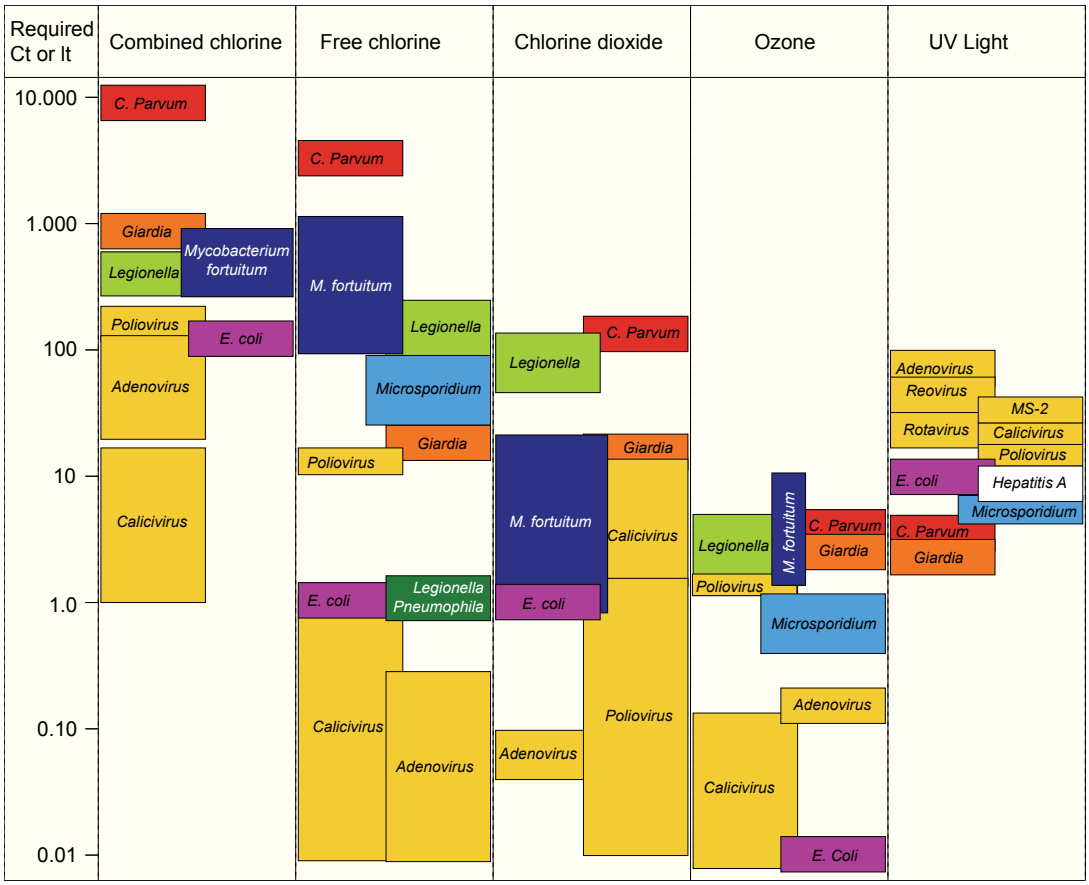
Disinfection



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This handout is based on *Drinking Water, Principles and Practices* by de Moel et al.

1. Introduction

The purpose of disinfection is to eliminate or inactivate pathogenic micro-organisms, so that waterborne diseases are avoided. The first use of disinfection as a continuous process in water treatment took place in Belgium in the early 1900s, where chlorine was used as the disinfecting reagent.
Since the introduction of filtration and disinfection at water treatment plants, waterborne diseases, such as typhoid and cholera, have been virtually eliminated. For example, in Niagara Falls, NY, USA, between 1911 and 1915, the number of typhoid cases dropped from 185 deaths per 100,000 people to nearly zero following the introduction of filtration and chlorination.

For nearly a century, chlorine gas or chlorine reagents (hypochlorite, etc.) were the most used disinfectantsfor drinking water production.
In 1974, researchers in the Netherlands and the United States demonstrated that trihalomethanes (THMs) were formed during chlorination.
Moreover, THMs and other disinfection byproducts (DBPs) have been shown to be carcinogenic, mutagenic, etc. Even if such health risks are small, they need to be taken seriously, since there is a large population exposed.

Nowadays, as a result of DBP concerns from chlorination, there are several other methods applied for disinfection, which include the use of ozone, UV, hydrogen peroxide and chloramines.

2. Purpose of disinfection

Although the epidemiological relationship between water and disease had been suggested as early as the 1850s, it was not until the development of the germ theory of disease by Pasteur in the mid-1880s that water as a carrier of disease-producing organisms was understood.
In the 1880s, while London was experiencing the "Broad Street Well" cholera epidemic, Dr. John Snow conducted his famous epidemiological study. Dr. Snow concluded that the well had become contaminated by a infected visitor.
Cholera was one of the first recognized waterborne diseases.
This incident was probably the first reported epidemic disease attributed to the direct recycling of non-disinfected water.

Now, over 100 years later, the list of potential waterborne diseases due to pathogens is considerably longer, and includes bacterial, parasitic,

Table 1 - Waterborne diseases from bacteria

Causative agent	Disease	Symptoms
Salmonella typhosa	Typhoid fever	Headache, neasea, loss of appetite, constipation or diarrhea, insomnia, sore throat, bronchitis, abdominal pain, nose bleeding, shivering and increasing fever, rosy spots on trunk. Incubation period: 7 - 14 days.
S. paratyphi *S. schottinulleri* *S. hirschfeldi C.*	Paratyphoid fever	General infection characterized by continued fever, diarrhea disturbances, sometimes rosy spots on trunk. Incubation period: 1 - 7 days.
Shigella flexneri *Sh. dysenteriae* *Sh. sonnei* *Sh. paradysinteriae*	Bacillary dysentery	Acute onset with diarrhea, fever, tenesmus and stool frequently containing mucus and blood. Incubation period: 1 - 7 days.
Vibrio comma *V. Cholerae*	Cholera	Diarrhea, vomiting, rice water stools, thirst, pain, coma. Incubation period: a few hours to 5 days.
Pasteurellla tularensis	Tularemia	Sudden onset with pains and fever; prostration. Incubation period: 1 - 10 days.
Brucella melitensis	Brucellosis (undulant fever)	Irregular fever, sweating, chills, pain in muscles.
Pseudomonas pseudomallei	Melioidosis	Acute diarrhea, vomiting, high fever, delerium, mania.
Leptospira icterohaemorrhagiae (spirochaetales)	Leptospirosis (Well's disease)	Fevers, rigors, headaches, nausea, muscular pains, vomiting, thirst, prostration and jaundice may occur.
Enteropathogenic *E. coli*	Gastroenteritis	Water diarrhea, nausea, prostration and dehydration.

Table 2 - Waterborne diseases from Parasites (Protozoa)

Causitive agent	Disease	Symptoms
Ascario lumricoidis (round worm)	Ascariasis	Vomiting, live worms in feces.
Cryptosporidium muris *Cryptosporidium parvum*	Cryptosporidiosis	Acute diarrhea, abdominal pain, vomitin, and low-grade fever. Can be life-threatening in immunodeficient patients.
Entamoeba histolytica	Amebiasis	Diarrhea alternating with constipation, chronic dysentery with mucus and blood.
Giardia lamblia	Giardiasis	Intermittent diarrhea.
Naegleria gruberi	Amoebid menigoecephalitis	Death.
Schistosoma mansoni	Schistosomiasis	Liver and bladder infection.
Taenia saginata (beef tapeworm)	Taeniasis	Abdominal pain, digestive disturbances, loss of weight.

and viral microorganisms, as shown in Tables 1, 2 and 3, respectively.

A major cause for the number of disease outbreaks in potable water is contamination of the distribution system from cross-connections and back siphoning with non-potable water. However, outbreaks resulting from distribution system contamination are usually quickly discovered and result in relatively few illnesses compared to the many cases of illness per incident when there is contamination of the source water or a breakdown in the treatment system.

Historically, about 46 percent of the outbreaks in public water systems are found to be related to deficiencies in source water and treatment systems, with 92 percent of the causes of illness due to these two particular problems.

All natural waters support biological communities. Since some microorganisms can be responsible for public health problems, the biological characteristics of the source water are one of the most important parameters in water treatment.

3. Pathogens of primary concern

Table 4 shows the attributes of three groups of pathogens of concern in water treatment, namely bacteria, viruses, and protozoa.

Bacteria

Bacteria are single-celled organisms typically with a size from 0.1 to 10 µm.

Shape, components, size, and the manner in which they grow characterize the physical cell structure.

Most bacteria can be classified into four shape categories: spheroid, rod, curved rod or spiral, and filamentous.

Cocci, or spherical bacteria, are approximately 1 to 3 µm in diameter.

Bacilli (rod-shaped bacteria) vary in size and range from 0.3 to 1.5 µm in width (or diameter) and from 1.0 to 10.0 µm in length.

Vibrios, or curved rod-shaped bacteria, vary in size from 0.6 to 1.0 µm in width (or diameter) and from 2 to 6 µm in length.

Spirilla (spiral bacteria) can be found in lengths up to 60 µm,.

Viruses

Viruses are microorganisms composed of the genetic material deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) and a protective protein coat (single-, double-, or partially double-stranded).

All viruses are obligate parasites, unable to carry out any form of metabolism and are completely dependent upon host cells for replication.

Viruses are typically 0.01 to 0.1 µm in size and are species specific with respect to infection, typically attacking only one type of host.

Although the principal modes of transmission for the hepatitis B virus and poliovirus are through food, personal contact, or exchange of body fluids, these viruses can also be transmitted through potable water.

Some viruses, such as the retroviruses (including the HIV group), appear to be too fragile for water transmission to be a significant danger to public health (Riggs, 1989).

Table 3 - Waterborne diseases from Human Enteric Viruses

Causative agent	Disease	Symptoms
Enterovirus Polio (3)	Muscular paralysis	Destruction of motor neurons
	Aseptic meningitis	Inflammation of meninges from virus
	Febrille episode	Viremia and viral multiplication
Enterovirus Echo (34)	Aseptic meningitis	Inflammation of meninges from virus
	Muscular paralysis	Destruction of motor neurons
	Guillain-Barre's Syndrome[1]	Destruction of motor neurons
	Exanthem	Dilation and rupture of blood vessels
	Respiratory diseases	Viral invasion of parechymiatous of respiratory tracts and secondary inflammatory responses intestinal infections
	Diarrhea	Not well known
	Epidemic myalgia	Viral invasion of cells with secondary infammatory responses
	Pericardits and myocarditis	Invasion of parencheyma cells
	Hepatitis	
Enterovirus Coxsackie (>24)	Herpengina[2]	Viral invasion of mucosa with secondary inflammation
Enterovirus A	Aculte lymphatic pharyngitis	Sore throat, pharyngeal lesions
	Aseptic meningitis	Inflammation of meninges from virus
	Muscular paralysis	Destruction of motor neurons
	Hand-foot-mouth disease[3]	Viral invasions of skin cells of hands-feet-mouth
	Respiratory disease	Viral invasion of parenchymiatous of respiratory tracts and secondary infammatory responses
		Viral invasion of cells of mucosa
	Infantile diarrhea	Viral invasion of parenchyma cells
	Hepatitis	Viral invasion of cells with secondary inflammatory responses
	Pericarditis and myocarditis	
Enterovirus B (6)	Pleurodynia[4]	Viral invasion of muscle cells
	Aseptic meningitis	Inflammation of meninges from virus
	Muscular paralysis	Destruction of motor neurons
	Meningoencephalitis	Viral invasion of cells
	Pericarditis, endocarditis, myocarditis	Viral invasion of cells with secondary inflammatory responses
	Respiratory disease	Viral invasion of parenchymiatous of respiratory tracts and secondary inflammatory responses
		Invasion of parenchyma cells
	Hepatitis or Rash	Viral invasion of vascular cells
	Spontaneous abortion	Viral invasion of insulin-producing cells
	Insulin-dependent diabetes	Viral invasion muscle cells
	Congenital heart anomalies	
Reovirus (6)	Not well known	Not well known
Adenovirus (31)	Respiratory diseases	Viral invasion of parenchymiatous of respiratory tracts and secondary inflammatory responses
		Viral invasion of cells and secondary inflammatory responses
	Acute conjunctivitis	Viral invasion of mucosa cells
		Viral invasion of lymph nodes
	Acute appendicitis	Viral invasion of parenchyma cells
	Intussusception	Sarcoma in hamsters
	Subacute thyroiditis	
	Sarcoma in hamsters	
Hepatitis (>2)	Infectious hepatitis	Invasion of parenchyma cells
	Serum hepatitis	Invasion of parenchyma cells
	Down's syndrome	Invasion of cells

Protozoa

Protozoa are single-cell eucaryotic microorganisms without cell walls that utilize bacteria and other organisms as food.

Most protozoa are free-living in nature and can be encountered in water; however, several species are parasitic and live on or in host organisms.

Host organisms can vary from primitive organisms such as algae to highly complex organisms such as human beings.

Several species of protozoa known to utilize human beings as hosts are shown in Table 2.

Within the past 40 years, several pathogenic agents never before associated with waterborne

Table 4 - Attributes of the three waterborne pathogens of concern in water treatment

Organism	Size (μm)	Mobility	Point(s) of origin	Resistance to disinfection	Removal by sedimentation, coagulation and filtration
Bacteria	0.1 - 10	Motile, Nonmotile	Humans and animals, water and contaminated food	Type specific - bacterial spores typically have the highest resistance whereas vegetative bacteria have the lowest resistance	Good, 2 to 3 - log removal
Viruses	0.01 - 0.1	Nonmotile	Humans and animals, polluted water, and contaminated food	Generally more resistant than vegetative bacteria	Poor, 1 to 3 - log removal
Protozoa	1 - 20	Motile, Nonmotile	Humans and animals, sewage, decaying vegetation, and water	More resistant than viruses or vegetative bacteria	Good, 2 to 3 - log removal

outbreaks have been found in the drinking water industry.

E-coli

The first documented case of outbreaks associated with enteropathogenic E. coli occurred in the 1960s in the United States.

Various serotypes of E. coli have been identified as the etiological agent responsible for disease in newborn infants, usually due to cross-contamination in nurseries.

Several well-documented outbreaks of E. coli (serotypes 0111:B4 and 0124:B27) have been associated with adult waterborne disease (AWWA, 1990, and Craun, 1981).

Giardia lamblia

Firstly identified in the sixties in the USA, Giardia lamblia is currently one of the most commonly identified pathogens responsible for waterborne outbreaks. It is a flagellated protozoan that is responsible for Giardiasis, a disease that can cause mild to extremedebilitation.

The life cycle of Giardia includes a cyst stage when the organism remains dormant and is extremely resilient (i.e., the cyst can survive to extreme environmental conditions).

Once ingested by a warm-blooded animal, the life cycle of Giardia continues with excystation.

The cysts are relatively large (8-14 μm) and can be removed effectively by filtration using diatomaceous earth, granular media, or membranes.

Giardiasis can be acquired by ingesting viable cysts from food or water or by direct contact with fecal material.

In addition to humans, wild and domestic animals have been implicated as hosts.

Currently, no simple and reliable method exists to assay Giardia cysts in water samples.

Microscopic methods for detection and enumeration are tedious and require examiner skill and patience. Giardia cysts are relatively resistant to chlorine, especially at higher pH levels and low temperatures.

Cryptosporidium

The first recorded Cryptosporidium infection in humans occurred in the mid-1970s

Cryptosporidium is a protozoan similar to Giardia. It forms resilient oocysts as part of its life cycle. The oocysts are smaller than Giardia cysts, typically about 4-6 μm in diameter. These oocysts can survive under adverse conditions until ingested by a warm-blooded animal, and then continue with excystation.

Due to the increase in the number of outbreaks of Cryptosporidiosis, a tremendous amount of research has focused on Cryptosporidium within the last 15 years.

Medical interest has increased because of its occurrence as a life-threatening infection to individuals with depressed immune systems.

In 1993, there was the largest documented waterborne disease outbreak in the United States, in Milwaukee, caused by Cryptosporidium.

An estimated 400,000 people became ill, 4,400 people were hospitalized, and 100 people died.
The outbreak was associated with deterioration of the raw water quality and a simultaneous decrease in effectiveness of the coagulation-filtration process, which led to an increase in the turbidity of treated water and the inadequate removal of Cryptosporidium oocysts.

Legionella pneumophila
In 1976 there was the first recorded outbreak of pneumonia caused by Legionella. A total of 221 people were affected and 35 of those afflicted died. The cause of the pneumonia was not determined immediately, despite an intense investigation by the Centers for Disease Control. Six months after the incident, microbiologists were able to isolate a bacterium from the autopsy lung tissue of one of the Legionnaires.
The bacterium responsible for the outbreak was found to be Legionella pneumophila (Witherell et al., 1988).
Following the discovery of this organism, other Legionella-like organisms were discovered. Twenty six species of Legionella have been identified, and seven are etiologic agents for Legionnaires' disease (AWWA, 1990).

Legionnaires' disease seems not to be transferred from person-to-person. Epidemiological studies have shown that the disease enters the body through the respiratory system.
Legionella can be inhaled via water particles less than 5µm in size from facilities such as cooling towers, hospital hot water systems, and recreational whirlpools (Witherell et al., 1988).

4. Mechanisms of pathogen inactivation

There are three primary mechanisms of pathogen inactivation:

- destruction or damage of the cellular structure by attacking major cell constituents, such as the cell wall or the semi-permeable membranes
- interference with energy-yielding metabolism through enzyme substrates in combination with prosthetic groups of enzymes, which render the enzymes non-functional
- interference with biosynthesis and growth by preventing synthesis of normal proteins, nucleic acids, coenzymes, or the cell wall.

Depending on the disinfectant and microorganism type, combinations of these mechanisms can also be responsible for pathogen inactivation.

The primary factors that control the disinfection efficiency in water treatment are:
(1) the ability of the disinfectant to oxidize or rupture the cell wall.
(2) the ability of the disinfectant to diffuse into the cell and interfere with cellular activity

5. Use of disinfectants in practice

The primary function of the use of disinfectants in water treatment is to inactivate pathogenic microorganisms. However, disinfectants are also used as oxidants for:

- control of nuisance Asiatic clams and zebra mussels
- prevention of algal growth in sedimentation basins and filters
- removal of taste and odors through chemical oxidation
- improvement of coagulation and filtration efficiency
- oxidation of iron and manganese
- removal of color
- prevention of regrowth in the distribution system and maintenance of biological stability.

The current use of disinfectants differs in different parts of the world.

USA
In the USA, most water treatment plants disinfect water prior to distribution.

The most commonly used disinfectants/oxidants are chlorine, chlorine dioxide and chloramines.
Table 5 displays the chemical usage as disinfectant or another role based on the survey of USEPA (Community Water Systems) of 1997. It is evident the predominance of chlorine in surface and groundwater disinfection treatment systems

Chloramine is used by some systems and is more frequently used as a post-treatment disinfectant.

Europe
In most of the Western European countries, the practice regarding disinfection and oxidation is completely different from that in the USA.
In Europe, disinfection of groundwater is seldom applied. The water is abstracted by hygienic means (closed wells, etc.), and the treatment and storage facilities are covered and protected. Since 2006, chlorination is no longer applied to surface water in the Netherlands, as mandated by the drinking water regulations. For primary disinfection in direct treatment systems (without infiltration or river bank infiltration), UV is used, either by itself or in combination with peroxide. Ozone is used sometimes. Chlorine dioxide is applied in most of the cases where post-disinfection is used.

Table 5 - Disinfection practice (USA)

Treatment	Ground-water	Surface water
Number of systems	31,579	3,347
Pre-disinfection	1%	4%
Primary disinfection/oxidation	66%	90%
Chlorine	64%	64%
Chlorine dioxide	0%	6%
Chloramines	0%	3%
Ozone	0%	1%
$KMnO_4$	2%	16%
Post-disinfection	32%	80%
Chlorine	31%	68%
Chlorine dioxide	0%	2%
Chloramines	0%	8%
Post-disinfection combinations	0%	3%

Gaseous chlorine is rarely used in Western Europe, according to safety regulations.

6. Disinfection byproducts

The type and amount of disinfection byproducts (DBPs) produced during treatment depends largely on the type of disinfectant, water quality, treatment sequences, contact time, and environmental factors such as temperature and pH.

DBPs include:
- halogenated organics, such as THMs, haloacetic acids, haloketones, and others that are produced primarily as a result of chlorination
- organic oxidation byproducts such as aldehydes, ketones, assimilable organic carbon (AOC), and biodegradable organic carbon (BDOC) that are associated primarily with strong oxidants such as ozone, chlorine, and advanced oxidation
- inorganics such as chlorate and chlorite associated with chlorine dioxide, and bromate that is associated with ozone, and has also been found when chlorine dioxide is exposed to sunlight.

Table 6 shows a list of disinfection residuals and disinfection byproducts (DBP) that may be of health concern.

Formation of DBPs
Halogenated organic byproducts are formed when natural organic matter (NOM) reacts with free chlorine or free bromine.
Free chlorine can be introduced to water directly as a primary or secondary disinfectant, through chlorine dioxide, or chloramines.
Free bromine results from the oxidation of the bromide ion in source water.
Factors affecting the formation of halogenated DBPs include the type and concentration of natural organic matter, oxidant type and dose, time, bromide ion concentration, pH, organic nitrogen concentration, and temperature.

Non-halogenated DBPs are formed when strong oxidants react with organic compounds found in water.

Table 6 - Chemicals with health risks related to disinfection

Chemical	Carcinogen
Disinfection residuals	
Free chlorine	
Monochloramine	
(Ammonia)	
Hydrogen peroxide	
Chlorine peroxide	
Inorganic byproducts	
Chlorate	
Chlorite	
Bromate	+
Iodate	
Organic oxidation byproducts	
Aldehydes	+
Carboxylic acids	
Assimilable Organic Carbon (AOC)	
Nitrosoamines	
Halogenated organic byproducts	+
Trihalomethanes (THM)	+
Haloacetic acids (HAA)	?
Haloacetonitriles	
Haloketones	+
Chlorophenols	
Chloropicrin	?
Chloral hydrate	
Cyanogen chloride	
N-Organochloramines	
MX	

Ozone and peroxone oxidation of organics leads to the production of aldehydes, aldo- and keto-acids, organic acids, and, when bromide ion is present, brominated organics (Singer, 1992).
Many oxidation byproducts are biodegradable and appear as biodegradable dissolved organic carbon (BDOC) and assimilable organic carbon (AOC) in treated water.

Bromide ion plays a key role in DBP formation.
Ozone or free chlorine oxidizes bromide ion to hypobromate ion/hypobromous acid, which subsequently forms brominated DBPs.
Brominated organic byproducts include compounds such as bromoform, brominated acetic acids and acetonitriles, bromopicrin, and cyanogen bromide. Only about one third of the bromide ions incorporated into byproducts has been identified.

DBP precursors
Numerous researchers have documented that NOM is the principal precursor of organic DBP formation).
Chlorine reacts with NOM to produce a variety of DBPs, including THMs, haloacetic acids (HAAs), and others.
Ozone reacts with NOM to produce aldehydes, organic acids, and aldo- and keto-acids; many of these are produced by chlorine as well

7. Disinfection kinetics

7.1 Chick's Law

In 1908 Harriet Chick found that the inactivation rate of micro-organisms could best be described by a first-order reaction (Chick´s Law):

$$\frac{dN}{dt} = -k \cdot N$$

or:

$$\ln(N/N_o) = -k \cdot t$$

where:
N = concentration of organism (- / m^3)
N_0 = initial concentration of organism (- / m^3)
t = time(s)
k = rate constant (1/s)

The rate constant k differs per type and concentration of disinfectant,,organism and temperature. The sensitivity of an organism to a certain specie depends on factors such as the penetration of the cell wall and the time needed to penetrate vital centers.
According to Chick's Law, the log-removal can be doubled providing the double of the contact time and considering that the disinfectant concentration (Figure 1) is constant.

It should be noted that Chick's Law is the same formula for natural decay with an increased decay constant caused by disinfection.

Due to the substantial amount of microorganisms involved in disinfection, log-removal is used to talk about efficiency of this treatment. The ratio of microorganisms inactivated to the original number can be for example 99% (2 logs) or 99.99 % (4 logs)

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7.2 Chick-Watson model

Also in 1908, Mr. Herbert Watson proposed his disinfection law:

$$C^n \cdot t = K_r$$

where:

C = concentration of disinfectant (mg/l)
n = empirical constant (-)
t = time (s)
K_r = empirical value for a percentage of inactivation (e.g., 99%)

In many cases, the empirical constant n can be assumed to be 1 (Figure 2).

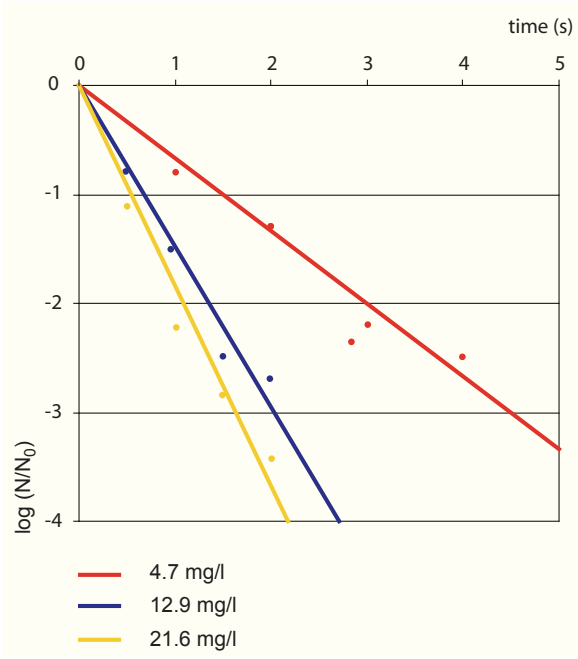

Figure 1 - Disinfection of Poliovirus Type 1 with 3 concentration Br_2

This means that for a certain inactivation, a certain C t -value is required, in which time t and concentration C are equally important.

Combining both laws (with n=1) results in the Chick-Watson law:

$$\ln(N/N_0) = -K_{CW} \cdot C \cdot t$$

where:

K_{cw} = specific lethality (l/mg.s)

In Figure 3, the data of Figure 1 is plotted according to the Chick-Watson model.
For a limited inactivation, the model fits the data rather well. The lower inactivation for the higher dose indicates a value n<1 (0.8-0.9). For higher inactivation, the required C t -value is more than the model assumes.

7.3 C t -values

In most cases the C t -value is used as the basis for disinfection.
In case of disinfection with UV radiation, the dose (mJ/cm^2) is calculated, instead of the C t value, by multiplying the UV light intensity (mW/cm^2) by the time of exposure (s),

There is information on C t -values and inactivation for many pathogens and disinfectants.

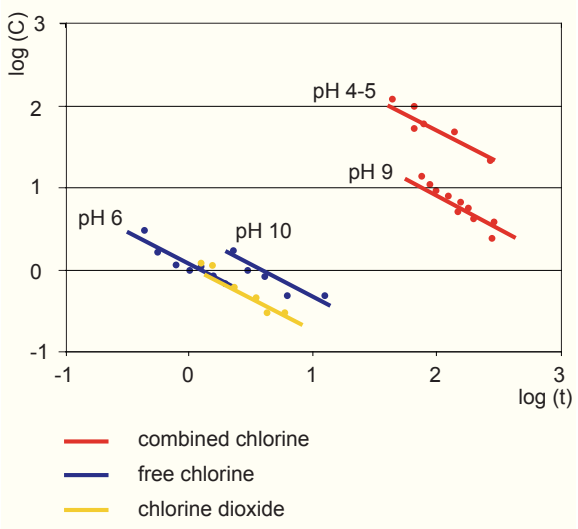

Figure 2 - Watson plot for 99% inactivation of Polio- virus Type 1

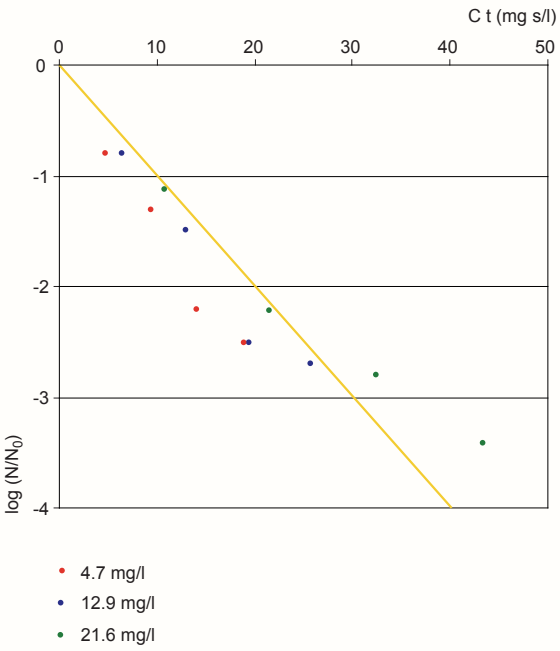

Figure 3 - Disinfection of Poliovirus Type 1 with 3 concentration Br_2 (Chick-Watson plot)

The US EPA (Environmental agency of the USA) specifies C t -values that must be met in order to regulate the control of pathogens within the Surface Water Treatment.

Currently, they have published tables for critical pathogens (e.g. Giardia, Cryptosporidium, viruses) for all relevant disinfection methods, and different log inactivation credits, at different water temperatures and pH.

An overview of the required C t -values for different disinfectant methods is shown in Figure 4.
Notice that Cryptosporidium Parvum and Giardia are difficult to inactivate with chemical disinfectants (high C t required) and easy to inactivate with UV radiation (low I t).
The opposite is true for viruses.

The range of required C t- values vary much more for chemical disinfectants (10^3 – 10^6) than for UV radiation (range 10^2).

Declining concentration
Since chemical disinfectants react with components in the water, their concentration declines in time.
Additionally, the disinfectant/oxidant might decompose. In the case of Ozone, the decomposition is a significant factor
To compare disinfection methods based on C t -values, reductions in the disinfectant concentration should be taken into account.

Temperature
At lower temperatures, disinfection requires higher C t -values for the same inactivation.
At 1 to 5 oC, the required C t -value might be 5 to 10 times higher than the C t -value at 25 °C.

Short-circuiting
The C t -values are based on batch experiments, in which the concentration and residence time are controlled.
In practice, however, disinfection is applied in full-scale contact tanks, having non-ideal residence times (residence time distribution, short-circuiting).

The Chick-Watson model can be used to determine the effect of a non-ideal flow in a disinfection reactor.
As an example the disinfection efficiency of a full plug flow reactor is compared with a reactor in which half of the flow has a residence time of 60%, and the other half a residence time of 140%. It is assumed that the plug flow reactor has an inactivation of log 4. The water at low residence time has an inactivation of (4.0*6=) 2.4, while the water in the high residence time has an inactivation of (4*1.4=) 5.6. The total inactivation is ($-\log(10^{2.4}+10^{5.6})/2$ =) 2.8.
This shows that short-circuiting has a substantial negative effect on the efficiency of disinfection, particularly when a high inactivation is required.

The t_{10} concept
According to US EPA regulations, the detention time is defined as the time in which 10% of the flow has passed the contactor (t10). When the

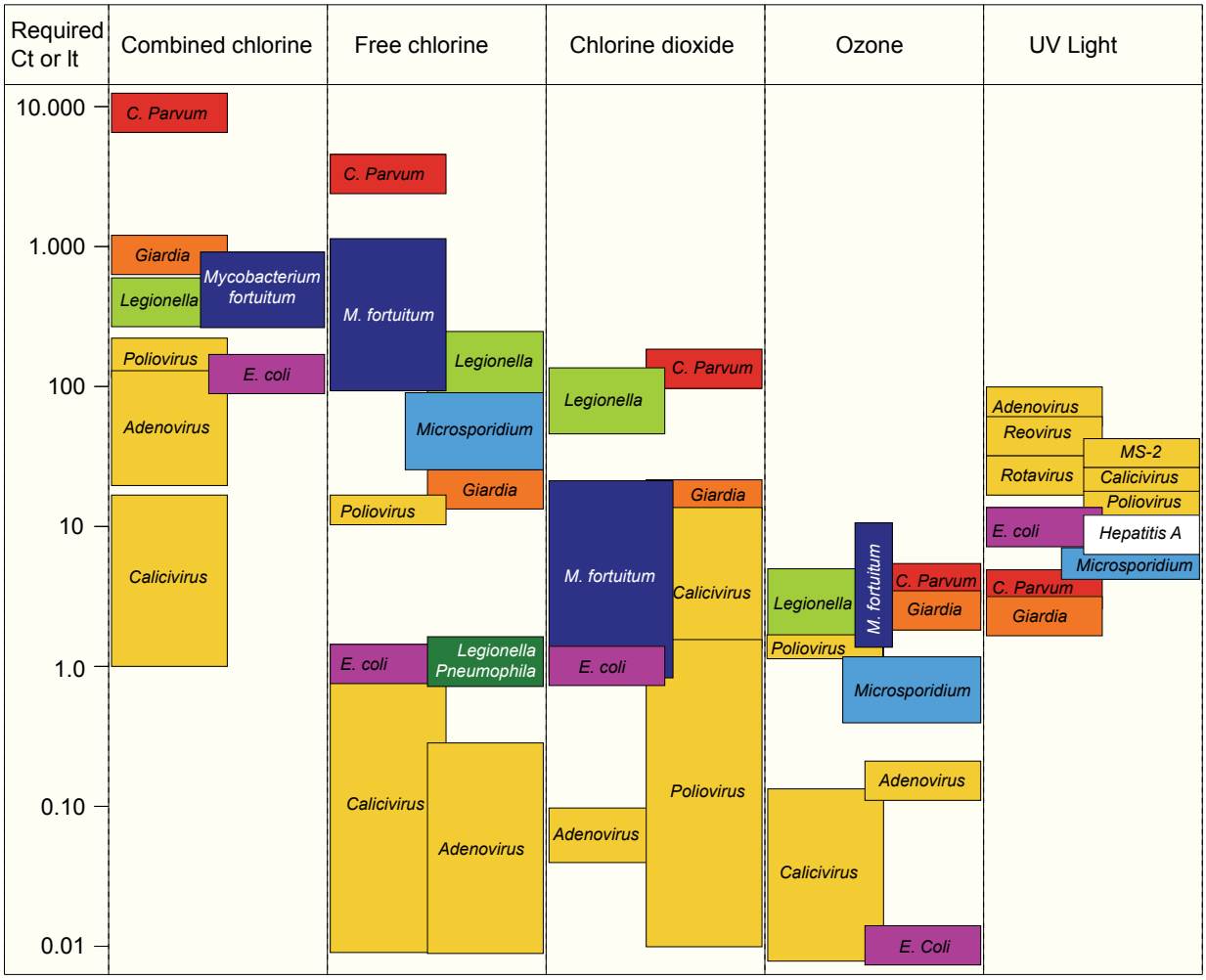

Figure 4 - Disinfection requirements for 99% inactivation (min mg/l or mJ/cm²)

contactors are poorly designed, the disinfection efficiency is greatly reduced.

In order to improve such reactors, conditions closer to plug flow can be achieved by proper flow splitting, baffling, and/or by designing long and narrow contactors.

Bypassing

Bypass occurs when part of the flow does not receive any disinfectant due to bad mixing caused by an uneven distribution of the flow.

If 1% of the flow is bypassing a log 4 disinfection reactor, the overall efficiency can be calculated as being log 2.

(influent, and bypass 10,000 organisms, disinfected main stream 1 organism, overall effect 10,000*0.01+1*0.99=100.99 organisms or log(100.99/10,000) = -1.996).

This example shows the dramatic reduction in disinfection caused by bypassing, in particular at a high disinfection requirement.

8. Disinfection methods

In the following section the advantages and disadvantages of using different disinfectants for drinking water treatment are presented.

Due to the wide variation of system sizes, water quality, and dosages applied, some of these advantages and disadvantages may not apply to all systems.

When considering the use of alternative disinfectants, the inactivation of pathogenic organisms is not compromised.

Pathogens pose an immediate critical public health threat due to the risk of an acute disease outbreak. Although most identified public health risks associated with DBPs are chronic, long-term risks, many systems will be able to lower DBP levels without compromising microbial protection.

8.1 Chlorine

Advantages

- Oxidation of soluble iron, manganese, and sulfides
- Enhancement of color removal
- Enhancement of taste and odor
- Eventual enhancement of coagulation and filtration of particulate contaminants
- Effective biocide
- Easiest and least expensive disinfection method, regardless of system size
- Most widely used for disinfection , and, therefore, the best known disinfectant
- Available as calcium and sodium hypochlorite. These solutions are more advantageous for smaller systems than chlorine gas because they are easier, safer, and need less equipment compared to chlorine gas
- Residual provision

Disadvantages

- Eventual deterioration in coagulation/filtration of dissolved organic substances
- Formation of halogen-substituted byproducts
- Eventual taste and odor problems, depending on water quality and dosage
- Hazardous corrosive gas
- Special leak container and scrubber facilities required for chlorine gas
- Sodium and calcium hypochlorite are more expensive than chlorine gas
- Degradation of sodium hypochlorite over time and with exposure to light
- Sodium hypochlorite corrosion anility
- Special storage requirement for calcium hypochlorite (must be cool, dry place because of its reaction with moisture and heat)
- Eventual precipitation in a calcium hypochlorite solution due to impurities and consequent need of antiscalant
- Formation of the byproduct chlorate athigher concentrations of hypochlorite solutions (unstable) solutions
- Less efficiency at high pH
- Formation of oxygenated byproducts that are biodegradable and which can enhance subsequent biological growth if the chlorine residual is not maintained.
- Release of constituents bound in the distribution system (e.g., arsenic) by changing the redox state

Generation

Chlorination may be performed using chlorine gas or other chlorinated compounds in liquid or solid form.

Chlorine gas can be generated by a number of processes including the electrolysis of alkaline brine or hydrochloric acid, the reaction between sodium chloride and nitric acid, or the oxidation of hydrochloric acid.

Since chlorine is a stable compound, chlorine gas, sodium hypochlorite, and calcium hypochlorite are typically produced off-site by a chemical manufacturer.

Primary uses

The primary use of chlorination is disinfection. Chlorine also serves as an oxidizing agent for taste and odor control, algal growth prevention, maintenance of a clear filter media, iron and manganese removal, hydrogen sulfide destruction, color removal, maintainance of the water quality at the distribution systems, and coagulation improvement.

Inactivation efficiency

Chlorine disinfection is extremely effective for bacteria, highly effective for viruses and less effective for protozoa, such as Giardia cysts and Cryptosporidium oocysts, being the last one highly resistant to chlorine.

Byproduct formation

When added to the water, free chlorine reacts with NOM and bromide to form DBPs, primarily THMs, some haloacetic acids (HAAs), and others.

Point of application

Chlorine can be applied at different treatment stages: in the raw water storage, pre-coagulation/post-raw water storage, pre-sedimentation/post-coagulation, post-sedimentation/pre-filtration, post-filtration (disinfection), or in the distribution system.

Special considerations
Due to its oxidation and corrosion power, special storage and handling of chlorine should be considered in the treatment plant planning.

8.2 Ozone

Advantages
- More effective than chlorine, chloramines, and chlorine dioxide for inactivation of viruses, Cryptosporidium, and Giardia.
- iron, manganese, and sulfides oxidation
- Enhancement of the clarification process and turbidity removal.
- Color, taste, and odors control.
- Very short contact time required
- In the absence of bromide, halogen-substitutes DBPs are not formed.
- Dissolved oxygen as , the only residual
- Biocidal activity not influenced by pH.

Disadvantages
- Formation of DBPs , particularly by bromate and bromine-substituted DBPs, in the presence of bromide, aldehydes, ketones, etc.
- Initial high cost of equipment.
- High energy and on-site generation requirement
- High corrosion tendency and toxicity.
- Biologically activated filters requirement removing assimilable organic carbon and biodegradable DBPs removal
- Rapid decay at high pH and warm temperatures.
- No residual.
- High level of maintenance and operator skill required.

Generation
Due to its instability, ozone should be generated in situ, which saves a lot of storage space.
Ozone can be generated from oxygen present in air or high purity oxygen. The feed gas source should be clean and dry, with a maximum dew point of -60 ^{o}C.
Power consumption for generation is between 8 to 7 kWh/kg O_3.

Primary uses
Primary uses include primary disinfection and chemical oxidation which aims to increase the biodegradability of organic compounds, to control taste and odor, and to reduce levels of chlorination

DBP precursors.
Ozone should not be used for secondary disinfection because it is highly reactive and does not maintain a reasonable residual level for the period of time desired in the distribution system.

Inactivation efficiency
Inactivation efficiency for bacteria and viruses is not affected by pH; at pH levels between 6 and 9. As water temperature increases, ozone disinfection efficiency increases.

Byproduct formation
Ozone itself does not form halogenated DBPs; however, if bromide ion is present in the raw water or if chlorine is added as a secondary disinfectant, halogenated DBPs, including bromate ion may be formed.
Other ozonation byproducts include organic acids and aldehydes.

Limitations
Ozone generation is a relatively complex process. Storage of LOX (if oxygen is to be the feed gas) is subject to building and fire codes.

Points of application
For primary disinfection, ozone addition should be prior to biofiltration/filtration and after sedimentation.
For oxidation, ozone addition can be prior to coagulation/sedimentation or filtration, depending on the constituents to be oxidized.

Safety considerations
The facilities for generation and application of ozone must consider its toxicity and the personnel

protection. Thus, ozone levels should be continuously monitored.

8.3 UV radiation

Advantages
- More effective than chlorine, chloramines, and chlorine dioxide for inactivation of viruses, Cryptosporidium, and Giardia.
- Very short contact time required
- DBPs are not formed.

Disadvantages
- Initial high cost of equipment.
- High energy requirement
- Efficiency influenced by transmittance of water
- No residual.
- High level of maintenance and operator skill required.

Generation
Low pressure and medium pressure UV lamps are used for generation.

Primary uses
UV radiation is primarily used as disinfectant, which requires a secondary chemical disinfectant to leave a residual in the distribution system.

Inactivation efficiency
This method is very effective against bacteria and viruses at low dosages (5 - 25 mW.s/cm2 for 2-log removal and 90 - 140 mW.s/cm^2 for 4-log removal). Much higher dosage is required for Cryptosporidium and Giardia (100 - 8,000 mW.s/cm^2 for 2-log removal)

Byproduct formation
Minimal disinfection byproducts are produced.

Limitations
The limitations of UV include few experience with this disinfectant and data with large flows.
Water with high concentrations of iron, calcium, turbidity, and phenols may not be applicable to UV disinfection.

Point of application
It is preferable to apply UV radiation prior to the distribution system.

Special considerations
Extremely high UV dosages for Cryptosporidium and Giardia are not practical for surface water treatment.

8.4 Chlorine dioxide

Advantages
- More effective than chlorine and chloramines for inactivation of viruses, Cryptosporidium, and Giardia.
- Iron, manganese, and sulfides oxidation
- Enhancement of the clarification process.
- Control of taste and odors resulting from algae and decaying vegetation, as well as phenolic compounds
- Under proper generation conditions (i.e., no excess chlorine), halogen-substituted DBPs are not formed.
- Easy to generate.
- Biocidal properties not influenced by pH.
- Residual presence.

Disadvantages
- Formation ofthe specific byproducts chlorite and chlorate.
- Formation of halogen-substitute DBPs due to excess chlorine caused by the generator efficiency and optimization difficulty .
- High costs associated with training, sampling and laboratory testing for chlorite and chlorate
- Equipment rentall, and high cost of sodium chlorite.
- On-site generation and measurement since that chlorine dioxide gas is explosive.
- Decomposes under sunlight.
- Eventual production of noxious odors .

Generation
Chlorine dioxide must be generated on-site, as needed and directly educed from or injected into a diluting stream.

Generators utilize sodium chlorite and a variety of feedstock such as Cl_2 gas, sodium hypochlorite, and sulfuric or hydrochloric acid.
Small samples of solutions, up to 1 percent (10 g/l) chlorine dioxide can be safely stored when protected from light, at a low temperature (<5 oC), and without unventilated headspace.

Primary uses
Chlorine dioxide is utilized as a primary or secondary disinfectant for taste and odor control, TTHM/HAA reduction, Fe and Mn control, color removal, sulfide and phenol destruction, and Zebra mussel control.

Inactivation efficiency
Most microorganisms are rapidly inactivated over a wide pH range. It is more effective than chlorine (for pathogens excluding viruses) and is not pH dependent between pH 5-10, but is less effective than ozone.

Byproducts formation
When added to water, chlorine dioxide reacts with many organic and inorganic compounds. The reactions produce chlorite and chlorate as end-products (compounds that are suspected of causing hemolytic anemia and other health effects). Chlorate ion is formed predominantly in downstream reactions between residual chlorite and free chlorine, when used as the distribution system disinfectant.
Chlorine dioxide aids in reducing the formation of TTHMs and HAAs by oxidizing precursors, and by allowing the point of chlorination to be moved farther downstream in the plant, after coagulation, sedimentation, and filtration have reduced the quantity of NOM.

Point of application
In conventional treatment plants, chlorine dioxide used for oxidation is fed in the raw water, in the sedimentation basins, or following sedimentation. To limit the oxidant demand, and therefore the chlorine dioxide dose and formation of chlorite, it is common to add chlorine dioxide following sedimentation.

Concerns about possible taste and odor complaints have limited the use of chlorine dioxide to provide a disinfectant residual in the distribution system. Consequently, public water suppliers who consider the use of chlorine dioxide for oxidation and primary disinfectant, may consider chloramines for secondary disinfection.

Special considerations
An oxidant demand study should be completed to determine an approximate chlorine dioxide dosage to obtain the required C t -value as a disinfectant.
In addition to the toxic effects of chlorine, chlorine dioxide gas is explosive at levels > 10% in air. Its dosage cannot exceed 1.4 mg/l so as to limit the total combined concentration of ClO_2, ClO_2^-, ClO_3^-, to a maximum of 1.0 mg/l.
Under the proposed DBP regulations, the MRDL for chlorine dioxide is 0.8 mg/l and the MCL for chlorite is 1.0 mg/l. Regulations concerning the use of chlorine dioxide vary from state to state.