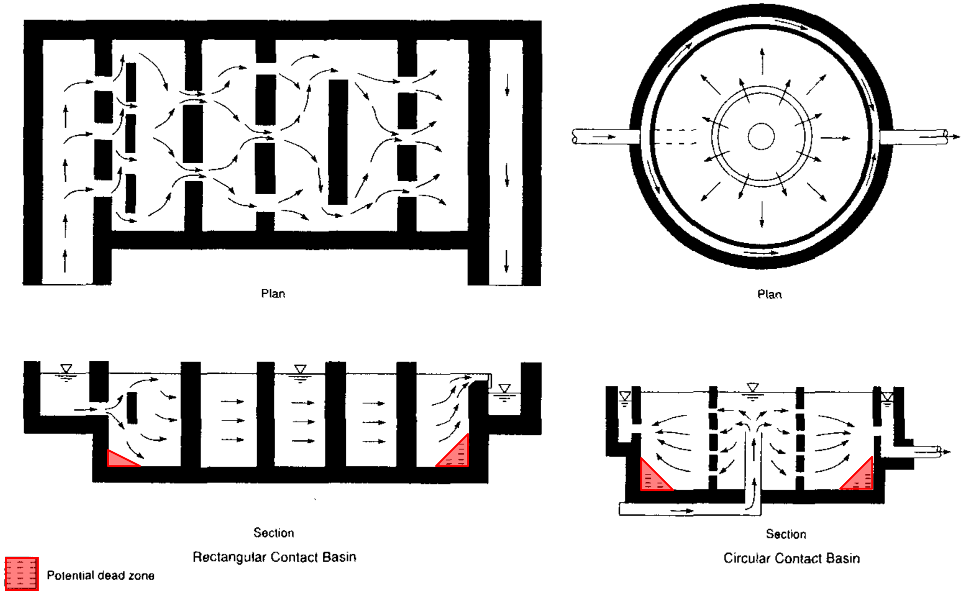




Chlorine Contact Tank Hydraulics Affects the Disinfection Performance Due to the Detention Time Distribution



Frequency distribution of ages versus dispersion number. (Source: Trussell and Chao, 1977.)



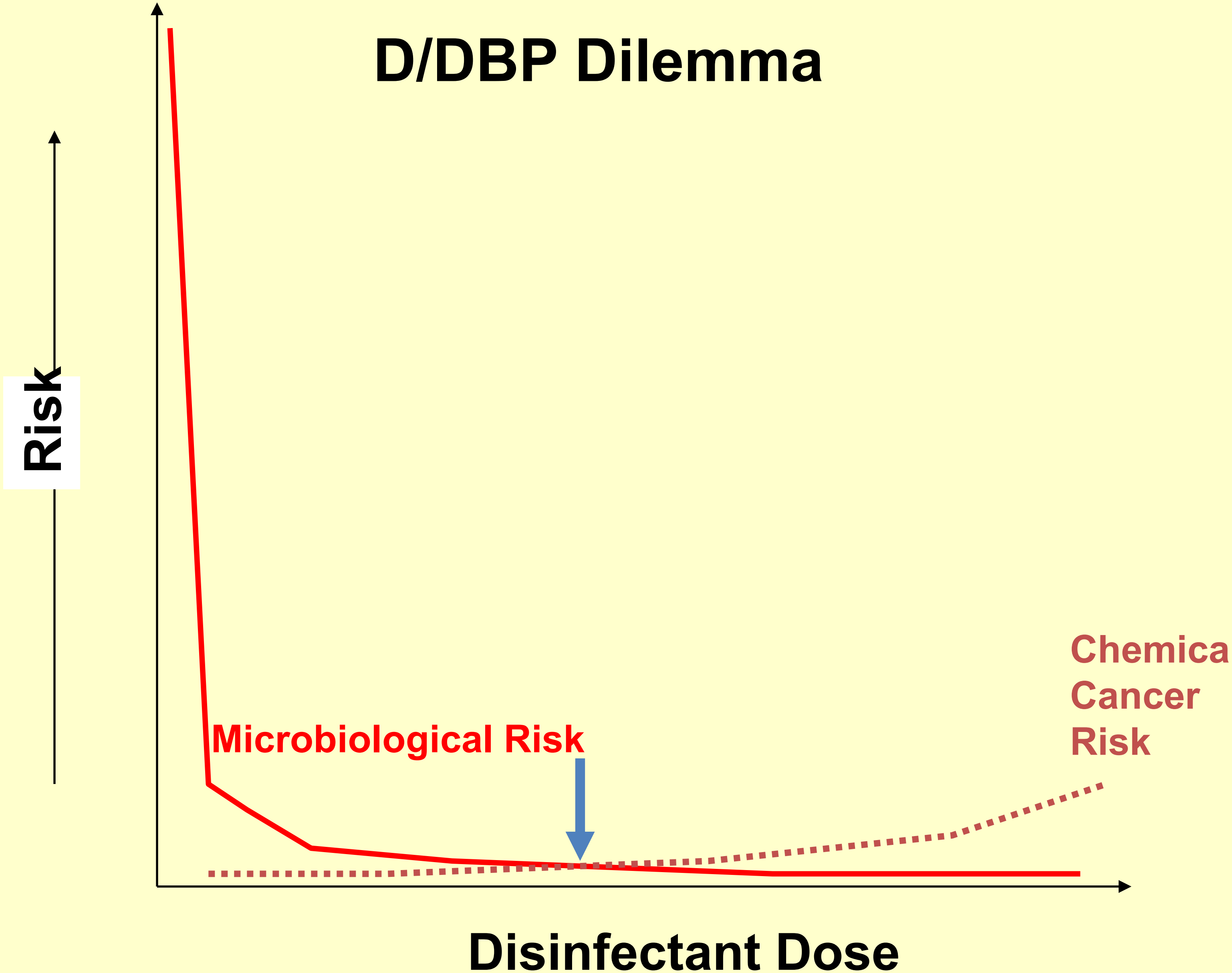
Examples of superior baffling conditions in basins. (*Source: Guidance Manual.*)

Baffling Condition	Factor	Description
Unbaffled	0.1	No baffling, low length to width ratio. Also applies to agitated basins (e.g. flocculation tanks)
Poor	0.3	unbaffled inlet/outlet. No baffles inside basin.
Average	0.5	Baffled inlet or outlet. Some inter-basin baffles.
Superior	0.7	Baffled inlet and outlet, serpentine inter-basin baffles.
Excellent	0.9	As above. Very high length-to-width ratio.
Perfect (plug Flow)	1.0	Used for pipe flow

An example of how a city is trying to meet the rule

Baseline: DAF + Ozone + BAC Filtration + Chloramination
UV Disinfection + Chlorination + Chloramination
UV Disinfection + Chlorination + Chloramination (Staged with the WTP)
DAF + Filtration + UV Disinfection + Chlorination + Chloramination
DAF + Ozone + BAC Filtration + UV Disinfection + Chloramination
Ultrafiltration + Chlorination + Chloramination
Integrated Pretreatment Ultrafiltration + Chlorination + Chloramination
DAF + Ultrafiltration + Chlorination + Chloramination
Ultrafiltration + Ozone + BAC + Chloramination
Ultrafiltration + GAC Contactors + Chlorination + Chloramination
Ultrafiltration + Nanofiltration + Chloramination
Ultrafiltration + UV Disinfection + Chlorination + Chloramination
UV Disinfection + GAC Contactors + Chlorination + Chloramination
Existing Conditions: Chlorination
DAF + Ozone + BAC + Ultrafiltration + Chloramination

D/DBP Dilemma



饮用水消毒与氯副产物困难的选择
(水源有微污染)

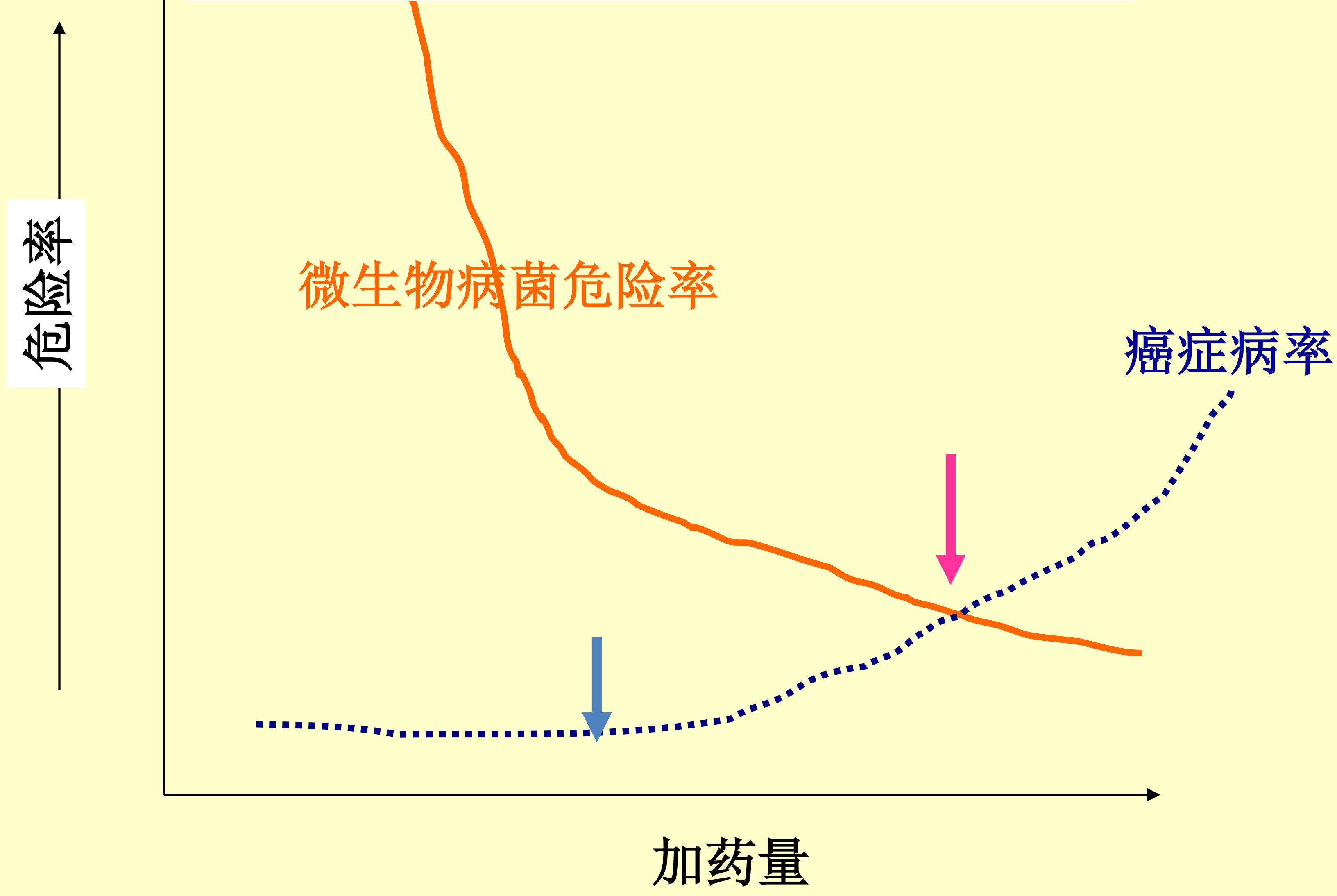
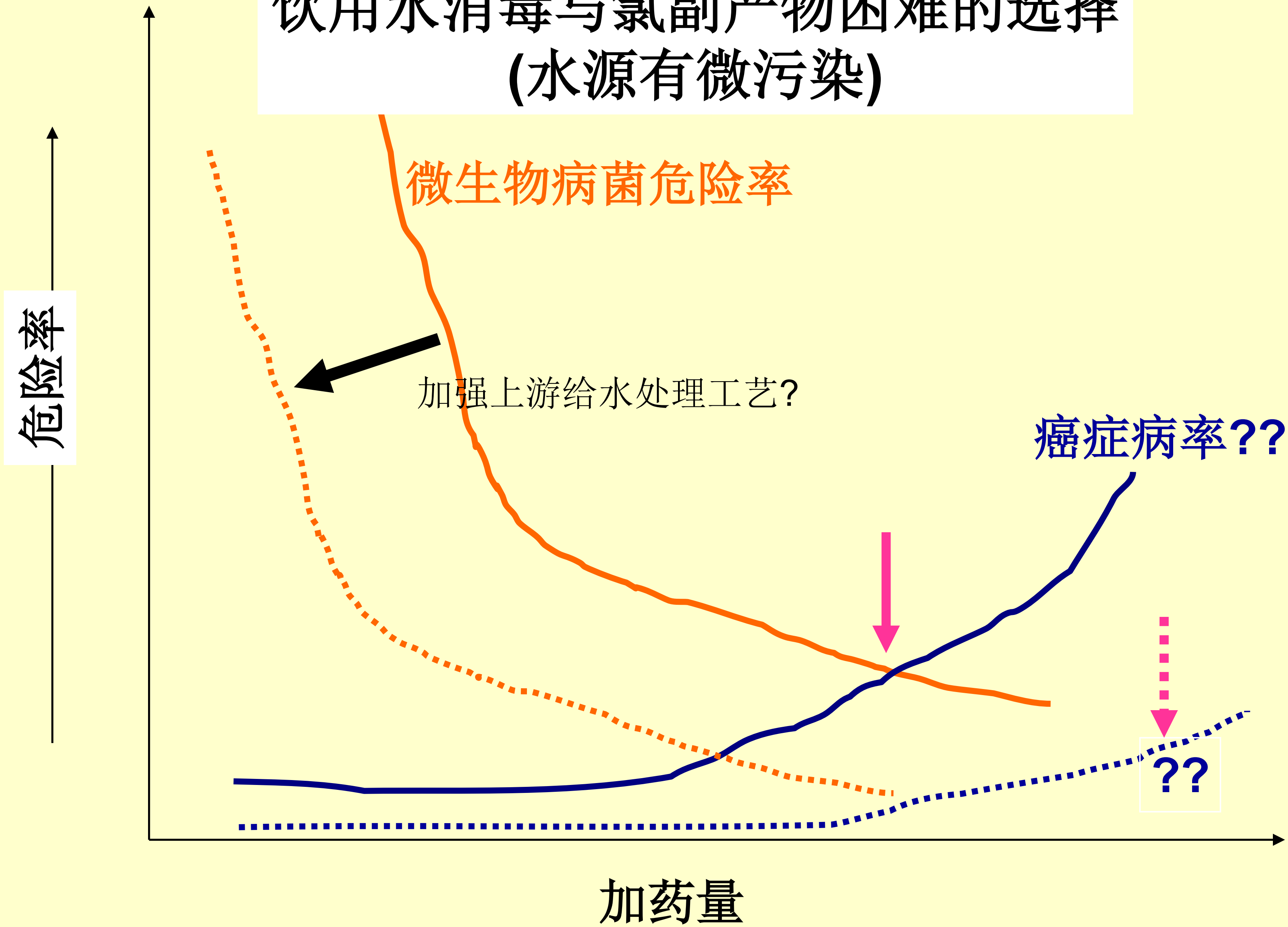


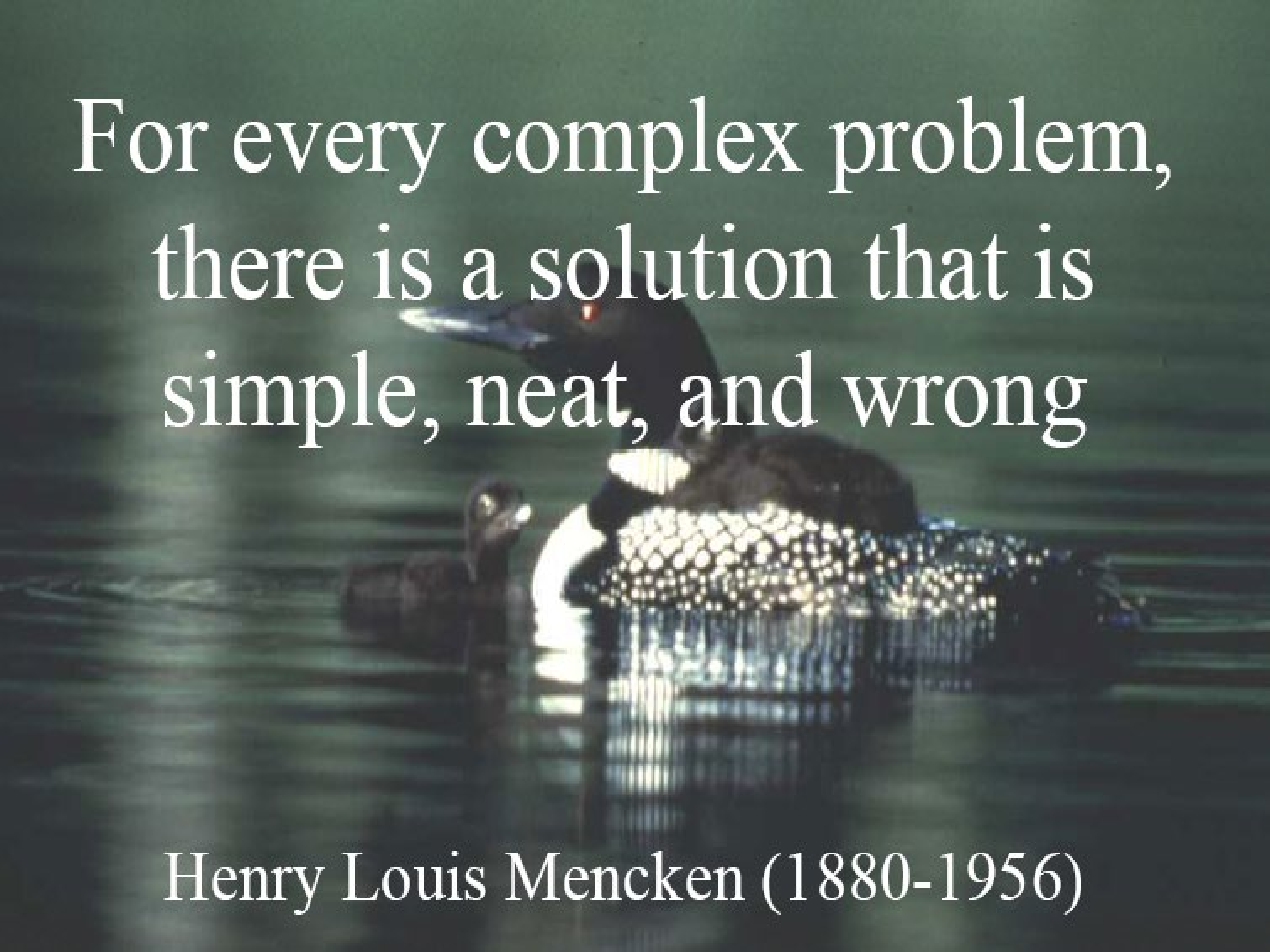
Table 2. Risks Which Increase the Chance of Death by One in One Million

Activity	*Cause of death*
Smoking 1.4 cigarettes	Cancer, heart disease
Drinking ½ liter of wine	Cirrhosis of the liver
Living 2 days in New York or Boston	Air pollution
Living 2 months in Denver on vacation from NY	Cancer caused by cosmic radiation
Living 2 months in average stone or brick building	Cancer caused by natural radioactivity
Traveling 6 minutes by canoe	Accident
Traveling 10 miles by bicycle	Accident
Traveling 300 miles by car	Accident
Flying 1000 miles by jet	Accident
Flying 8000 miles by jet	Cancer caused by cosmic radiation
One chest x-ray	Cancer caused by radiation
Eating 40 tablespoons of peanut butter	Liver cancer caused by aflatoxin B
Drinking Miami drinking water for 1 year	Cancer caused by chloroform
Drinking 30 12-oz. cans of diet soda	Cancer caused by saccharin
Eating 100 charcoal-broiled steaks	Cancer from benzopyrene

Source: Richard Wilson, "Analyzing the Daily Risks of Life," *Technology Review*, February, 1979, p. 45.

饮用水消毒与氯副产物困难的选择
(水源有微污染)




For every complex problem,
there is a solution that is
simple, neat, and wrong
Henry Louis Mencken (1880-1956)