Water Treatment – Disinfection

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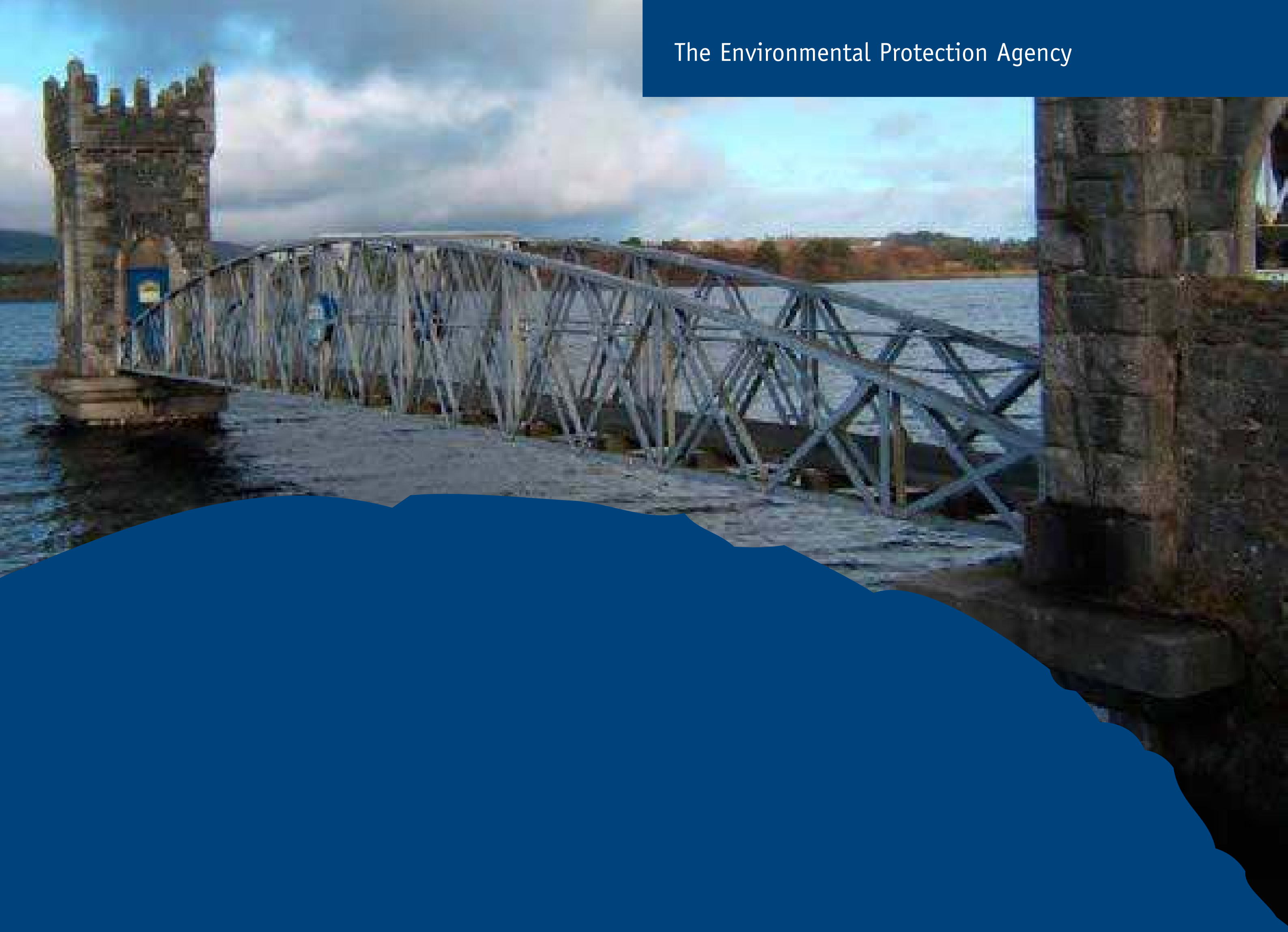

Water Treatment Manual: Disinfection

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Environmental Protection Agency

The Environmental Protection Agency (EPA) is a statutory body responsible for protecting the environment in Ireland. We regulate and police activities that might otherwise cause pollution. We ensure there is solid information on environmental trends so that necessary actions are taken. Our priorities are protecting the Irish environment and ensuring that development is sustainable.

The EPA is an independent public body established in July 1993 under the Environmental Protection Agency Act, 1992. Its sponsor in Government is the Department of the Environment, Community and Local Government.

OUR RESPONSIBILITIES

LICENSING

We license the following to ensure that their emissions do not endanger human health or harm the environment:

- waste facilities (e.g., landfills, incinerators, waste transfer stations);
- large scale industrial activities (e.g., pharmaceutical manufacturing, cement manufacturing, power plants);
- intensive agriculture;
- the contained use and controlled release of Genetically Modified Organisms (GMOs);
- large petrol storage facilities;
- waste water discharges.

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- Conducting over 2,000 audits and inspections of EPA licensed facilities every year.
- Overseeing local authorities' environmental protection responsibilities in the areas of - air, noise, waste, waste-water and water quality.
- Working with local authorities and the Gardaí to stamp out illegal waste activity by co-ordinating a national enforcement network, targeting offenders, conducting investigations and overseeing remediation.
- Prosecuting those who flout environmental law and damage the environment as a result of their actions.

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- Independent reporting to inform decision making by national and local government.

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- Quantifying Ireland's emissions of greenhouse gases in the context of our Kyoto commitments.
- Implementing the Emissions Trading Directive, involving over 100 companies who are major generators of carbon dioxide in Ireland.

ENVIRONMENTAL RESEARCH AND DEVELOPMENT

- Co-ordinating research on environmental issues (including air and water quality, climate change, biodiversity, environmental technologies).

STRATEGIC ENVIRONMENTAL ASSESSMENT

- Assessing the impact of plans and programmes on the Irish environment (such as waste management and development plans).

ENVIRONMENTAL PLANNING, EDUCATION AND GUIDANCE

- Providing guidance to the public and to industry on various environmental topics (including licence applications, waste prevention and environmental regulations).
- Generating greater environmental awareness (through environmental television programmes and primary and secondary schools' resource packs).

PROACTIVE WASTE MANAGEMENT

- Promoting waste prevention and minimisation projects through the co-ordination of the National Waste Prevention Programme, including input into the implementation of Producer Responsibility Initiatives.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

MANAGEMENT AND STRUCTURE OF THE EPA

The organisation is managed by a full time Board, consisting of a Director General and four Directors.

The work of the EPA is carried out across four offices:

- Office of Climate, Licensing and Resource Use
- Office of Environmental Enforcement
- Office of Environmental Assessment
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet several times a year to discuss issues of concern and offer advice to the Board.

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1. INTRODUCTION

Drinking water supplies in Ireland are predominantly sourced from surface waters or groundwaters influenced by surface water. In recent reports on “The Provision and Quality of Drinking Water in Ireland” the Environmental Protection Agency (EPA) found that 81.6% originates from surface water (i.e. rivers and lakes) with the remainder originating from groundwater (10.3%) and springs (8%). Source waters, susceptible to surface contamination, particularly surface waters and groundwater and spring sources contain micro-organisms such as bacteria, viruses and protozoan parasites (e.g. *Cryptosporidium)* which can present a risk to human health if not effectively treated and disinfected.

Since 2008 the EPA has set out as its policy that the most effective means of consistently ensuring the safety of a drinking water supply is through the use of a comprehensive risk assessment and risk management approach that encompasses all steps in water supply from catchment to consumer. The EPA has advised Water Service Authorities to implement the World Health Organisation (WHO) Water Safety Plan approach to risk assessment and risk management.

The overriding objective of water treatment is the removal or inactivation of pathogenic micro-organisms to prevent the spread of waterborne disease. It is important that water treatment works be equipped with adequate disinfection systems, when pristine water supplies collected from catchments totally under the control of the water supply authority are now a rarity.

Removal of pathogenic organisms is effected by processes involving addition of coagulant chemicals followed by sedimentation and filtration and by other filtration processes such as membrane filtration.

In contrast to removal, the concept of inactivation of pathogens in water relates to the effect that the application of a disinfectant has in destroying the cellular structure of the micro-organisms or in disrupting its metabolism, biosynthesis or ability to grow/reproduce. In the case of bacteria, inactivation describes the subsequent inability of the microorganism to divide and form colonies. For viruses, inactivation measures the inability of the microorganism to form plaques in host cells. For protozoan *Cryptosporidium* oocysts, it measures the inability of the microorganism to multiply, thereby preventing consequent infection of a host by *Cryptosporidium*.

The philosophy underlying disinfection of all water supplies is to use the best quality source of water available and to provide multiple barriers to the transmission of any pathogenic organisms to consumers.

1.1. Objective of the updated manual

The objective of this disinfection manual is to provide practical guidance and information to the following:

a) Water Service Authorities and Private Water Suppliers to allow them to design and operate water treatment systems to provide rigorous disinfection, whilst maintaining compliance with other water quality parameters, particularly in relation to disinfection by-products.

b) The respective supervisory authorities for both public and private water supplies under current Drinking Water Regulations

It is an update of the earlier EPA Disinfection Manual, published in 1998, and reflects changes in technology and regulations over the past 10 years. Areas of particular importance in this respect are:

- the development of risk based approaches for water treatment,
- the increasing recognition that there is a need for integration of disinfection processes within a multi-barrier approach to water treatment in a way which maximises overall disinfection efficiency,
- increasing use of alternative disinfection technologies such as ultraviolet (UV) disinfection and the development of associated dose validation techniques and regulations

It is acknowledged that considerable health and safety risk is associated with the handling and use of disinfectant chemicals used for the pre-treatment and disinfection of drinking water supplies. This Guidance Manual does not deal with the hazards posed by the generation, storage or use of these chemicals in water treatment or disinfection, the interaction of these chemicals or the associated risks for plant operators managing the production of drinking water for Water Service Authorities or private drinking water suppliers. The Safety, Health and Welfare Act 2005 addresses the responsibilities of Water Service Authorities and private suppliers in the management of these operator risks. These drinking water suppliers must also consult with chemical suppliers and the particular material safety data sheets for chemicals used and prepare hazard statements, compliant with Regulation (EC) No 1272/2008 and the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), to deal with the associated physical, health and environment hazards.

1.2. The Drinking Water Regulations (SI 278 of 2007)

The current national EC (Drinking Water) (No 2) Regulations SI 278 of June 2007 (downloadable at http://www.irishstatutebook.ie/2007/en/si/0278.html), transpose Council Directive 98/83/EC into Irish law, and are used to regulate the supply of:

"all water, either in its original state or after treatment, intended for drinking, cooking, food preparation or other domestic type purposes, regardless of its origin and whether it is supplied from a distribution network, from a private source or by tanker or similar means."

Water supplies which fall under the remit of the regulations include individual supplies of greater than 10 cubic metres per day on average, supplies serving more than 50 persons, and supplies which are part of a commercial or public activity.

The verification of compliance and enforcement of these regulations is the function of the "Supervisory Authority" which the regulation defines as follows:

- The EPA in respect of drinking water supplied by a Water Service Authority
- Water Service Authorities in respect of drinking supplied by private suppliers within their functional areas

The regulations prescribe the quality standards to be applied, and related supervision and enforcement procedures in relation to supplies of drinking water, including requirements as to sampling frequency, methods of analysis, the point of compliance monitoring, the provision of information to consumers and related matters.

Regulation 5 stipulates that "measurement of compliance with the parametric values specified in Part 1 of the Schedule shall be made in the case of—

(a) water supplied from a distribution network or a private source, at the point within a premises at which it emerges from the tap or taps that are normally used for the provision of water for human consumption;

(b) water supplied by tanker or similar means, at the point at which it emerges from it;

(c) water used in a food-production undertaking, at the point where the water is used in the undertaking.

The main provisions of SI 278 of 2007 that particularly refer to drinking water disinfection are as follows:

A. Regulation 4 directs that

"*Water shall be regarded as wholesome and clean if -*

(a) it is free from micro-organisms and parasites and from any substances which in numbers or concentrations, constitute a potential danger to human health, and

(b) it meets the quality standards specified ….." in Part 1 of the attached Schedule

B. Regulation 7 (10) stipulates that the Supervisory Authority shall ensure

"*additional monitoring is carried out on a case-by-case basis (whether by itself or the relevant water supplier) of substances and micro-organisms for which no parametric value has been specified in Part 1 of the Schedule, if there is reason to suspect that such substances or micro-organisms may be present in amounts or numbers that constitute a potential danger to human health"* and may issue direction to a supplier where it is of the *"opinion that—*

(a) non-compliance with a water quality standard or other parametric value specified in Part 1 of the Schedule, or

(b) the presence of any substance or micro-organism for which no water quality standard has been prescribed,

in water intended for human consumption, or the inefficiency of related disinfection treatment, constitutes, or may constitute, a risk to human health"

C. Regulation 9 requires that if Water Service Authorities

"… in consultation with the Health Service Executive, considers that a supply of water intended for human consumption constitutes a potential danger to human health, the authority shall…..ensure that — (a) the supply of such water is prohibited, or the use of such water is restricted, or such other action is taken as is necessary to protect human health",

D. Regulation 13 sets out as follows the obligations of Water Service Authorities and regulated Private Water Suppliers with respect to the monitoring and verification of disinfection systems;

"*where disinfection forms part of the preparation or distribution of water intended for human consumption, the efficiency of the disinfection treatment is verified and that any contamination from disinfection by-products is kept as low as possible without compromising the disinfection, in accordance with such directions as the relevant supervisory authority may give".*

Refer to the following EPA publication for further guidance on the use of the Regulations for both public and supply water supplies.

- *European Communities (Drinking Water) (No. 2) Regulations 2007 A Handbook on the Implementation of the Regulations for Water Service Authorities for Public Water Supplies* (available at www.epa.ie).

- *European Communities (Drinking Water) (No. 2) Regulations 2007 A Handbook on the Implementation of the Regulations for Water Services Authorities for Private Water Supplies* (available at www.epa.ie).

SI 278 of 2007 does not have an indicator parameter value for *Cryptosporidium* other than a requirement to investigate for *Cryptosporidium* if tested water from a surface water source or a source influenced by surface water is non compliant for *Clostridium perfringens*.

There are no international standards for *Cryptosporidium* in drinking water. The only previous treatment standard for *Cryptosporidium* was the UK Drinking Water Inspectorate (DWI) *Cryptosporidium* treatment standard (i.e. not exceeding an average of 1 oocyst in 10L water, based on filtering of a minimum of 40L water per hour over 23 hours). This has been revoked, consequent to new Drinking Water Regulations, published in the UK in Jan 2008, which similarly focus attention on "*potential danger to human health"* rather than removal of protozoan oocysts.

1.3 Disinfection technologies

In the developed world the use of water supply disinfection as a public health measure has been responsible for a major reduction in people contracting illness from drinking water. However many of these disinfectant chemicals if overdosed or used inappropriately, as part of a water treatment process, can result in the formation of disinfection by-products. Disinfection by-products are formed when disinfection chemicals react with organic or inorganic compounds. Research shows that human exposure to these by-products may have adverse health effects.

The most common chemical disinfectant for water treatment, and the one that has historically made the greatest contribution to the prevention of waterborne disease worldwide, is chlorine. Chlorine for water treatment is generally obtained and used as either liquefied chlorine gas or as sodium hypochlorite solution. The latter is available as a commercial product or can be generated through On-Site Electrochlorination (OSE).

Regulatory implications for the use of chlorine relate primarily to by-products. The most well known of these are the trihalomethane (THM) compounds, although another group of by-products of increasing concern in water supply are the haloacetic acids (HAAs).

Chlorine is used not only as a primary disinfectant in water treatment, but is also added to provide a disinfectant residual to preserve the water in distribution, where the chlorine is in contact with the water for much longer than during treatment. In many situations, this is the more significant factor in terms of organochlorine by-product formation, and is a driver in the implementation of chloramination in other countries. In chloramination, chlorine is normally added first as the primary disinfectant for treatment, followed by ammonia after the chlorine contact tank to form monochloramine prior to distribution. Monochloramine is less effective as a disinfectant than chlorine, but provides a much more stable residual in distribution, and has the added benefit that it does not produce THMs or HAAs.

Alternatives to chlorine as a primary disinfectant exist. Ozone is a very effective disinfectant, and where it is used for other purposes, usually for removal of organic micropollutants such as pesticides, it provides benefits in terms of reducing the microbiological challenge to downstream disinfection. However, ozone also forms by-products, particularly bromate. Chlorine dioxide is used as a primary disinfectant and in distribution worldwide, but there are limitations to its use because of the inorganic by-products chlorite and to a lesser extent chlorate. Where these chlorite by-products are elevated consequent to high ClO_2 doses, an additional chemical dosing process is required involving the addition of ferrous salts to reduce levels to below the WHO guideline limit of 0.7mg/l.

Many of these disinfectants are also employed as oxidation agents to improve the efficiency of coagulation/filtration, reduce iron and manganese, remove taste and odour and control algal growth. The possible cumulative effect of these oxidants on by-product formation in combination with their use for disinfection purposes also needs to be understood and risk assessed.

In addition to chemical disinfectants, UV irradiation has been used for many years for disinfection in water treatment. Its implementation is increasing worldwide, partly to reduce the amount of chlorine used and minimise the potential for by-product formation, but also because of recent recognition that it provides effective inactivation of *Cryptosporidium* and other pathogenic protozoa. Like ozonation, UV does not provide a residual for distribution and in an Irish context will principally be used in conjunction with a residual generating chemical disinfectant.

1.4 Risk based approach

The provision of drinking water free from harmful micro-organisms has traditionally been assured by monitoring the numbers of bacteria which are indicators of faecal contamination. This monitoring is done on drinking water entering supply and at certain fixed and random locations within the distribution system.

There is now international recognition within the water industry that this approach to safeguarding the quality of water may not always be sufficient and that development and adoption of risk management plans offer improved protection.

In 2008, the EPA adopted the WHO Drinking Water Safety Plan (DWSP) approach to ensuring drinking water is “safe” and “secure”. A drinking water supply is deemed to be safe if it meets quality standards each time the supply is tested. A drinking water supply is deemed to be secure if there is in place a management system that has identified all potential risks and reduction measures to manage these risks

The benefits of the risk-based approach are as follows:

- It puts greater emphasis on prevention through good management practice and so less reliance is placed on end product testing of treated water where the opportunity for corrective action is limited,
- It offers a systematic approach to managing the quality of drinking water at all stages from source to tap, and
- It provides transparency to increase trust and confidence in water supplies.

The World Health Organisation (WHO) have promoted this risk based approach through guidance for Drinking Water Safety Plans accepted worldwide as providing an integrated framework for operation and management of water supply systems. This involves an assessment of how particular risks can be managed by addressing the whole process of water supply from source to tap. Water treatment is a key barrier within the DWSP approach to prevent the transmission of waterborne pathogens. The DWSP approach requires that the range of pathogens likely to be present is identified and that treatment processes known to be capable of eliminating these organisms are applied. The assessment must take into account extreme events (e.g. heavy rainfall causing run-off from grazing land) which can increase the microbial burden in the source water.

The DWSP approach puts as much emphasis on assessing and managing risk in the catchment as on treatment and distribution. Elements of this "source to tap" approach for managing microbiological risk are illustrated in Figure 1.1.

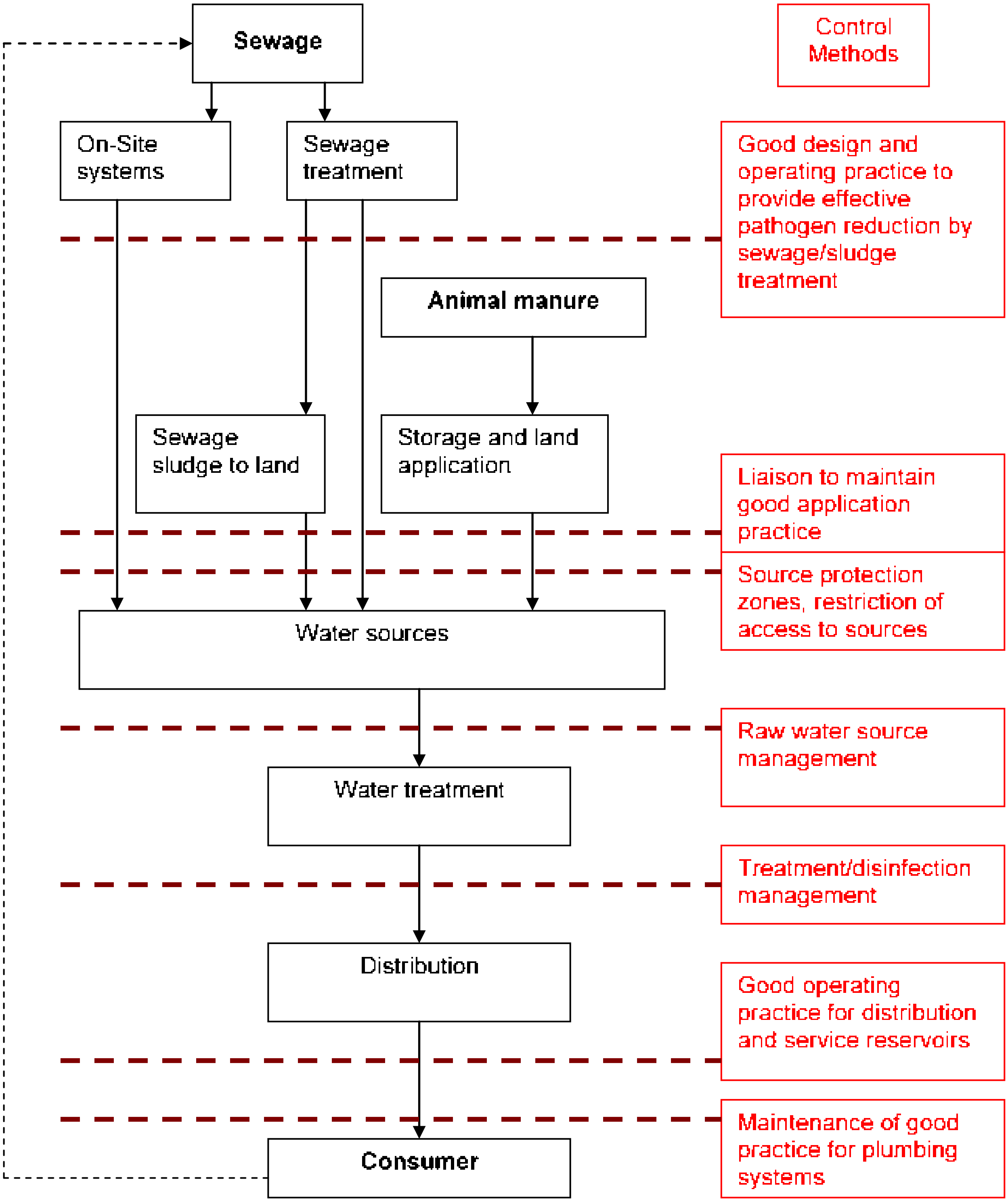

Figure 1.1 Sources and control of faecal contamination from source to tap

1.5 Integration of disinfection within overall treatment

Disinfection does not necessarily start and end at the inlet and outlet of a contact tank. Other parts of the treatment process may provide disinfection by removing micro-organisms as well as ensuring the water is suitable for disinfection with chlorine or other disinfectants.

Many water treatment works abstracting from surface waters, such as rivers and reservoirs, have long adopted the ‘multi-barrier’ approach to water treatment, where a number of treatment processes are employed to provide treatment and disinfection. Failure of an upstream process such as clarification or filtration may mean that the chlorination stage will not be able to achieve disinfection. Both chemical coagulation based treatment followed by rapid gravity filtration and slow sand filtration can provide effective removal of protozoan pathogens, bacteria and, sometimes to a lesser extent, viruses.

Although chemical coagulation can be optimised for particulate, turbidity and microbial removal, there is still a need to ensure other impurities such as colour are removed. Optimisation of coagulation will require examination with respect to type of coagulant, dose and pH. Physical conditions such as position of dosing point, mixing and flocculation need to be considered. Aids to coagulation, such as polyelectrolytes, may be useful. Pre-oxidation may also improve particle removal by subsequent treatment.

Filtered water quality can change during filter runs, and managing this can have a significant effect on reducing microbial risk. At the beginning of a filter run, there is what is known as the ripening period, where filtered water will show higher turbidity and particle counts. This can be a source of potential microbial breakthrough. Actions may be taken to reduce the impact of this ripening period on final water quality. These can include a slow or delayed return to service or filtering to waste or returning filtered water to the head of the works at the start of a filter run.

Recycling of filter backwash water can return pathogens removed by the filters back to the start of the treatment process. This increase in pathogen load may pose a challenge to treatment with an associated risk of filter breakthrough. Disposal of filter backwash is preferable unless treatment is available to provide a good quality supernatant for recycling, and the recycling is carried out over extended periods. Adequate treatment of filter backwash prior to recycling should not increase risk unacceptably. The US EPA Filter Backwash Recycling Rule (2001) requires systems that recycle backwash water to return specific recycle flows through all processes of the system’s existing conventional or direct filtration system or at an alternate location approved by the state.

In respect of the disposal of filter backwash, Water Service Authorities should refer to the Department of Environment, Community and Local Government Circular Letter WSP1/05 on the Management of Water Treatment Sludges.

Supernatant from sludge treatment processes may also introduce a risk if recycled. If disposal to sewer is not possible then discharge of supernatant to receiving water if treated properly or recycling to part of a treated washwater recovery system would be preferable, so that some treatment and/or settlement is possible. This poses a lower risk than recycling to the head of the works.

In the USA the idea that various component parts of a treatment works can provide overall disinfection is accepted by the US Environmental Protection Agency and may be found as part of the regulatory framework within the Surface Water Treatment Rule. Under the SWTR, surface water systems must achieve a minimum removal of specific micro-organisms. For instance, a treatment works must reduce the source water concentration of *Giardia* by 99.9% and viruses by 99.99%.

The level to be achieved depends to some extent on the source water, and although an overall target for log removal of pathogens is expected to be achieved, the decision as to which treatment processes will be used to achieve this is left to the Water Service Authority. Certain types of treatment are expected to be present, and other treatment processes must be approved in order to contribute log removal ‘credits’. To claim these credits it must be demonstrable that these processes are working within normal operating parameters.

Treatment upstream of disinfection is also crucial to the performance of any disinfection processes. If the bacteriological loading entering the disinfection stage is too great then disinfection will not be able to achieve the required reduction in numbers of bacteria and pathogens. In addition to this, conventional disinfection practices will require treated water to achieve certain standards in terms of turbidity, pH and other parameters prior to their application. There are also raw water characteristics that can exert a chlorine demand e.g. ammonia, iron and manganese. Any upstream processes must be able to prepare the water so that disinfection is not compromised, for example in relation to turbidity removal. Upstream processes can also be critical to minimise the risk from disinfection by-products. With chlorination, for example, this would require removal of organic precursors for THMs and HAAs; these precursors are very effectively removed by well operated chemical coagulation based treatment.

1.6 Principles for the selection of an appropriate disinfection system

This manual is intended as a guide to the disinfection technologies currently available and as a guide to their application and operation in practice. The selection of the appropriate disinfection system should be made on an individual supply by supply basis. The EPA does not favour or endorse any particular disinfection method but recommends that the selection and application of an appropriate disinfection technology should have regard to the following principles:

- The assessment of catchment and source risks with respect to the clarity, organic content, and the likely risk of pathogenic micro-organisms in the source water.

- The evaluation of particular source risk following analysis of raw water monitoring to determine the extent of pathogen removal/inactivation required of the disinfection system. The disinfection technology must be capable of removing or inactivating all pathogens potentially present in the final water.

- The determination of the pre-treatment process(es), necessary to ensure the required pre-treatment of the water (with respect to colour, turbidity and TOC) and/or inorganic chemical removal, upstream of the disinfection system to ensure it is capable of performing adequately.

- An assessment of the adequacy of contact time for chemical disinfection technologies and the necessity to ensure that minimum contact times required for disinfection are achieved.

- The verification of the efficiency of the disinfection treatment. Any disinfection technology used must be capable of being verified, and that such verification is recorded, at all times as required by Regulation 13.

- An assessment of the requirement to ensure that a residual disinfectant is present in the distribution network for all but very small distribution networks.

- An assessment of the capital and operational cost of the disinfection technology. Where disinfection technologies achieve equally effective outcomes the water supplier should have regard to the financial implications from the capital and ongoing operational aspects to ensure that the most cost effective solution is selected.

The above factors should be considered by a water supplier on a site specific basis to determine the disinfection system to be operated at each water treatment plant.

While the manual discusses the commonly used and widely accepted technologies, the absence of an emerging or new disinfection technology from this manual should not be interpreted as precluding it from use. The above principles should be used to assess any new or novel disinfection technology. Where the technology is found to be effective, verifiable and cost effective it can be considered for use for the disinfection of drinking water.

2. WATERBORNE PATHOGENS AND THEIR CHALLENGE TO WATER TREATMENT AND DISINFECTION

2.1 Waterborne pathogens

The greatest microbial threat to drinking water supplies arises from the likelihood of contamination from faeces of human and animal origin containing harmful micro-organisms.

Table 2.1 shows the types of waterborne pathogens that may originate in the faeces of humans or other animals; these include bacteria, viruses and protozoa and helminths (i.e. parasitic worms).

Table 2.1. Characteristics of waterborne pathogens

Size (µm)	Pathogen	Resistance [1] to Chlorine	Relative [2] Infectivity	Significance with respect to the protection of human health
Bacteria				
0.1 - 10	*Salmonella* spp.	*Low*	*Moderate*	Most cause gastro-intestinal illness but certain species may give rise to more serious illnesses. The majority are relatively sensitive to chlorination, and do not persist in the environment for long periods of time. *E coli* and *Campylobacter* can arise from animal sources. While most bacteria require high numbers to initiate infection, some bacteria such as *E coli O157, Shigella* and *Salmonella* do not require to be present in high numbers.
	Shigella spp	*Low*	*High*	
	Yersinia enterocolitica	*Low*	*Low*	
	Campylobacter spp.	*Low*	*Moderate*	
	Escherichia coli (pathogenic)	*Low*	*Low*	
	Verocytotoxigenic *E-coli including E-coli-O157*	*Low*	*High*	
	Pseudomonas aeruginosa	*Moderate*	*Low*	
	Mycobacterium spp.	*High*	*Low*	
Viruses				
0.05 - 0.1	*Rotavirus*	*Moderate*	*High*	The majority of infections result in gastro-intestinal illness but other complications may occur. Viruses leading to human infection tend to be specifically of human origin. They can persist for long periods of time in the environment and have a moderate resistance to chlorination. High human infectivity requiring low numbers to initiate infection.
	Astrovirus	*Moderate*	*High*	
	Norovirus	*Moderate*	*High*	
	Parvovirus	*Moderate*	*High*	
	Adenovirus	*Moderate*	*High*	

Size (μm)	Pathogen	Resistance to Chlorine [1]	Relative Infectivity [2]	Significance with respect to the protection of human health
Protozoa				
4 - 15	*Entamoeba histolytica* *Cryptosporidium spp.* *Giardia spp.*	High High High	High High High	Protozoa are causative agents of gastro-intestinal illness. They can arise from both human and animal sources. They can persist for long periods of time in the environment and are resistant to chlorination. Low numbers are required to initiate infection.
Helminths (Parasitic Worms)				
Visible	*Drancunculus medinesis* *Schistosoma*	*Moderate* *Moderate*	High High	The reported incidence of infection in developed counties is very low, and does not present a hazard in relation to treated drinking water supplies in Ireland

[1] At conventional doses and contact times and with a pH between 7 and 8, Low means 99% inactivation at 20°C in generally, 1 minute, Moderate 1-30 minutes and High >30 minutes

[2] From epidemiological evidence, High means infective doses between 1 - 100 organisms, Moderate 100-10,000 and Low >10,000

Faeces of human origin are likely to present the greatest hazard since the range of pathogens will be the greatest and will include all pathogens types. In contrast, faeces of animal origin, predominantly arising from livestock although wildlife can be a significant source in certain situations, contain mainly pathogenic bacteria and protozoa with human pathogenic viruses being absent to a large extent.

2.2 Indicators of disinfection performance

The monitoring of micro-organisms as a means of assessing the quality of drinking water has been used for a considerable time.

Bacterial microorganisms were chosen which were associated with faeces, which occurred in sufficiently higher numbers than the pathogens and which were relatively easy to isolate in the laboratory. The traditional role for these bacteria was as a measure of the extent of the pollution and an indication of the likelihood that pathogens associated with faeces may also be present in raw water. Subsequently, the same bacteria were also used to measure the efficiency of water treatment processes.

Separate terms have been proposed to avoid confusion between the two different roles that these bacteria were fulfilling. The term ***index*** has been applied here where the bacteria are fulfilling their original role and are being used to assess the extent of faecal contamination of raw water. The term ***indicator*** represents their use as a measure of process performance or treatment efficiency. Historically, coliforms and more specifically *E. coli* have fulfilled both the roles of index and indicator parameters for disinfection performance.

Chemical dosage rates are usually based on a chemical concentration combined with a contact time for exposure of the micro-organism to the chemical. Micro-organisms vary widely in their susceptibility to chlorine disinfection. Bacteria are generally amongst the most susceptible micro-organisms with an ascending order of resistance from viruses, bacterial spores, to acid-fast bacteria and with protozoan cysts being the most resistant. Consequently applying a chlorine dose that is effective against the more resistant micro-organisms will also be effective against many of the others. However, relying on using coliforms and *E. coli,* which are very susceptible to chlorination, as indicators of disinfection efficacy may not provide sufficient guarantee that other more resistant micro-organisms have also been inactivated.

Enteric viruses can occur in very high numbers in faeces and most are much more robust in the environment than bacteria. Consequently, they may be present when indicator bacteria, used to assess their occurrence, are absent.

The situation is similar for the parasitic protozoa, *Cryptosporidium* and *Giardia*, which are considerably more resistant than bacteria to chlorine disinfection. However the occurrence of waterborne human illness due to protozoan parasites such as *Cryptosporidium* and *Giardia* and the resistance of such protozoa to chlorination has focussed attention on the consequent challenges which these protozoa pose to treatment and chemical disinfection processes. *Cryptosporidium* is the reference protozoan pathogen with respect to water treatment and disinfection due to the fact that it is the most persistent in the aquatic environment and is also the smallest protozoan in size thus making difficult its consistent removal by rapid gravity filtration.

Much has been done to find better index and indicator micro-organisms but, at present, there is no single micro-organism that satisfactorily meets all the desired criteria. The only reliable indicator of chlorination performance for real-time control of bacteria and viruses is the existence of a target chlorine residual concentration after a specified contact time. Similar principles apply to other chemical disinfectants (chlorine dioxide, ozone). In the case of UV disinfection, the monitoring of UV intensity is a measure of the irradiation concentration and the consequent inactivation of protozoa.

2.3 *Cryptosporidium* and cryptosporidiosis

2.3.1 Introduction

Cryptosporidium is a waterborne protozoan pathogen, originating from the faeces of humans, other mammals, reptiles, bird and fish, which causes gastro-intestinal illness in humans called cryptosporidiosis. Cryptosporidiosis is self-limiting disease in healthy hosts but represents a life-threatening problem in immuno-compromised individuals for which there is no effective treatment.

Although the first description of the genus dates from 1907, its medical importance as a source of human illness was not reported until 1976. Possible transmission routes for protozoan parasites to humans are varied and include

- Direct human to human,
- Direct animal to human with the typical spring seasonality in Ireland associated with occupational exposure to calves & lambs
- Food
- Recreational water and swimming pools
- Drinking water which facilitates indirect transmission from human or animal.

The possibility of waterborne transmission was brought into sharp focus following a major waterborne outbreak in Milwaukee USA in 1993 with 403,000 reported cases. In the intervening years, there has been intense scientific interest in the discovery and identification of species and genotyping of *Cryptosporidium,* in accordance with the International Code of Zoological Nomenclature (ICZN).and in the prevention of human illness caused by *Cryptosporidium* and in the treatment and disinfection of water to prevent waterborne transmission to humans.

2.3.2 Taxonomy of *Cryptosporidium*

The taxonomy of the genus *Cryptosporidium* is in development and is being advanced following the establishment of a framework for naming *Cryptosporidium* species and the availability of new taxonomic tools, which should clarify the identification of different species and genotypes of *Cryptosporidium.* In addition, it will aid the assessment of the public health significance of *Cryptosporidium* in animals and the environment, characterise transmission dynamics and help track infection and contamination of sources.

Many species of Cryptosporidium have been found to infect a predominant host species and in some exceptions additional or minor hosts

Current WHO Guidance identifies thirteen different species of *Cryptosporidium*. Table 2.2 is reproduced from the WHO Guidance for Drinking Water Quality on *Cryptosporidium* and sets out the host specificity of different species and their association with waterborne transmission to humans.

Table 2.2 Host specificity of Cryptosporidium species and their association with waterborne transmission

Species	Hosts	Isolated from human cases	Implicated in waterborne outbreak
C. hominis	Humans	Frequently	Yes
C. parvum	Cattle Sheep & other mammals	Frequently	Yes
C. meleagridis	Turkeys, Humans	Occasionally	No
C. muris	Rodents	Very Occasionally	No
C. andersoni	Cattle	No	No
C. felis	Cats	Very Occasionally	No
C. canis	Dogs	Very Occasionally	No
C. wrari	Guinea Pigs	No	No
C. baileyi	Birds	No	No
C. galli	Birds	No	No
C. serpenti	Snakes	No	No
C saurophilum	Lizards	No	No
C. molnari	Sea Bass and sea bream	No	No

In addition to the foregoing, additional species are being identified and some species such as *C. suis* (pigs), *C. andersoni* (cattle) and *Cryptosporidium* cervine genotype (linked with sheep and deer particularly in the case of upland catchments) have been identified as having a weak association with the infection of humans as minor hosts.

Two types, *Cryptosporidium parvum* (originating from cattle and other mammals) and *Cryptosporidium hominis* (from humans), are commonly isolated from humans hosts or associated with waterborne outbreaks of human illness. In the latest Health Protection Surveillience Report (HSPC) report on the Epidemiology in Ireland, speciation of positive human Cryptosporidium specimens reveal the association of *C. parvum, C. hominis, C. cervine, C. felis* and a *Cryptosporidium* genotype associated with rabbit, with human cryptosporidiosis infection.

2.3.3 Life Cycle

The organism (see Plate 2.1.A) exists in the environment as an oocyst of 4-6µm in size which contain four sporozoites protected by an outer shell. After ingestion, the oocyst shell wall opens (see Plate 2.1B), triggered by body temperature and interaction with digestive fluids. These sporozoites (see Plate 2.1.D) emerge from the hard shell that envelopes them (see Plate 2.1.C) and replicate the oocysts in the digestive tract of the host

This replication of the oocysts within the digestive system of the host and the human illness caused by the body's efforts to shed the replicating *Cryptosporidium* oocysts is the condition known as cryptosporidiosis.

Following excretion by the host, the environmentally robust thick walled oocysts remain in the environment until re-ingestion by a new host. This thick outer oocyst shell protects the sporozoites against physical or chemical damage such as chlorine disinfection chemicals and sustains the resilience of the organism in the environment for long periods of time without losing their infectivity to a new host (e.g. several months in fresh water, 12 weeks in estuarine water @ 20°C & salinity of 10 parts per thousand (ppt), 4 weeks in seawater @ salinity of 30 ppt).

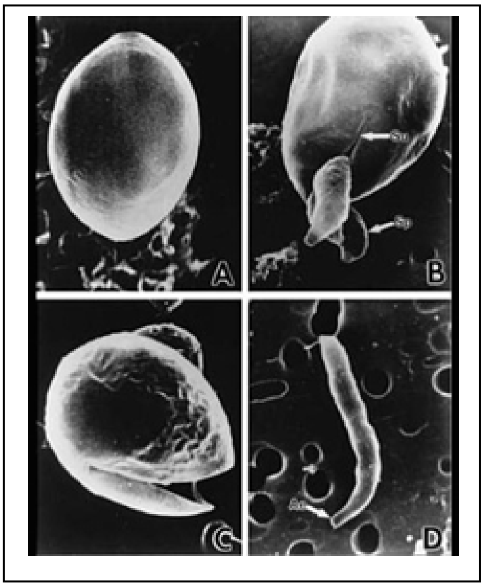

Plate 2.1 Excysting Cryptosporidium sporozoites

2.3.4 Human infectivity

The susceptibility of human hosts to cryptosporidiosis and the risk of this infection manifesting as human illness is complex and dependent on host genetic predisposition, acquired immunity through prior exposure, the age of the host or the degree to which the immune and digestive system of the host is compromised by illness or medical treatment. The predominant symptoms are profuse watery diarrhoea accompanied by nausea, cramps, vomiting, fatigue, no appetite and fever. In immuno-compromised persons, infection causes illness in almost all cases. Diarrhoea is chronic and accompanied with mortality risk due to dehydration and the inability of the host to shed the oocysts from their body.

Over recent years there have been many outbreaks of cryptosporidiosis linked to water supplies, caused by contamination with faecal material from animals (mainly cattle and sheep) or humans (sewers, sewage treatment effluents, on-site sewage treatment systems).

In 2004, under the Infectious Diseases (Amendment) (No 3) Regulations 2003 (S.I. 707 of 2003), cryptosporidiosis became a notifiable disease in Ireland.

In May 2007 a report by Semanza and Nichols on cryptosporidiosis surveillance and waterborne outbreaks in Europe reported that Ireland and the UK in 2005 had by far the highest incidence rate of notified cases at 13.7 and 9.3 cases per 100,000 persons respectively. It is not coincidental that Ireland and the UK have the highest proportion of surface water sources in the EU. However, the notification requirements for cryptosporidiosis may also be a factor. In 2008 the Annual Health Protection Surveillance Centre (HPSC) Report reported that the incidence rate in Ireland was 9.3 cases per 100,000 persons with *C. parvum* the most common species recorded and the highest incidence rate recorded in children under five years old.

2.3.5 Removal of *Cryptosporidium* by water treatment processes

Since the mid 1980s, the water industry has become increasingly aware of the risk to human health associated with parasitic protozoa. Of the common protozoa associated with waterborne infection of humans, *Cryptosporidium* is the reference protozoan pathogen with respect to water treatment and disinfection. Where present in raw water, *Cryptosporidium* presents a serious challenge to water treatment processes. By comparison to other waterborne protozoa, *Cryptosporidium* is the most resistant to chemical disinfection particularly commonly used chlorination disinfection and by virtue of its size is the hardest to consistently remove by filtration. The oocysts are also resistant to chlorine dioxide and ozone under normal water treatment conditions and within the range of water temperatures experienced in Irish conditions thereby placing limitations on its efficacy due to the high Contact Time (Ct) required for *Cryptosporidium* inactivation at low temperatures. Without inactivation using UV disinfection, management of risk to human health from pathogenic protozoa relies mainly on their removal by water treatment process such as coagulation/filtration.

At 4 to 6 μm in diameter, oocysts are too small to be removed effectively by rapid gravity sand filtration. Removal therefore relies on the achievement of effective chemical coagulation and flocculation, followed by efficient removal of floc by filtration or clarification/filtration processes. This should achieve better than 99.9% removal of oocysts which, for the concentrations found in raw waters of typically less than 10 per litre, would give a very low probability of detection in final waters and reduced risk to public health. Removal can also be achieved by a properly designed, operated and matured slow sand filtration process,

To maximise oocyst removal in coagulation filtration treatment processes it may be necessary to optimise coagulation for particle removal, without compromising removal of other contaminants such as colour or organics. This optimisation relies on the type of coagulant used, the efficient initial mixing at the point of chemical addition to achieve a very rapid dispersion of chemicals and control of raw water pH. There may also be a role for polyelectrolyte flocculant aids at many works to produce denser stronger flocs to maximise removal in clarifiers and filters. Pre-ozonation may also improve particle removal by subsequent treatment.

Floc removal can be effective using filtration alone when raw water colour/TOC and turbidity is low. The benefits achieved from clarification prior to filtration are that it provides an additional treatment “barrier”, and reduced solids loading to the filters leading to longer filter runs and reduced risk of breakthrough. However, most works would initiate backwash based on turbidity breakthrough to prevent deterioration in filtered water quality. The "ripening" period at the beginning of the filter run, with higher turbidity and particle counts in the filtered water, has been shown to be a source of potential oocyst breakthrough. Consideration should be given to actions to reduce the impact of this ripening period on final water quality, such as the implementation of slow start up, delayed start, filter to waste or recycling of filtered water at the beginning of the run. Good performance of clarification will lead to longer filter runs, giving the benefits of fewer backwashes and subsequent ripening periods. Sudden fluctuations in filtration rate, or stopping and restarting the filter, can also be a potential source of oocyst breakthrough, and should be avoided or minimised.

Recycling of backwash water has the potential for returning oocysts removed by the filters back to the head of the works, increasing the challenge to treatment and should be avoided where possible. Where recycling of backwash water is unavoidable, it should only be considered following the efficient settlement of the backwash water to provide a good quality supernatant for recycling, and the recycling is carried out over extended periods. Such an arrangement should not increase risk unacceptably. Works which use recycle should have turbidimeters on the recycle line, typically alarmed at 10 NTU, and should avoid high recycle flowrates (e.g. no more than 10% of the raw water flow).

Liquors from some sludge treatment operations also introduce a risk if recycled, and these should be discharged to sewer if possible. If not, recycle to washwater recovery tanks or thickener balancing tanks would be preferable, rather than recycling to the head of the works.

Slow sand filtration should give similar performance for oocyst removal to chemical coagulation based treatment where the raw water has a low TOC/turbidity. The existence of a biological ecosystem growth layer within the slow sand filter beds facilitates the removal of turbidity and waterborne pathogens. This removal is dependent on the proper design of slow sand filter beds with respect to their design flow rate, sand depth and uniformity, temperature of water to be treated and their maturation period. Numerous studies to determine the viability of this treatment process for the removal of *Cryptosporidium* has reported removal efficiencies of 3 log (99.9%) for mature beds (>2 months) constructed to accepted design standards and when operated within the usual range of raw water temperatures in Ireland

Membrane filtration processes are highly effective at removing oocysts but require high level of operator skill and maintenance and regular integrity testing to verify their proper operation.

Treatment which is effective for oocyst removal would also give benefits in terms of microbial removal generally i.e. for other protozoan parasites (particularly *Giardia*), bacteria and viruses.

2.3.6 Risks and hazards associated with previous cryptosporidiosis outbreaks

A review of the literature relating to previous outbreaks of cryptosporidiosis show that contributory risk factors always comprise some of the following source and treatment deficiencies:

1. Water source deficiencies
    - inadequate management of catchment of water supplies with sources of high faecal contamination located upstream of water abstraction points
    - natural flooding events instrumental in flushing high levels of oocysts
    - water abstraction points within the catchment in a location vulnerable to peak flood events
    - unknown sources of *Cryptosporidium* prior to outbreak
    - groundwater springs and wells adversely influenced by surface water following rainfall events
    - wells with inadequate protection resulting in contamination by sewage /septic tanks

2. Treatment deficiencies
    - no treatment barriers to *Cryptosporidium* in surface water supplies
    - inadequate treatment of surface waters as a barrier to *Cryptosporidium*
    - inappropriate disinfection processes for inactivation of *Cryptosporidium*
    - deficiencies in the installation, maintenance or calibration of monitoring instrumentation
    - failure of plant personnel to respond to faulty monitoring equipment
    - filter backwash return to head of works
    - altered or suboptimal filtration during periods of high turbidity
    - inadequately backwashing of filters
    - filtration bypassed due to high water demand in the supply area
    - plant not automated or designed to cope with spate conditions

While the importance of source protection and source/catchment management plans cannot be overstressed, many of the best practice guidelines for water treatment operation which have emanated from the EPA in Ireland and from the DWI in the UK have sought to optimise operation of existing treatment plant facilities with a view to reducing oocyst breakthrough past the filtration phase of plants.

2.3.7 Efficacy of UV light for inactivation of pathogens including *Cryptosporidium*

The microbial effectiveness of UV light varies as a function of wavelength as set out in Fig 2.1.

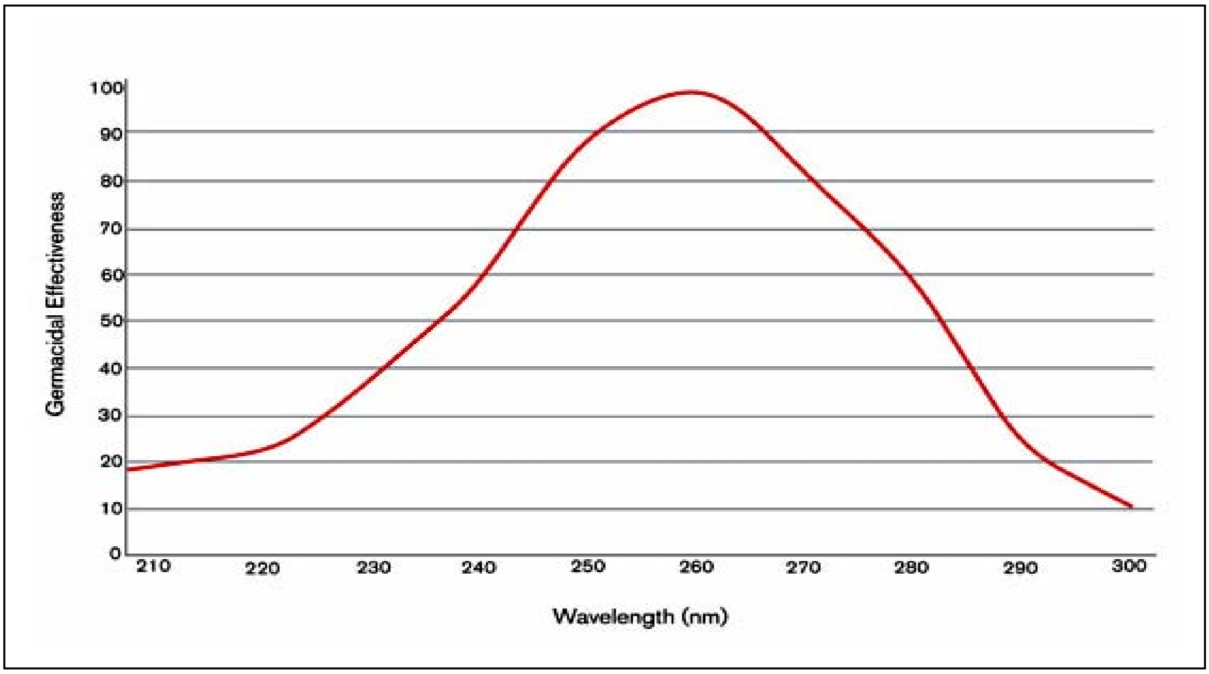

Fig 2.1 Germicidal Effectiveness of UV Light

For most micro-organisms, the UV action peaks in the UV-C range at or near 260 nm, has a local minimum near 230 nm, and drops to zero near 300 nm, which means that UV light at 260 nm is the most effective at inactivating micro-organisms. Because no efficient way to produce UV light at 260nm is available and mercury produces UV light very efficiently at 254 nm, the latter has become the standard.

Inactivation of the oocyst is effected by damage to the nucleic acids within the DNA and RNA of the sporozoites consequent to absorption of UV light in the UVC range (200-280nm) thereby preventing the oocyst replication within the host digestive system. This genetic prevention of oocyst replication by UV prevents the development of the human illness condition, cryptosporidiosis. In the case of bacteria and viruses, UV light inactivates by inhibiting the bacteria from dividing and forming colonies and in the case of viruses renders them unable to form plaques in host cells.

Considerable advances have been made in the US by the US EPA in the development of risk based Drinking Water Regulation the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) and Guidance Manuals for the design and validation of UV installations (UVDGM).

While UV doses of less than 20 mJ/cm^2 readily inactivate most waterborne pathogenic bacteria and parasitic protozoa, a higher irradiance is necessary to inactivate some viruses particularly adenovirus. Adenovirues are readily inactivated by chlorination.

Adenoviruses, of which there are 51 antigenic types, are mainly associated with respiratory diseases and are transmitted by direct contact, faecal-oral transmission, and occasionally waterborne transmission. Adenoviruses have been found to be prevalent in rivers, coastal waters, swimming pool waters, and drinking water supplies worldwide. Type 40 and 41 can cause gastroenteritis illness resulting in a fever-like illness often with associated conjunctivitis which may be caused by consumption of contaminated drinking water or inhalation of aerosolised droplets during water recreation.

Fig 2.2 below sets out the UV dose in mJ/cm^2 required, in accordance with the USEPA UV Guidance Manual, for 4-log (99.99%) inactivation of common waterborne pathogens.

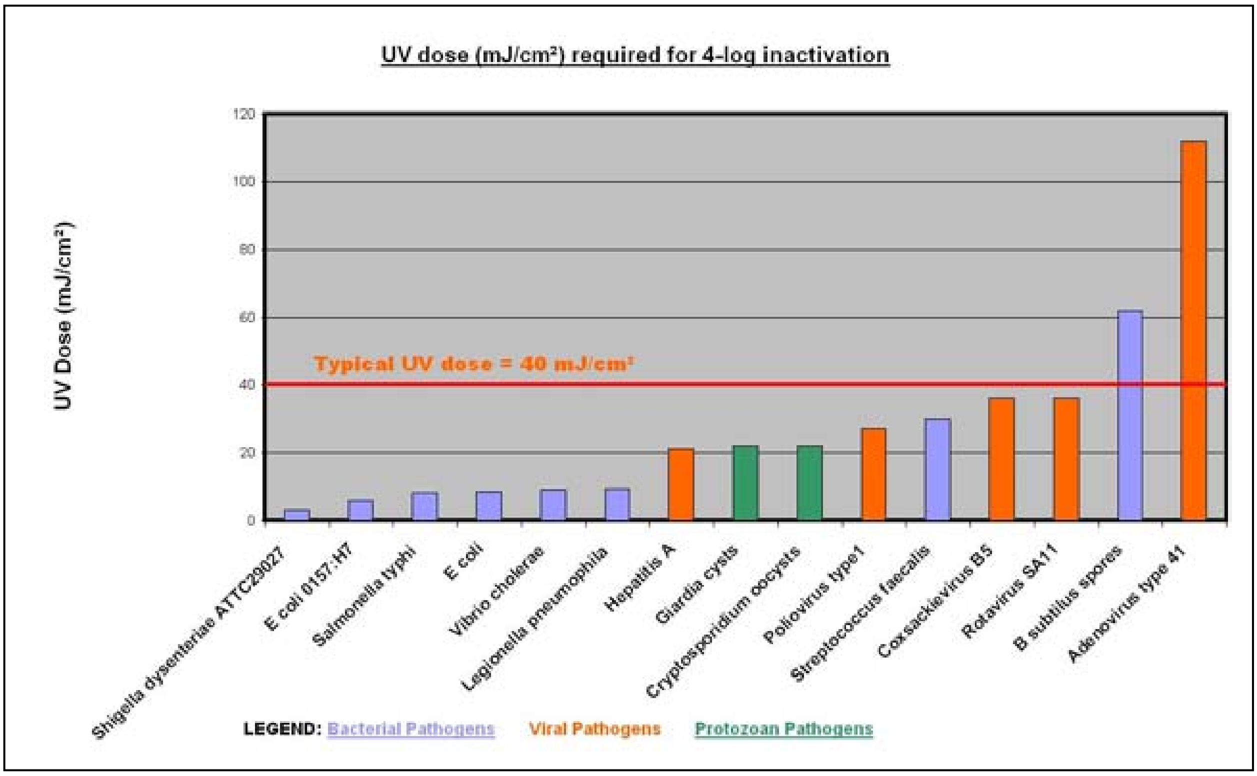

Fig 2.2 Required UV dose for 4-log inactivation of common waterborne pathogens

Most existing proprietary UV disinfection systems are marketed and validated as units with capability to inactivate the full spectrum of possible waterborne pathogens such as bacteria, viruses and protozoan parasites such as *Cryptosporidium*. Consequently most proprietary UV disinfection units are typically validated in accordance with USEPA, German Association for Gas and Water (DVGW) and Austrian (ONORM) protocols for a UV dose (fluence) of 40mJ/cm^2.

2.4 The incidence of vericytotoxigenic *E. coli* in Ireland

A total of 226 confirmed and probable cases of Verocytotoxigenic *E. coli* (VTEC) were recorded in Ireland in 2008, representing an increased incidence rate of 5.3 per 100,000 persons, one of the highest incidence rates in Europe. The figures are a particular concern given that up to 10 per cent of patients with VTEC infection develop haemolytic ureamic syndrome which may result in long term abnormal kidney function. The incidence of VTEC was highest among young children with the elderly or immuno-compromised persons also vulnerable groups.

Forty-two VTEC outbreaks, of which nine were general and 33 family outbreaks, were reported in 2008, accounting for 145 of the 213 confirmed cases. Twenty-nine outbreaks were reported as being due to VTEC O157, seven due to VTEC O26, and six were caused by a mixture of VTEC strains.

Person-to-person transmission was suspected to have played a role in 21 of the outbreaks in 2008, including three associated with crèches. The second most common route of transmission was water-borne with drinking water from untreated private wells an important risk factor for infection particularly following periods of heavy rainfall.

In common with many bacteria, VTEC strains have a low resistance to Chlorination and UV disinfection and are readily inactivated using either disinfection technology.

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3. THE USE AND EFFICACY OF DIFFERENT DISINFECTION TECHNOLOGIES

3.1 Introduction

While the current Drinking Water Regulations specify parametric values for various chemicals in the treatment of drinking water, compliance with microbiological parametric values are of primary concern in the protection of human health from drinking water.

Different disinfectant technologies can be used to manage the source risks consequent to the presence of organic and inorganic impurities in source waters and to meet the pathogen inactivation demands of a water supply system.

These technologies can be used as part of a treatment process and/or subsequent disinfection processes for;

- The physical removal and chemical oxidation of organic and inorganic impurities in water and the attendant consequent reduction in pathogens
- The control of residual organic or inorganic compounds in treated water as a means of limiting regulated disinfection by-products in final drinking water to consumers
- The chemical disinfection of drinking water following its physical and chemical treatment as a means of primary disinfection to effect inactivation of residual pathogens in the final drinking water e.g. the use of Contact Time (Ct) appropriate to the verification of disinfection efficacy using chlorination, ozonation, chlorine dioxide and other chemical disinfectants
- The non-chemical disinfection of drinking water following treatment as a means of primary disinfection in the final drinking water e.g. UV treatment for full spectrum inactivation of pathogens, verifiable by compliance with its validation certification
- The maintenance of a disinfectant residual within the distribution system to quality assure the wholesomeness and cleanliness of drinking water to the consumer tap e.g. using chlorination, chloramination and chlorine dioxide

Following physical treatment of water, primary disinfection describes the main disinfection method employed to inactivate waterborne pathogenic micro-organisms. Primary disinfection is often supplemented by downstream secondary disinfection to maintain a residual level of disinfectant within the distribution system in order to quality assure drinking water to the point of compliance i.e. the consumer’s tap as determined in the Drinking Water Regulations. Assuming that the efficacy of primary disinfection has been verified, secondary disinfectants are added as the final element of a treatment process or at a re-chlorination booster station to protect against re-contamination following connection of mains and services and control the growth of micro-organisms in the systems storage reservoirs and distribution network. As the purpose of primary and secondary disinfection differs, a particular disinfection technology may or may not be appropriate to fulfil both disinfection roles.

The following key factors influence the selection of a disinfection system:

- The effectiveness of the disinfectant in destroying pathogens of concern;
- The quality of the water to be disinfected;
- The formation of undesirable by-products as a result of disinfection;
- The ability to easily verify the operation of the chosen disinfection system by reference to system validation, collation of monitoring data and alarm generation.

- The extent of the site or building in which the proposed disinfection process is located and the availability therein of necessary ancillary equipment e.g. chemical contact volumes, instrumentation etc necessary for the proper operation and verification of the disinfection process
- The ease of handling, and health and safety implications of a disinfectant;
- The preceeding treatment processes;
- The overall cost.

3.2 The importance of water treatment prior to disinfection

3.2.1 General

The type of treatment prior to primary disinfection, and the way that treatment is managed and operated, can have a very significant influence on the performance of disinfection.

The turbidity of treated water is a key measure of its suitability for disinfection. It is noted that the SI 278 of 2007 states that "in the case of surface water treatment, a parametric value not exceeding 1.0 NTU in the water ex treatment must be strived for".

However both the current (3rd Edition) WHO guidelines and recent EPA Advice Note no 5: Turbidity in Drinking Water published in November 2009 recommended lower turbidity levels in final treated water. The WHO guidelines recommend a median turbidity should be below 0.1 NTU for effective disinfection. This 0.1NTU level should be regarded as being aspirational as the capability the measurement of turbidity at levels below 0.1NTU is difficult and impractical by some treatment technologies such as slow sand filtration.

The EPA recommendation in Advice Note 5 to Water Service Authorities and private water suppliers in the group scheme sector requiring treatment plants to be "optimised to obtain turbidity levels < 0.2NTU in the final water" is the current guidance for high *Cryptosporidium* risk catchments. This recommendation of 0.2 NTU is prior to lime addition as addition of lime (for pH correction) can raise the turbidity. This elevation in turbidity caused be lime does not indicate a risk of oocyst breakthrough.

3.2.2 Treatment prior to disinfection

In the case of chlorination, upstream treatment may be used to reduce:

- Chlorine demand, particularly from total organic carbon (TOC), allowing higher chlorine concentration to be achieved with less potential for by-product formation,
- The variability of water quality thereby allowing more reliable control over chlorine residual,
- The turbidity of the water and thereby provide less shielding of the micro-organisms from the effects of disinfection chemicals and UV,
- The microbiological challenge to disinfection because of more effective removal of micro-organisms by upstream treatment.

Similar considerations apply to other disinfectants e.g. upstream treatment reduces ozone demand and UV absorbance.

3.2.3 Conventional treatment

Conventional treatment involving rapid gravity sand filtration can be categorised according to:

- Whether or not chemical coagulation is used – rapid gravity filtration without coagulation is largely ineffective at removing micro-organisms and chlorine demand, whereas coagulation greatly enhances removal of both by filtration.
- The number of stages of treatment – generally the more treatment barriers that are used, the greater the risk reduction.

Clarification prior to rapid gravity filtration can significantly improve the security of subsequent filtration. GAC adsorption and manganese removal after filtration can provide some additional security, even though their primary function is not filtration. GAC can also help to provide lower and more stable chlorine demand.

Similarly slow sand filters can also provide excellent treated water quality ahead of disinfection for a limited range of raw water quality (e.g. where colour is < 30 Hazen). In addition to physical removal of organic and inorganic impurities in water, the action of slow sand filters also includes a biological process layer called a "schmutzdecke," formed on the sand surface, where particles are trapped and organic matter is biologically degraded. Slow sand filters are effective in removing suspended particles from raw water resulting in effluent turbidities below 1.0 NTU and can achieve 90 to 99% percent reductions in bacteria and viruses while also providing a high level of protozoan removal.

3.2.4 Other processes

A high degree of security will be provided by membrane plants in relation to microbial removal and, depending on the type of membrane process used, control of by-products.

Ozonation within the treatment stream will also provide a high degree of security, particularly if it is installed for removal of pesticides or taste and odour compounds, by achieving very effective inactivation of most micro-organisms and also, in some situations, by reducing chlorine demand. Pre-ozonation (of raw water) will provide less benefit in these respects, because ozone doses are lower and ozone demand of raw water is higher, resulting in lower ozone concentrations for shorter periods.

3.3 The Ct concept for chemical disinfection systems

Disinfection performance is usually defined as log inactivation:

Log inactivation = $\log_{10}$ (original viability or infectivity/treated viability or infectivity)

Hence 90% removal/inactivation is defined as 1 log, 99% as 2 log, 99.9% as 3 log etc. This provides a more straightforward way of comparing high levels of removal.

Disinfection kinetics is described by the Chick-Watson law (AWWA, 1990):

$$\frac{dN}{dt} - - C^n N$$

where

N = concentration of viable organisms
k = rate constant
C = concentration of disinfectant
n = constant
t = time

For constant C, the integrated form of the Chick-Watson law is:

$$\ln\left(\frac{N}{N_0}\right) = -C^n t$$

where N_0 = initial concentration of viable organisms

In practical terms, the value of the constant n is often assumed to be close to 1, in which case:

$$\ln\left(\frac{N}{N_0}\right) = -Ct$$

The underlying assumption is that disinfectant concentration remains constant during the course of the contact time. This may be true for laboratory experiments in demand free systems, but it is not the case at water treatment works, where the demand of the system causes a gradual decline in the active concentration of the disinfectant.

Effective chemical disinfection requires the maintenance of a specified concentration (C) of disinfectant and contact time (t), to achieve a target value for Ct. There will be minimum values for contact time and, more significantly, a disinfectant concentration below which the Ct concept will not apply, because values of C and t are so low as to drastically impair disinfection performance. In practice, however, this is unlikely to be a significant consideration for water treatment applications.

The Ct concept is particularly valuable in providing a means for comparing the disinfection effectiveness of chemical disinfectants. For a given microorganism, strong disinfectants possess low Ct values and poor disinfectants high Ct values. For different organisms, Ct values provide a comparison of the resistance of different organisms to the same disinfectant. In addition the Ct concept allows the calculation of contact time (at a given disinfectant concentration) or the concentration (at a given contact time) to be calculated to achieve a required percentage or log inactivation.

In general, the temperature dependency of rate constants can be described by the Arrhenius law (Levenspiel, 1972):

$$k = k_0 e^{-E/RT}$$

where

k_0 = frequency factor
E = activation energy, kJ/kmol
R = universal gas constant = 8.3144 kJ/kmol
T = absolute temperature, °K

A value of k at some reference temperature may be quoted, rather than a value of the frequency factor, along with the activation energy, to quantify the relationship. The activation energy always has a positive value, so reaction rate increases with increasing temperature. A value of E = 44500 kJ/kmol would mean the rate doubles for every 10° K increase.

Combining temperature dependency of the rate constant with the simplified (n=1) Chick-Watson law for disinfection, the time required to achieve a given degree of inactivation with a given disinfectant residual declines with increasing temperature:

$$\ln\left(\frac{t_1}{t_2}\right) = \frac{E}{R}\left(\frac{T_2 - T_1}{T_1 T_2}\right)$$

The nature of temperature dependency will be specific to a particular disinfectant.

The pH value at which disinfection occurs also affects disinfection efficiency and associated by-product formation. In the case of the most common disinfection method, (i.e. chlorination) there is a strong pH dependence because the form of the disinfectant in the water changes with pH. This is discussed in more detail in Chapter 4

Although log inactivation is not included as part of current Irish Drinking Water Regulations, the US EPA has developed Ct disinfection tables based on this concept. These Ct tables are used extensively worldwide to

- express the percentage of pathogens inactivated (killed or unable to replicate) following exposure to a disinfection process;
- compare the effectiveness of the different disinfection processes and the varying parameters including disinfectant concentration, temperature, pH and disinfectant type.

The extent to which Water Service Authorities and private water suppliers should target Ct values to achieve specific values of log inactivation will depend on the consideration of a site specific Water Safety Plan approach to catchment, source and treatment risks upstream of the primary disinfectant. This consideration should take account of the type of source, the variability of source water quality, the adequacy of treatment barriers upstream of primary disinfection and the proposed use or otherwise of multiple disinfection technologies.

Appendix 2.1 provides tools and information for calculating Ct, and making allowance for pH and temperature, for specific situations.

3.4 Chemical disinfection technologies

3.4.1 Chlorine

"Chlorine" is a generic term for the active chemical species - hypochlorous acid - that acts as a disinfectant. It is formed from several chemicals (elemental chlorine, sodium and calcium hypochlorite) when they are dosed to water. "Chlorination" is the generic term for disinfection using these chemicals. These sources of chlorine are described in more detail in Chapter 4.

In Ireland, and globally, chlorine remains the most widely used disinfectant chemical in drinking water treatment for both primary disinfection of treated water and for the maintenance of a residual in distribution systems. It is also commonly used in the oxidation and removal of iron and manganese in water treatment upstream of disinfection.

3.4.2 Monochloramine

Monochloramine is formed when ammonia and chlorine are dosed, and react, under well controlled conditions. The process is known generically as "chloramination". Good process control is essential to prevent the formation of strong tastes and by-products.

The disinfection capability of monochloramine is poor compared with chlorine, and it is generally used to provide a disinfectant residual or preservative, during distribution, rather than being used for primary disinfection.

The key advantages of monochloramine are:

- it does not form trihalomethanes (THMs), or other chlorination by-products when in the presence of organic matter;
- the taste threshold is typically much greater than for chlorine alone. As a result the introduction of chloramination can significantly reduce customer complaints relating to chlorine tastes.

For these reasons chloramination is becoming increasingly popular in the UK for providing a disinfectant residual in distribution. The process is described in more detail in Chapter 4.15.

3.4.3 Ozone

Ozone is a very powerful disinfectant compared with either chlorine or chlorine dioxide. It is the only chemical that can provide effective inactivation of either *Giardia* or *Cryptosporidium* at dose levels not much greater than those used routinely for water treatment. It is, however, an expensive disinfection technology in terms of capital and operating costs and to date in Ireland has primarily been used as a pre-disinfection treatment process for the destruction of organic micropollutants, particularly pesticides and taste and odour compounds, and their removal, when used in conjunction with Granular Activated Carbon (GAC) filtration.

Although such application simultaneously provides disinfection, chlorine is usually used as a primary disinfectant after an ozonation process on waters abstracted from surface sources. In other countries, ozone may be used as the primary disinfectant, in conjunction with a suitable design of contact tank to ensure an appropriate contact time is achieved. The use of ozone as a disinfectant is discussed in more detail in Chapter 5

3.4.4 Chlorine dioxide

Chlorine dioxide is a more powerful disinfectant than chlorine, and the pure chemical does not form THMs by reaction with humic substances. Chlorine dioxide is generated on demand, usually by reaction between sodium chlorite and hydrochloric acid; it can also be made by reaction between sodium chlorite and chlorine, although careful control is required to ensure by-product formation is small. Chlorine dioxide is likely to be substantially more expensive than chlorine. Its use is described in more detail in Chapter 6.

3.4.5 Copper silver ionisation

Currently there is inadequate scientific data available to verify the effectiveness of this technology as an effective disinfectant technology.

Proprietary disinfection systems based on copper and silver ions have been used internationally for the control of *Legionella in public buildings,* in spa pools and cooling water towers.

Most proprietary copper/silver systems use electrolytic ion generators to control the concentrations of the dissolved metals. Electrolytic generators usually are composed of a negatively charged cathode and a positively charged anode made of the metal or an alloy of the metals to be ionized. The electrodes are contained in a chamber through which passes the water to be disinfected. A power source provides current at a potential, causing the copper and silver in the anode to ionize and dissolve in the passing water. The concentration of metal ions in water leaving the electrolytic cell depends on the current and water flow past the electrodes. Therefore, production of metal ions can be controlled by the current applied to the electrodes while the rate at which water flows through the chamber determines the concentration of dissolved ions.

The claimed biocidal effect of copper and silver ions is based on the following mechanisms;

- When introduced into the interior of a bacterial cell, their affinity for electrons renders enzymes and other proteins ineffective, compromising the biochemical process they control.
- Cell surface proteins necessary for transport of materials across cell membranes are also inactivated
- Copper ions bind with the phosphate groups that are part of DNA molecules, which results in unraveling of the double helix and consequent destruction of the molecule.

Unlike chlorine, Copper Silver Ionisation systems do not result in halogenated organic by-products such as trihalomethanes (THM), chloramines and chloroform. The copper and silver ions are stable and pertain in treated water to maintain an effective residual and prevent recontamination in pipework.

The chemical composition of the water to be treated has to be considered before selecting the process. The control and monitoring of the rate of release of copper and silver ions into the water supply is important and linked to scale build-up and cleanliness of the sacrificial electrodes. Electrodes must be cleaned (unless they are self cleaning), and replaced regularly. The rate of dosage must be adjusted depending on water conditions which can change daily. Testing the water to check its quality and that the system is working must also be done regularly. As silver ion concentrations are difficult to maintain above pH 7.6, there is also a necessity to monitor and control pH levels in the water.

However the literature contains reservations regarding the efficacy of these systems to disinfect water with the following chemical composition;

- hard waters which can cause fouling of electrodes or
- waters with high dissolved solids concentration which will precipitate available silver ions.

The literature also suggests that certain microorganisms develop resistance, following extended exposure to heavy metal ions resulting in many of these systems becoming less effective through time.

The EU Directive 98/83/EC and the Irish implementing Regulations SI 278 of 2007 do not state any standards considering silver concentrations in the drinking water but state a maximum level of 2 mg/L for copper. While the USEPA have a maximum concentration for silver of 0.1 mg/l in water supplies, the WHO states that available data is inadequate to permit derivation of a health-based guideline value for silver.

However the WHO sets out that a concentration of 0.1mg/litre could be tolerated without risk to human health based on a lifetime NOAEL (no adverse exposure level) of 10g per person for the clinical condition of silver intoxication called argyria.

The WHO Guidelines in its second addendum to the Third Edition of its Guidelines for Drinking Water Quality (2008) notes that *"Silver is sometimes promoted as a disinfectant, but its efficacy is uncertain, and it requires lengthy contact periods. It is not recommended for treating contaminated drinking-water".* This, together with insufficient data from potable water treatment applications upon which to base process validation, would raise questions over its suitability for water supply use.

3.4.6 Hydrogen peroxide (H_2O_2) and peroxone (Ozone and H_2O_2)

The use of hydrogen peroxide in the treatment of potable water has been very limited. This is in part due to its instability in storage and the difficulty in preparing concentrated solutions. It is a strong oxidising agent, but a poor disinfectant achieving little or questionable inactivation of bacteria and viruses.

Hydrogen peroxide can be stored onsite, but is subject to deterioration with time and is a hazardous material requiring secondary containment for storage facilities.

Although of little value itself, hydrogen peroxide has been used in conjunction with other disinfectants to achieve improved oxidation of organic matter. Its use with ozone and ultraviolet light produces increased concentrations of hydroxyl radicals. These are short-lived, very strongly oxidising chemical species, which react with the organic matter.

One of the most common of these processes involves adding hydrogen peroxide to ozonated water, a process commonly referred to as peroxone consequent to the addition of hydrogen peroxide. Hydroxyl radicals are produced during the spontaneous accelerated decomposition of ozone. By accelerating the ozone decomposition rate, the hydroxyl radical concentration is elevated, which increases the oxidation rate. This procedure increases the contribution of indirect oxidation over direct ozone oxidation. As an oxidizing agent, peroxone can be used to remove natural organic carbon, organic micropollutants such as pesticides and increase the biodegradability of organic compounds.

However while peroxone is an effective disinfectant, slightly more effective than ozone against bacteria, viruses, and protozoa, it is difficult to use it for disinfection purposes because it is highly reactive and does not maintain a measurable residual level for CT calculations. The difficulty in verifying peroxone systems in use makes it inappropriate for use as a drinking water disinfectant.

3.4.7 Chloro-isocyanurate compounds for emergency chlorination of drinking water

For routine treatment of public water supplies, there is little or no use of other disinfectants. Some chemicals, such as chloro-isocyanurate compounds are widely used as a stable source of chlorine for the disinfection of swimming pools and in the food industry, Sodium dichloroisocyanurate is used for temporary emergency disinfection applications as a source of free available chlorine in the form of hypochlorous acid (HOCl) with the attendant residual formation of cyanuric acid from its addition to water. The WHO is currently preparing guideline text on Sodium dichloroisocyanurate for inclusion in their future 4th edition of their *Guidelines for Drinking Water Quality.* In their background document for development of *Guidelines for Drinking-water Quality* the WHO advised that "*The amounts of sodium dichloroisocyanurate used should be the lowest consistent with adequate disinfection, and the concentrations of cyanuric acid should be managed to be kept as low as is reasonably possible".*

3.5 Non- chemical disinfection systems

3.5.1 Ultraviolet (UV) radiation

Effective primary disinfection can be provided by a suitable intensity and duration of UV radiation to give a UV "dose" usually expressed in mJ/cm^2 (= mWs/cm^2, the product of UV intensity in mW/cm^2 and contact time in seconds). The target dose will depend on the application, but a dose of 40 mJ/cm^2 is commonly used for UV disinfection systems, validated for the broad spectrum inactivation of possible waterborne pathogens such as bacteria, viruses and protozoan parasites such as *Cryptosporidium*. In an Irish context, where over 90% of water sources are either from surface waters or surface influenced ground waters, chlorination usually follows UV disinfection for residual generation and the quality assurance of disinfection in the distribution system

Key advantages of UV disinfection are that it is a compact process and can be suited to sites with space constraint. In addition to being effective for inactivation of *Cryptosporidium* and other pathogens, when UV irradiation is used in conjunction with chlorination, it can reduce the subsequent chlorination dose. More detail on the applications of UV disinfection is given in Chapter 7.

3.6 Advantages and limitations of disinfection methods

An overview of the key technical advantages and limitations of the disinfectants described in Section 3.4 and 3.5 is given here. This is separated into the use of systems for primary disinfection and their use in the maintenance of a residual disinfectant in distribution systems. In the latter case, only disinfectants that can provide a long-lasting residual are compared. More details for each disinfectant are provided in the relevant following section.

3.6.1.Primary disinfection

Table 3.1 Advantages/limitations of primary disinfection systems

Process	Advantages	Limitations
Chlorination	Well understood disinfectant capability. Established dosing technology.	Chlorination by-products and taste and odour issues can affect acceptability. Ineffective against *Cryptosporidium*.
Chloramination	No significant by-product issues. Generally less taste and odour issues than chlorine.	Considerably less effective than compared with chlorine. Not usually practical as a primary disinfectant.
Ozone	Strong oxidant and highly effective disinfectant compared with chlorine. Benefits of destruction of organic micropollutants (pesticides, taste and odour compounds).	Bromate by-product and increased assimiable organic carbon (AOC) can impact on re-growth in distribution. Complex, energy intensive and expensive equipment compared with chlorination. Residual insufficiently long lasting for distribution.
Chlorine dioxide	Can be more effective than chlorine at higher pH, and less taste and odour and by-product issues.	Weaker oxidant than ozone or chlorine. Dose limited by consideration of inorganic by products (chlorate and chlorite).
UV	Generally highly effective for protozoa, bacteria and most viruses and particularly for *Cryptosporidium.* No significant by-product implications.	Less effective for viruses than chlorine. No residual for distribution.

3.6.2 Maintaining a disinfectant residual in distribution

Table 3.2 ***Advantages/limitations of secondary disinfection systems***

Process	**Advantages**	**Limitations**
Chlorination	Stable residual in clean networks. Potential for using chlorine for both primary disinfection and distribution, makes for straightforward application.	By-product formation during distribution. Loss of residual in distribution systems with long residence times.
Chloramination	Stable residual with no significant by-product issues. Generally lower rate of taste and odour complaints than for chlorine.	Needs effective control of process to avoid taste and odour due to either dichloramine or trichloramine. Mixing with non-chloraminated supplies in network can cause taste and odour issues.
Chlorine dioxide		Limited by consideration of inorganic by-product formation (chlorite and chlorate).

As set out above chemical disinfection methods are generally more effective against bacteria and viruses, with little or no effect in the case of chlorination for the inactivation of protozoan pathogens. On the other hand UV light is very effective against protozoan pathogens with additional effectiveness against bacteria and, to a lesser extent, viruses in water.

3.7 The effect of water quality parameters on disinfection efficacy

The effectiveness of disinfection methods can be influenced by different water quality parameters in the water to be treated.

3.7.1 Chemical disinfection

The stronger the oxidation properties of the chemical disinfectant and the larger the dose, the less will be the contact time necessary for disinfection. However smaller chemical dosage is desirable to avoid or reduce by-product formation requiring a corresponding increase in contact time to achieve microbial inactivation.

Turbidity in the water can encapsulate and protect pathogens from the action of chemical disinfectants. Total organic carbon (TOC), when persisting in water past the treatment stage upstream of disinfection, is a precursor to chemical disinfection by-product formation. The dissolved fraction of TOC (i.e. dissolved organics) reacts with chemical disinfectants thereby reducing their effectiveness for pathogen inactivation.

In general all chemical disinfectants are more effective for microbial inactivation, requiring reduced dosage, as temperature increases.

The pH of the water, in the case of chlorination, has a significant effect on its effectiveness particularly requiring increases in the dosage rate above a value of 7.5. Chlorine dioxide is more effective as a disinfectant than chlorine at higher pH. Ozone disinfection is not affected by pH in the common treated water range of 6-9.

3.7.2 UV disinfection

The main water quality parameter used to specify UV disinfection systems and by which their performance is governed is UV transmittance (UVT) which is defined as set out in Figure 3.1 overleaf.

UVT is the percentage of the light emitted which is transmitted through the fluid, for a path length of 1 cm, Reduction in UVT is caused by the scattering and absorbance of UV in the water by natural organic matter in particulate or dissolved form or by inorganic chemical compounds such as iron and nitrates. UVT levels in excess of 85% are typically associated with treated surface waters from a treatment process following filtration. Good quality groundwater would typically have higher UVT.

The importance of UVT levels in the water with respect to the sizing of UV disinfection systems is that the power requirements of a UV disinfection system required to achieve a desired UV dose is approximately doubled for every 5% decrease in the UVT of the water to be disinfected.

The fouling of the quartz sleeves, which encapsulates the UV lamps, can occur, consequent to chemical parameters in water to be treated. This sleeve fouling can also result in the blocking of UV light and reduced UV transmission to the water. While variations in pH and temperature are not known to affect UVT, iron and hardness in water can cause accumulation of mineral deposition on the quartz sleeves.

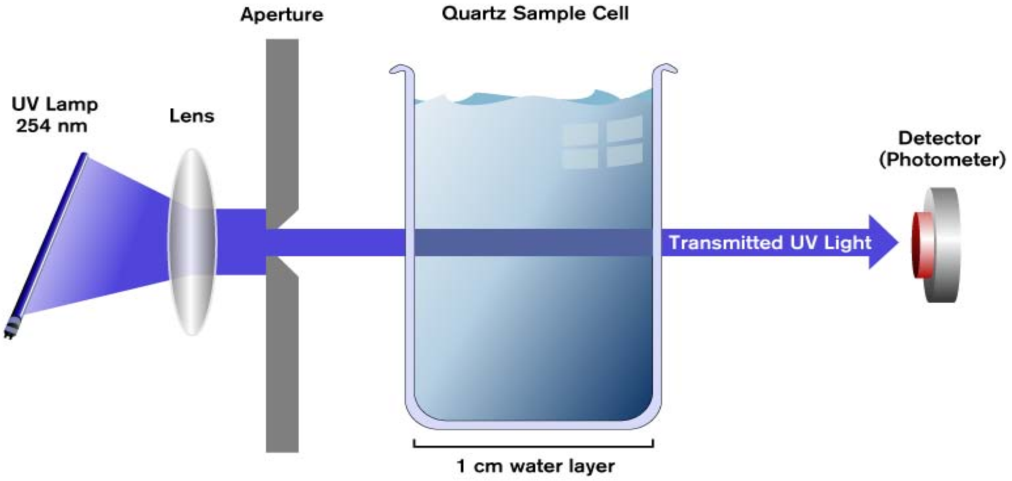

Figure 3.1. ***Schematic of UV transmittance measurement***

3.8 Combinations of disinfectants

There can be either constraints or benefits to disinfectants being used in combination, whether this occurs by design, or, as occurs more often, a consequence of a particular process sequence. Rather than list all possible combinations of disinfectants, the following summarises areas that are likely to be of practical significance.

3.8.1 Synergistic benefits of combinations

There are published reports from laboratory tests of synergistic benefits from using two or more disinfectants, i.e. the overall inactivation is greater than the sum of the inactivation achieved for each disinfectant individually.

For example, one benefit from ozonation before UV treatment is that ozone can degrade natural organics which cause UV absorption thereby allowing the UV dose to be a more effective disinfectant and more energy efficient.

Chlorine dioxide also shows a synergistic effect when combined with other disinfectants such as ozone, chlorine, and chloramines. Combination of disinfectants is known to lead to greater inactivation when the disinfectants are added in series rather than individually.

However, this is rarely, if ever, taken into account for practical applications. Combination of disinfectants would need to take into account interactions between them.

There are also benefits from two or more disinfectants in dealing with a range of different types of pathogen of different sensitivities to disinfectants e.g. UV is effective for *Cryptosporidium*, but much less effective for many viruses, whereas chlorine is effective for viruses but not *Cryptosporidium*.

If one considers the graphical representation of UV and chlorination dosage necessary to inactivate a range of common pathogens as set out in Fig 3.2, it is clear that there is a benefit in the multi-barrier use of both disinfection methods in the provision of full-spectrum pathogen control.

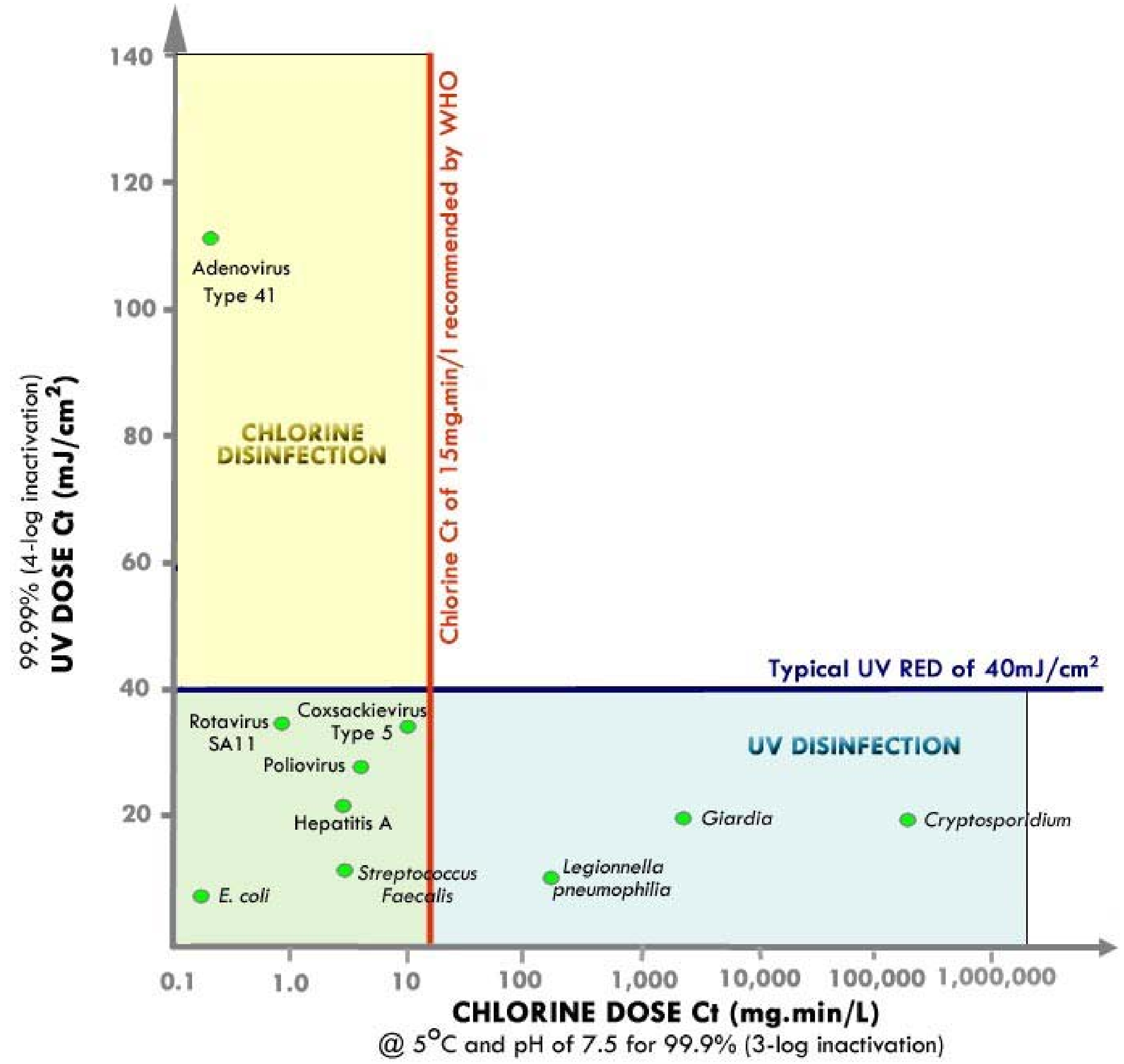

Figure 3.2 Synergistic uses of UV and chlorination disinfection systems

3.8.2 Constraints on combinations of disinfectants

When used as a final treatment stage, chlorination is unlikely to interact significantly with other processes.

Chlorine is reduced by UV treatment. Although the extent of chlorine reduction is small (e.g. 0.1 to 0.2 mg/l at a dose 40 mJ/cm^2) it is best if chlorine is dosed after UV.

Chlorine reacts with ozone to produce chlorate. However, it is unlikely that sufficiently large ozone residual would reach a final chlorination process, for such chlorate formation to be an issue.

Chlorine also reacts with chlorine dioxide to produce chlorate, but it unlikely that these oxidants would be used in such a way as to allow this interaction to occur.

3.8.3 Situations where a specific disinfectant is either favoured or unsuitable

UV disinfection can be particularly attractive where there is insufficient space at site for a chlorine disinfection contact tank.

Chlorine should not be dosed upstream of a GAC process as the GAC will reduce the chlorine, leaving little or no chlorine residual downstream.

Chlorinated water is sometimes used for filter backwashing. There may be some potential for THM formation with organic material within the filter. Conversely there may be benefits to using chlorinated water to control biological nuisances. If it is suspected that the use of chlorinated water for backwashing is contributing to exceedances of the THM parametric value consideration should be given to dechlorinating the water prior to use for backwashing (e.g. dosing with thiosulphate). Chlorinated water should not be used to backwash filters with GAC.

3.9 By-product implications of disinfectants

Disinfection processes can result in the formation of both organic and inorganic disinfection by-products (DBPs).

The most well known of these are the organochlorine by-products such as trihalomethane (THM) compounds and haloacetic acids (HAAs), related to chlorination, although the latter group of by-products is of increasing concern in water supply.

The concentrations of these organochlorine by-products are a function of the nature and concentration of oxidisable organic material in the water, the pH of the water, the water temperature, the free chlorine concentration, it's contact time with the organic material but are not related to the type of chlorine source used.

However, there are also inorganic by-products, particularly chlorate and bromate, which can result from the increased use of hypochlorite rather than chlorine gas, as the dosed chlorine chemical and its impact is greater with increasing storage time of the hypochlorite solution.

The by-product issues of concern with the main disinfection processes are summarised in Table 3.3 and are discussed in more detail in subsequent Chapters 4-10 with respect to individual disinfection systems.

Table 3.3 By-product implications of different disinfectants

Process	**By-product issues**
Chlorination	Trihalomethanes, trihaloacetic acids are formed by reaction with natural organic matter in water. Where chlorine is obtained from hypochlorite, chlorate and bromate formation can be an issue depending on bromide content of salt used in manufacture and subsequent conditions of storage of hypochlorite. Can be controlled by appropriate product specification and management of storage.
Chloramination	No significant by-product issues. Nitrite formation in distribution has been an indirect issue.
Ozone	Bromate formation in waters with high concentration of bromide.
Chlorine dioxide	Dosage rates in the future are likely to be limited by consideration of inorganic by products (chlorate and chlorite) in accordance with current international practice.
UV	No significant by-product issues.

Surface water sources are more susceptible to organochlorine by-product formation than groundwaters because they receive organic matter in runoff from lake and river catchments. This organic matter comprises mostly humic substances from decaying vegetation, much of which can be in dissolved form as well as in colloid form. The concentration of this organic matter in surface water catchments can vary quickly after severe rainfall events or more slowly on a seasonal basis. The greater the portion which makes its way through the treatment process the greater the potential for the production of disinfection by-products.

While properly operated coagulation filtration processes will remove most of the colloids, oxidation processes and/or GAC filtration may be required to reduce elevated levels of dissolved organic matter prior to disinfection The key to limiting organochlorine by-product formation is effective treatment for the reduction of TOC which in its various forms is the precursor of these by-products

Surface waters in contrast to groundwaters vary in temperature seasonally with an increase in the rate of organochlorine by-product formation when temperatures increase.

Over the usual range of final treated water pH, the impact of pH on organochlorine by-product formation differs in respect of THMs and HAAs. Where excessive residual TOC exists in the treated water following treatment and the dose rate is sufficiently high to form by-products, THM formation increases with increased pH while HAAs increases in tandem with decreasing pH.

Following application of chlorine as part of the treatment process, organochlorine by-products can continue to form within downstream treated water storage and distribution systems depending on the length of retention times in storage tanks and pipelines and the strength of the disinfectant dose required to maintain chlorine residual in the peripheral areas of a distribution system.

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4. CHLORINATION AND CHLORAMINATION

4.1 Introduction

Chlorine is the most widely used disinfectant for the inactivation of waterborne pathogens in drinking water supplies and historically has arguably made the greatest contribution to the public health protection of consumers. In addition to its use as a primary disinfectant post treatment, the residual level which remains in the distribution systems ensures that the microbiological compliance can be quality assured to the consumer tap as well as safeguarding against recontamination in the distribution system.

Chlorination is a relatively simple and cost effective process which does not require extensive technical expertise and which is capable of dealing with supply systems of varying size by altering dosing systems or storage for chemical contact accordingly.

In Ireland, chlorination has historically been achieved using systems involving the storage and dosage of chlorine gas. Some of these gas installations remain in active use and will require ongoing guidance on their use for water disinfection and for management of associated health and safety risks. However, due to the toxic nature of chlorine gas, these installations have serious health and safety risks, which have to be managed.

The ongoing development and availability of other chlorination technologies such as:

- liquid sodium hypochlorite storage and dosage systems;
- advances in electrochlorination technology involving the on site batch manufacture of sodium hypochlorite.

has allowed Irish municipal and private water suppliers to reconsider these alternatives when planning new chlorination installations or upgrading existing installations as a replacement for chlorine gas. Most of the newer installations installed in the Irish market now use these liquid hypochlorite technologies as alternatives to gaseous chlorination.

Chloramination involves the addition of ammonia (NH_3) usually following chlorination (HOCl) to form monochloramine (NH_2Cl). Due to the fact that monochloramine is a much weaker disinfectant than chlorine, it's primary use is as a secondary disinfectant to maintain a residual in distribution networks, due to the difficulty in establishing adequate Ct values for primary disinfection.

4.2 Dosing sequence of post-treatment chemicals for optimum disinfection

Following treatment of drinking water supplies, chlorine is often dosed in conjunction with UV disinfection for primary or targeted pathogen inactivation and other post-treatment chemicals for plumbosolvency control and fluoridation.

It is important that the effects and influences of the various post treatment chemical additions on the efficacy of the disinfection systems are understood so that the sequence of their application optimises the disinfection process.

pH correction of final water supplies for plumbosolvency control, following alum coagulation treatment and filtration, usually involves the elevation of final water pH levels to a level slightly above the pH saturation level of a particular treated water. pH saturation varies for different treated waters and is typically a level between 7.0 and 8.3 pH. The correct pH saturation level of particular treated water is dependent on the residual alkalinity level remaining in the final filtered water. Low alkalinity waters following treatment often have consequent pH saturation levels close to or above a pH of 8. This chemical elevation of pH level causes a calcium carbonate deposit on the inside of lead pipes thereby reducing leaching of lead into drinking water supplies. As a result pH correction for plumbosolvency, using either the addition of lime, sodium carbonate or liquid sodium hydroxide, usually follows chlorination.

As will be discussed later in Section 4.4, the effectiveness of chlorination as a disinfectant depends on pH and the consequent dominance of hypochlorous acid (HOCl) formation over hypochlorite ion (- OCl^-), following the addition of sodium hypochlorite to water. As this HOCl dominance decreases rapidly between a pH of 7.0 and 8, the effect of plumbosolvency pH correction on the subsequent chorine dose necessary for effective disinfection should be taken into account.

When UV disinfection is applied to water with free or total chlorine residual, a reduction in the chlorine residual results, which is proportional to the delivered UV dose. A reduction of approx 0.2mg/litre in the residual was observed in bench-scale testing at UV doses up to 40 mJ/cm^2 (Wilczak and Lai 2006). Therefore UV is best located upstream of chlorination dosing points otherwise it is necessary to allow for this reduction in chlorine by UV. If UV disinfection itself is used as the primary disinfectant, a reduced chlorine Ct requirement should exist downstream

Fluoridation as such is not a water clarification or disinfection process but a means of adding a small dose of fluoride (within a range of 0.6-0.8mg/l) to water supplies for dental health reasons in accordance with the recommendation of the 2002 Forum on Fluoridation. Fluoridation is achieved by the addition of Hydrofluosilicic Acid (H_2SiF_6) to water, which releases fluorine in solution. Fluoridation is usually dosed following UV disinfection (where used as a disinfectant), post-treatment pH correction (where necessary for plumbosolvency control) and chlorination chemicals.

A flow diagram as set out in Figure 4.1 below, indicates the preferred recommended sequence for chlorine disinfection chemical dosing relative to the other common post-treatment chemicals used in water treatment processes.

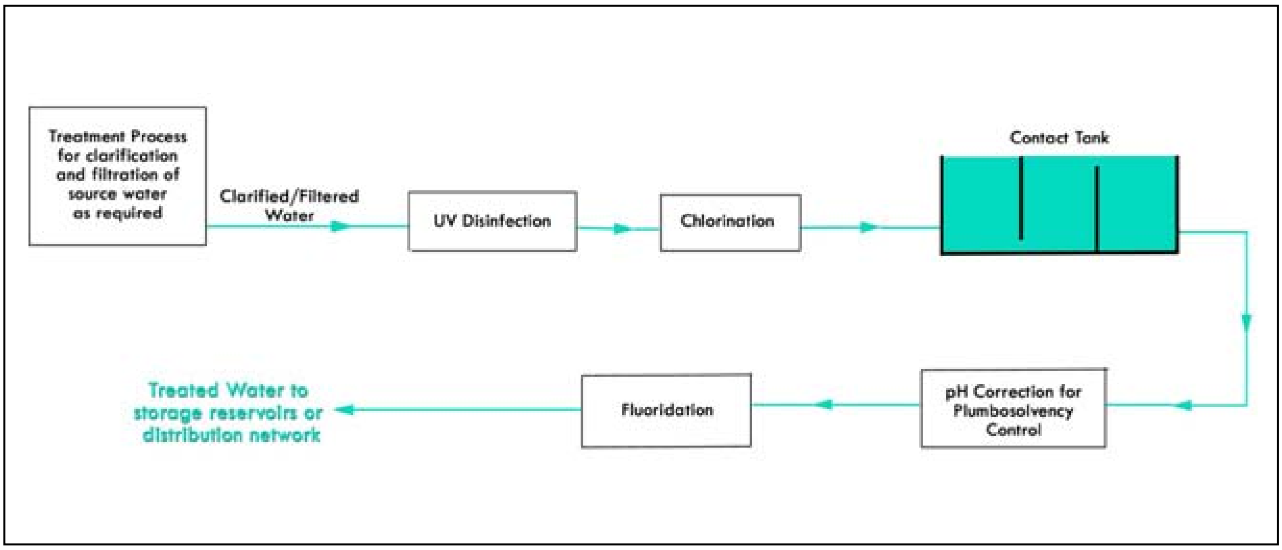


Figure 4.1 Suggested sequence of post treatment chemical dosing

In an ideal situation, the use of static mixers following each post treatment chemical addition is best practice to ensure adequate mixing before each subsequent addition. Many existing treatment plants however have limited space and hydraulic head to accommodate the inclusion of static mixers between dosing points and in actuality rely on subsequent contact tanks, pumping plant and treated water storage to ensuring complete mixing.

4.3 Range of chlorination technologies

The major sources of chlorine as a drinking water disinfectant are as follows.

4.3.1 Chlorine gas

Chlorine is manufactured off site as a gas, liquefied under pressure and stored as a liquid. The liquefied gas is delivered to treatment works as cylinders (33 kg and 71 kg net Cl_2) and drums (864 kg and 1000 kg net Cl_2). For the largest sites it can be delivered in bulk and stored in a specially designed tank.

Chlorine is highly toxic and rigorous Health and Safety procedures must be followed, and safety facilities provided, including breathing apparatus and chlorine detectors with alarms.

To minimise risk, most of the system for delivering gas to the treatment process is designed to operate under vacuum. The vacuum is provided by an ejector which also serves to provide intense mixing of the gas with the so called “motive water” that delivers the resultant solution of chlorinated water to the dosing point. Good mixing should be provided at the point of dosing, using in-line static mixers if necessary, particularly if the flow divides shortly afterwards.

A schematic of a gas chlorination system, using chlorine cylinders, is given in Figure 4.2, as an example only.

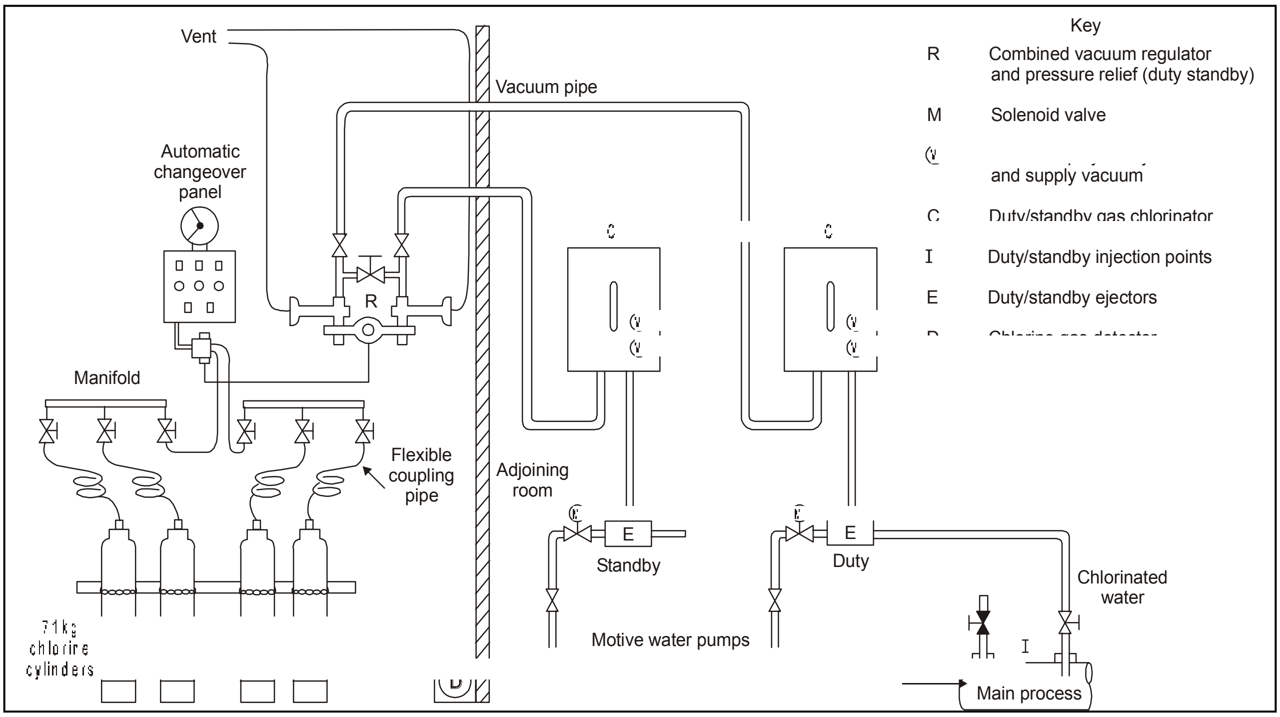


Figure 4.2 Chlorine gas system – example installation

4.3.2 Gas chlorinator systems

Chlorine gas is withdrawn from its pressurised container and, in the case of vacuum operated chlorinators, is reduced to lower than ambient pressure by means of a standard vacuum regulator check unit, which may be combined with a pressure relief valve. The gas is metered through an adjustable orifice. The rate of gas flow, which is indicated by a flowmeter, is controlled by adjusting the area of the orifice. A vacuum regulating valve dampens fluctuations and gives smooth operation. A vacuum relief valve prevents excessive vacuum within the equipment. Control of the rate of flow of gas may be varied manually or automatically, so that a constant residual concentration of chlorine is left in a flow of water to form a concentrated chlorine solution.

This mixture leaves the chlorinator as a chlorine solution (HOCl) ready for application. The operating vacuum is provided by a hydraulic injector. The inlet stream of water passes through a venturi tube or orifice at the heart of the injector causing the water velocity to increase and its pressure to fall, so that at that moment it can suck in the chlorine gas with which it mixes. Downstream of the constriction the pipe diverges, so that the original pressure is nearly fully regained. If the regained pressure is insufficient to inject the chlorine solution into the main water supply it is necessary to use a pump made of non-corroding metals to inject it through a corrosion-resistant conduit to a chlorine diffuser.

Vacuum operated chlorinators were developed to shut off the chlorine supply if the injector water flow stops and to prevent chlorine leaks at the injector - any loss of vacuum will shut off the chlorine supply. The primary advantage of vacuum operation is safety. If a failure or breakage occurs in the vacuum system, the chlorinator either stops the flow of chlorine into the equipment or allows air to enter the vacuum system, rather than allowing chlorine to escape into the surrounding atmosphere. In case the chlorine inlet shut-off fails, a vent valve discharges the incoming gas outside the chlorinator building. It is important that these vent lines discharge as far away as possible from an air intake.

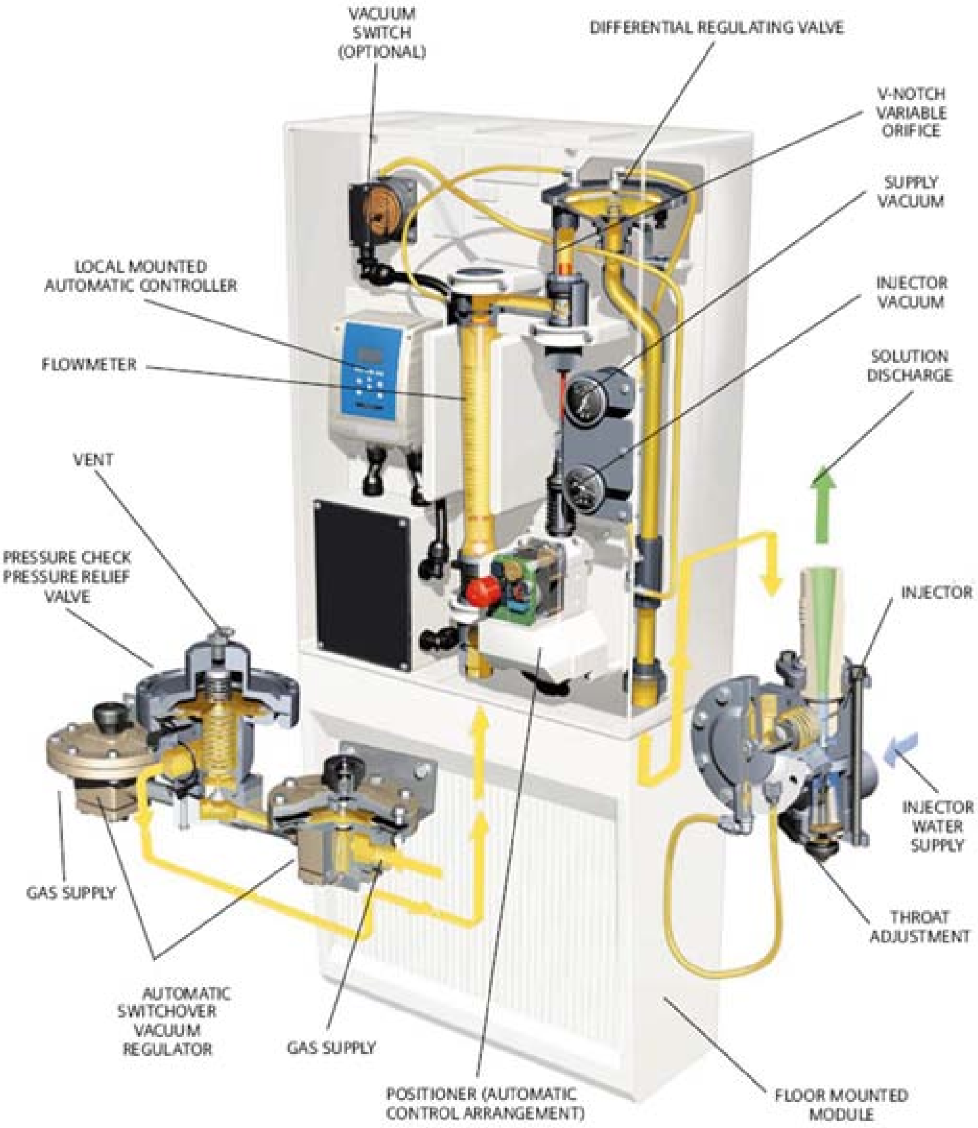


Figure 4.3 Typical Gas Chlorination equipment

The main components are summarised in Table 4.1. (see Figure 4.3 also)

Table 4.1. Chlorinator system components

PART	PURPOSE
Vacuum Regulator	Reduces the gas pressure from the container (minimum 1 bar) to the sub-atmospheric pressure of the chlorinator and adjusts the gas-flow rate to correspond to the vacuum set by the adjustment of the V-notch plug within its orifice.
Pressure Relief System	Discharges chlorine gas to the outside through the pressure relief vent or valve, if excessive gas pressure in the chlorinator should occur.
Positioner	Controls the rate of gas flow through the chlorinator by adjusting the position of the V-notch plug within its orifice, generally by automatic control with a manual override.
Flowmeter	Indicates chlorinator feed rate. (Read the widest part or top of the float or centre of the ball for rate marked on tube).
Differential Regulating Valve	Ensures that the vacuum differential across the gas control V-notch plug is consistent.
Pressure Check Valve	Prevents water back-feeding into the chlorinator from the injector.
Vacuum Relief System	Admits air into the chlorinator system through the vacuum relief vent or valve, if excessive vacuum should occur.
Pressure Gauges	Indicate gas pressure at the containers and water pressure at the injector.
Vacuum Gauges	Indicate vacuum in the chlorination system.
Injector	Creates the vacuum for the system and sucks the chlorine gas into the operating water supply to form the chlorine solution for injection into the water supply to be disinfected.
Vacuum Switch	A local or remote mounted vacuum switch provides an alarm in the event of a high or low vacuum condition signifying a loss of gas feed
Gas Warning Light, Audible Alarm and Air Blower Switch	Give warning that a pre-determined level of chlorine gas has been detected in the air of the chlorine store and enables air blower to be switched on to displace gas from store via the low level inlet and air duct to the outside.

Further practical guidance on the storage and operation of chlorine gas systems is included in Appendix 2.5.

4.3.3 Commercial sodium hypochlorite

a) Introduction

Commercial sodium hypochlorite is manufactured by reaction between chlorine and sodium hydroxide and is supplied as an aqueous solution with a maximum concentration equivalent to ca. 15% w/w Cl_2. Although more expensive than gaseous chlorine, the use of bulk delivered sodium hypochlorite can counteract the cost of increased health and safety measures, is easier and safer to use and reduces the risk of chlorine gas release especially when installations are in close proximity to surrounding properties.

b) Degradation of bulk delivered sodium hypochlorite

Sodium hypochlorite is chemically unstable and gradually converts to sodium chlorate with the attendant release of gas which is mainly oxygen.

The commercial product has caustic soda (ca. 0.5%) added to improve stability. It must be handled with care as it is extremely corrosive with a high pH (11-13) which will attack and corrode all metal including metal pipe and fittings. In fact, the use of metal anywhere in a hypochlorite system is not recommended as corrosion will occur and the metals will permeate the hypochlorite solution. The presence of metals in solution will also contribute to the decomposition of the hypochlorite solution as set out below.

Bulk delivered hypochlorite solutions have been observed to degrade according to second order decay kinetics:

$dC/dt = - kC^2$

Degradation varies as a function of the square of concentration (strength) of bulk sodium hypochlorite delivered.

Factors affecting the degradation of sodium hypochlorite solutions include:

- The presence of certain metals i.e. Iron, Copper, Cobalt, Nickel - (product quality);
- Exposure of bulk hypochlorite solution to UV Light i.e. sunlight;
- Deterioration of sodium hypochlorite solution with time is more rapid at higher temperature.

Some commercial products are delivered at lower strength e.g. 10%, to provide more stability. Examples of decay are given in Table 4.2 to illustrate relative stability at a range of initial concentrations, at 20°C in the dark, based on data provided by hypochlorite suppliers.

Table 4.2 Illustrative examples of chlorine decomposition in hypochlorite solution @ 20°C

Initial concentration	**After 20 days**	**After 100 days**
15% available chlorine	13%	10%
13% available chlorine	12%	8%
10% available chlorine	9%	8%
6.5% available chlorine	6.2%	6%

Long-term storage of hypochlorite solution can also lead to formation of chlorate at excessive concentration in the resulting hypochlorite solution as the decay volume is almost entirely transformed into chlorate.

The rate of decomposition increases with increased chlorine concentration and temperature. As this decomposition is associated with a reduction in chlorine concentration, the continued dosing of the hypochlorite solution requires higher doses as storage time increases to achieve the same chlorine residual into the treated water with the attendant dosing of increasing chlorate levels in the dosed solution

Consequently delivered hypochlorite should be used in rotation and dated and controlled so as to minimise excessive storage and consequent deterioration.

In order to prevent excessive degradation of hypochlorite product and excessive dosage of consequential chlorates formed, water suppliers should consider whether the concentration of hypochlorite ordered could be reduced vis-à-vis the available storage tank volume, the size of cost effective chemical delivery to site, the feasible frequency of product replenishment, the ambient temperature expected during the estimated storage period and the appropriateness or otherwise of using chillers to regulate temperature.

c) The design of storage and dosing systems

Hypochlorite dosing systems are relatively simple but need to take account of design issues surrounding the control of gas release from the bulk hypochlorite in dosing pumps and piping and scale formation.

Vapour or gas bubbles can form due to gasification (i.e. the degradation of the NaOCl produces a gas which is mostly oxygen) particularly if sodium hypochlorite is below atmospheric pressure, which can lead to gas locking of the suction line in a diaphragm pump. Pumps should therefore be provided with flooded suction (i.e. the pump inlet should always be below liquid level in the storage tank). Tanks must be properly vented out of all structures to the atmosphere.

The most common dosing systems use diaphragm metering pumps. The pump action can cause a vacuum to develop and can cause any dissolved gases in the sodium hypochlorite to vaporise, resulting in the pump losing its prime and a lower applied chlorine dose.

Consequently dosing arrangements must have a positive head on the pump suction to aid in the prevention of gasification with the pump inlet always below the minimum tank liquid level. In addition, piping system configurations which will trap sodium hypochlorite between two closed isolation valves or check valves should be avoided.

A pulsation damper, a pressure relief valve, a calibration cylinder and a loading valve normally form part of the well designed dosing system. Some dosing pump suppliers offer automatic auto-degas valves systems as a means of solving this problem. Sodium hypochlorite is dosed either through an injection fitting (pressurised pipes) or through a spreader bar submerged within an open channel. The pulsation damper should be fitted close to the dosing pump, suitably sized and pressurised for the duty. Pulsation damping also improves dispersion. A loading valve is also required where the back pressure at the pump delivery side is insufficient (typically less than about 0.7 to 1.0 Bar), unless a suction demand valve is installed on the suction side.

A pressure relief valve (PRV) is required on the delivery side of the pump, to protect the diaphragm from rupture, should the delivery pipework become blocked. Operation of the PRV should be detected and alarmed: the outlet of the PRV could, for example, be directed to a small "catch-pot", equipped with a suitable float switch. Systems shut down or pumps that are not in use should contain methods to relieve any build up of pressure.

The pH of sodium hypochlorite is high because sodium hydroxide is used in its manufacture to reduce decomposition and increase the stability of the product. Care is needed when dosing hard waters or waters with carbon dioxide present as the highly alkaline product can lead to reduced pipe diameter, lower flow rates, reduce pump capacities and scale formation at dosing points.

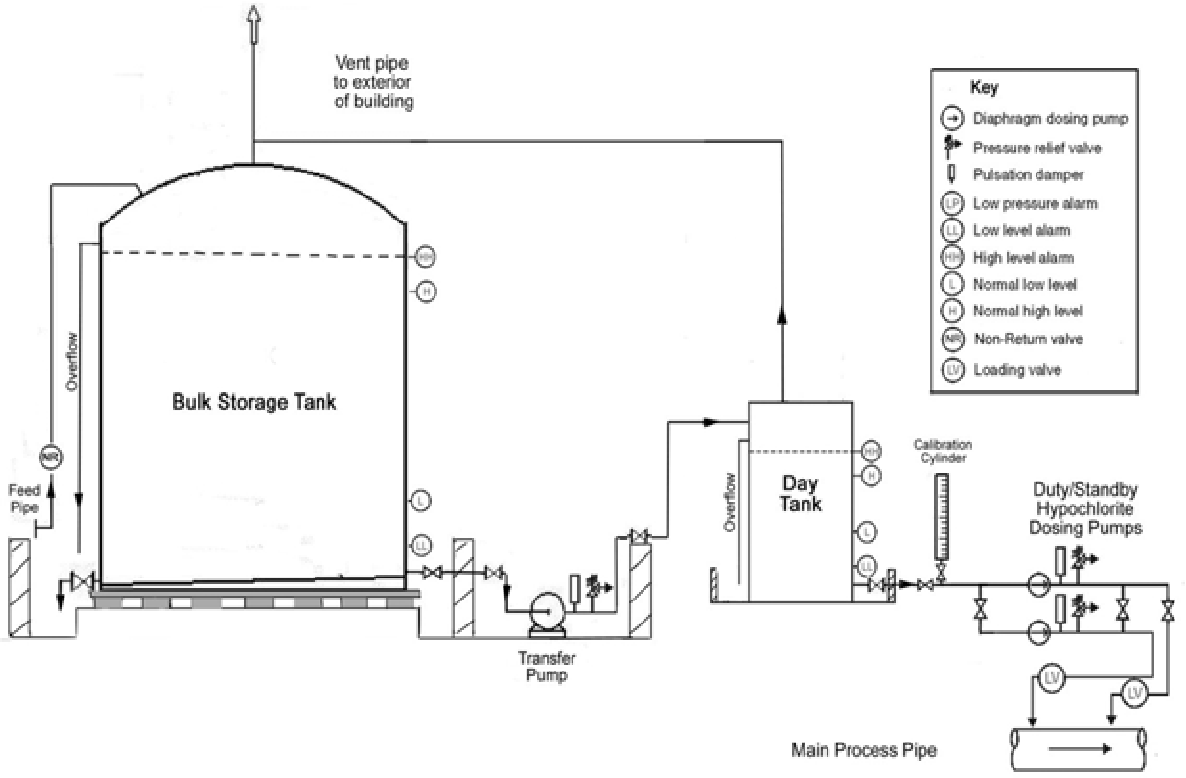


Figure 4.4 Schematic of typical storage and dosing installation for bulk hypochlorite

Further practical guidance on the storage and operation of bulk delivered NaOCl systems is included in Appendix 2.5.

4.3.4 Sodium hypochlorite – manufactured on site

On-site electrochlorination (OSE) is based on electrolysis of dilute brine to produce batches of sodium hypochlorite (0.5 to 1.0 % w/w Cl_2) on demand. The product is stable at these low concentrations and is typically stored for no more than 24 to 36 hours. The equipment uses softened water to prevent scaling of the electrodes. Hydrogen gas is a by-product – the explosion hazard is addressed by forced venting of storage tanks such that the atmosphere in the tank is not explosive.

A range of systems is available, all based on the electrolysis of dilute brine (aqueous sodium chloride), which is made up on site from high purity salt. Salt consumption rates of proprietary systems are typically 3kg of salt per kg of equivalent chlorine. Within the electrolysis cell is a matrix of plate type electrodes manufactured from metals which are resistant to the chemically aggressive environment present during electrolysis. The electrode reactions for the product are:

At anode $2Cl^- - 2e^- \rightarrow Cl_2$

At cathode $2H_2O + 2e^- \rightarrow 2OH^- + H_2$

Overall $Cl^- + H_2O \rightarrow OCl^- + H_2$

The simple overall representation of the electrochemical reaction is:

$NaCl + H_2O$	=	$NaOCl$	+	H_2
Sodium + Water Chloride	=	*Sodium + hypochlorite*		*Hydrogen (gas)*

Batches of hypochlorite are generated by continuous electrolysis of brine. A generalised schematic for such a system is given overleaf in Figure 4.5 as an example.

The key variables which determine the overall efficiency of a given system are: the feed rates of brine and dilution water; the temperature of the dilute brine entering the cell, and the electrode (particularly anode) condition. The conditions under which the product hypochlorite is stored can also impact on the rate of degradation of the product and therefore on the overall efficiency of chlorine generation.

Water is used in the electrolysis process, both to prepare saturated brine and also to dilute the brine prior to the EC cell(s). The high pH within the cell during electrolysis will rapidly precipitate dissolved calcium and magnesium salts naturally present in some waters, forming scale on the electrode surfaces and reducing electrolysis efficiency. To avoid this, an ion exchange (cationic) softener is used to treat the water supply to reduce the total hardness of the feed water typically less than 15 $mgCaCO_3/l$. Even where the natural hardness of the feed water is low, softening is usually installed because of the additional purification provided in terms of removal of manganese and iron which could otherwise precipitate in the electrolysis cells and on electrodes.

Cell designs vary from one manufacturer to another, and various claims are made as to the relative merits of each. The anode typically comprises a titanium base with a precious metal oxide coating; the cathode is made of either Hastelloy C (a nickel based alloy) or titanium.

A greater electrolysis voltage is required at low temperatures (lower electrical conductivity) and this can lead to stripping of the metal oxide coating on the anode. This may require that the dilute brine entering the cell is heated indirectly via heat exchange with the warmer cell product. Additional thermostatically controlled electrical heating is provided in situations where feedstock temperature can fall below $6^{o}C$. A benefit of heating is the enhanced electrolysis efficiency at higher temperatures, although too great an electrolyte temperature leads to accelerated formation of chlorate by-product, and deterioration in overall efficiency.

The electrolyser system is designed to produce hypochlorite with a chlorine concentration usually in the range 7 to 9g Cl_2/l (or 0.7 to 0.9% w/v).

The product from the EC cell, a mixture of aqueous sodium hypochlorite and hydrogen gas, passes to the storage tank. A blower is used to force air into the tank head space during hypochlorite generation, the air reduces the hydrogen concentration to < 1% v/v (25% of lower explosive limit of 4% v/v) and assists ventilation. The diluted hydrogen gas is vented to the atmosphere via a vent above the storage tank. With most electrolytic systems an atmospheric gas monitor is installed to monitor hydrogen concentration in the electrolyser room.

The hypochlorite product is relatively stable, although degradation does occur, principally due to:

- volatisation of chlorine (accelerated during forced air venting);
- decomposition of hypochlorite to O_2 and NaCl if the tank is contaminated;
- chemical reaction to form chlorate (very slow relative to commercial hypochlorite because of relatively small hypochlorite concentration).

The maximum storage time of product in the tank should ideally be limited to between 36 and 48 hours, although up to 72 hours should not lead to excessive degradation if storage tanks are clean.

Further practical guidance on the operation of systems for the on-site generation and storage of sodium hypochlorite is included in Appendix 2.5.

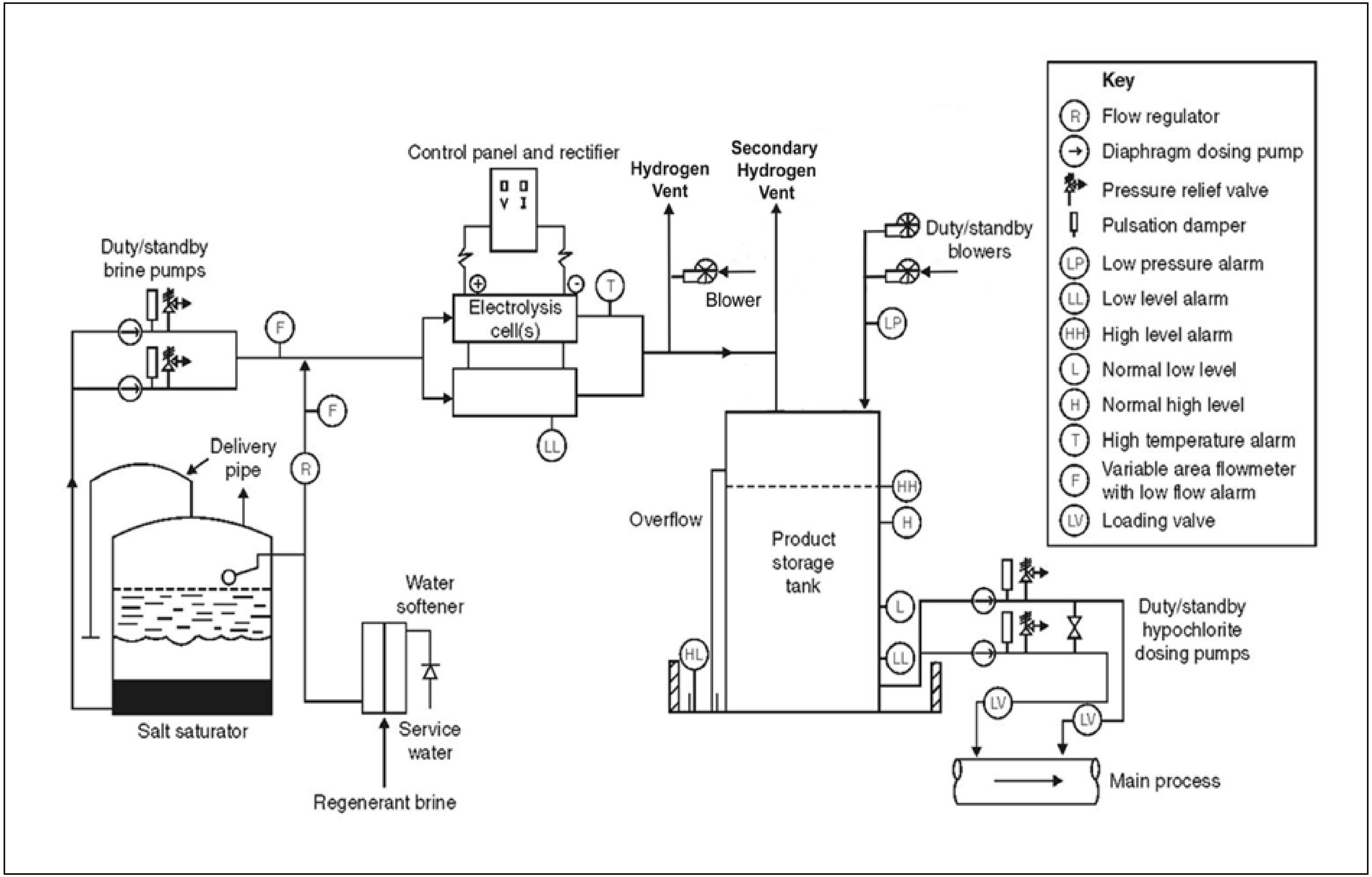


Figure 4.5 Example of on-site electrolytic chlorination installation

4.3.5 Calcium hypochlorite ($Ca(OCl)2$)

Calcium hypochlorite, which is sold as a white powder and as tablets, is typically used to boost chlorine concentration in service reservoirs or sometimes for chlorination at small works.

Granular calcium hypochlorite comes in the form of chlorinated lime (a mixture of $Ca(OH)_2$, $CaCl_2$ and $Ca(OCl)_2$) or high test hypochlorite (HTH). All forms of calcium hypochlorite are made with added inert materials (i.e. 30-35% w/w in the case of HTH tablets and 65-80% w/w in the case of chlorinated lime in powder form).

Calcium hypochlorite feeders are manufactured for large and small flows. For larger flows volumetric or gravimetric feeders drop a measured amount (in volume or weight) into a dissolution tank (always accompanied by mixing), where it dissolves and where the solution is later dosed via a dosing point in the same way as sodium hypochlorite. If one assumes the use of chlorinated lime containing 33% w/w of chlorine, a 1% w/v ($10gCl_2$/litre) solution can be made by mixing 30kg of HTH tablets in 1000 litres of water. 100 litres of this solution would be sufficient to dose $1{,}000m^3$ of water.

The use of these feeder devices for calcium hypochlorite is not popular for large flows which are usually treated by liquid sodium hypochlorite (in commercial or site generated form) or chlorine gas (historically).

For smaller flows (typical in medium-sized and small schemes), high test hypochlorite in solid tablet form is used (ca. 65% w/w Cl_2). These tablets lose less than 1 to 2% w/w Cl_2 per year if stored under appropriate conditions. Application in tablet form tends to be limited to small chlorine usage ($<500m^3$/day) due to cost and the practical difficulties of making up aqueous solutions of hypochlorite from the solid product. These tablets are typically used in conjunction with tablet erosion feeders.

Smaller tablets are designed for individual use and contain measure amounts of chlorine for disinfection of a particular volume of water.

Solutions should be prepared on a batch basis for use. Both granular calcium hypochlorite and tablets include additives to prevent powdering of the active material and to stop the adsorption of moisture. This inert material must be separated from the dissolved active hypochlorite so as to prevent clogging and blockages of pumps and equipment.

In the case of calcium hypochlorite, separation of diluted calcium hypochlorite from inert materials can be achieved as follows:

- from granular product, by the provision of a separate mixing tank upstream of the dosing tank and mechanically mixing. Following proper mixing the inert insoluble material is allowed to settle prior to decantation of the dissolved liquid only to the dosing tank.
- from granular product, by allowing mixed batched solution to stand for a period of 24 hours prior to dosing so that inert residues settle out prior to use
- by the use of tablet erosion feeders

4.4 Chemistry of chlorine

4.4.1 Free available chlorine

When either gaseous chlorine or sodium hypochlorite or calcium hypochlorite is added to water, they react to produce two compounds hypochlorous acid, HOCl and, in its disassociated form, the negatively charged hypochlorite ion OCl^- cumulatively known as “free available chlorine”

$$Cl_2(g) + H_2O \rightarrow HOCl(aq) + H^+(aq) + Cl^-(aq)$$

$$NaOCl + H_2O \rightarrow HOCl(aq) + Na^+(aq) + OH^-(aq)$$

$$Ca(OCl)_2 + 2H_2O \rightarrow 2HOCl(aq) + Ca^{2+}(aq) + 2OH^-(aq)$$

Hypochlorous acid is more reactive than the hypochlorite ion and is also a stronger disinfectant and oxidant.

4.4.2 Effect of pH and temperature

Hypochlorous acid dissociates to produce the hypochlorite ion:

$$HOCl \rightleftharpoons H^+ + OCl^-$$

The extent to which these reactions occur, and therefore the proportions of HOCl and OCl^- in solution, is a function of pH and temperature.

At low pH (more acidic), hypochlorous acid dominates while at high pH the hypochlorite ion dominates. This relationship is shown in Figure 4.6 below.

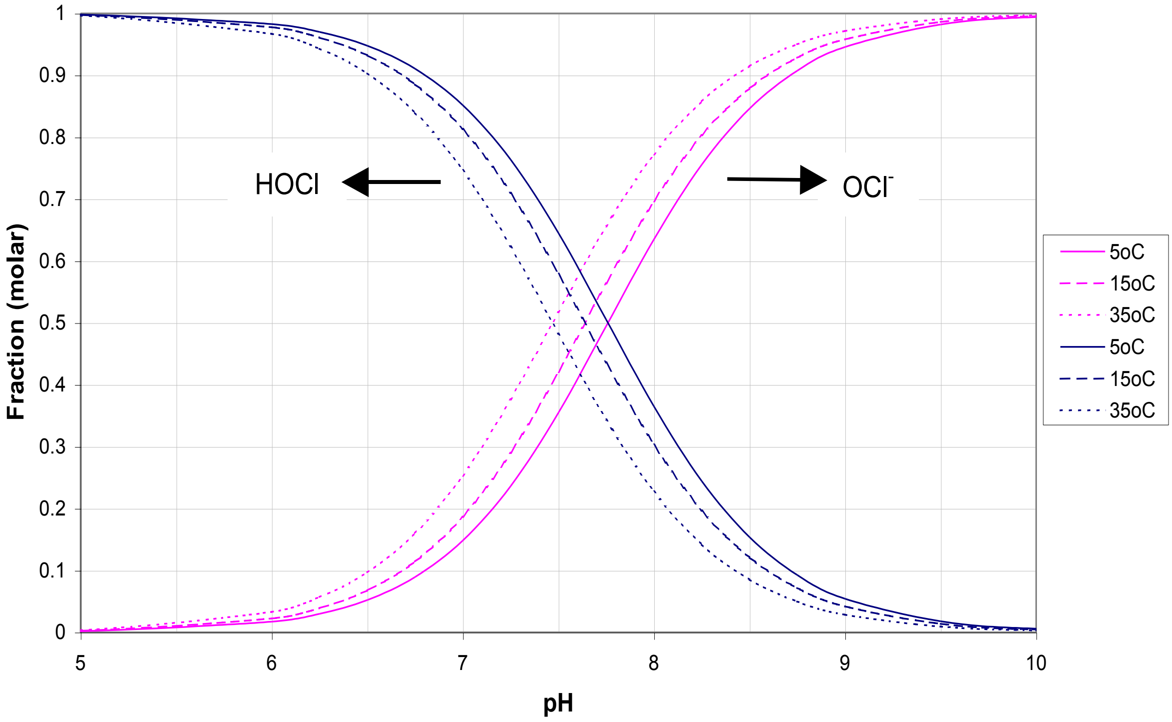


Figure 4.6 pH and temperature dependency of HOCl – OCl^- equilibrium

Hypochlorous acid is a much stronger oxidant than the hypochlorite ion, and thus disinfection is more effective at neutral to acidic pH than at alkaline pH.

A relationship for the temperature dependency of K_a (Morris, 1966) is:

$$\ln K_a = 23.184 - 0.0583T - \frac{6908}{T}$$ *where T = temperature, °K*

And $$K_a = \frac{[OCl^-][H^+]}{[HOCl]}$$

Below pH 4, chlorine exists in solution as the elemental form Cl_2. The sum of the concentrations of elemental chlorine, hypochlorous acid and hypochlorite ion is referred to as free available chlorine. In practice, the pH range experienced in water treatment precludes elemental chlorine, so free available chlorine is simply the sum of hypochlorous acid and hypochlorite ion concentrations.

At a given pH the amount of HOCl decreases with increasing temperature, because of increased dissociation. However, in terms of disinfection performance, this effect is compensated for by the greatly increased activity of oxidation at higher temperature, as discussed. As a result, for a given pH value, improved disinfection performance occurs at a higher temperature.

4.4.3 Reaction with ammonia: “breakpoint chlorination”

Chlorine reacts with ammonia to form chloramines:

$NH_3 + HOCl \rightarrow H_2Cl + H_2O$ (monochloramine)

$NH_2Cl + HOCl \rightarrow HCl_2 + H_2O$ (dichloramine)

$NHCl_2 + HOCl \rightarrow Cl_3 + H_2O$ (trichloramine).

The significance of each of these three reactions is influenced by pH, the absolute and relative concentrations of ammonia and chlorine, as well as temperature and reaction time. Within the pH range 6.5 to 8.5, as the molar chlorine:ammonia ratio is increased above 1:1, additional reactions occur which result in the further conversion of monochloramine to dichloramine, and eventually the decomposition of dichloramine.

The overall reaction can be represented by:

$$2NH_3 + 3HOCl \rightarrow N_2 + 3HCl + 3H_2O$$

This has traditionally been used in water treatment as a means of eliminating ammonia, the process being termed “breakpoint chlorination” or “superchlorination”. Theoretically, a molar ratio (chlorine:ammonia) of 1.5:1 (mass ratio 7.6:1 Cl:NH_3-N) oxidises all ammonia to nitrogen, and increasing this ratio results in a free chlorine residual. In practice the breakpoint typically occurs at a molar ratio of about 2:1 (mass ratio 10:1) due to other reactions.

4.5 Disinfection performance

4.5.1 Primary disinfection

The original WHO recommendations for the use of chlorine as a disinfectant stipulated a minimum free chlorine concentration of 0.5 mg/l (C) after 30 minutes contact time (t) at a pH of less than 8, provided that the turbidity is less than 1 NTU.

The product of these two values **C** X **t** is the commonly used term to describe the efficacy of chemical disinfection systems that form residual concentrations in the water following chemical dosing.

The recommended WHO value for chlorination corresponds to a Ct of 0.5 x 30 = 15 mg.min/l. This is very much a generic recommendation, and a more considered site-specific approach to setting Ct values is recommended.

A site specific approach may need to take into account:

- The levels of contamination with pathogens expected, and any specific pathogens of concern for the site (catchment risk);
- The extent and performance of treatment prior to final disinfection;
- The design of the contact tank, in relation to short-circuiting;
- Expected variations in temperature and pH.

WHO guidelines (2004) include recommendations for chlorine Ct values for different types of micro-organisms. Table 4.3 sets out Ct values for 99% inactivation of common waterborne pathogens. The virus data are for *Coxsackie* A2 which have a high resistance to chlorine compared with other viruses, and therefore would provide a conservative indicator for design of chlorination systems.

Table 4.3 Recommended Ct values for 99% (2-log) inactivation

	Temperature (°C)	**pH**	**Ct (mg.min L^{-1})**
Bacteria	<2	7	0.08
	<2	8.5	3.3
Viruses	<5	7 – 7.5	12
	10	7 – 7.5	8
Giardia	0.5	7 – 7.5	230
	10	7 – 7.5	100
	25	7 – 7.5	41

These generic recommendations are based on inactivation data that show that micro-organisms vary markedly in their susceptibility to disinfection. The ascending order of resistance is from bacteria, viruses, bacterial spores to protozoa (e.g. *Giardia, Cryptosporidium*). Protozoa are not readily inactivated by chlorination conditions generally used in water treatment, particularly *Cryptosporidium*, and their removal must be achieved primarily by optimisation of other treatment processes.

4.5.2 Secondary disinfection

The requirement to achieve adequate Ct for inactivation of waterborne microorganisms in drinking water is only important at the location of primary disinfection installations i.e. locations following treatment where the necessary microbial inactivation of microorganisms in water is affected.

At secondary disinfection stations and chlorine booster station located on distribution networks, the achievement of Ct based on downstream contact volume and chlorine concentration is not required. Chlorine is dosed to provide or boost the measurable free chlorine residual in the water for continued verification of microbiological water quality and to prevent contamination in the network. The aim of boosting chlorine in the network should be to ensure that **at least 0.1 mg/l free residual chlorine is present at the extremities of the distribution network**.

Verification of the efficacy of primary disinfection in accordance with Regulation 13(1) of SI 278 of 2007 will ensure that secondary chlorine dosing is needed for residual generation only.

4.6 Effective contact time (t)

4.6.1 Contact time under ideal conditions

In an ideal contact tank, of volume V, through which water passes at a volumetric flow rate Q, the residence time equals the theoretical hydraulic residence time (HRT), τ, where:

$$\tau = \frac{V}{Q}$$

The term ‘plug flow’ is commonly used to describe the flow in such an ideal system and the contact time for disinfection would simply be τ

4.6.2 Contact time in real systems

Such ideal flow is never observed in real systems. The residence time of individual sub-volumes of water passing through a system is not equal. In the case of a disinfection contact tank, a proportion of the water may short-circuit the tank and thus have a residence time less than τ; another proportion of the water may recirculate, or get caught in quiescent zones, and have a residence time greater than τ.

The true situation with regard to flow in a system is characterised by the distribution of residence times: generally known as the residence time distribution (RTD). A common approach to dealing with the non-ideality of flow in disinfection systems is to consider t_x, defined as the time in which the fastest flowing *x*% of liquid passes through the tank. Conversely, t_x is the minimum residence time of the remaining (100-*x*)% of the liquid.

The relationship between t_x and the HRT, τ, is:

$$t_x = \left(\frac{t_x}{\tau}\right)$$

where (t_x/τ) = correction factor.

In a perfect plug flow reactor (PFR), residence time is uniform, and hence $(t_x/\tau) = 1.0$ and $t_x = \tau$. The further away from plug flow, the smaller the correction factor for a given value of *x*, and hence the smaller t_x will be relative to the HRT. The Ct (i.e. Ct_x) value will therefore be lower for a given concentration of chlorine.

US EPA guidance (USEPA, 1999) for disinfection is based on $x = 10$ i.e. t_{10} value, which is associated with 90% of the water passing the contact volume having a greater residence time than this value.

The RTD, and therefore t_x can be readily determined by means of tracer tests.

4.6.3 Quantifying contact time tracer tests

In a tracer test, an inert indicator is dosed at the inlet of a tank, and is monitored in the outlet.

The simplest form of test from which to derive t_x is a step change test. A step change in the dosing of the tracer is started at time 0, and continued until the outlet concentration has increased to equal the inlet concentration. The outlet concentration is simply plotted against time, and the time at which the outlet concentration equals *x*% of the inlet concentration is t_x. Such tests are ideal where a suitable chemical (chlorine, phosphate, fluoride) is already being used.

Sometimes it is more convenient to perform a "spike" tracer test. The tracer is dosed as a single slug at time 0, and the outlet is monitored for a suitable period. The plot of outlet tracer concentration against time is the system RTD, and t_x can be found directly by determining the area under the RTD curve and finding the time that partitions the first *x*% of the area. An illustration of this is shown in Figure 4.7.

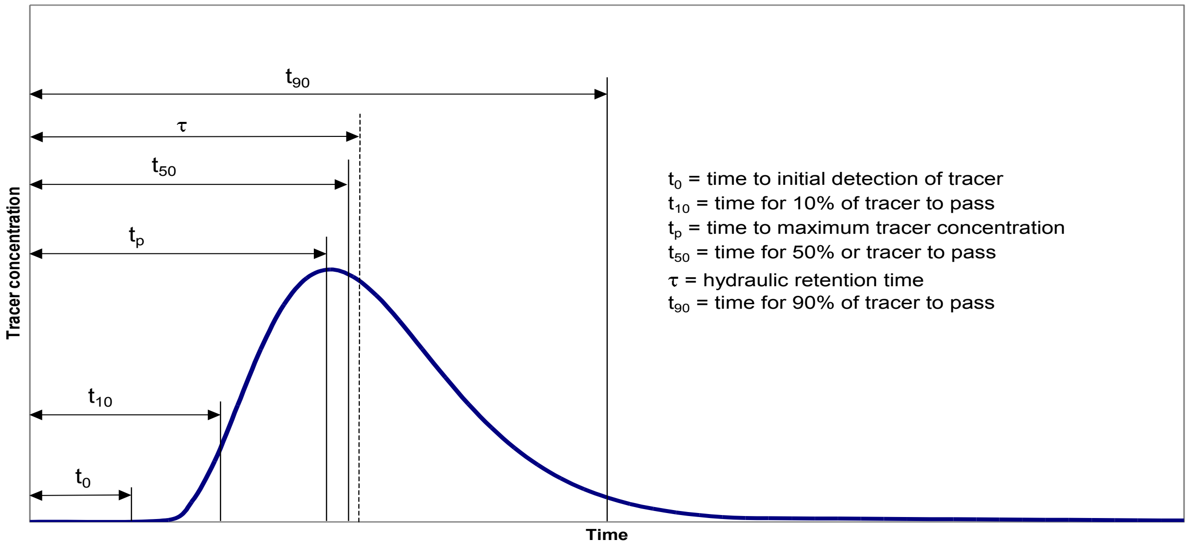


Figure 4.7 Illustration of tracer concentration at outlet after a "spike" test

4.6.4 Materials for use as tracers

In principle, many materials could be used as tracers, provided they do not exceed regulatory concentrations, are non-toxic, do not cause aesthetic problems, or can be effectively flushed from the system before water is put into supply.

Examples of possible tracers include:

- *Lithium chloride*. Lithium is rarely found in natural waters and can be measured to 0.1 g/l. A standard approach is to apply sufficient lithium chloride to achieve a notional mean concentration (mass of lithium applied/tank volume) in the tank under test. In the UK the Drinking Water Inspectorate permits the use of lithium salts provided the concentration in the water supplied to the consumer does not exceed 0.1 mg/l Li, so it is possible, in principle, to carry out short-term tests of live systems using lithium.
- *Chlorine*. Provided chlorine demand is stable over the duration of the test and the rate of chlorine decay is not excessive (no ammonia, good quality treated water), chlorine can be used as a tracer by monitoring chlorine residual at the tank outlet after a step change in dose.
- *Sodium chloride* can be used as a tracer, by monitoring conductivity. However, if the water already has a naturally high conductivity, the amount of salt required could be excessive in relation to compliance with water quality standards.

Other options include fluoride and phosphate, where these are being dosed for fluoridation or plumbosolvency control.

Tracers that can be detected at low concentrations are preferred, because high concentrations can result in density currents influencing the hydraulics. The use of chlorine or fluoride would provide the most practical option for tracer tests.

4.6.5 Practical guidance on effective contact time

As a guide, the minimum duration of a tracer test is 3 x HRT. The actual duration should be sufficient to achieve a target minimum recovery of applied tracer. A value of 90% has been suggested (USEPA, 1999):

- In a step test it is not necessary to reach steady-state outlet concentration, provided the target tracer recovery is achieved.
- For a spike test this effectively requires continuing sampling until measured tracer concentration has dropped to the background level.

Flow rate should be kept constant for the duration of the test. Ideally, tracer tests should be performed for a range of flow rates.

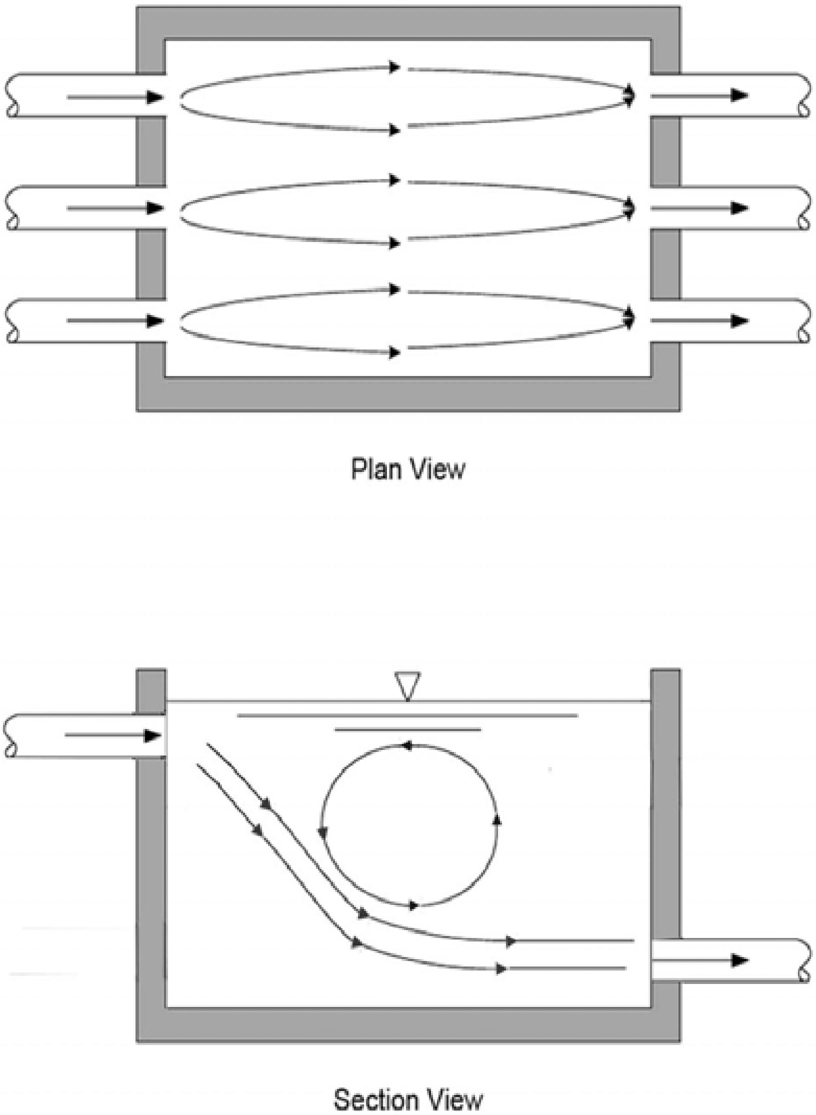
In the absence of tracer test data, an initial estimate of non-ideality can be made by consideration of the tank design, in particular provision of baffling.

Values of t_{10}/τ suggested by USEPA (1999) are shown in Table 4.4 below.

Table 4.4 Suggested values for t_{10}/τ in respect of different baffling arrangements

Condition	t_{10}/τ	Description	Graphic
Unbaffled	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities.	
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles.	Figure 4.8
Average	0.5	Baffled inlet or outlet with some intra-basin baffles.	Figure 4.9
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders.	Figure 4.10
Perfect	1.0	Very high length to width ratio (pipeline flow).	

Source; US EPA, LT1ESWTR Disinfection Profiling and Benchmarking Technical Guidance Manual 2003



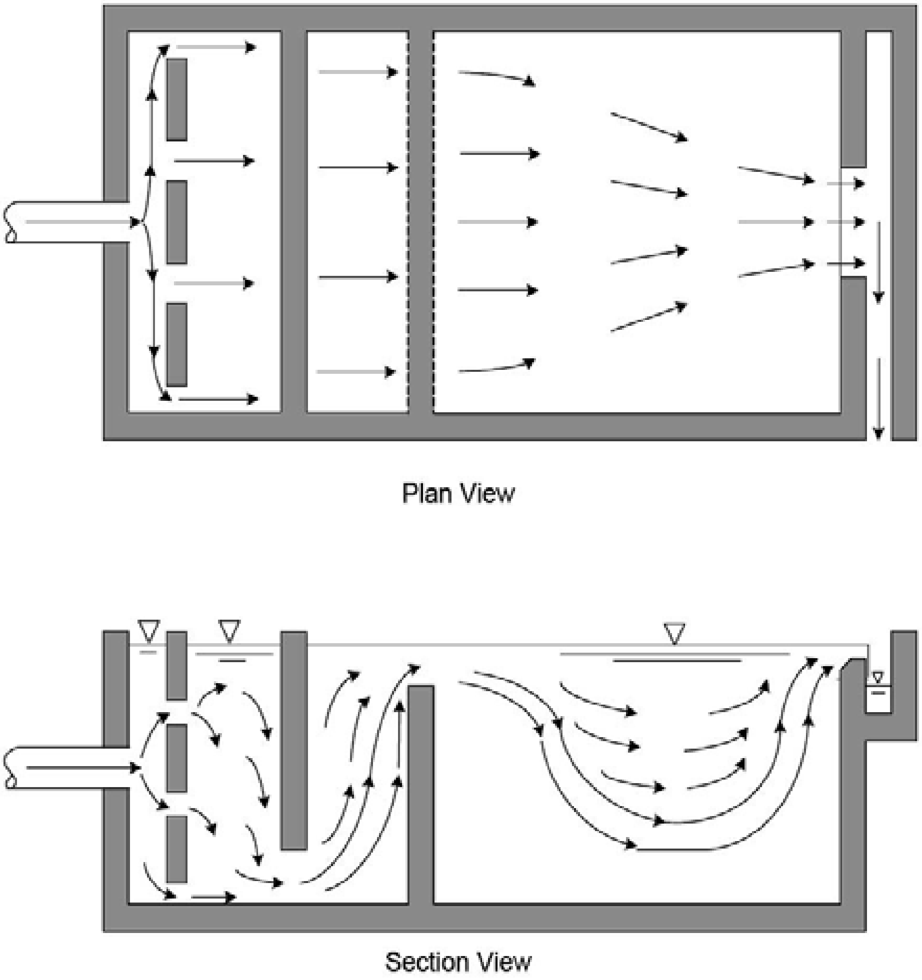
Source. US EPA (2003). LT1ESWTR disinfection profiling and benchmarking. Technical Guidance Manual

Figure 4.8. Poor baffling arrangements in contact tank

For a poorly baffled tank, the contact time used for calculation of Ct using the t_{10} value would be less that one-third of that derived from dividing the tank volume by flowrate.

A good contact tank will have structures in place that:

- Prevent jetting at the inlet;
- Distribute the flow across the full width and depth in the direction of flow;
- Prevent streaming at the outlet.



Source. US EPA (2003). LT1ESWTR disinfection profiling and benchmarking. Technical Guidance Manual

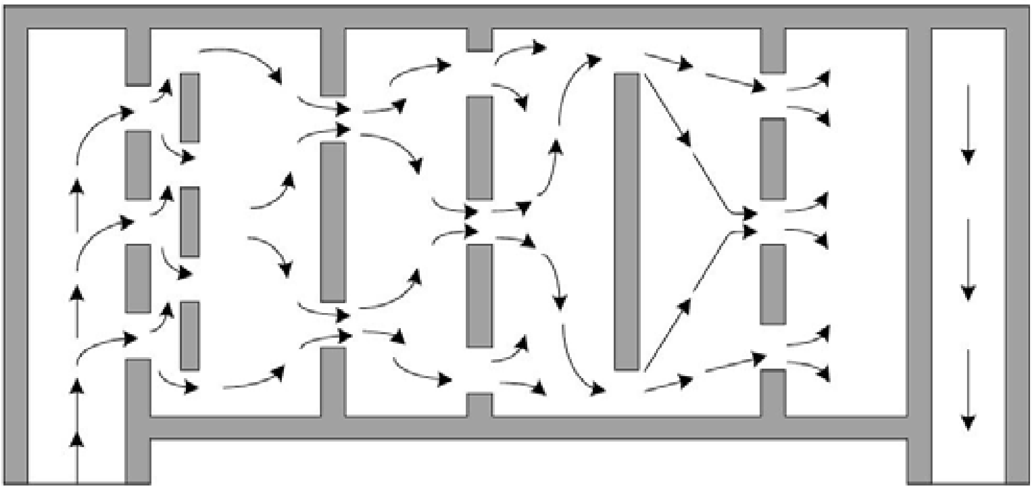
Figure 4.9 Average baffling arrangements in contact tank

Compartmentalisation of the tank will, in principle, have a beneficial effect on hydraulics.

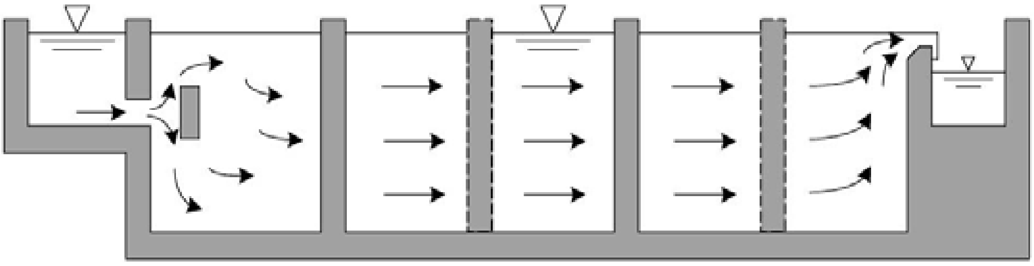
Features to be avoided include:

- Submerged pipe inlet with no break plate or other means of preventing jetting;
- Outlet weirs or launders that are not full width;
- Bell-mouth outlets in the main body of the contact tank.

For new-build contact tanks it is now common practice to test the proposed design with Computational Fluid Dynamics (CFD) analysis, from which the RTD and t_x can be predicted. The incorporation of structures within a tank to promote even flow distribution carries a capital cost.



Plan View



Section View

Figure 4.10 Superior baffling arrangements in contact tank

Source: US EPA (2003). LT1ESWTR disinfection profiling and benchmarking. Technical Guidance Manual

4.6.6 The use of service reservoirs for chlorine contact

The principal functions of service reservoirs include the provision of a buffer volume to equalise water production facilities with peak system demands and a storage volume for firefighting and emergency use. However, the design of the service reservoirs often gives little consideration to the flow patterns formed within the tank, other than using top water inlets to limit loss from the reservoirs in the event of pumped main leakage and placing inlet and outlet at opposite sides of the reservoir.

As a consequence, these storage assets can be hydraulically very inefficient, with large areas of tanks containing very slow moving or stagnant water making them unsuitable for use as contact tanks. However, if there is a dedicated main to the service reservoir without any consumer connections, this would provide effective contact time to be taken into account in the Ct calculations. In smaller schemes the practice of burying lengths coiled small diameter pipes downstream of dosing points is sometimes employed to provide contact time.

Computational Fluid Dynamics (CFD) analysis of such reservoirs particularly those with low length to width ratios show that short-circuiting of the flow occurs with subsequent formation of dead zones in the flow field which can have a detrimental impact on the quality of the water discharged to the distribution network. Increased length to width ratios and the inclusion of baffle walls in the design of such reservoirs can increase their efficacy for chlorination contact.

In addition, changes in operation which affect the ratio of inflows, outflows and operating levels can significantly change the flow profile through the tank. The shape of the diurnal curve of water demand can vary significantly between different supply areas because of differences in water use and local economies. These differences should be taken account of in determining the impact of such daily usage patterns on the effectiveness of service reservoirs for chlorine contact.

4.6.7 Mitigation of inadequate chlorination contact

A review of existing treatment and disinfection installations is required to determine if there is sufficient chlorine contact time to ensure that plants do not have:

- Incomplete chemical mixing;
- Inadequate contact tank size...etc

Poor chlorination contact times can result from:

- incomplete chemical mixing;
- inadequate contact tank size/configuration;
- inappropriate dosing points;
- the proximity of consumers to disinfection installation on pumped distribution networks;
- growing water demand pending implementation of water conservation and /or additional infrastructural investment.

The prompt provision of additional contact tankage by Water Service Authorities can also often be compromised or delayed by existing site constraints and the need for further land acquisition.

The rectification of obvious deficiencies in chemical dosing locations together with the achievement of proper disinfectant mixing using mechanical mixers, correct pH control and improving residual monitoring will all help to mitigate the risk to human health posed by insufficient chlorine contact.

In addition to the foregoing, the addition of an alternative oxidation technology (such as chlorine dioxide or ozone) or UV disinfection as a primary disinfection system, upstream of chlorination, can relieve the need to add the additional contact time and reduce the subsequent chlorine dose. In some instances a primary disinfection method such as a validated UV disinfection system may prove to be a more cost effective solution than the costs associated with a contact tank constructed in accordance with the best practice set out in Section 4.6.5 above.

4.7 Defining chlorine concentration (C)

Disinfection occurs from initial dosing and dispersion of chlorine at the inlet to a contact volume (e.g. contact tank or length of pipe) to the outlet. Three approaches can in principle be used for defining the value for C:

- the concentration can be estimated from the area under the chlorine decay curve in the tank;
- an average oxidant concentration can be derived from the arithmetic mean of the initial dose and the residual concentration;
- the outlet residual can be used to provide a conservative estimate of concentration.

The first of these is the most accurate estimate in relation to the effect of the chlorine, but not readily derived in practical situations. It can be shown that the arithmetic mean overestimates concentrations compared with the calculated decay values, whereas the residual underestimates the effective concentration. Free chlorine residual therefore provides a conservative value, which is also practical to monitor, and it is recommended that the free chlorine residual be used for control purposes.

4.8 Monitoring and control of chlorination

4.81 General

An appropriate regime for monitoring and control of chlorination is necessary to ensure that the desired chlorine dose and residual concentration match the target for Ct under defined conditions of flow, temperature and pH. At sites where these change slowly, manual adjustment of set points may be adequate to maintain a balance between cost of treatment, security and by-product formation.

Separate control of pH is often used, but, in the absence of this or as part of the control regime, alarms on pH should be set to avoid any impairment of chlorination performance with increasing pH. Where pH control is not used, the Ct could be automatically adjusted by increasing the residual in response to increasing pH (bearing in mind the implications for THM formation).

Other water quality parameters may need to be considered at some sites. On-line measurement of increasing chlorine demand may give early warning of an impending problem with achieving the target Ct. At sites, where turbidity can increase significantly, suitable alarms and/or control systems should be in place to prevent this impairing chlorination performance. This could involve automatic control of residual to increase Ct in response to increased turbidity, although the control required could be difficult to quantify in relation to turbidity.

As well as flow proportional control of chlorine dose, the effects of flow variation on the Ct and contact tank performance should also be considered. In principle, a change in flowrate to increase or decrease t could be accompanied by an inversely proportional change in chlorine residual (C) to maintain the target Ct. However, this may not be a viable approach for many works, where operation to a fixed chlorine residual would be more practical. The target residual should then maintain the desired Ct at the maximum design flow (i.e. minimum t), to provide greater security. If the flow profile at a works makes it preferable to define C for the average flow, it would be necessary to increase the residual concentration at times of higher flow to maintain the target Ct.

Additionally, there may be situations where the degree of short-circuiting and therefore effective contact time changes significantly with variation in throughput. Ideally this would be taken into account in controlling the residual concentration, by identifying the flow-specific effective t_x values. However, this could be difficult to achieve at some works, and the minimum effective contact time for the range of flow conditions should be used to establish the target residual concentration.

Validation of the monitoring and control regime will require routine checks on SCADA data that target residuals are being achieved, as well as frequent sampling for coliform analysis. At sites perceived as higher risk, weekly or monthly large volume samples (1 litre or more) can provide assurance that regulatory standards are being met with a high enough margin of safety

4.8.2 Principles of control systems

In practice there is a hierarchy in the sophistication of control of chlorine dosing for disinfection. While some sites may practice flow proportional dosing (i.e. to maintain a constant concentration of chlorine), the majority will have flow proportional dosing with automated feedback control of the residual based on a set-point entered by the operator as the free chlorine level he wishes to achieve.

Some sites provide automatic control of set-point based on the outlet residual - so called, cascade control. Wider experience of such control is that set-points do not need frequent adjustment and that automated adjustment can cause control instability unless systems are very carefully set-up.

Figure 4.11 shows the concept of “simple” and cascade feedback control based on duplicated measurements.

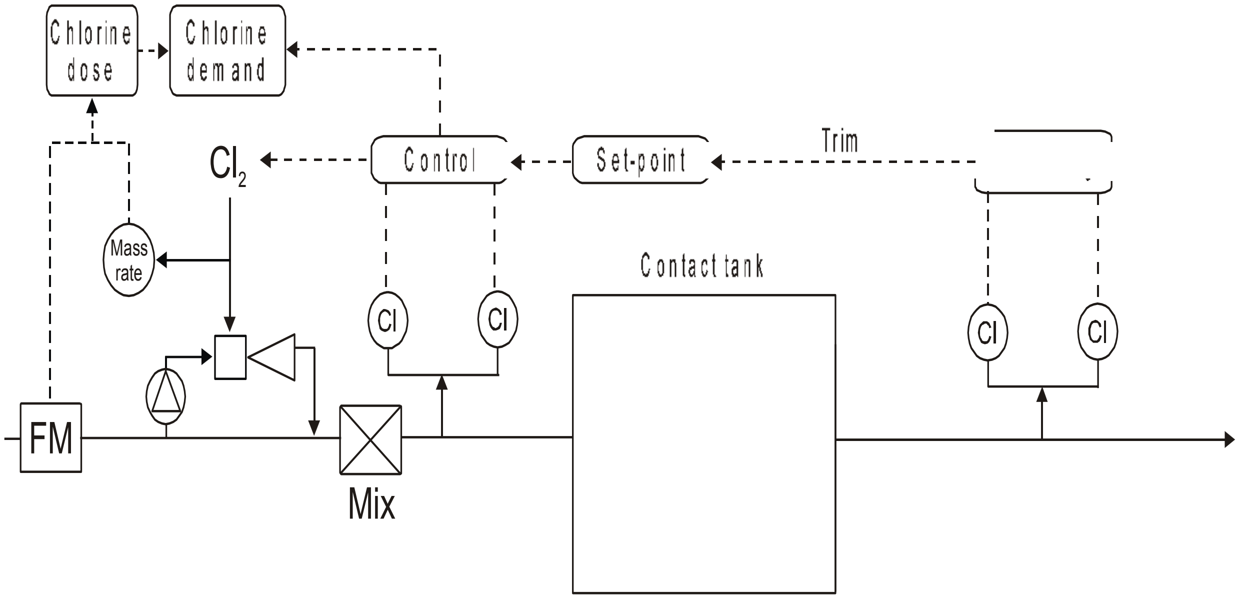


Figure 4.11 ***Schematic showing simple and cascade control of chlorine dosing prior to contact tank***

Further practical guidance on the calibration and maintenance of chlorine monitors is included in Appendix 2.6.

4.8.3 Multiple redundancy

The importance of ensuring effective disinfection requires a reliable control system.

The principle of redundancy (i.e. having more than one piece of equipment in place capable of performing some critical duty) has been widely adopted for the measurement of chlorine residual in chlorine dosing control loops.

While some international water utilities currently use triple redundancy for chlorine measurements, many are moving to dual redundancy on large schemes. The move from triple to dual redundancy is influenced by several factors:

- The reliability of sensors and their associated electronics has improved substantially, so the reduced likelihood of failure with three instruments compared with two for a given maintenance frequency is less significant;
- Three sensors require 50% more maintenance than two;
- Triple/dual redundancy only works where measurement systems are independent. Each system should have its own sample supply, power supply, buffer pump (if applicable) etc. In practice there are triplicated systems with, for example, a common power supply; duplicate buffer pumps. Another key risk of common mode failure is present where sample lines are shared. In this case neither dual nor triple redundancy offers protection against faults caused by the sampling system. One approach is to have a separate sample flow alarm to protect against this failure mode. All single sample lines on duplicated or triplicated instruments should include an alarm for loss of sample flow.

In summary, a properly designed dual redundancy system where risk of “common mode” failures has been minimised, is potentially much more reliable than a compromised triple redundancy system.

It is recommended that dual redundancy be employed for free chlorine monitoring following chlorination on schemes serving populations >5000 persons.

The decision to use dual redundancy chlorine monitors on smaller public schemes and private group schemes (supplies to <5000 persons) should be made by the water supplier based on a risk assessment to be undertaken in accordance with the Drinking Water Safety Plans (DWSP) approach which will take cognisance of the following:

- In the case of primary disinfection at treatment plants, the catchment, source and treatment risks upstream of the disinfection point should be assessed to determine the quality and variability of raw water quality and the capability of water treatment processes and instrumentation upstream of disinfection to consistently produce a treated water that can be effectively disinfected by the chlorination system and verified by adequate Ct in the scheme headworks;
- In the case of secondary or booster chlorination stations on distribution networks, the additional distribution system risks downstream of the disinfection point should be assessed.

Refer to Section 8 and Appendix 1.1 of the Manual for further guidance on Drinking Water Safety Plans and the catchment, source and treatment risks associated with the treatment and disinfection of drinking water.

4.8.4 Chlorine demand

Chlorine “demand” is the reduction in chlorine concentration that occurs due to reaction between chlorine and contaminants in the water. Part of the reduction will be almost instantaneous (e.g. reaction with ammonia), part will be gradual (e.g. reaction with natural organic matter). The instantaneous demand is the difference between the initial mass dose of chlorine and the subsequent measurement of chlorine residual immediately downstream.

On-line monitoring of both “instantaneous” and longer term demand (e.g. across a contact tank) is feasible using either existing measurements, or measurements that can be added at relatively low cost. Longer term demand (e.g. across the contact tank) simply requires comparison of the inlet and outlet residuals. Data averaging may be required due to the time lags involved and the variability in the inlet residual that is under feedback control. Implementation of “instantaneous” demand monitoring requires calculation of the mass rate of chlorine which is then divided by process flow. Mass rate of chlorine can be determined readily for chlorine gas and commercial hypochlorite, but is more difficult to determine for hypochlorite generated on site.

- Chlorine gas: can be estimated indirectly from position of the gas control valve (e.g. the “V notch” valve) or can in principle be determined directly from a suitable flowmeter.
- Commercial hypochlorite: can be determined from volumetric flowrate and analysis of chlorine content.
- Hypochlorite generated on site: this is a difficult application as chlorine content varies with the operating conditions at generation and decays relatively quickly unless storage conditions are optimised.

There are several possible causes of a marked change in chlorine demand: e.g. inaccuracy in chlorine measurement, loss of treatment efficiency, pollution of raw water. Proper implementation of demand monitoring against suitable upper (and lower) limits will increase security of disinfection, and can provide early warning of development of treatment problems and potential difficulties in maintaining the target Ct.

4.9 Organic chlorination by-products

4.9.1 General

Chlorination by-products arise as a result of using chlorine in the production of drinking water. They include organochlorine compounds formed by reaction between chlorine and organic matter in the water being treated, and inorganic by-products (e.g. bromate, chlorate and chlorite) which may arise during the production and storage of sodium hypochlorite. The formation of organochlorine compounds is not influenced by the initial source of chlorine (i.e. whether chlorine gas, sodium hypochlorite, calcium hypochlorite).

The principle concern with chlorination by-products is their potential health effect, although their impact on taste and odour may be a further consideration in some situations.

4.9.2 Organic by-products

To date the major organochlorine by-products of concern have been the four chlorinated compounds, known collectively as the trihalomethanes (THMs):

- bromoform (tribromomethane);
- dibromochloromethane;
- bromodichloromethane;
- chloroform (trichloromethane).

The current national Drinking Water Regulations SI 278 of 2007 implementing the EU Directive stipulates a maximum of 100 μg/l total THMs at the consumers tap, which is a widespread standard in individual member states.

The concentrations of THM compounds produced by chlorination are a function of pH, temperature, free chlorine concentration, contact time, and concentration and nature of oxidisable organic material in the water. For many situations where chlorine is used in distribution (rather than chloramination), the majority of THMs are formed in the distribution system. Generally, the approaches used to restrict THM production are:

i) Avoid chlorinating raw surface water and untreated groundwater susceptible to surface contamination , and treat the water in advance of chlorination to remove precursors (as indicated by colour, TOC, UV absorbance) as far as possible;

ii) Limit free chlorine concentrations and contact times to the minimum required for the process (and distribution systems);

iii) Dechlorinate as soon as possible after breakpoint chlorination;

iv) Use chloramination to provide a residual in disinfection;

v) Keep pH low as THM formation increases with pH increase;

vi) Consider the use of an alternative oxidant or UV for primary disinfection.

Whilst it is possible to remove THMs using air stripping, GAC or nanofiltration, this approach is costly compared with minimising formation, and is little used. The efficiency of TOC removal, the main precursor of disinfection by-product formation, is very much dependent on pH and alkalinity with optimal removal at a pH 6.5 or below.

US EPA Guidance on the Microbial and Disinfection By-product Rule recommends removal requirements when measured TOC levels are in excess of 2 mg/litre with various recommended removal efficiencies based on alkalinity.

Another group of organochlorine by-products of increasing concern in water supply are the haloacetic acids (HAAs). There is a total of nine possible HAAs that include chlorine and bromine, referred to as “HAA9”:

- Monochloroacetic acid, MCAA
- Dichloroacetic acid, DCAA
- Trichloroacetic acid, TCAA
- Monobromoacetic acid, MBAA
- Dibromoacetic acid, DBAA
- Tribromoacetic acid, TBAA
- Bromochloroacetic acid BCAA
- Dibromochloroacetic acid, DBCAA
- Dichlorobromoacetic acid, DCBAA

Considerations for restricting the production of HAAs are similar to those for THMs, except that HAA production *decreases* with increasing pH.

4.10 Inorganic chlorination by-products

4.10.1 Chlorate and chlorite

Chlorate and chlorite are produced from decay of commercial hypochlorite solution during storage. Bromate can be produced consequent to electrolytic generation of hypochlorite, either on site or during commercial production. In contrast, chlorine gas contributes no inorganic by-products of consequence.

WHO have set a provisional guideline value of 0.7 mg/l for both chlorate and chlorite based on health considerations. These guideline values are unlikely to present a problem for commercial hypochlorite, provided that the product meets the relevant European standard (see Section 4.13) and storage times and conditions are managed appropriately.

The current UK Regulations have a value of 0.7 mg/l for chlorate when OSE is used, but 0.5 mg/l for the sum of chlorine dioxide, chlorate and chlorite when chlorine dioxide is used. No limits for chlorate or chlorite are in place when commercial hypochlorite is used. The USEPA have a Maximum Contaminant Limit of 1.0 mg/l for chlorite, but only at treatment works using chlorine dioxide.

4.10.2 Bromate

Bromate in drinking water can result from the following:

- The presence of bromide in commercially produced sodium hypochlorite and the increased use of same instead of chlorine gas;
- The presence of bromide in the salt used for electrolysis to produce hypochlorite;
- Its production in ozonation processes where bromide is naturally present in the water.

WHO have set a provisional guideline value for bromate of 0.01 mg/l. This value (specified as 10 µg/l) is included in the EU Directive.

4.11 Dechlorination

4.11.1 General

The main role of dechlorination in water treatment is to allow high chlorine concentrations to be used to achieve disinfection, followed by a reduction in chlorine to a concentration suitable for distribution (superchlorination/dechlorination). In these situations, dechlorination is usually achieved though dosing of reducing chemicals such as sulphur dioxide, sodium thiosulphate or sodium bisulphite, to provide a high degree of control over the dechlorination process. Superchlorination/dechlorination in this context is rarely practiced in Ireland but may be a possible solution at disinfection installations where inadequate Ct exists downstream.

There may also be situations where dechlorination is needed before discharge of chlorinated water to the environment, or to protect downstream processes. Other less controllable dechlorination systems might then be used, such as activated carbon or aeration. UV can also provide dechlorination, and whilst it is unlikely to be installed solely for this purpose there may be situations where it is appropriate.

Chlorinated waters from potable water systems are released to the environment through activities such as water main flushing, disinfection of new mains, distribution system maintenance, water main breaks, filter backwash and other utility operations. Although chlorine protects humans from pathogens in water, it is highly toxic to aquatic species in receiving waters.

Although feed waters to membrane systems often have to be treated with chlorine to retard microbiological growth prior to the membrane separation process, chlorine can cause damage to more delicate treatment processes such as reverse osmosis (RO) membranes and deionization resin units. Similarly chlorine residual in water for use in haemodialysis and the food industry is not tolerated because of contamination and unwanted chemical reactions and its effect on the taste and smell of liquids. Consequently once residual chlorine has performed its oxidation, superchlorination or disinfection function, it may require to be removed, in order to satisfy some of the foregoing constraints on water use and disposal.

Dechlorination is commonly achieved using one (or more) of the following methods:

- Chemical removal of Chlorine;
- Aeration;
- Granular activated carbon (GAC) filter.

4.11.2 Chemical removal of chlorine

The most commonly used reducing agents for de-chlorination are sodium thiosulphate ($Na_2S_20_3$), although sodium sulphite (Na_2SO_3) and sodium bisulphite ($NaHSO_3$) are also used.

The choice of a particular dechlorination chemical is dictated by site-specific issues such as the nature of water release, strength of chlorine, volume of water release, and distance from receiving waters.

Sodium thiosulphate is the most commonly used chemical used for dechlorination since it is less hazardous and consumes less dissolved oxygen (DO) from the water than sodium bisulphite and sodium sulphite. Sodium bisulphite is used due to its lower cost and higher rate of dechlorination. Sodium sulphite tablets are chosen due to ease of storage and handling, and its ease of use for dechlorinating constant, low flow rate releases.

The dechlorination reaction with free or combined chlorine will generally occur within 15 to 20 seconds. The dechlorination chemical should be introduced at a point in the process where the hydraulic turbulence is adequate to assure thorough and complete mixing. If no such point exists, mechanical mixing should be provided.

4.11.3 Aeration

Aeration using bubble diffusers or aerated packed columns is the least effective means of dechlorination, with its effectiveness decreasing with increasing pH. This process is slow, especially when the initial chlorine concentrations are low and is not effective for removing chloramines from the water as the chlorine-ammonia bond is not broken by aeration.

4.11.4 Activated carbon (GAC)

Granular activated carbon (GAC) is a specialized filter media used principally for dechlorination or removal of organic compounds and colour from water.

Activated carbon removes free chlorine by adsorption. Free chlorine in the form of HOCl reacts with activated carbon to form an oxide on the carbon surface. Chloramines and chlorinated organics are adsorbed more slowly than free chlorine. Activated carbon (charcoal) filters remove both chlorine and chloramines effectively and has the added benefit of removing chemicals and other contaminants that may be present at low concentrations.

The efficacy of dechlorination process is dependent on such factors as influent chlorine concentration, pH, the empty bed contact time (EBCT) utilised, and the presence, or otherwise, of dissolved organic species which may reduce the carbon's effectiveness for dechlorination. Generally, EBCT's of 5 - 10 minutes are utilised for chlorine removal. Carbon filtration reduces total dissolved organic carbon concentrations by up to 65% and various halogenated compound by 97–100% though the removal rate should be determined by pilot tests.

The activated carbon media, once spent, can be re-activated with high pressure steam. This leaves the carbon with numerous minute spores or binding sites on its surface. As an aside, the higher the specific surface area of the media (or the smaller the media particles), the more binding sides there will be for a given mass. Contaminant molecules in the water supply travel into the pores and are trapped there. The media does not become exhausted by the chlorine, but rather by other contaminants present in the water. Eventually all the pores become filled and the activated carbon needs to be changed or re-activated. The frequency of changing will depend on the type and concentration of the contaminants in the water supply. During service, frequent backwashing of the GAC filter media to remove particulates that accumulates on the surface of the carbon has a positive effect on both filtration efficiency and dechlorination efficiency

4.11.5 UV irradiation

UV is not widely used as a primary de-chlorination process, but it is growing in acceptance.

Medium-pressure UV systems reduce both free chlorine and combined chlorine compounds (chloramines) into easily removed byproducts. Between the wavelengths 180 and 400 nm, UV light produces photochemical reactions that dissociate free chlorine to form hydrochloric acid. The peak wavelengths for dissociation of free chlorine range from 180 to 200 nm, while the peak wavelengths for dissociation of chloramines (mono-chloramine, di-chloramine and tri-chloramine) range from 245 to 365 nm. Up to 5 parts per million (ppm) of chloramines can be successfully destroyed in a single pass through a UV reactor, and up to 15 ppm of free chlorine can be removed.

The UV dosage required for dechlorination depends on total chlorine level, ratio of free versus combined chlorine, background level of organics and target reduction concentrations. The usual dose for removal of free chlorine is 15 to 30 times higher than the normal disinfection dose. The use of UV dechlorination ahead of membranes results in them staying cleaner longer because the dose for dechlorination is so much higher than the normal UV dose used for disinfection if dechlorination was not the goal.

In practice the required UV dose is affected by a number of parameters making it more difficult for the designer to optimize a solution. These other factors include:

- the UV transmittance (UVT) of the water (high concentrations of chlorine will actually lower the UVT)
- the presence or lack of other chemicals, particularly organics, in the water.

When used to dechlorinate water with poor UV transmittance, medium pressure UV light can cause algal growth inside pipelines. This is caused by the system geometry permitting long-wavelength light to travel extended distances. As the penetration depth increases, all of the germicidal light will be absorbed by the fluid, leaving visible light that stimulates algal growth. This problem can be overcome by modifying the chamber geometry to prevent the passage of long wavelength visible light out of the reactor.

4.12 Standards for chlorine chemicals

Chemicals used in the production of potable water must meet the European standard relevant to that chemical. In the case of chlorination chemicals, the key standards are those for chlorine gas, sodium hypochlorite and sodium chloride for use in on-site generation of hypochlorite.

Table 4.5 below summarises the maximum concentration of inorganic by-product added per mg/l dose of chlorine equivalent, based on the assumption that the chemical just meets the relevant standard. Some contaminants are not of significance to the chlorine chemical, thus in the case of chlorine gas, the chlorate, chlorite or bromate content is negligible, and no limits are set for these species.

Table 4.5 Chlorination chemical standards: limits for chlorite, chlorate and bromate

Contaminant	**Maximum contaminant per mg Cl_2 dosed**		
	Chlorine gas ***IS EN 937: 1999**	**Commercial Sodium Hypochlorite** ***IS EN 901:2007**	**Sodium Hypochlorite from OSE** ***IS EN 14805:2008 (salt)**
Chlorite	Insignificant	Insignificant	Insignificant
Chlorate	Insignificant	0.042 mg	Insignificant
Bromate	Insignificant	2.5 to 5 µg	**1.2 to 2.4 µg

* IS EN = European standard incorporated into Irish standards, where a range is given this relates to the different product specifications allowable under the standard.

** Bromate by-product in On-Site Electrochlorination hypochlorite has been determined by assuming 3.5 kg salt per kg Cl_2 and that all bromide in salt is oxidised to bromate.

4.13 Managing chlorination within a risk based approach

The development and implementation of DWSPs would benefit from a structured way of identifying an appropriate chlorination Ct, taking into account the design of the system, and ways of maintaining a suitable Ct, allowing for variation in feed water temperature, quality and flowrate. An approach for this is illustrated in Figure 4.12

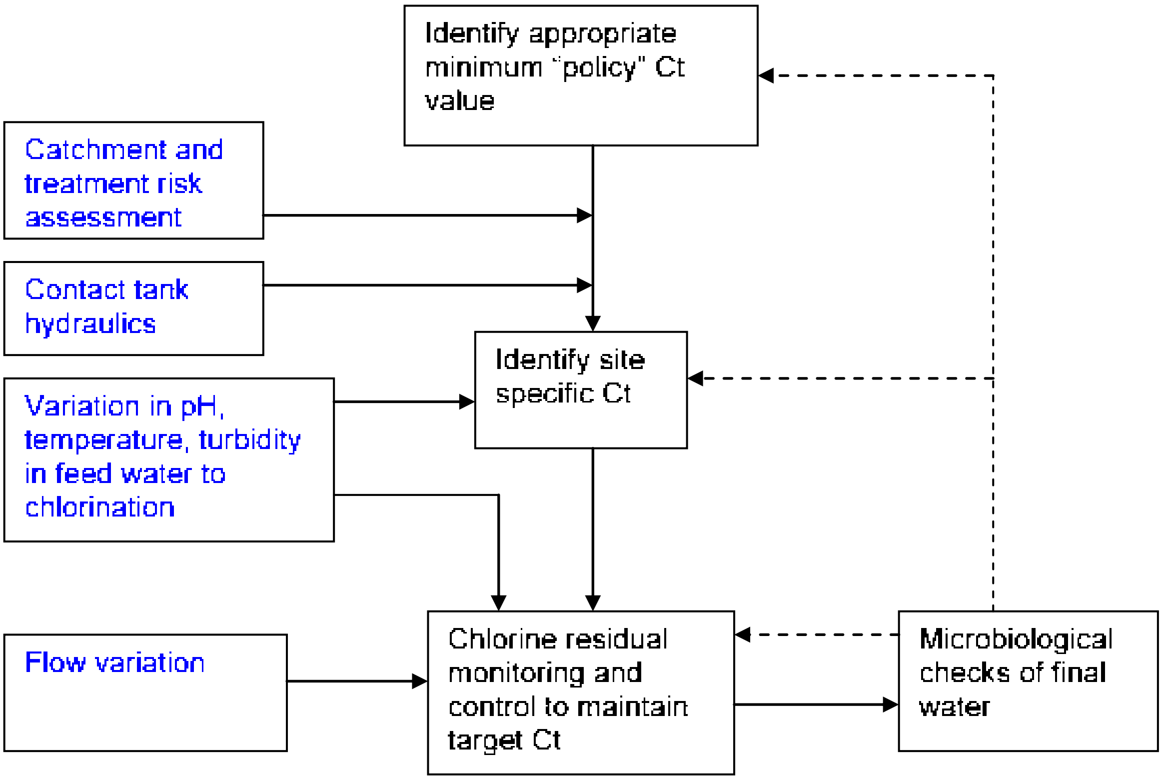


Figure 4.12 Approach for implementing and maintaining chlorination conditions

4.13.1 Identifying a minimum "policy" Ct value

Identification of a Ct policy could be based on specified pathogens of concern, and treatment policy for removal of pathogens less susceptible to chlorination. Where an existing Ct policy has been in place for an extended period and is believed to be generally appropriate and reliable, there may be no need to alter this, provided that a site-specific review of its suitability is carried out. In some cases there may be scope to reduce the Ct.

In the absence of an existing policy, the WHO recommendation for a Ct of 15 mg.min/l, based on the Ct data for bacteria and viruses shown in Table 4.3, is recommended to provide a secure target even at lowest water temperature, particularly if a Ct is used with adjustment for pH and turbidity less than 0.5 NTU. Furthermore, because the residual after the contact tank is used as the basis for control, for most waters the real Ct will be significantly higher than this because of the higher dose to allow for chlorine decay during contact.

Alternatively, Ct values could be derived using *Coxsackie* A2 virus as a suitable, relatively resistant, target micro-organism. Policy would also need to define the effective contact time, as described in Section 4.7 (i.e. t_x value) and the point where chlorine concentration is controlled to provide the desired C value (normally at the contact tank outlet).

There will be a minimum contact time and, more significantly, chlorine concentration below which disinfection will be seriously impaired, and the Ct concept will no longer apply. This will vary from one micro-organism to another, and is likely to be more significant for the more resistant species. For water treatment applications, this is unlikely to be a significant practical consideration for most sites, because of the constraints already in place in relation to contact times and residual control systems.

4.13.2 Site-specific Ct

Identification of a suitable site-specific Ct values may need to take into account:

- The raw water quality and the pathogens to be targeted over the year including extreme conditions;
- The extent and performance of treatment prior to final disinfection;
- The design of the contact tank, particularly in relation to short-circuiting;
- Expected variations in temperature and pH.

The design of the contact tank needs to be evaluated either with tracer tests or through CFD modelling, so that appropriate contact times can be identified for deriving the Ct (see Section 4.7). This should take into account the range of flowrates experienced at the works, because the degree of short-circuiting may vary with the throughput. Recommendations for tracer tests are provided in Section 4.7.

For the majority of works, pH of the water reaching final chlorination is unlikely to vary significantly. However, if variation is expected, the Ct should be specified for defined pH conditions, and controlled accordingly. For many surface water treatment works, wide variations in water temperature can be expected, with lowest temperatures often occurring at times when the treatment challenge is greatest and treatment performance has greatest risk of impairment i.e. poor raw water quality during winter periods combined with reduced efficiency of coagulation at low water temperature. Derivation of site-specific Ct values should take these risk factors into account. Refer to Appendix 2.1 “Practical Guidance for Plant Operators on Measures to ensure the security and verification of Chlorinated Water Supplies” for further guidance tools on the estimation of site-specific Ct values.

Allowance for the effects of temperature and pH could be based on the proportion of $HOCl$ present, (Section 4.4), assuming that only $HOCl$ has a significant disinfection effect, (although this may be an excessively conservative approach). For example at pH 7.5, the proportion of $HOCl$ is 50%, so the chlorine concentration would have to be doubled to provide the required C value, neglecting any benefit from OCl^-. Based on the USEPA guidance for Giardia inactivation, in the pH range 6.5 to 8.5 each pH increase of 0.5 units requires a Ct increase of roughly 20%. This probably provides a good compromise for practical application.

Generally, for temperatures around ambient, the rate of reaction doubles for each increase by 10°C. This can be observed in the data for free (available) chlorine inactivation of *Giardia* and viruses (Table 4.6). Therefore, Ct values might be adjusted if needed to take account of seasonal variations in the temperature of surface sources of water, so that an equivalent degree of inactivation is achieved.

Table 4.6 Effect of temperature on Ct requirements for inactivation by free (available) chlorine

Removal (log$_{10}$)	***Giardia***			**Viruses$^{(a)}$**		
	<1 °C	**10 °C**	**20 °C**	**<1 °C**	**10 °C**	**20 °C**
0.5	40	21	10	*	*	*
1.0	79	42	21	*	*	*
2.0	158	83	41	6	3	1
3.0	237	125	62	9	4	2

* data not available (a) based on data for inactivation of Hepatitis A virus (HAV). Source: US EPA (2005)

4.13.3 Monitoring, control and verification of chlorination systems

Principles of chlorination monitoring and control are discussed in Section 4.9. These should be applied to maintain the desired dose and residual concentrations to maintain the target Ct under defined conditions of flow, temperature and pH. For sites where changes in these will occur slowly, manual adjustment of set points may be adequate to maintain a balance between cost of treatment, security and by-product formation.

The main control of chlorine dose is by way of feedback of chlorine residual concentration measured by continuous residual monitoring.

Where pH fluctuations are expected, including plants where pH correction is used, alarms on pH should be set to avoid any impairment of chlorination performance with increasing pH. Where pH control is not used, the Ct could be automatically adjusted by increasing the residual in response to increasing pH (bearing in mind the implications for THM formation).

Other water quality parameters may need to be considered at some sites. On-line measurement of increasing chlorine demand may give early warning of an impending problem with achieving the target Ct. At sites where turbidity can increase significantly, suitable alarms and/or control systems should be in place to prevent this impairing chlorination performance. This could involve automatic control of residual to increase Ct in response to increased turbidity, although the control required could be difficult to quantify in relation to turbidity.

As well as flow proportional control of chlorine dose, the effects of flow variation on the Ct and contact tank performance should also be considered. In principle, a change in flowrate to increase or decrease t could be accompanied by an inversely proportional change in chlorine residual (C) to maintain the target Ct. However, this may not be a viable approach for many works, where operation to a fixed chlorine residual would be more practical. The target residual should then maintain the desired Ct at the maximum design flow (i.e. minimum t), to provide a greatest security. If the flow profile at a works makes it preferable to define C for the average flow, it would be necessary to increase the residual concentration at times of higher flow to maintain the target Ct.

Additionally, there may be situations where the degree of short-circuiting and therefore effective contact time changes significantly with variation in throughput. Ideally this would be taken into account in controlling the residual concentration, by identifying the flow-specific effective t_x values. However, this could be difficult to achieve at some works, and the minimum effective contact time for the range of flow conditions should be used to establish the target residual concentration.

Validation of the monitoring and control regime will require routine checks on SCADA data that target residuals are being achieved, as well as frequent sampling for coliform analysis. At sites perceived as higher risk, weekly or monthly large volume samples (1 litre or more) can provide assurance that regulatory standards are being met with a high enough margin of safety.

4.13.4 Recommendations for establishing and maintaining Ct (primary disinfection)

- Identify a generic “policy” Ct, and minimum free chlorine residual and contact time. Define the pH, turbidity and temperature range for this Ct e.g. 15mg.min/l at pH of 7.5 or less, temperature above 10°C and turbidity of less than 0.5 NTU.
- Modify the policy Ct for site-specific application if needed, taking into account catchment risk and treatment upstream of chlorination. For example a lower Ct could be applied for membrane treatment, or if ozonation or UV are included in the treatment stream.
- Evaluate hydraulics of the contact tank to establish effective contact time based on a policy t_x value for the appropriate range of flows. A t_{10} value or better should be used. As far as possible, make allowance for any changes in hydraulics related to flowrate (identify flow-specific t_x values) or depth of water if this can vary.
- Identify if the control system would allow variation in residual with flowrate to maintain the target Ct over the range of flows. If not, define whether the site-specific residual relates to average or maximum design flow and the associated effective contact times. If applicable to less than the maximum flow, provide a control system or guidance to operators to increase the chlorine residual at higher flows.
- If pH is not controlled, provide a control system or guidance to operators to increase the chlorine residual for higher pH e.g. a 20% increase in residual for every 0.5 increase above pH 7.5.
- Provide a control system or guidance to operators to increase the chlorine residual for lower water temperature e.g. a 20% increase in residual for temperatures in the range 5-10°C, and 50% increase for temperatures below 5°C, depending on how the policy Ct is derived initially.
- Provide a control system or guidance to operators to increase the chlorine residual for higher turbidity e.g. 30% increase for turbidity in the range 0.5 to 1 NTU.

4.13.5 Recommendations for the maintenance of chlorine residuals in distribution networks

A free chlorine residual in piped distribution networks is required to quality assure the continued microbiological quality of treated drinking water as it passes through distribution pipework to the point of compliance under current Drinking Water Regulations (i.e the consumer tap) following verification of primary disinfection, using:

- Ct values appropriate to the primary chemical disinfectant used;
- Appropriate other verification methods associated with non-chemical primary disinfection technologies.

This free chlorine residual in distribution can be as result of the residual remaining following verification of chlorination as part of a primary disinfection system or following secondary booster chlorination at an appropriate point(s) in the distribution network. The dose rate will be determined by chlorine residual decay across a given pipe distribution network which is site specific to headworks storage volumes, physical characteristics of the network, the water age within the network and the efficacy of periodic mains scouring carried out. The dose rate required to manage this chlorine decay and the resultant chlorine residual at the first consumer following chlorination has to be balanced against the perceived chlorinous taste and odour by consumers Most individuals are able to taste or smell chlorine in drinking-water at concentrations well below the maximum 5 mg/l, and some at levels as low as 0.3 mg/l.

Water Services Authorities and private water suppliers should ensure that there is **at least 0.1 mg/l free residual chlorine is present at the extremities of the distribution network** where residual chlorine levels are likely to be at their lowest.

4.14 Advantages and limitations of chlorination as a disinfectant

Chlorination can be used as:

- an oxidant within a treatment process for removal of soluble iron, manganese, and hydrogen sulfides, taste and odor control, prevention of algal growths and improving coagulation and colour removal in water treatment.

but is most often employed as:

- a primary disinfectant (on good quality groundwater and post filtration in a treatment process);
- a secondary disinfectant (in distribution systems to maintain a free chlorine residual and prevent regrowth in the subsequent distribution system).

As the foregoing uses involve the dosage of both chlorine gas and hypochlorite solution to waters of varying quality using a large range of dosages applied through a large range of distribution network sizes, some of the following advantages and limitations may not apply universally to all networks which are chlorinated.

4.14.1 Advantages

- Chlorination is an extremely effective disinfectant for the inactivation of bacteria and viruses;
- Its primary advantage is the production of a residual for the maintenance of water quality in distribution systems;
- It Is the easiest and least expensive disinfection method, regardless of distribution system size;
- The technology for chlorination is well developed as it is the most widely used and best known disinfection method;
- Chlorine is available as calcium and sodium hypochlorite whose solutions are more advantageous for smaller systems than chlorine gas and are consequently safer and require less complex equipment and instrumentation compared to chlorine gas;
- Although sodium hypochlorite is being increasingly generated on site using the OSE process all commonly used chlorination chemicals are relatively stable compounds which can be manufactured off site, imported and stored for use on site.

4.14.2 Limitations

- *Cryptosporidium* and other protozoan waterborne pathogens are highly resistant to chlorination;
- Chlorination is less effective as a disinfectant at high pH due to the predominance of the hypochlorite ion over hypochlorous acid;
- When added to the water, free chlorine reacts with natural organic matter (NOM) and bromide in the water to form disinfection by-products, (primarily THMs and some haloacetic acids (HAAs));

- Because chlorine in either gaseous or hypochlorite solution form are hazardous and extremely corrosive, special storage and health and safety considerations regarding handling of these chemicals have to considered in the design of treatment plants and disinfection installations and in the framing of emergency response plans. Chlorine gas requires special leak containment measures and associated sensors and air handling/scrubber facilities. In the case of hypochlorite solutions, their separate containment is necessary to prevent cross-containment with acids and the consequent release of chlorine gas;
- Depending on the water quality to be treated and the required dosage rates to be applied drinking water can have taste and odour problems, the perception of which can vary among consumers;
- Sodium hypochlorite degrades over time and with exposure to light resulting in the formation of chlorate as a byproduct;
- Sodium and calcium hypochlorite are more expensive than chlorine gas;
- Calcium hypochlorite in solid must be stored in a cool, dry place because of its reaction with moisture and heat. It also forms a precipitate following mixing with water due to additives mixed with the chemical.

4.15 Chloramination

4.15.1 Chemistry

The chemistry of the formation of combined chlorine has been described in Section 4.4.3 in the context of processes where ammonia that is naturally present is completely oxidised to nitrogen.

In the case of chloramination, ammonia and chlorine are dosed in a controlled manner such that monochloramine (NH_2Cl) is the primary product of the on-site generation process:

$$NH_3 + HOCl \rightarrow H_2Cl + H_2O$$

The process of chloramination is dependent on both the pH of the water and the relative concentration ratio of the ammonia added to the preceding chlorine dose.

Figure 4.13 below sets out the effect of varying pH on the distribution of chloramine species formed in water. Other than having a direct effect on the relative proportions of chloramine species pH has no direct effect on the efficacy of the chloramination disinfection

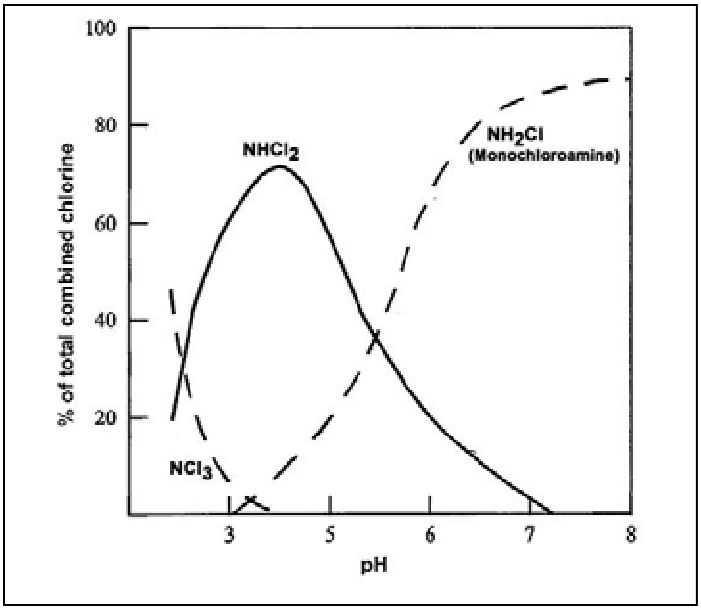


Figure 4.13. Distribution of chloramine formation with varying pH
(based on chlorine ammonia ratio of 5:1; Temp 20°C ; Contact time of 2 hours

The rate of monochloramine formation in water is also a function of pH formation with optimum formation established at a pH of 8.3.

Water pH levels below 7.5 or chlorine to ammonia ratios exceeding 5:1 increase the formation of dichloramine ($NHCl_2$) and Trichloramine (NCl_3), which both have strong chlorine tastes, when they exceed concentrations of 0.8 mg/L and 0.02 mg/L (respectively).

Excessive chlorine levels produce THMs, while excess ammonia increases the potential for nitrification in the distribution system.

4.15.2 Ammonia dosing systems

Ammonia for use in chloramination processes is generally obtained from one of the following:

- Anhydrous ammonia gas
- Commercially available solutions of:
  - ammonium chloride;
  - ammonium sulphate.

Selection will generally be based on consideration of economics and safety. For the largest systems, ammonia gas has least cost but represents the greatest chemical hazard.

Anhydrous ammonia is supplied in pressurised tanks and requires similar dosing equipment to that used for chlorine gas chlorination. Anhydrous ammonia is fed to the process using an ammoniator; a self contained unit with pressure regulating valve, gas flow meter feed rate control valve and piping to control the flow of ammonia to the process. Anti-siphon or check valves should be used to prevent the backflow of water to the ammoniator.

Similarly the dosing of liquid ammonia chemicals used installation similar to the dosing of sodium hypochlorite. Structurally robust fibre reinforced plastic and stainless steel tanks are compatible materials for storage tanks with good mixing downstream of ammonia addition vital to prevent the formation of dichloramine and trichloroamine.

Dosing pumps should be diaphragm metering pumps fitted with pulsation dampers and pressure relief valve and back pressure valves at the dosing points.

4.15.3 Disinfection performance of the chloramination process

As monochloramine is less effective as a disinfectant than chlorine (200 times less effective), high Ct values are required for its use a primary disinfectant. At 10°C, the USEPA cites Ct values of 1850 mg.min/l and 1491mg.min/l for 3-log inactivation of Giardia and 4-log inactivation of viruses respectively.

It is however an attractive alternative to chlorination as a secondary disinfectant in some instances since it does not react as readily with organic materials to form THMs while leaving a measurable residual in the distribution system which is more stable and long lasting than chlorine.

The USEPA has set minimum and maximum residual levels of 0.4 and 4.0mg/l for chloramine dosing, measured as Cl_2, The upper limit is based on the maximum dose level on the theoretical breakpoint curve below which monochloramine is the primary chloramine formed. Below this maximum 4.0mg/l level there is no known or expected risk to human health

For new works, as an initial guide, the residual value for monochloramine leaving the treatment works should be the same as would be applied for free chlorine for properly treated water. Like chlorine, residual doses of monochloramines leaving a treatment plant depend on the size of the distribution network with dosage rates typically less than 2 mg/l. Monochloramine residuals persist in distribution systems for longer than free chlorine residuals.

There are no circumstances where the dose of monochloramine should be substantially greater than the existing free chlorine concentration.

4.15.4 Practicalities of implementation

Where chloramination is considered justified, there are a number of issues to consider at the planning stage prior to its use as a secondary disinfectant in place of chlorination.

a) *Informing stakeholders*

There will be a need to inform stakeholders before changing disinfectant.

It is inevitable that chloraminated and chlorinated water will mix when chloramination is introduced. It is not possible to negate the effect of such mixing, and tastes and odours may occur. It is important that all customers, and the customer service department, are informed of the change so that customer complaints/queries can be minimised and dealt with efficiently.

As with free chlorine, chloramines are toxic to some species. Chloramine can cause problems because it is more stable and persists for longer. One example, is where fish keepers may remove free chlorine by allowing water to stand and fish deaths result after a changeover to the longer lasting chloramine.

Health authorities would need to be informed because of the possible implications for kidney dialysis water treatment systems. These systems use activated carbon to remove free chlorine. It should be borne in mind that a greater contact time with the carbon is required for chloramine.

b) *Monitoring quality change*

It is important that a programme of monitoring is in place to ensure that should introduction of chloramination result in deterioration then action can be taken immediately. Good practice would be to introduce additional monitoring in the weeks before, during and after chloramination is implemented. Such monitoring might include, for example: THMs, heterotrophic plate counts, ammonium and nitrite, as well as chloramine. Such monitoring will assist detection of possible problems as well as highlighting benefits.

As chloramine displaces chlorinated water, during initial implementation, any booster chlorination stations will need to be turned off. This needs to coincide with the arrival of water that contains sufficient chloramine to ensure that the system is not without disinfectant for an unacceptable period.

4.15.3 Monitoring and control

Setting up the monitoring and control requirements for a chloramination process, particularly when this is being done for the first time, requires careful attention to a number of key issues. The following is an overview of these issues.

a) *Monitoring and control*

The chloramination process involves dosing of ammonia in accurate proportion to free chlorine. A range of control options can be applied to the control of this process.

In the most basic system the ratio between chlorine dose (or residual) and ammonia is automatically controlled to a set-point. Figure 4.14 shows an example of a control system that might be used for chloramination after a contact tank. The chlorine residual after the tank is used to control the ammonia dose. For greater security, particularly in systems that use a solution of ammonia salt, additional downstream monitoring of ammonia is used to trim the dose. For the greatest security, downstream free chlorine is also monitored.

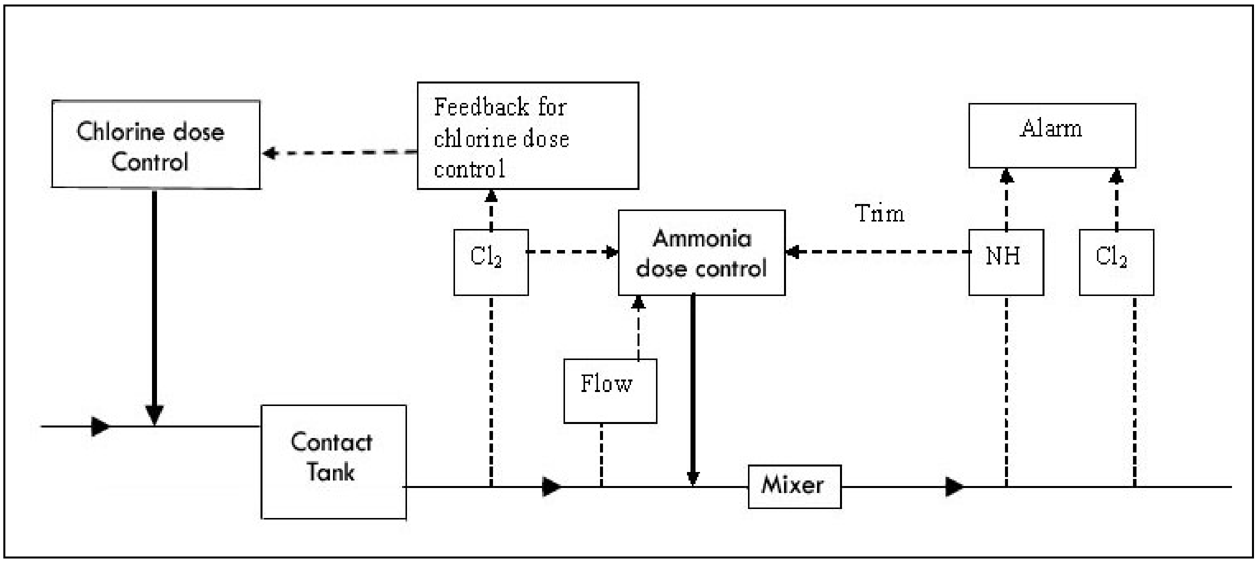


Figure 4.14 **Example of chloramination control**

b) *Selection of ratio of chlorine to ammonia-N*

The standard, textbook approach to the selection of the ratio of chlorine to ammonia is based on the breakpoint curve and would suggest a ratio of 5:1 (chlorine as Cl_2: ammonia-N) by weight. Systems should therefore be designed to provide a ratio of 5:1 but it is recommended that the system is started up at a ratio of 4.5:1 by weight. There are good reasons for operating below the 5:1 ratio, as the presence of a small amount of free ammonia is found to increase the stability of the monochloramine.

The free ammonia and free chlorine should be measured and the ammonia dose adjusted to provide a trace (approximately 0.02 mg/l as NH_3) of free ammonia in the water. There is no reason why the dose should be less than 4:1.

4.15.4 Advantages of chloramination as a secondary disinfectant

- Chloramines are not as reactive with organic material as free chlorine and consequently form lower disinfection by-products;
- A monochloramine residual is more stable and persistent in the distribution system than chlorine and chlorine dioxide;
- Monochloramine has been shown to be effective against the formation of biofilms in distribution networks;
- If the dose rates of chlorine and ammonia is properly controlled, chloramines can lessen chlorinous taste and odour concerns by not interacting as readily with organic compounds.

4.15.5 Limitations of chloramination

- Chloramines must be manufactured on site;
- The disinfection capability of chloramines is much less than for other methods of disinfection;
- Distribution system should be risk assessed before supply with chloraminated water with respect to patients undergoing dialysis, aquariums and fish farming enterprises;
- Chloramines do not oxidize iron or manganese in water;
- Risk of chlorinous taste and odour formation.

The chemistry of chloramination is not straightforward, as it is for chlorination. The process for generating chloramine requires accurate control at the treatment works to ensure that the desired product (monochloramine) is formed and not dichloramine or trichloramine. Overall experience is that this risk is very small for control systems that are well designed and operated.

There is also a risk in networks which are not single source and where chloraminated and chlorinated water can blend in unsuitable proportions. There is a risk that the disinfection residual will be reduced and/or dichloramine may be formed which has a strong chlorine taste.

- Nitrification due to excess ammonia in the distribution network

  Chloramination is achieved through a controlled reaction between chlorine and ammonia. Under ideal conditions all of the ammonia can react but it is more usual that small concentrations of ammonia are present after chloramination. Additionally the combined chlorine can decay releasing free ammonia. Whilst free ammonia is subject to regulation, the main concern relates to nitrite, which is subject to tighter regulation. Ammonia can be converted to nitrite by naturally occurring bacteria that are harmless to human health. This process is known as nitrification, and in extreme cases can lead to marked depletion of oxygen, but generally the issue is the concentration of nitrite. Nitrate can also be formed but, generally, not at concentrations of concern. Originally exceedance of the regulatory limit for nitrite was one of the major barriers to wider application of chloramination. A past revision of the Water Quality Regulations increased the allowable concentration of nitrite at the tap from 0.1 to 0.50 mg/l NO_2, and this has made chloramination more favourable.

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5 OZONE

5.1 Properties of ozone

Ozone (O_3) is a very powerful oxidising agent which is in widespread use in water treatment, particularly in continental Europe and in more recent years in Ireland as both a treatment oxidant and as a primary disinfectant.

It is an unstable gas which has to be generated as required on site. It is a more effective bactericide and virucide than chlorine; effective against *Giardia*; and the most effective of all the chemical disinfectants used in water treatment against *Cryptosporidium*. It decays more rapidly than other disinfectants, so does not maintain a persistent residual. Ozone can only be used as a primary disinfectant and should be coupled with a secondary disinfectant for a complete disinfection system for generation of a verifiable residual in distribution networks.

Ozone is a toxic, bluish, unstable, potentially explosive gas and is a hazard to plants and animals (Braker and Mossman, 1980). Ozone produces an irritation of the nasal passages in low concentrations. The 8-hour Occupational Exposure Limit (NAOSH, 1994) for ozone is 0.2 mg/m^3, the 15 minute OEL is 0.6 mg/m^3, much lower than those for chlorine, and its odour perception threshold is less than 0.02 mg/m^3. Ozone leak detectors should be installed to give audible/visible warnings and shut down the generators in the event of a leak.

The gas is highly corrosive in the presence of moisture; hence piping and other equipment must be constructed of resistant materials.

5.2 Applications of ozone

In addition to its use for primary disinfection of drinking water supplies, ozone is also used for several other purposes:

- Oxidation of iron and manganese
- Enhancing flocculation
- Improving removal of algae
- The oxidation of colloidal organic compounds for colour removal and the reduction in levels of organic carbon as subsequent chlorination DBP precursors
- The oxidation of trace organic compounds, including other micropollutants compounds that produce taste and odour, phenolic compounds and some pesticides
- Biological stabilisation (in conjunction with GAC)

When ozone is dosed, oxygenation will occur to some extent, depending on the existing dissolved oxygen concentration and contactor characteristics, so some improvement in organoleptic quality may be discerned.

The key variables that determine ozone's effect in the oxidation of DBP precursors, prior to chlorination, are dose, transfer efficiency, pH, alkalinity, pressure, contact time and the nature of the organic material. At low pH levels, precursor destruction is quite effective; above some critical pH, ozone is less effective, and sometimes increases the amount of chlorination by-product precursors. For most humic substances this critical pH is 7.5, which is about the level at which decomposition of ozone to hydroxyl free radicals increases rapidly, thus increasing organic oxidation rates.

Higher alkalinities help reduce THM formation potential (THMFP). This is because alkalinity scavenges any hydroxyl free radicals formed during ozonation, leaving molecular ozone as the sole oxidant, which has a lower oxidation potential than the hydroxyl free radical. Given neutral pH and moderate levels of bicarbonate alkalinity, THMFP level reductions of 3 - 20 percent have been shown at ozone doses ranging from 0.2 to 1.6 mg ozone per mg carbon.

It is important when considering ozonation that the objectives for doing so are clear, because the optimum dose and contact time, and the most appropriate location in the treatment train and contactor configuration, all depend on the treatment objective.

Parallel reactions will occur, so a single ozonation stage may achieve more than one treatment objective, but problems may arise if inappropriate combinations of objectives are attempted. So, pesticide removal may occur across a bubble diffuser ozone contactor installed for disinfection; but if there is manganese present the diffusers – and possibly downstream GAC - may become clogged with precipitated manganese.

5.3 Disinfection performance

Ozone requires less contact time and lower concentrations than chlorine, chlorine dioxide and chloramines to achieve disinfection, but its instability and reactivity means that it is unable to provide an enduring disinfection residual in distribution. The stability of ozone decreases with increasing pH and temperature. At 15°C and a pH of 7.6 the lifetime of the residual is reported to be in the order of 40 minutes, but at higher temperatures it can be as low as 10 - 20 minutes. This occurs due to a decrease in the efficiency of transfer of ozone into water as temperature increases.

Dissolved ozone can react directly or indirectly with the water into which it is dosed. Direct reactions occur with the ozone molecule. Indirect reactions occur with hydroxyl radicals that are formed when molecular ozone decomposes in water. In practice, reactions by both mechanisms are likely to occur in parallel, with the prevailing water quality influencing the extent to which hydroxyl radicals are formed.

Published Ct values for ozone are given in Tables 5.1 to 5.3.

Table 5.1 Ct values (mg.min/l) for inactivation of *Giardia* cysts by ozone, pH 6-9,

Log Inactivation,	**Temperature, °C**				
	≤1	**5**	**10**	**15**	**20**
0.5	0.48	0.32	0.23	0.16	0.12
1.0	0.97	0.63	0.48	0.32	0.24
2.0	1.90	1.30	0.95	0.63	0.48
3.0	2.90	1.90	1.43	0.95	0.72

Source: USEPA, 1999a

Table 5.2 Ct values (mg.min/l) for inactivation of viruses by ozone, pH 6-9,

Log Inactivation,	**Temperature, °C**				
	≤1	**5**	**10**	**15**	**20**
2.0	0.90	0.60	0.50	0.30	0.25
3.0	1.40	0.90	0.80	0.50	0.40
4.0	1.80	1.20	1.00	0.60	0.50

Source: USEPA, 1999a

Table 5.3 Ct values (mg.min/l) for inactivation of *Cryptosporidium* oocysts by ozone,

Log Inactivation,	**Temperature, °C**				
	≤1	**5**	**10**	**15**	**20**
0.5	12	7.9	4.9	3.1	2.0
1.0	24	16	9.9	6.2	3.9
2.0	48	32	20	12	7.8
3.0	72	47	30	19	12

Source: Federal Register, 2006 and WHO Guidelines for Drinking Water Quality - *Cryptosporidium*. 2006

WHO (2008) give a Ct for 2 log removal of bacteria of 0.02 mg.min/l at 5°C, pH 6-7; and for 2 log removal of *Cryptosporidium*, 40 mg.min/l at 1°C and 4.4 mg.min/l at 22°C.

Hydroxyl radical reactions tend to have higher reaction rates, which has given rise to processes which promote the formation of hydroxyl radicals (and, as a consequence, accelerate ozone decay), for example by applying ozone in combination with hydrogen peroxide or UV irradiation (such combination processes are referred to as advanced oxidation processes, (AOPs). For primary disinfection there will be a requirement to achieve some target Ct value, for which purpose promoting ozone decay is disadvantageous because of the need to maintain the ozone residual.

5.4 By-product formation

5.4.1 Organic by-products

Ozone is known to react with natural organic matter (NOM) and may produce a range of by-products including aldehydes, ketones and quinones (Langlais et al, 1991). Complete mineralisation of organic material by ozone does not usually occur to any great extent under drinking water disinfection conditions. Regulated halogenated organic by-products such as trihalomethanes (THMs) are not formed by ozonation (Langlais et al, 1991), and ozonation can have the additional benefit of reducing overall THM formation arising from chlorine dosing downstream.

The action of ozone on organic matter generally increases the biodegradable fraction, measured as an increase in assimilable organic carbon (AOC) or biodegradable dissolved organic carbon (BDOC) and which, if allowed to enter supply without further treatment, may promote growth in the distribution network. Hence, if ozone is used for disinfection, a process should be included downstream which is able to ameliorate the increase in biodegradability.

This is most often achieved by the use of granular activated carbon (GAC) filtration downstream of ozonation and the achievement of microbiological activity in the filter where BDOC/AOC removal is enhanced. As ozone introduces large amounts of oxygen to the water, its addition to water also promotes biological growth on the filter media. Biological activity develops to higher levels on GAC than on sand filters because of the higher specific surface area of GAC.

5.4.2 Bromate

Ozone oxidises the bromide ion (Br^-) to bromate (BrO_3^-), for which there is a regulatory maximum permitted concentration of 10 µg/l. It is important that the potential to form bromate is investigated at an early stage if ozonation is under consideration. A number of factors contribute to the extent of bromate formation, with the following trends being apparent (Amy et al, 1995).

Bromate formation:

- increases with increasing bromide ion concentration
- increases with increasing pH, up to a pH of 8.5
- increases with increasing alkalinity
- increases with increasing Ct
- increases as the ratio of ozone dose to DOC increases
- increases with increasing temperature
- declines as ammonia concentration increases

Amy et al (1995) observed a threshold ozone dose/DOC ratio of ≈ 0.5 mg/mg below which bromate formation was below the limit of detection, but found no equivalent threshold concentration of bromide ion.

These trends provide possible approaches for restricting bromate formation if there is a risk of exceeding the regulatory limit. Dividing the total ozone dose between multiple chambers separated by reaction zones in which the ozone residual decays may help keep the ozone/DOC ratio low. Lowering the pH, quenching ozone residual with bisulphite or adding ammonia may be feasible in some cases.

5.5 Ozonation equipment

The established technology for generating ozone is by corona discharge of dry air or oxygen. There are other methods (UV irradiation of oxygen at 140-190 nm; electrolysis) but these have yet to find widespread application for water treatment. The use of oxygen enables ozone to be generated at higher concentrations, which is more energy efficient and beneficial for mass transfer, but carries the additional cost of the oxygen. There are some air-fed installations which have the facility to enrich the feed gas with oxygen, which may be justifiable where there are infrequent short-term peak ozone demands (Langlais et al, 1991). The main features of an ozonation plant are illustrated in Figure 5.1.

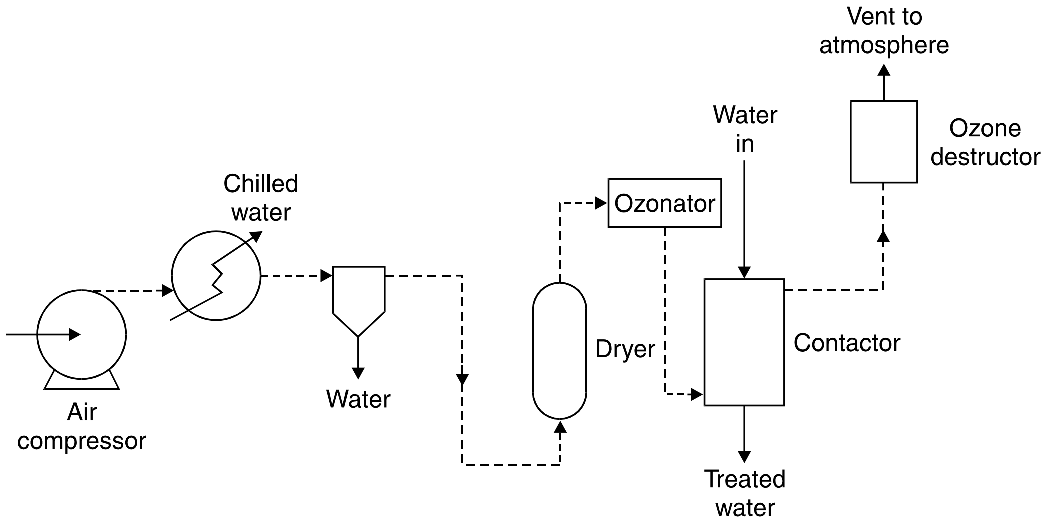

Figure 5.1 Schematic of air-fed ozonation system

5.5.1 Gas Preparation

a) Air

Air used for ozone generation must be dry, as water vapour causes arcing inside the generator, leading to loss of production and energy waste, and can also result in the formation of nitric acid. The required dryness depends on the generator, but the maximum operating dew point is unlikely to be above -60°C and may be lower than -80°C (Langlais et al, 1991). To achieve this level of dryness, desiccant driers are used, with parallel beds that alternate between drying and regenerating modes. Larger systems may also have refrigerant driers upstream of the desiccant driers to reduce the moisture loading, and some further upstream drying may also be achieved by compression. The air must be free from dust particles, which can cause arcing and a loss of efficiency, and hydrocarbons, the presence of which reduces efficiency.

b) Oxygen

Oxygen can be bought in as liquid (LOX) or produced on site. In the latter case, separation technologies include pressure swing adsorption (PSA), vacuum swing adsorption (VSA) and cryogenic separation. LOX requires relatively little capital investment but has a high unit cost. Cryogenic separation is capital-intensive. PSA and VSA are intermediate in terms of capital investment, PSA being the older, more established technology but VSA potentially being lower cost. The choice depends on a number of factors, but LOX is likely to be favourable for small installations, cryogenic separation for large installations, and PSA or VSA for intermediate installations.

5.5.2 Electrical supply

The most common electrical supply unit provides a low frequency, fixed voltage supply. For larger installations, a medium frequency, variable voltage supply is used to reduce power costs and because it allows for a higher output of ozone. Medium frequency units may require a higher operating pressure (Langlais et al, 1991).

Because very high voltage electricity is used in ozone generation, there are associated safety hazards. Ozone production equipment however has various fail-safe protection devices which will automatically shut off the equipment when a potential hazard develops.

5.5.3 Ozone generator

The corona discharge occurs between two concentric electrodes. In conventional generators, the tubular inner, high tension, electrode is covered in glass, a dielectric material. The inner electrode is mounted inside a stainless steel tube which is the outer ground electrode. The feed gas passes through the gap separating the electrodes. Some 90 - 95% of the energy input heats the dielectric and must be removed by applying cooling water. Greater outputs have been achieved by, among other developments, adjusting the discharge gap and using alternative dielectrics such as alumina.

5.5.4 Ozone contactors

Ozone is generated in the gas phase and must be dissolved. Some form of gas-liquid contactor is therefore necessary. The solubility of ozone is appreciably lower than that of chlorine. The most common form of contactor is the bubble diffuser, comprising two or more chambers in series separated by vertical baffles. A grid of porous diffusers is mounted near floor level in the first chamber, and possibly in one or more downstream chambers, through which ozonated gas is injected. Water flows down the first chamber, counter-current to the rising gas bubbles, and then alternately up and down through subsequent chambers. The diffusers produce bubbles of 2-3 mm diameter, which provide a high interfacial area. The chambers are typically 5-6 m deep, which, by increasing pressure, assists mass transfer. Having diffuser grids in more than one chamber allows the dose to be divided, which provides dose control flexibility. Generally, no ozone is applied to the last chamber, which serves to provide reaction time; there may also be reaction-only chambers between dosed chambers. Counter-current flow is beneficial for mass transfer. A greater ozone decay rate also benefits mass transfer, but will require a higher dose to achieve a given Ct value. This type of contactor is inherently quite large, which makes it particularly suitable for disinfection applications. The volumetric gas-liquid ratio is important, because there is a reliance on the rising bubbles to provide mixing energy. If the gas-liquid ratio is too low, the bubbles will rise as discrete plumes and the water will tend to channel between the plumes, the result of which will be a decline in transfer efficiency and uneven dosing. This needs to be considered at the design stage, especially if high-concentration oxygen-fed generators are proposed.

There are alternative contactor configurations, most notably turbine mixers and eductors, in which an external source of energy (the mixer or eductor pump) provides a high-shear environment in which the ozonated gas is dispersed as microbubbles, giving a very high interfacial area. Such contactors are much more compact than diffuser chambers, but have higher operating costs. For disinfection applications, there will still be a need to provide appropriate contact time.

5.5.5 Off-gas destruction

Complete ozone transfer is not achieved in practice and the off-gas from contact chambers will contain ozone, at a toxic concentration. The off-gas must therefore be processed to destroy remaining ozone before being vented to the atmosphere. Two methods are used: thermal and catalytic. Thermal destructors heat the off-gas to temperatures of up to 400^{o}C, at which ozone decay is virtually instantaneous. Catalytic destructors have a reaction chamber filled with a material which catalyses ozone decay, avoiding the need for high temperature. Some pre-heating is still required to reduce relative humidity and prevent condensation on the catalyst, which would impair performance.

Although there is in principle scope for recycling off-gas, it is not commonly done in practice.

5.5.6 Monitoring and verification of the process

As with all chemical disinfection systems, process verification is based on

- the measurement of Ct values for water entering the distribution system to verify the achievement the required log inactivation of the targeted pathogens,
- the maintenance of a measurable residual in the distribution system
- limiting the levels of inorganic by products in drinking water supplied to consumers

Determining the actual Ct achieved in a multiple chamber contactor is not straightforward.

In reaction-only chambers, the dissolved ozone concentration declines from inlet to outlet as the ozone decays, but it is unlikely to be a linear decline.

In bubble diffuser contact chambers, various dissolved ozone concentration profiles can occur, depending on the decay rate, the mass transfer rate, the flow configuration (co- or counter-current) and what the ozone concentration is at the inlet (where there is more than one contact chamber).

Recommendations for assigning effective C values for various chambers are given by USEPA (1991) and Lev and Regli (1992); they require knowing the concentration at the outlet of each chamber.

Due to the dissipation of residual prior to distribution of drinking water to consumers, ozonation is only used for primary disinfection purposes and in the Irish context is always used in conjunction with other disinfection systems for downstream maintenance of residual in distribution. When used with bulk delivered hypochlorite for residual generation, water suppliers should be aware of potential for bromate formation by both disinfection systems

5.5.7 Maintenance

Maintenance of ozone generators and ancillary equipment must be carried out in accordance with suppliers' specifications, by appropriately trained staff.

5.6 Advantages and limitations of ozonation

The advantages of ozonation are that:

- it is a very effective disinfectant for bacteria, viruses and *Giardia*;
- it is more effective against *Cryptosporidium* than other chemical disinfectants;
- it is less sensitive to pH variation as a disinfectant than chlorine;
- it does not directly produce THMs or HAAs;
- other treatment benefits, such as pesticide removal, may occur in parallel.

The limitations of ozonation are that:

- it provides no disinfectant residual into distribution;
- ozone decays particularly at high pH levels
- the capital cost of ozonation equipment is high compared to other chemical disinfectants
- it is also expensive to operate compared to other disinfectants as it requires on-site generation and high energy input;
- it requires complex plant for which a high skilled maintenance input is required;
- post process GAC filtration is usually required to remove the consequent increased levels of AOC/BDOC formed by the oxidation process;
- bromate formation can be a disinfection by-product.

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6. CHLORINE DIOXIDE

6.1 Properties and chemistry of chlorine dioxide

Chlorine dioxide has a melting point of -59°C, a boiling point of 11°C and a molar mass of 67.45 g mol^{-1}. Unlike chlorine, which reacts with water, chlorine dioxide dissolves in water, but does not react with it.

The solubility of ClO_2 in water depends on temperature and pressure: at 20°C and atmospheric pressure the solubility is about 70 g/l. In waterworks practice, ClO_2 is generated under vacuum with solutions known to have reached 40 g/l. Due to its low boiling point, ClO_2 is readily expelled from water solutions by passing air through the solution, or by vigorous stirring of the water. As air concentrations of 10 percent or greater are explosive, it is therefore important that systems handling chlorine dioxide are sealed to ensure that loss of the gas cannot occur.

During oxidation reactions chlorine dioxide readily accepts an electron to form chlorite:

$ClO_2 + e^- \rightarrow ClO_2^-$

In drinking water, chlorite formation is usually the dominating reaction end product, with typically up to 70% of the chlorine dioxide being reduced to chlorite. Chlorate (ClO_3^-) and chloride (Cl^-) can also form from chlorite:

$ClO_2^- + 2OH^- \rightarrow ClO_3^- + H_2O + 2e^-$

$ClO_2^- + 2H_2O + 4e^- \rightarrow Cl^- + 4OH^-$

6.2 Generation of chlorine dioxide

Because of its highly reactive nature, chlorine dioxide is never stored, transported or used as a gas because it is explosive under pressure. Instead, it is produced on-site as a solution on demand through one of the following reactions:

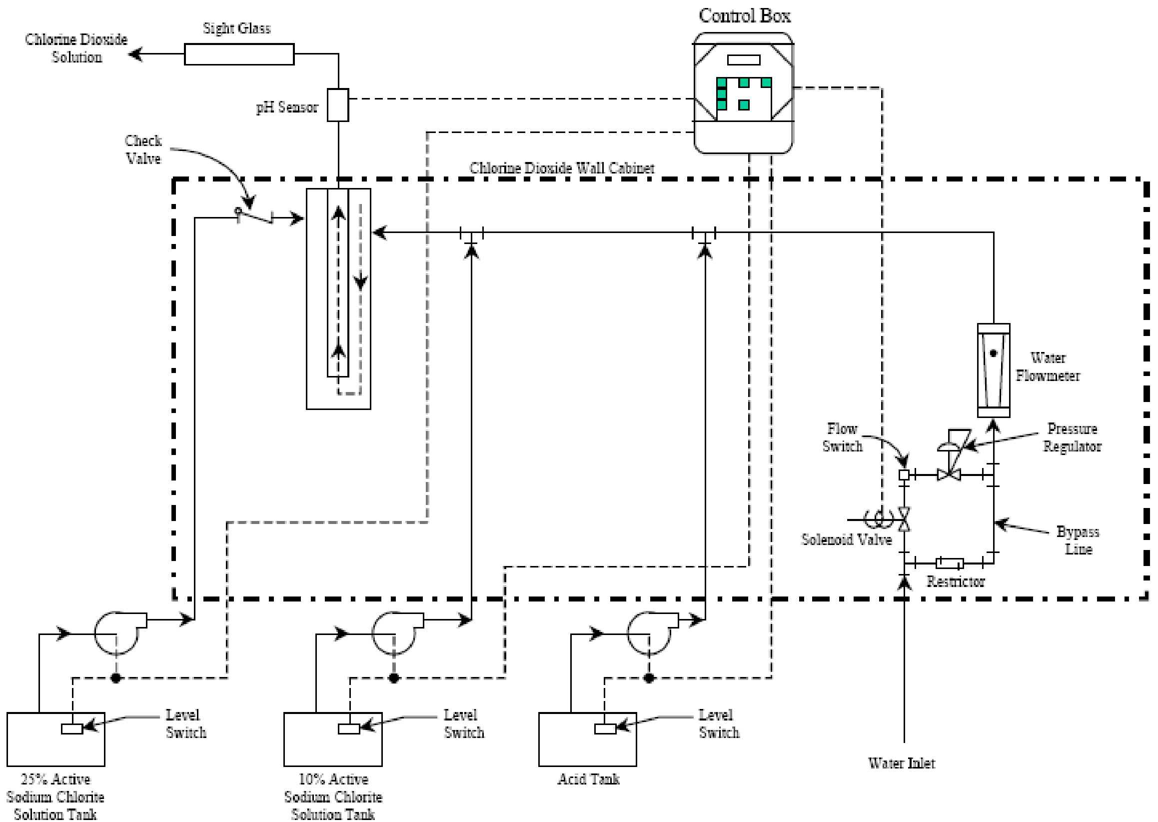
$5NaClO_2 + 4HCl \rightarrow 4ClO_2(aq) + 5NaCl + 2H_2O$ (acid:chlorite solution)

$2NaClO_2 + Cl_2(g) \rightarrow 2ClO_2 + 2NaCl$ (chlorine gas:chlorite solution)

$2ClO_2^- + HOCl + H^+ \rightarrow + 2ClO_2(aq) + Cl^- + H_2O$ (chlorine solution:chlorite solution)

$2NaClO_2(s) + Cl_2(g) \rightarrow 2ClO_2(g) + 2NaCl(s)$ (chlorine gas:solid chlorite)

The chlorine dioxide yield from the acid:chlorite process, as shown typically in Fig 6.1 below, is usually less than 80% of that from the chlorine:chlorite processes, but recent developments using catalysts may have increased the yield. The reaction rate is slow compared with the chlorine processes, and production rates for acid:chlorite are limited e.g. less that 10 kg/d (US EPA, 2005/1).



Source: USEPA EPA Guidance Manual - Alternative Disinfectants and Oxidants

Fig 6.1 Chlorine Dioxide Generation using Acid: Chlorite solution method

The chlorine gas:chlorite solution process, as shown typically in Fig 6.2 below, is much faster and gives a product approaching 95% purity. The chlorite solution is “vapourised” and reacted under vacuum with Cl_2.

In the chlorine solution:chlorite solution process, yield of up to 98% has been reported in laboratory reactors, but commercial reactors usually have a lower yield and the reaction is relatively slow. This is the most common type of reactor (US EPA, 2005/2).

In the chlorine gas:solid chlorite process, dilute, humidified Cl_2 reacts with specially processed solid sodium chlorate. This process is only dependent on the feed rate of Cl_2 and the product is free of chlorate and chlorite as these remain in the solid phase.

Other types of ClO_2 generators are available such as

- ClO_2 generation by transformation of sodium chlorate with hydrogen peroxide and sulphuric acid or
- electrochemical production from sodium chlorite solution (Gates, 1998)

and are used in the pulp and paper industry for pulp bleaching.

The chlorate based processes will also generate ClO_2 through reaction with acid and have previously not been thought capable of producing ClO_2 of the purity needed for water treatment. However, chlorate /peroxide/ H_2SO_4 process is now being widely marketed as a disinfectant for larger municipal applications. The main advantage of using chlorate rather than chlorite is that chlorate is considerably cheaper.

The disadvantage with the electrochemical process is high concentrations of chlorate in the product.

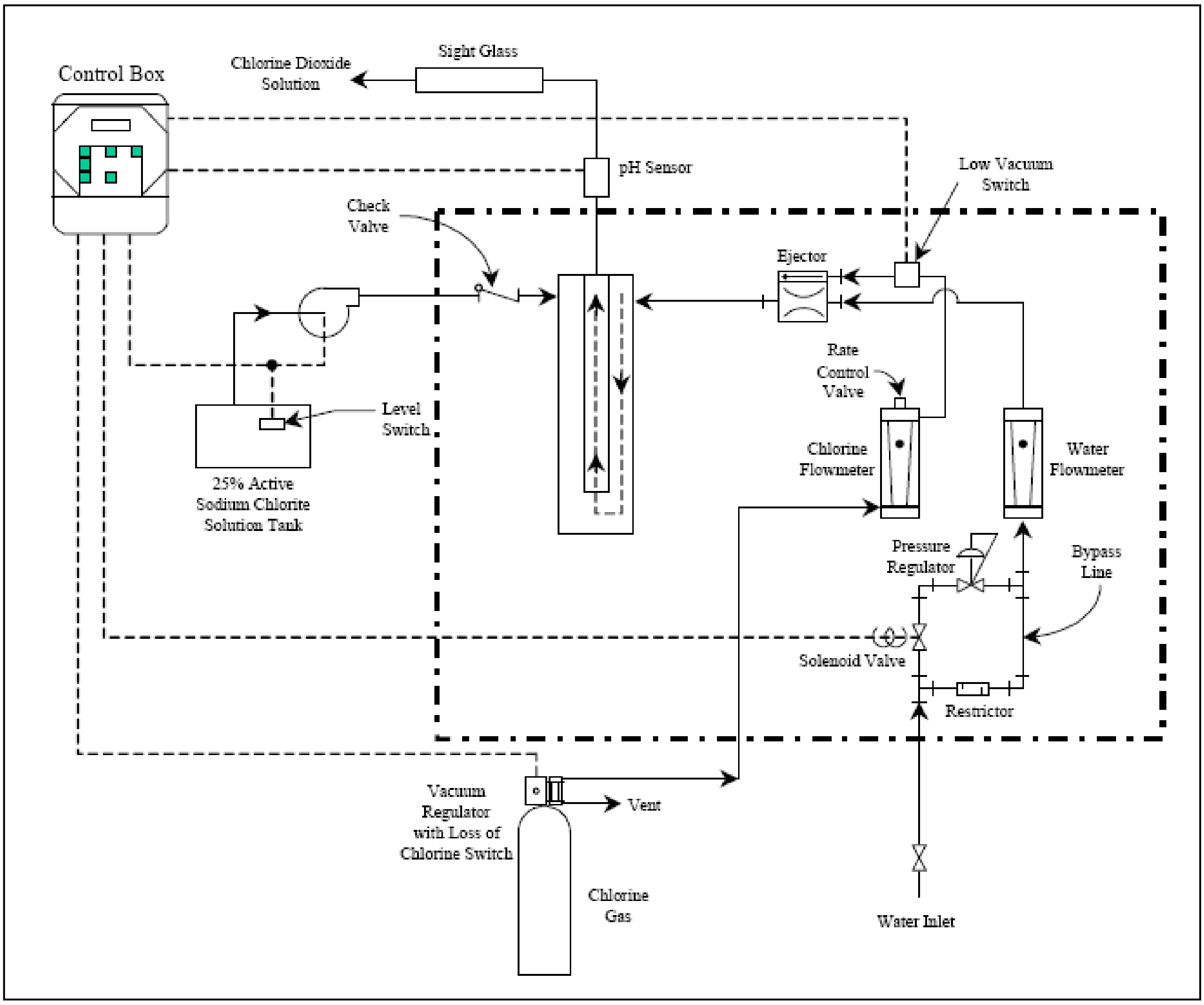


Fig 6.2 **Chlorine Dioxide Generation using Chlorine gas: Chlorite solution method**

6.3 Disinfection performance

Chlorine dioxide is a strong oxidant and it is effective in the inactivation of pathogens. Its oxidizing ability is lower than ozone but much stronger than chlorine and chloramines. The pathogen inactivation efficiency of chlorine dioxide is as great as or greater than that of chlorine but is less than ozone. However different microorganisms have different sensitivity to ClO_2, e.g. *Cryptosporidium* require an order of magnitude higher Ct values compared to *Giardia* and viruses.

Table 6.1 below provides a summary of US EPA Ct credits for *Cryptosporidium*, *Giardia* and viruses using ClO_2. These Ct values are also quoted in the latest WHO Guidelines. Different viruses also have different sensitivity to ClO_2 (Thurston-Enriquez et al., 2005) and the Ct values proposed by the US EPA probably provide a margin of safety.

Table 6.1 ***Ct in mg min/l for 2 log inactivation of Cryptosporidium, Giardia and viruses using chlorine dioxide***

Temperature	**1°C**	**5°C**	**10°C**	**15°C**	**20°C**
Cryptosporidium	1220	858	553	357	232
Giardia	+	17	15	13	+
Viruses	+	5.6	4.2	2.8	+

+ data not available

Source: USEPA LT2ESWTR Toolbox Guidance Manual 2010 and
WHO Risk Assessment of *Cryptosporidium* in Drinking Water. 2009 Table 6

Generally, chlorine dioxide is more effective as a disinfectant than chlorine at higher pH but similar or poorer at lower pH (White, 1999); chlorine dioxide performance is generally quoted as not being pH sensitive in the range experienced in water treatment, whereas chlorine is much more effective at lower pH. The results from Thurston-Enriquez et al. (2005) suggest that there could be some pH sensitivity for chlorine dioxide, but this varied between the viruses examined.

Table 6.2 provides a summary of US EPA Ct values for *Cryptosporidium*, *Giardia* and viruses using ClO_2, Cl_2 and O_3 at 10°C and pH 6-9.

Table 6.2 ***Required Ct values (in mg min/l) for inactivation of microorganisms by ClO_2 compared with Cl_2 and O_3 at 10°C and pH 6-9***

	Inactivation Level	**ClO_2**	**Cl_2**	**O_3**
Cryptosporidium	0.5-log	138	N/A	4.9
Cryptosporidium	3-log	830	N/A	30
Giardia	0.5-log	4	17	0.23
Giardia	3-log	23	104	1.43
Viruses	2-log	4.2	3	0.5
Viruses	4-log	25.1	6	1.0

Source: USEPA, 2003 and WHO Guidelines for Drinking Water Quality- *Cryptosporidium*. 2006 Table 6
N/A - not applicable. Chlorine is ineffective against *Cryptosporidium*.
Cl_2 Ct values for pH 7

Chlorine dioxide is generally at least as effective as chlorine for inactivation of bacteria of sanitary significance, and Ct values less than those for viruses shown in Table 4.3 would be suitable. For example effective inactivation of waterborne bacterial pathogens (e.g. *Salmonella, Shigella*) has been demonstrated in the laboratory with chlorine dioxide concentrations of 0.1 mg/l and contact times of 5 minutes (White, 1999).

Based on Tables 6.1 and Table 6.2 above and given the range of temperatures experienced in Ireland (i.e. 3-18°C), there are limitations on the use of Chlorine dioxide for *Cryptosporidium* inactivation due to the large effective contact times necessary at the lower end of the Irish temperature range.

6.4 By-products

6.4.1 Chlorites

Chlorite is usually the main by-product from the use of ClO_2. This is produced from reduction of chlorine dioxide by reaction with organics (or iron and manganese) in the water. Unreacted chlorite can also be present for systems using chlorite solution. Chlorite is not present in the product if gaseous Cl_2 and solid chlorite is used when generating ClO_2.

As up to 70% of the added ClO_2 can be reduced to chlorite, this limits the amount of ClO_2 that can be added and thereby the amount of disinfection that can be achieved. High concentrations of total organic carbon (TOC) and reduced metals can also consume ClO_2 and produce chlorite without the ClO_2 achieving any disinfection.

High pH values (pH>9) also lead to enhanced chlorite production and works with softening or corrosion control with increased pH may experience more problems with chlorite.

Chlorite is a weaker oxidant than ClO_2 but will with time be reduced to chloride. This means that the sum of ClO_2 and chlorite can decrease in distribution. The rate of reduction will vary depending on parameters such as temperature and disinfectant demand and no general advice can be given.

6.4.2 Chlorate

Production of chlorine dioxide from chlorine and chlorite is via a dimer intermediate $\{Cl_2O_2\}$:

$Cl_2 + ClO_2^- \rightarrow \{Cl_2O_2\} + Cl^-$

Under conditions of high concentrations of both reactants, this dimer breaks down to form mainly chlorine dioxide. However, at low concentrations of reactants, or if chlorine is in excess, chlorate can be formed:

$\{Cl_2O_2\} + H_2O \rightarrow ClO_3^- + Cl^- + 2H^+$

$\{Cl_2O_2\} + HOCl \rightarrow ClO_3^- + Cl_2 + H^+$

Acidic conditions (pH<3) favour the degradation of $\{Cl_2O_2\}$ to chlorate rather than ClO_2 and also favour the direct oxidation of chlorite to chlorate.

Use of other oxidants e.g. ozone after chlorine dioxide can result in oxidation of chlorite to chlorate. There is also a photolytic mechanism for breakdown of chlorine dioxide to chlorate.

In summary, conditions favouring chlorate formation are:

- High $Cl_2:ClO_2^-$ ratios.
- High concentration of free chlorine at low pH.
- Low chlorite concentration at low pH.
- High pH (>11) causing disproportionation of chlorine dioxide;
  $2ClO_2 + 2OH^- \rightarrow ClO_2^- + ClO_3^- + H_2O$.
- Decomposition of ClO_2 due to exposure to sunlight/UV.
- Use of ozone after chlorine dioxide.

The effects of pH indicated above should not normally be a problem in water treatment. Chlorate is not present in the product if gaseous Cl_2 and solid chlorite is used when generating ClO_2.

6.4.3 Regulatory limits for chlorites and chlorates

The chlorine dioxide by-products of particular concern are chlorate and chlorite, arising from chemical reduction of chlorine dioxide and from chlorite used in the production process. It should be noted that dialysis patients are potentially sensitive to the toxic effects of chlorate or chlorite.

There is currently no EU Directive or Irish Drinking Water Regulations limit on chlorate and chlorite.

In the UK, use of chlorine dioxide is limited by regulatory standards for products used in water treatment (Regulation 31), with a maximum combined concentration of 0.5 mg/l for chlorine dioxide + chlorate + chlorite entering supply. This only applies where chlorine dioxide is used, and there is otherwise no standard for chlorate or chlorite in the drinking water regulations. A consequent maximum dose would be around 0.7 mg/l in order not to exceed combined concentration of 0.5 mg/l for chlorine dioxide, chlorate and chlorite. The remaining 0.2 mg/l could either be lost through evaporation of ClO_2 or reduction of ClO_2 to chloride.

WHO have set a provisional guideline value of 0.7 mg/l for both chlorate and chlorite individually, based on health considerations.

The US EPA has a maximum contaminant level (MCL) of 1 mg/l for chlorite at plants using ClO_2 and a maximum residual disinfection level (MRDL) of 0.8 mg/l for ClO_2. They recommend a maximum dose of 1.4 mg/l chlorine dioxide to maintain chlorite below the MCL, on the basis that 70% of the chlorine dioxide could be converted to chlorite. Typical dosages of chlorine dioxide used as a disinfectant in drinking water treatment range from 0.07 to 2.0 mg/l (US EPA, 1999). In Canada the maximum dose of ClO_2 is set to 1.2 mg/l (Health Canada, 2008).

6.4.4 Organic by-products

One of the main benefits with ClO_2 compared to Cl_2 is that ClO_2 does not produce chlorinated organic compounds. Trihalomethanes (THMs) and haloacetic acids (HAAs), the most common by-products with chlorine, will therefore not form from use of high purity ClO_2.

During the acid:chlorite reaction, side reactions can result in the production of chlorine. In the chlorine solution:chlorite solution process, if chlorine is used in excess of the stoichiometric requirements, chlorine can also be present in the product. The chlorine associated with the chlorine dioxide can then cause chlorinated organic by-products to form, but to a much smaller extent than if Cl_2 was used on its own. The amount of chlorine associated with the chlorine dioxide needs to be minimised by control of the reactions.

Halogenated by-products could also form if ClO_2 is used as a primary disinfectant followed by Cl_2 as a secondary disinfectant, as the organic precursors may still be present for reaction with the chlorine.

ClO_2 can also oxidise bromide (Br^-) to bromine (Br_2), which forms bromated THMs and HAAs. These reactions can be a potential problem in areas with high bromide concentrations (US EPA, 2007). Other sources suggest that bromide is only oxidised by ClO_2 or chlorite when simultaneously exposed to UV radiation.

Organic by-products therefore seems to be a minor problem when using ClO_2 but potential problems should be considered if ClO_2 is followed by chlorination, or in areas with high bromide concentrations.

6.4.5 Other by-products

Few investigations have looked at the formation of non-halogenated by-products using ClO_2 but it has been suggested that ClO_2 will produce similar by-products as ozonation (US EPA, 1999). However, ClO_2 will not oxidise bromide to bromate (BrO_3^-), as ozone does.

6.4.6 By-products control

Control over chemical doses and reaction rates should minimise chlorite and chlorate formation during chlorine dioxide generation for a particular systems.

The majority of chlorate and chlorite formation will usually be at the treatment works. However, it can continue in distribution from residual chlorine dioxide reacting with organics in the water.

Because chlorate can form in the presence of other oxidants, e.g. chlorine, ozone, the use of chlorine dioxide with other oxidants should be implemented with care. UV light can also enhance chlorate formation and use of ClO_2 before UV treatment should also be implemented with this in mind.

Chlorite can be removed using powdered activated carbon (PAC) at relatively high doses (10-20 mg/l) and this is not likely to be cost effective if not used for other purposes, such as taste and odour. Different PACs will also have different capacity for chlorite removal. Chlorite can also be removed by granular activated carbon (GAC) by a combination of adsorption and chemical reduction. If free chlorine and chlorite are present in the GAC influent, chlorate is likely to form. Ferrous iron (Fe^{2+}) is efficient in chlorite removal, chloride being the likely end product. Using ClO_2 as pre-oxidant before ferrous iron coagulation could therefore be a potential option. Generally, the best option to minimise the formation of chlorite is to reduce the oxidant demand before the addition of ClO_2. Keeping the pH in the range of 6-9 during the contact time will also ensure disinfection efficiency and minimise chlorite formation.

In areas with high bromide concentration, brominated THMs and HAAs can be reduced by adding ClO_2 after treatment to reduce the concentration of natural organic matter.

6.5 Operation and verification of ClO_2 systems

Assuming a requirement for at least 2 log *Cryptosporidium* inactivation and a water temperature of 10-20°C, the *Ct* needed would be 232 - 553 mg.min/l. If a chlorine dioxide concentration after contact of 1 mg/l could be achieved, contact time of 4 - 9 hours (at perfect flow conditions) would therefore be needed. For unbaffled contact tanks and service reservoirs (with t_{10}/. value of 0.1 as per Table 4.4), commonly used as part of scheme headworks in Ireland, the effective contact time *t* may be as high as 40-90 hours.

With such long contact times the chlorine dioxide dose may need to be very high (well in excess of the US EPA recommended maximum of 1.4 mg/l) to achieve a 1 mg/l residual, with implications for chlorate and chlorite formation. To achieve these Ct values, the water treated would need to have a low demand for chlorine dioxide (i.e. low organic content, for example good quality groundwaters) to maintain acceptable chlorate and chlorite levels in the treated water. This will limit the potential of chlorine dioxide for *Cryptosporidium* control, although it would be appropriate for other disinfection applications.

Packaged systems are available, which generate up to 10 kg/h chlorine dioxide, at 90-95% efficiency in relation to the stoichiometric ratio. Small systems (<2 kg/h) are normally designed to operate with diluted reagents, larger systems use undiluted commercial grade reagents which reduces the chlorate formation.

Equipment requirements vary depending on the type of ClO_2 generator used, and can include:

- chlorine gas handling and metering plant,
- storage and dosing facilities for acid, chlorite and hypochlorite,
- monitoring systems for reagent dosing to control reaction rates, particularly in relation to minimising by-product formation,
- on-line ClO_2 monitoring to ensure dosing and residual control.

Health and safety implications and operating requirements will be different to those for chlorine, and this will need to be reflected in operator training.

Chlorine dioxide is degraded by UV light to produce chlorate, and treated water should therefore be protected from sunlight. If UV disinfection is used in combination with ClO_2 then ClO_2 needs to be added after the UV disinfection or sufficiently ahead of the UV reactor so that there is no residual entering the UV reactor. Use of other oxidants after chlorine dioxide can increase chlorate formation from oxidation of chlorite.

Process verification is based on

- the measurement of Ct values for water entering the distribution system to achieve the required log inactivation of the targeted pathogens,

- the maintenance of a measurable residual in the distribution system

- limiting the levels of inorganic by products in drinking water supplied to consumers

In the USA, the regulations permit the use of DPD reagent, Lissamine Green B (LGB) and amperometric titration for monitoring chlorine dioxide for reporting purposes. For chlorite, LGB, amperometric titration or ion chromatography (IC) must be used. In other US states where chlorate is regulated, this must be measured using IC.

The current US regulations require that ClO_2 and chlorite to be monitored at least daily at the point of entry into the distribution system and must be analysed using one of the above methods. In addition to the daily monitoring, chlorite analysis is required monthly for the distribution system from three representative sample locations (beginning, middle and end of distribution system). The average of these three sample points must be below 1.0 ppm.

Other methods, sampling points and equipment may be used for process control and there are on-line monitors available for ClO_2 and chlorite, but not for chlorate.

6.6 Advantages and limitations of chlorine dioxide as a disinfectant

6.6.1 Advantages

The advantages of chlorine dioxide are as follows;

- Chlorine dioxide is an effective disinfectant against bacteria, virus and *Giardia*, and is more effective against *Giardia* than chlorination.
- The efficiency of ClO_2 is relatively unaffected by pH changes in the pH region of 6-9, whereas the performance of Cl_2 decreases with increasing pH
- As ClO_2 does not chlorinate organic compounds, the formation of THMs and HAAs will be greatly reduced compared to chlorination
- Chlorine dioxide is a strong oxidant and as part of a treatment process can effectively oxidise compounds such as iron, manganese, sulphides as well as chlorinated phenols and some other taste and odour causing compounds and is suggested to destroy THM precursors (White, 1999). Reduced arsenic (arsenite) can be oxidised to arsenate, which will enhance arsenic removal.
- Chlorine dioxide is relatively easy to generate
- Chlorine dioxide can provide residuals in final water
- Due to the non formation of chlorinated by-products, chlorine dioxide may be appropriate for disinfection, downstream of slow sand filtration (which does not remove colour or dissolved organic carbon, and therefore chlorination by-product precursors, from the filtered water)

6.6.2 Limitations

The limitations of chlorine dioxide are as follows

- Low level of inactivation of *Cryptosporidium* oocysts without large contact tank volumes when disinfecting water within the usual temperature range of source waters in Ireland.
- ClO_2 dosing forms specific inorganic by-products i.e. chlorite and chlorate.
- As ClO_2 gas is explosive under pressure, it must be generated on-site
- During the generation of ClO_2, chlorate can also form if the process is not controlled properly but the risk can be eliminated if using the chlorine gas :solid chlorite process
- The odour threshold for ClO_2 is quoted as 0.2 mg/l (Suffet et al, 1995), so it may cause taste and odour problems. Due to its low boiling point (11°C), ClO_2 can quickly vapourise and give rise to a strong chlorinous odour when drawn from the customers tap. Volatile organic compounds (VOCs) in customer's homes are also known to react with ClO_2 to form kerosene-type odours. Generally, however, there is no reason to believe that taste and odour problems would be worse with chlorine dioxide than with chlorine.
- Although residuals can persist in distribution, the low boiling point, together with its high reactivity, means that ClO_2 residuals dissipate quickly. As with other oxidants, rapid mix basins will result in loss of chlorine dioxide which will also be removed by activated carbon.

- Residuals are also likely to be limited by future EU regulatory limits for chlorite and chlorate by-products. Due to these by-products and taste and odour issues, the use of chlorine dioxide as a secondary disinfectant to provide a disinfectant residual is somewhat limited especially in moderate to high TOC waters
- Difficulties with ClO_2 generator efficiency and optimisation can form excessive Cl_2 as a by-product resulting in some THM and HAA formation
- Even though ClO_2 will not chlorinate organic compounds, bromide and iodide in the water can be oxidised and form brominated and iodated THMs and HAAs.
- ClO_2 is degraded by exposure to UV irradiation or sunlight Consequently ClO_2 should not be dosed upstream of UV reactors.
- The high cost of laboratory analysis for chlorite and chlorate by-products

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7. ULTRAVIOLET (UV) DISINFECTION SYSTEMS

7.1 Introduction

In Chapter 2 the key issues, relating to the prevalence of *Cryptosporidium* in water and infectivity of the human illness cryptosporidiosis, caused by the replication of the protozoan oocysts in the digestive system of the host, were discussed, together with the methodology of oocyst inactivation by exposure to UV light.

When ultraviolet (UV) radiation is absorbed by the cells of microorganisms, it damages the genetic material (DNA) within the cell in such a way that the organisms are no longer able to grow or reproduce, thus preventing the human illness cryptosporidiosis. DNA damage mainly results from irradiation at wavelengths within the UV-C region of the spectrum (200-280 nm) and is maximised at around 254 nm. This is the principle by which UV is used for disinfection.

UV dose (or fluence) is typically expressed in units of mJ/cm^2 or J/m^2 (where 1 mJ/cm^2 = 10 J/m^2) and is a function of UV intensity (or fluence rate), mW/cm^2, and exposure time, s. (1 mWs/cm^2 = 1 mJ/cm^2). Suppliers of proprietary UV disinfection systems market equipment which is capable of applying a specified dose over a defined range of operating conditions (i.e. flow rate, water quality) and which is validated to inactivate bacteria, protozoan pathogens such as *Cryptosporidium*, and viruses.

UV may be employed as the sole form of disinfection for a borehole from a groundwater aquifer with consistently good water quality and a short distribution network or for a single house system. However in countries like Ireland where surface water sources predominate resulting in variable raw water quality and the need to remove organic and inorganic impurities using pre-treatment, supplies are almost always chlorinated to quality assure water within scheme distribution networks to the consumer’s tap.

7.2 UV disinfection systems

A schematic of a UV reactor is shown in Figure 7.1, with more information on its constituent elements provided below.

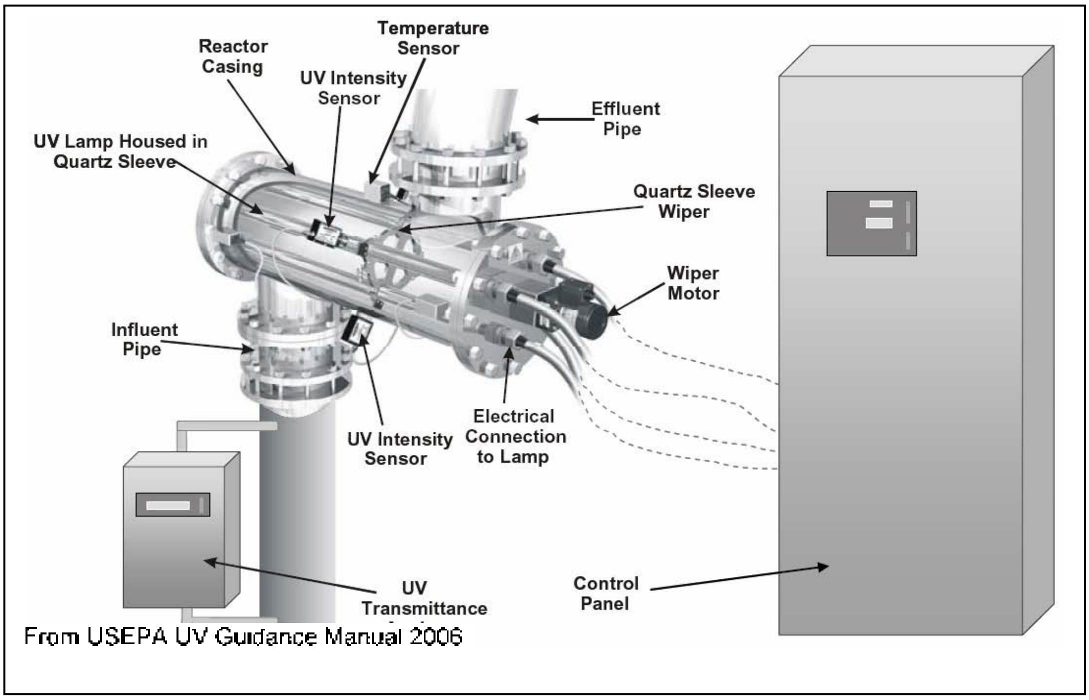


Figure 7.1 **Schematic of typical UV Reactor**

7.2.1 UV lamps

UV light can be produced by a variety of lamps. Low pressure (LP), Low Pressure High Output (LPHO) and Medium Pressure (MP) mercury vapour lamps are normally used for full-scale potable water applications. The light output from mercury-based UV lamps depends on mercury vapour pressure within the lamp. In

LP or LPHO UV lamps, the mercury exists at a low vapour pressure and at a moderate temperature (40ºC & 200°C) which produces monochromatic UV light at 253.7 nm.

In medium-pressure (MP) UV lamps, a higher vapour pressure and higher operating temperature increases the frequency of collisions between mercury atoms, which produces polychromatic UV light over a broad spectrum in the range of 180-300nm, with an overall higher intensity, only a proportion of which is in the germicidal range.

The microbial effectiveness of UV light varies as a function of wavelength. For most microorganisms, the UV action peaks in the UV-C range at or near 260 nm, has a local minimum near 230 nm, and drops to zero near 300 nm, which means that UV light at 260 nm is the most effective at inactivating microorganisms. Because no efficient way to produce UV light at 260nm is available and mercury produces UV light very efficiently at 254 nm, the latter has become the standard.

When power is applied to the UV lamp electrodes, an electrical arc is generated from ionized gas or gas mixtures, which conduct electricity. As the arc temperature rises, mercury in the lamp converts to a gaseous vapour state. This mercury vapour conducts electricity, completing the circuit, releasing UV light photons as the vapour conducts electricity.

The wavelength of UV light emitted from mercury lamps varies depending on the type of UV lamps used. The proprietary UV disinfection systems can be broken down into systems using three different technologies, namely, low pressure, low pressure high output and medium pressure.

The typical properties of the different types of mercury lamps used in such systems is set out below in Table 7.1.

Table 7.1. Typical properties of different UV lamp technologies

	LP	LPHO	MP
UV output range	254nm	254nm	<200nm to >600nm
Typical Power/lamp	40-85W	100-500W	1-30kW
Efficiency	35%	30%	15%
Warm-up Time	2 min	5 min	10 min
Operating Temp	40°C	200°C	800°C
Lamp Life	12,000 hours(15 months)	12,000 hours (15 months)	5,000 hours (7 months)
Power \Variability	No (on/off)	60% to 100%	30% to 100%

Relative to MP lamps, LP lamps have a lower power input and germicidal UV output, a higher efficiency and longer life; but many more LP than MP lamps are needed for a given dose, so MP plants are smaller for the same duty. The characteristics of LPHO lamps are intermediate between LP and MP.

As the age of mercury vapour lamps increases their output reduces through the quartz sleeve coupled with the depletion of the available mercury in the lamp. Typically the sizing of UV disinfection system are based on the UV dose at the *end of lamp life* (EOLL), expressed as an aging factor percentage, which is 80% using USEPA guidance & 70% using DVGW or ONORM protocols (i.e. German and Austrian validation standards). Aging factor is the measure of the output of a new lamp and the output of a lamp at the validated end-of-lamp life. For this reason suppliers specify a maximum burn time before lamps must be replaced.

7.2.2 UV reactors

For potable water treatment applications, lamps are mounted in closed reactor vessels.

Different UV reactor configurations are available depending on the UV manufacturer and the site constraints of the specific installation e.g. reactors can be in-line, S-shaped or U-shaped.

UV lamps may be oriented parallel, perpendicular or diagonal to the flow direction. In a reactor with a square cross-section, they are typically placed with lamp arrays perpendicular to flow whereas with a circular cross-section, they are typically parallel to flow. The optimal spacing between lamps is also important and depends on the UV transmittance (UVT) of the water, the output of the lamp and the hydraulic mixing within the reactor.

LP and LPHO systems are used for both small and medium size installations but as the hydraulic flows get larger, LPHO systems are less compact in size due to the need for many more lamps than MP systems for a given UV dose.

Headloss must be considered at the plant design stage to ensure that adequate head is available. Inlet and outlet configurations should avoid short-circuiting, eddies and dead zones within the reactor. Straight inlet configurations with gradual changes in cross-sectional area can help to create flow conditions for optimal dose delivery.

The superior turndown capability of MP reactors, as set out in Table 7.1 above, enables the system instrumentation to effect power modulation in response to variable water quality (i.e. UVT) and flow rates. This becomes more important as a means of achieving cost effective operation of larger UV disinfection systems for different flows and treated water UVT.

7.2.3 UV sensors and UVT analysers

UV disinfection systems are typically fitted with one or more UV sensors and a UVT analyser upstream of the reactor. The UV sensors in the case of MP systems are designed to measure the portion of UV intensity within the germicidal range while the UVT analyser determines the transmittance of the water to be treated.

The UV sensors provide continuous measurement of UV intensity at points in the reactor. Some designs have one sensor per lamp. A reliable measurement of intensity is essential for dose control, and the performance of sensors must be periodically verified against reference sensors.

The US EPA recommends that

- The calibration of duty UV sensors be verified with respect to an off-line identical reference UV sensor ***at least monthly***
- “on-line UVT analyzers be evaluated ***at least weekly*** by comparing the on-line UVT measurements to UVT measurements using a bench-top spectrophotometer”.

7.3 Performance of UV disinfection systems

7.3.1 Disinfection effectiveness

As a general rule, UV disinfection effectiveness follows the trend:

Bacteria > Protozoan Pathogens > Viruses and bacterial spores

Table 7.2 below provides a summary of examples of inactivation data from laboratory tests from three published sources.

Table 7.2 UV dose requirements (mJ/cm^2) for inactivation of micro-organisms

Target	**Log Inactivation**							
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Protozoa								
Giardia cysts[1]	1.5	2.1	3.0	5.2	7.7	11	15	22
Cryptosporidium oocysts[1]	1.6	2.5	3.9	5.8	8.5	12	15	22
Viruses								
"Viruses"[1]	39	58	79	100	121	143	163	186
Adenovirus type 40[2]		56		111		167		
Poliovirus[2]		7		15		22		30
Adenovirus type 41[3]								112
Hepatitis A[3]								21
Coxsackievirus B5[3]								36
Poliovirus type 1[3]								27
Rotavirus SA11[3]								36
Bacteria								
B subtilus spores[1]		28		39		50		62
E coli[1]		3		4.8		6.7		8.4
Streptococcus faecalis[2]		9		16		23		30
Vibrio cholerae[2]		2		4		7		9
Enterobacter cloacae[3]								10 (33)
Enterocolitica faecium[3]								17 (20)
Campylobacter jejuni[3]								4.6
Clostridium perfringens[3]								23.5
E. coli 0157:H7[3]								6 (25)
E. coli wild type[3]								8.1
Klebsiella pneumoniae[3]								20 (31)
Legionella pneumophila[3]								9.4
Mycobacterium smegmatis[3]								20 (27)
Pseudomonas aeruginosa[3]								11 (19)
Salmonella typhi[3]								8.2
Shigella dysenteriae ATTC29027[3]								3
Streptococcus faecalis								11.2
Vibrio cholerae								2.9 (21)

[1] USEPA UV Manual 2006
[2] Hijnen WAM, Beerendonk EF and Medema GJ, 2006
[3] Bolton JR and Cotton CA, 2008 - values in brackets include photoreactivation data

Unlike chlorine, the performance of UV for disinfection is largely independent of water temperature and pH.

Some microorganisms have enzyme systems that enable them to repair damage inflicted by UV, either in the light (photorepair) or dark (dark repair).

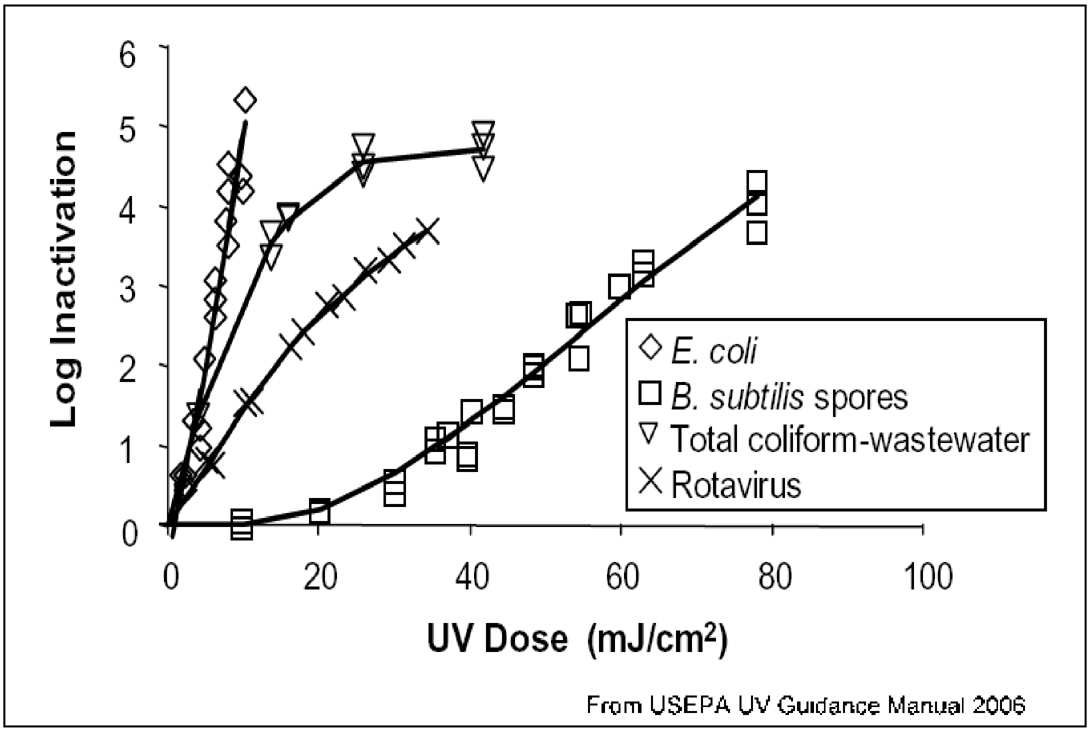
Photorepair is generally not of a concern in water treatment, because treated water is normally kept in the dark in pipes and reservoirs following UV disinfection. The USEPA UV Guidance Manual also reports that at dose rates quoted for protozoan inactivation, dark repair is not possible

Knudson (1985) found that bacteria have the enzymes necessary for photorepair. Unlike bacteria, viruses lack the necessary enzymes for repair. Shin et al. (2001) reported that *Cryptosporidium* does not regain infectivity after inactivation by UV light.

7.3.2 Required dose

The UV dose response of a micro-organism is a measure of its sensitivity to exposure to UV light and is unique to each micro-organism. UV dose-response is determined by irradiating water samples containing the micro-organism with various UV doses and measuring the concentration of viable infectious micro-organisms before and after exposure. The resultant dose response curve is a plot of the resultant log inactivation of the organism versus the applied UV dose rate.

Figure 7.2 sets out typical dose response curves for some common water borne bacteria and viruses.



From USEPA UV Guidance Manual 2006

Figure 7.2 Typical Dose Response curves

If UV is being installed for primary disinfection, the dose must achieve adequate inactivation of a range of pathogens. The Austrian ONORM standards, which apply to UV equipment intended for the disinfection of potable water, justify the stipulated dose of 40 mJ/cm^2 on the grounds that it assures 'a 6-log-reduction of health-related water transmittable bacteria, and a 4-log-reduction of health-related water transmittable viruses… according to the state of the art'.

Most proprietary UV reactors at the smaller end of the UV disinfection duty range (i.e. <5000m^3/day) are validated in accordance ONORM or DVGW protocols for a dose of 40mJ/cm^2. For such reactors validated only for a dose of 40mJ/cm^2, log inactivation theory is not directly applicable as the validated UV packages sold will provide all the necessary log removal for most water disinfection applications.

However if UV is being installed specifically as a barrier to *Cryptosporidium* or some other pathogen, then, using USEPA validation protocols, it may be justifiable to select the dose given in Table 7.2 for the particular log inactivation determined by site specific catchment risks and clarification capability or otherwise of the treatment process, upstream of UV disinfection.

7.3.3 By-product formation

UV by-products of potential concern for water supply arise primarily from reaction of UV at wavelengths below 240 nm with organics or nitrate in the water (von Sonntag and Schuchmann, 1992). Natural organics can be broken down by UV to produce more biodegradable material such as aldehydes or carboxylic acids, which may cause problems with biofilm growth in distribution.

Potentially, the natural organics can be changed such that they react more readily with chlorine to form chlorination by-products such as trihalomethanes (THMs) or haloacetic acids (HAAs). However, according to the USEPA UV Manual, at disinfection dose levels such organic by-products are not an issue, which is supported by the results of Liu et al (2002) and Kashinkunti et al (2004).

Nitrite can be formed by reduction of nitrate by UV light at wavelengths below 225 nm. As well as being subject to regulatory control, nitrite can significantly increase the chlorine demand of water. Nitrite formation is related to the use of MP lamps, because of the wider range of wavelengths emitted, and not with LP lamps where almost all of the output is around 254 nm.

MP lamps used for water treatment usually include sleeves which screen out the lower wavelengths which produce nitrite. This should also reduce the potential for organic by-product formation from lower wavelength UV. Research by Sharpless and Linden (2001) and IJpelaar et al (2003) has supported the conclusion that MP UV is unlikely to cause a problem of nitrite production at disinfection dose levels.

Work carried out for DWI in 1997-8 identified the same by-products as the studies referred to above. The conclusions were that nitrite and biodegradable organics were only likely to be a problem at UV doses of 100mJ/cm^2 or more. No impact of UV on chlorination by-products or nitrogen-containing by-products (including nitrosamines) was identified. However, UV irradiation of groundwater containing very high levels of tetrachloroethene produced the HAA dichloroacetic acid at concentrations above the WHO Guideline Value with UV doses of 100mJ/cm^2.

7.4 Water quality issues affecting the performance of UV disinfection systems

Water quality at the inlet of a UV reactor can impact the performance in three respects:

- how readily UV light is transmitted through the water as measured by UVT, coupled with potential shielding of microorganisms from the radiation;
- potential reduction in UV intensity by fouling of the quartz sleeves;
- upstream treatment processes and addition of oxidants.

Thus water quality must be reviewed at any site where UV is being considered. To allow for seasonal variation, sampling data for surface waters and groundwater subject to surface water contamination should be available for at least one year.

7.4.1 UV transmittance of water

The main water quality parameter used to specify UV disinfection systems and by which the performance is judged is UV transmittance (UVT) as defined previously on Section 3.7.2.

Reduction in the UV transmittance of the water, as measured by UVT, is caused by the scattering and absorbance of UV in the water consequent to the following:

- natural organic matter or the fraction of TOC in the water in the form of particulate matter (such as suspended solids, turbidity or colour)
- the fraction of TOC in the water in the form dissolved organic carbon)in the water
- inorganic chemical compounds such as iron and nitrates.

UVT is related to UV absorbance, usually for a path length of 1 cm:

$$\mathrm{UVT} \quad 00 \times 10^{A}$$

where UVT = UV transmittance, % and

A = absorbance at defined wavelength (254 nm) in 1 cm cell.

UVT can therefore be calculated from the standard laboratory measurement of UV absorbance, making a correction for the path length where appropriate. It can be seen from the above relationship that, whereas absorbance is proportional to path length, UVT is not. To convert between UVT measured at different path lengths:

$$UVT_z = 00\left[\frac{UVT_y}{100}\right]^{z/y}$$

where UVT_z, UVT_y = UVT in path lengths z, y, %

The German standard gives guideline values of UV_{254} absorbance ≤ 10 m^{-1} and UVT (1 cm) ≥ 70.8%. Norwegian regulations require UVT (1 cm) ≥ 78.6% (Lund, 2009).

Although turbidity affects the UVT of the water to be treated, there is no direct correlation between turbidity and the effectiveness of UV dosages; any link between turbidity and UVT will depend on the extent to which turbidity scatters the UV light rather than absorbing it and this can differ between waters.

UVT readings are usually higher and more stable for waters abstracted from ground water aquifers compared with waters abstracted from surface waters. Groundwater wells/boreholes in limestone areas are more susceptible to seasonal variation due to contamination from the surface. Slow sand filtration due to their ineffectiveness at reducing the smaller particulate organic matter (i.e. colour) and the dissolved organic carbon fraction often do not achieve the UVT levels required for effective use of UV disinfection.

On the other hand, well operated coagulation based treatment processes are effective at removing particulate matter and reducing dissolved organic carbon. Water treated by such coagulation/filtration based treatment process typically achieves UVT levels above 85%.

Typically UV reactors should be designed for installation as part of a treatment process following filtration, based on analysis of a programme of sampling. This testing of samples should identify the worst case UVT, taking account of seasonality of surface water quality and the proven ability of the pre-filtration process to reduce colour, turbidity and other chemical constituents.

Design of UV systems needs a representative range of data for UV absorbance, taking into account seasonal influences. There are reported examples of systems being installed with insufficient data, and not being able to achieve the design dose at times of low UVT.

The historical record of UVT for the water to be treated by UV is one of the most important parameters in the design of UV reactor systems. UVT testing can be cheaply carried out as part of routine sampling programmes using a spectrophotometer which is a standard provision in most modern laboratories. The UVT record should ideally be a minimum of one year duration and include any seasonal spikes; this data will help to identify the need or otherwise for process augmentation upstream of the UV reactor. If a full year's UVT monitoring is not possible, then grab samples of the process water or treated water to be subjected to UV irradiation should be tested during a range of weather conditions. It may be possible to use correlations with colour or TOC to fill gaps in historic data for UV absorbance and UVT.

The importance of proper UV reactor design and procurement is borne out by the fact that, for every 5% decrease in UVT, only half the volume of water can be disinfected using the same predetermined dosage rate.

7.4.2 Fouling of the lamp's quartz sleeve

Compounds present in the water can foul the external surfaces of the lamp sleeves and other wetted components of UV reactors which can reduce the applied UV intensity and consequently disinfection efficiency.

The fouling of the sleeve which encapsulates the UV lamp can occur due to other chemical parameters in water to be treated resulting in blocking of the UV light. While variations in pH and temperature are not known to affect the UVT of water, iron and hard water can cause accumulation of mineral deposition on the quartz sleeves that encapsulate the UV bulbs within UV reactors.

This inorganic fouling is a complex problem related principally but not only to hardness and iron levels in the water, resulting in the accumulation of coatings on quartz sleeves. Hard waters have greater fouling potential particularly from compounds for which solubility decreases with increasing temperature e.g. $CaCo_3$, $CaSo_4$, $MgSO_4$, $Al_2(SO_4)_3$ and from oxidation by-products and precipitation of inorganic constituents within the water to be treated.

Waters containing high concentrations of iron (more than 0.1 mg/l), hardness (greater than 140 mg/l as $CaCO_3$), hydrogen sulphide and organics are more susceptible to fouling, and effective cleaning regimes are needed. Recorded levels above 0.5 mg/L iron may require sleeve chemical cleaning every few days particularly for higher temperature MP systems. The German standard gives guideline values for iron (≤ 50 g/l Fe), manganese (≤ 20 g/l Mn). and 'calcite precipitation capacity' (≤ 50 mg/l $CaCO_3$).

Mechanical wipe and chemical cleaning systems for lamps and UV sensors within the reactors should be a critical part of the UV system specification. Cleaning frequency varies in accordance with the chemistry of the water and the lamp type.

7.4.3 Upstream treatment processes and addition of oxidants

Total organic carbon consisting of particulates and colloidal matter in water (i.e. turbidity and colour) together with dissolved organic fraction affect the performance of UV reactors. The former shelters pathogens from UV radiation and scattering UV light while the latter increases the absorbance of UV light as it passes through the water

The current Advice Note no 5 from the EPA recommends “that treatment plants should be optimised to obtain a turbidity level of <0.2 NTU in the final water” “where there is a risk of the presence of *Cryptosporidium* in the raw water”. Where the turbidity levels are above 0.2 NTU and/or TOC levels are in excess of 2-3 mg/litre, supplementary process modifications to clarify the water, upstream of UV disinfection, may be necessary to significantly improve the performance of UV reactors. Maximising the UVT by upstream treatment can optimize the design capital cost and operating costs of the UV reactors.

Coagulation/filtration processes remove natural organics and particulate matter in water resulting in higher UVT levels and a consequent reduction in both the power requirements and operating costs of UV systems.

Oxidants such as ozone and chlorine increase UVT and oxidise precipitating metals such as iron and manganese. However, residuals of treatment chemicals such as ozone and potassium permanganate in the water reaching the UV reactor can also reduce UVT. Activated carbon removes soluble organics and oxidation by-products.

Caution should be exercised when proposing UV disinfection systems downstream of slow sand filtration due to the fact that slow sand filters alone do not remove all colour or the dissolved organic fraction in raw water. As these parameters affect UV absorbance and conversely the UVT of the water, slow sand filtration may not yield a low enough UVT or a stable UVT following changes in raw water quality.

When used as a disinfection process with chlorination, UV disinfection systems should always precede chlorine addition due the reduction in chlorine residual levels consequent to UV irradiance. The positioning of UV reactors upstream of chlorination systems may also reduce chlorine demand of the water to be treated and ultimately reduce dosage rates and consequently operating costs/ THM production. In cases where UV treatment preceeds chlorination, secondary chlorination is being practiced and there is there no requirement for a minimum Ct, however the chlorine dose applied should ensure that **at least 0.1 mg/l free residual chlorine is present at the extremities of the distribution network**.

7.5 The specifications and design of UV disinfection systems

Before specifying a UV disinfection system for use as part of a treatment process for the production of treated potable water, a number of key design decisions should be taken regarding the proposed installation and its configuration within the treatment process, namely:.

- An analysis of water quality data should be undertaken to determine if appropriate pre-treatment is needed to;-
  - remove turbidity,
  - control UVT by reducing colour and dissolved organic carbon fractions of organic matter in the water

- reduce potential for quartz sleeve fouling.

Such design decisions should be made based on a record of water quality data which should ideally include a minimum of 1 years UVT reading of the process water to be treated.

- The UV dose to achieve the required log inactivation of the target organisms should be determined by a risk assesement based on site specific catchment and treatment risks . This UV dose should take account of risk and prevalence of *Cryptosporidium* in untreated water and the role of UV disinfection as part of a multi-barrier approach to pathogen control in the treated water supply.
- The establishment of maximum and minimum flow rate through the reactor(s) is vital to facilitate the accurate sizing of the UV reactor based on manufacturer's literature and the attendant system validation certification. The establishment of minimum UVT and maximum flow rate for the installation is vital to ensure that the required dose (in accordance with validation certification) is applied to the water based on the worst case design condition.
- Establish, by consideration of process throughput and process tank storage/contact volume downstream, the need for standby redundant reactor(s) to allow for UV disinfection system breakdown and/or maintenance. The hydraulic retention time of downstream water storage should be established. A standby reactor may not be required if this storage is adequate to permit shut down of the treatment plant or remote disinfection station for the timescale necessary to effect necessary maintenance works on UV reactors and associated instrumentation, without disruption or compromise of supply to consumers.
- UV lamps contain mercury vapour, a hazardous substance that will be released if a lamp is broken. Used lamps are listed (20 01 21) as hazardous waste in the European Hazardous Waste List (Council Decision 94/904/EEC). Due to the vulnerable nature of UV lamps and their enclosing quartz sleeves, UV reactors are best placed in gravity pipelines where debris is absent, operating pressures are low and where the risk of water hammer is slight.
- Consequent to the foregoing vulnerability of UV reactor components, the inclusion of UV disinfection systems in high lift rising mains, with the risk of appreciable water hammer consequent to sudden pump shut down is not recommended
- Available space and hydraulic gradient as part of the hydraulic profile of the installation should be determined in advance to allow for the head losses associated with reactors and the pipe manifold configuration without affecting daily treatment process production

7.6 Dose validation

7.6.1 Why dose validation is needed

With chemical disinfection it is possible to continuously monitor process performance by real-time measurement of chemical residual and inferred contact time. The combination of chemical residual and contact time, defined by the Ct value, is an operational surrogate for disinfection efficacy.

UV does not leave a residual, so there is no directly equivalent means of continuously monitoring the disinfection efficacy of UV reactors. If the UV intensity in a reactor were uniform, dose could be estimated from the residence time distribution and the intensity (equivalent to the Ct for chemical disinfectants). However, the UV intensity varies within reactors. Microorganisms passing through a reactor do not all receive the same dose, because of variations in trajectory and residence time arising from the reactor's hydraulics as well as the variation in UV intensity. Both are functions of the reactor design.

A process of dose validation is therefore required, by which suppliers must demonstrate that a UV reactor will apply a target dose under defined operating conditions, to provide the necessary confidence that an installed reactor will perform as intended. This is usually undertaken by independent third party testing facilities for UV reactor manufacturers in respect of their different models of UV reactors.

A number of validation standards have been devised, most notably:

- Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule, EPA 815-R-06-007, November 2006 (hereafter referred to as the USEPA UV Manual);

- Plants for the disinfection of water using ultraviolet radiation – Requirements and testing – Low pressure mercury lamp plants, ÖNORM M 5873-1, March 2001; (hereafter collectively referred to as the Austrian standards).

- Plants for the disinfection of water using ultraviolet radiation – Requirements and testing – Part 2: MP mercury lamp plants, ÖNORM M 5873-2, August 2003

- German standard, in three parts (W 294-1, -2 and -3, DVGW / DIN, June 2006), the requirements of which are similar to the Austrian standards (hereafter, equivalence is implied unless stated otherwise).

- NSF/ANSI Standard 55 validation protocol for smaller domestic and commercial UV disinfection units. Class A units validated under this protocol deliver a 40 mJ/cm^2 UV dose at the alarm set-point and offer a 4-log reduction (99.99%) in bacteria, virus and protozoan cysts *(Giardia lamblia* and *Cryptosporidium*).

Common to these standards is the requirement to validate performance using biodosimetry.

It is recommended that proprietary UV disinfection systems used for either general spectrum disinfection of waterborne pathogens or *Cryptosporidium* inactivation as part of a treatment process should possess dose validation certification based on biodosimetry and testing by an independent third party certification company in accordance with any of the above (or alternative equivalent) validation standard.

Unvalidated UV disinfection systems that have already been installed by WSAs can be validated retrospectively. The UV disinfection system will need to be taken offline for period of time and biodosimetry can be used to obtain a dose response curve. However this process can be difficult.

7.6.2 Principles of biodosimetry

Biodosimetry is a procedure in which the full-scale UV reactor is challenged with a non-pathogenic surrogate test microorganism under a range of operating conditions (e.g. flow rate, lamp output, UVT). There are two principal steps, as shown in Figure 7.3 below:

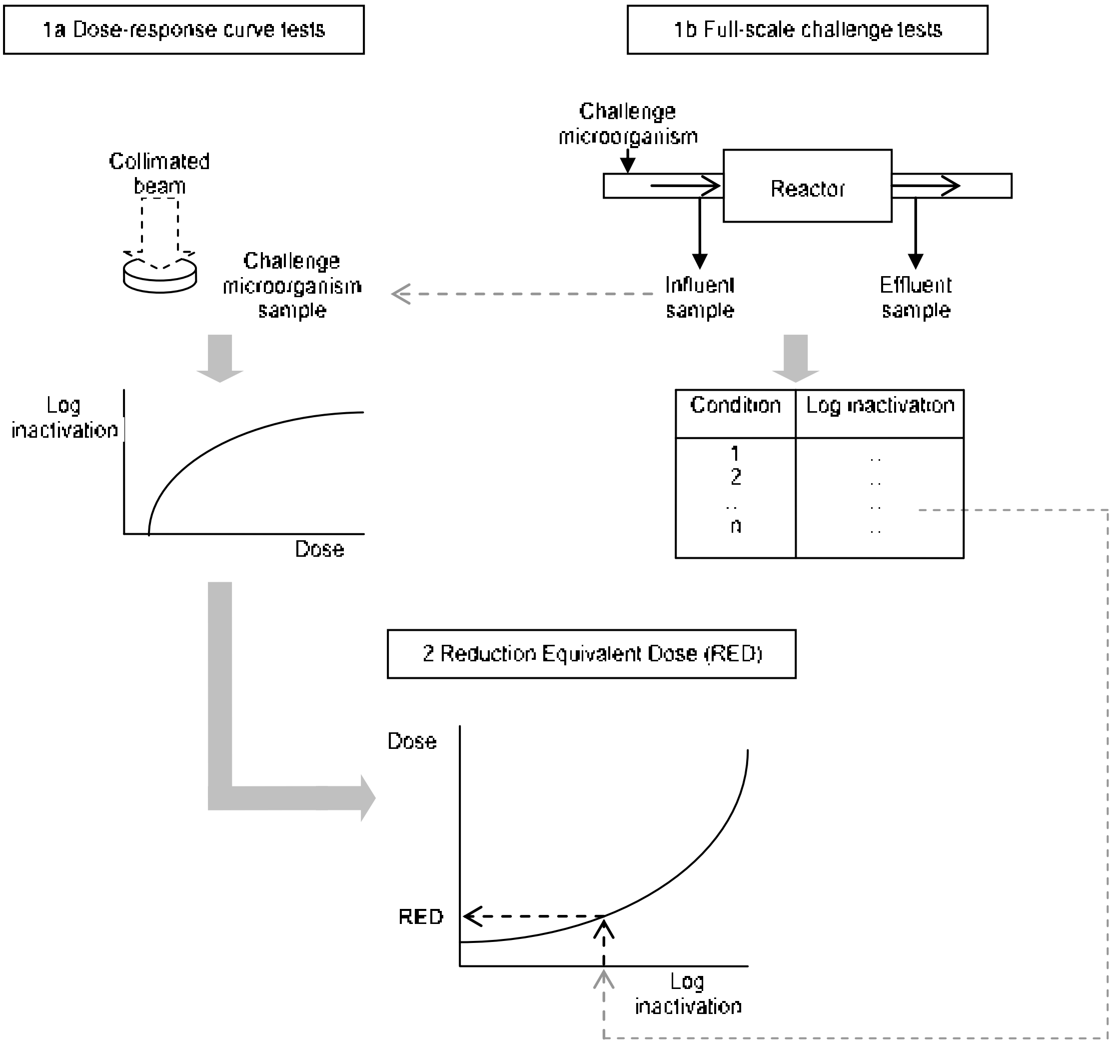


Figure 7.3 Principal steps of biodosimetry.

1. Two experimental tests are performed:
    a) The UV dose-response curve (log inactivation as a function of dose) is determined for the surrogate microorganism using a laboratory collimated beam reactor.
    b) The full-scale reactor is challenged with the surrogate microorganism under a defined matrix of operating conditions, and the log inactivation determined for each set of conditions.
2. The dose-response curve from 1(a) is then used to find the effective dose that corresponds to each log inactivation observed in 1(b) (this effective dose is termed the Reduction Equivalent Dose, RED, in the USEPA UV Manual, and Reduction Equivalent Fluence, REF, in the Austrian standards).

The foregoing validation standards require that UV reactor validation testing must certify that systems meets target log inactivation requirements under the specified design criteria which are varied during the test and include:

- Water UVT
- Flow rate
- UV intensity
- Lamp configuration
- Simulated end of lamp life

7.6.3 Differences between systems validated to USEPA UV Manual and Austrian standards

The Austrian standards specify the surrogate microorganism to be used, and require that the derived RED values are 40mJ/cm^2, under stated operating conditions. This validation certification is based on the broad spectrum use of UV for the inactivation of bacteria, viruses and protozoan pathogens commonly in use in Europe for the disinfection of deep aquifer ground waters without the use of attendant chlorination.

The approach taken by the USEPA UV Manual is designed to validate a target inactivation of a given pathogen under stated operating conditions. It does not specify the surrogate microorganism to be used. This complicates interpretation of the derived RED values, because UV sensitivity influences how microorganisms respond when passing through a reactor. Bias factors (tabulated in the Manual) that make allowance for these differences must be applied to obtain a Validated Dose from each RED. These factors are specific to the target pathogen and the target inactivation of that pathogen.

The USEPA do not specify the dosage rate and can facilitate the inactivation of a targeted pathogen depending on the disinfection goal determined by the risk based approach associated with the LT2ESWTR.

In countries like Ireland and the UK where

- surface water sources predominate with attendant pre-treatment ahead of disinfection
- supplies are almost always chlorinated to quality assure water to the consumers tap
- UV is predominately used as a barrier to *Cryptosporidium*

it may be valid, considering Table 7.2 above that a lower UV dose may be acceptable for such UV disinfection systems which are specifically used as a barrier to *Cryptosporidium* only.

The need for verification of UV systems for *Cryptosporidium* inactivation only is easily achievable using USEPA validated systems based on the calculated dose approach, discussed in Section 7.7.1 below. The use of UV systems, based on German or Austrian validation protocols at 40mJ/cm^2 and the UV Intensity dose approach, discussed in Section 7.7.1 below, are not readily verifiable for dose rates less than 40mJ/cm^2.

7.7 Operation, monitoring and verification of UV disinfection systems

7.7.1 Dose control

Two alternative approaches can be used to control the UV dose, as illustrated in Figure 7.4.

The **UV intensity set point approach** relies on UV intensity (UVI) readings by UV sensors to change the lamp output in the UV reactor in response to changes in UVI and the flow rate. This is essentially feedback control, with built in allowance for ageing of the lamps over time.

Control of the UV reactor can be based on a single set point to maintain the UV intensity at the UV sensors at predetermined levels; or a variable set point approach to allow the intensity to be varied with changing flow rates to maintain the desired dose. A single set point is simpler to implement, but a variable set point is more energy efficient as it can be reduced at low flow (with longer contact time in the reactor).

In the **Calculated Dose approach**, the required UV dose is estimated using a dose-monitoring equation, based on flow rate, UV intensity measurement, UVT and lamp status. This is essentially feed forward control with a feedback component (UV intensity), and sets the lamp output to maintain the required dose under varying conditions of flow and water quality.

This approach requires a greater complexity, but offers more flexibility in maintaining an appropriate targeted dose in an energy efficient way.

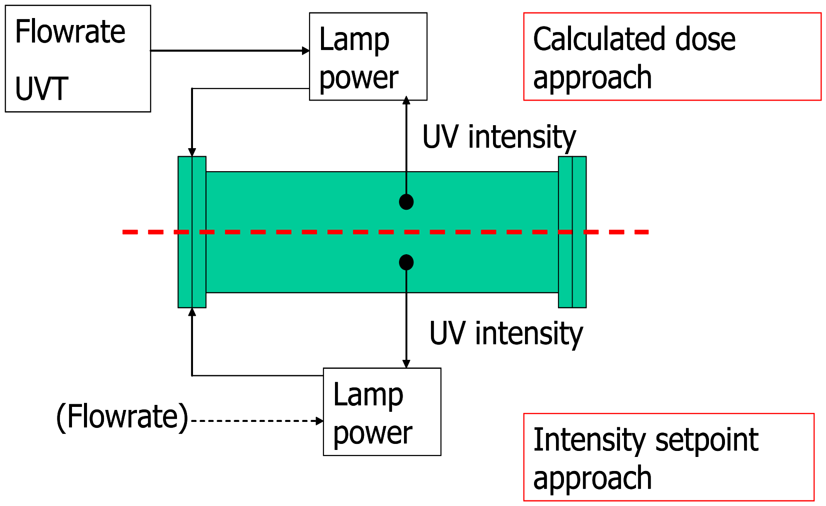


Figure 7.4 Approaches for UV dose control

The status of each individual lamp should be monitored and alarmed in the case of failure, and burn time recorded. Lamps should be replaced when burn time reaches the limit recommended by the supplier.

Further practical guidance on the uses and relative merits of both dose monitoring approaches in operation is included in Appendix 2.2.

7.7.2 Sleeve cleaning

How often quartz sleeves need to be cleaned will depend on the factors noted in Section 7.4.2 above including the quality of the water being treated, the water treatment chemicals used prior to disinfection and the arrangements for cleaning the sleeves. Cleaning systems are proprietary, and may include chemical and physical mechanisms or a combination of the two, and can be on-line or off-line.

7.7.3 Monitoring of system operation

Validation testing determines a set of operating conditions for flow, UVT and UV intensity that can be monitored by a Water Services Authority to ensure that actual installations are operated within the specified parameters, consistent with the validation certificate, to ensure that the UV dose necessary for the required pathogen inactivation is delivered at all times.

A UV system is capable of continuous use if the simple routine maintenance is performed at regular intervals. By checking the following items regularly, the operator of a UV system can determine when maintenance is needed:

- check UV sensor for significant reduction in lamp output;
- test the UV sensor(s) against reference instruments in accordance with supplier's instructions to ensure reliability of UV intensity readings;
- monitor process for major changes in normal flow conditions such as incoming water quality and UVT;
- check for fouling of quartz sleeves and UV intensity monitor probes;
- check indicator light display to ensure that all of the UV lamps are energized;
- monitor elapsed time meter, microbiological results and lamp log sheets to determine when UV lamps require replacement; and
- check quartz sleeves for discoloration. This effect of UV radiation of the quartz is called solarization. Excessive solarization is an indication that a sleeve is close to the end of its useful service life. Solarization reduces the ability of the sleeves to transmit the necessary amount of UV radiation to

the process.

Further practical guidance on the monitoring and verification of UV disinfection systems in operation is included in Appendices 2.2 and 2.3.

Domestic or commercial units, validated to NSF/ANSI Class A protocols, are required to have a UV sensor with a visual and/or auditory alarm when the proper 40mJ/cm^2 dose is not being transmitted through the water flow.

There is a possibility of compromised performance for a period of time during start up (e.g. as the bulb warms up). The WSA should be aware of any such period of time and should not put water treated during this period into supply.

7.8 Summary of advantages and limitations of UV disinfection systems

When considering the appropriateness or otherwise of UV as a primary disinfection method or as a supplementary process to deal with a specific risk micro-organism, it is useful to summarise the advantages and limitations of the UV disinfection systems compared to alternative technologies.

7.8.1 Advantages of UV disinfection

- As can be seen from Figure 7.2 above, bacteria and pathogenic protozoa such as *Cryptosporidium* are inactivated readily at low UV doses with higher doses required for virus inactivation.
- UV disinfection, unlike chlorination, ozonation and chlorine dioxide, at the current reduction equivalent dose (RED) of 40mJ/cm^2, does not result in the formation of organic disinfection by-products.
- The inclusion of a UV disinfection system within a treatment works requires a small space requirement for the reactors, and associated instrumentation and ballast panels
- A reduction in the chlorine demand of the water is often experienced downstream of UV disinfection
- The capital costs of UV disinfection systems are much lower than ozonation and membrane filtration and for medium to large installations roughly follow the ratio of 1(UV): 5(ozonation): 10 (membranes)
- Similarly operating costs of UV systems for medium to large installations follow a corresponding cost ratio comparison of 1(UV): 3(ozonation): 8 (membranes)

7.8.2 Limitations of UV disinfection

- UV disinfection does not leave a residual in treated water and so offers no protection against re-infection in distribution pipework
- UV disinfection is unsuitable for use on treated surface influenced waters or groundwater sources that have a UVT (1 cm) of less than 75%, based on a comprehensive sampling record which includes seasonal variations in water quality.
- UV disinfection is limited in dealing with chemical impurities in waters as it does not remove colour or oxidise iron or manganese present in water. Consequently UV disinfection is only suitable on high quality groundwaters which do not require treatment or on final process waters which have reduced particulate matter, organics or chemical impurities following treatment
- UV radiation has no effect on taste or odour issues should they arise in the water to be treated
- The only potential by-product formed by UV is the formation of nitrite from the reaction of UV irradiance at a wavelength below 240nm with nitrate in water, which poses a potential problem for MP systems only, as LP and LPHO systems transmit monochromatic UV light at 254nm only. However proprietary MP systems usually include quartz sleeves that filter out the small portion of the UV spectrum in the lower frequency thereby eliminating the possibility of by-product formation in MP systems.

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8. MANAGING MICROBIAL RISK AND DISINFECTION

Managing microbial risks in water supply relies primarily on:

- identifying catchment risk and, as far as possible, applying control measures to mitigate the risk,
- ensuring that treatment and disinfection systems are designed to deal effectively with expected microbial loads and raw water quality,
- monitoring and control of treatment to ensure that operating conditions maintain the design capabilities,
- prevention of microbial contamination in distribution and customer premises.

This is consistent with the Drinking Water Safety Plan approach for water supply risk management, outlined below.

8.1 Drinking Water Safety Plans

Drinking Water Safety Plans (DWSPs) are a risk-based approach to managing water quality designed to ensure delivery of safe drinking water in terms of both quality and quantity. They were originally outlined in the 3rd Edition of Guidelines to Drinking Water Quality published by the World Health Organisation in 2004, which states that “The most effective means of consistently ensuring the safety of a drinking-water supply is through the use of a comprehensive risk assessment and risk management approach that encompasses all steps in water supply from catchment to consumer”. Drinking Water Safety Plans have been adopted by many countries.

In 2010, the Office of Environmental Enforcement in their “Handbooks on the Implementation of the Regulations for Water Service Authorities for Public and Private Water Supplies”

advise that

“The EPA regards the implementation of the WHO recommendations by WSAs as part of a robust DWSP as a key measure to ensuring the delivery of a safe and secure water supply. The EPA recommends that WSAs adopt the DWSP approach to ensuring safe and secure water supplies.”

DWSPs require a whole system assessment from catchment, through treatment and distribution and to the customers tap. By knowing what is in the catchment, it is possible to understand the source water for a works and target treatment effectively. Network operations and customer education will help to prevent deterioration of the delivered water. Source to tap pathways will exist for chemical as well as microbiological risks.

The aim of a DWSP is to consistently deliver a safe supply of drinking water which has the trust of the customers. In order to deliver a DWSP, the following steps need to be followed:

- Identify people required to set up the DWSP team and decide on an appropriate methodology for DWSP development.
- Identify all the hazards and hazardous events that can affect the safety of a water supply from the catchment, through treatment and distribution to the customers tap.
- Assess the risk presented by each hazard and hazardous event.
- Identify significant risks and assess if controls or barriers are in place.
- Validate the effectiveness of controls and barriers (i.e. identify if any significant risks exist despite all controls and barriers working).
- Identify action plan to reduce risks to an acceptable level.
- Demonstrate that the system is consistently safe.
- Review and update the hazards, risks and controls if necessary.

- Keep accurate records for audit and justification of outcomes.

This approach is illustrated in Figure 8.1.

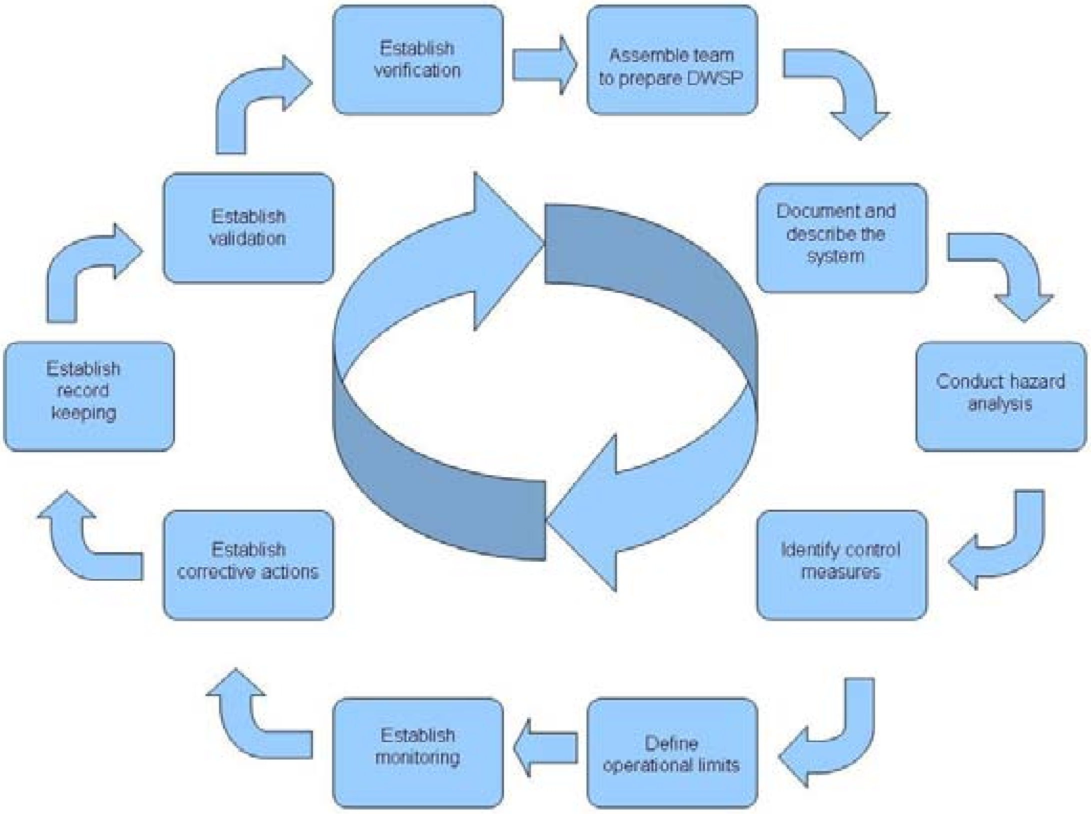

Figure 8.1 Drinking Water Safety Plan Methodology

In risk assessment, risks are usually defined as the frequency or likelihood of a particular hazard or event, couple with the consequence of that event if not adequately identified and prevented. A common way of ranking risk is through a scoring system which categorises the likelihood and consequence separately, and combining these in a frequency/consequence matrix, Table 8.1, an example of this, taken from the WHO manual, to provide a way of identifying the highest risks and prioritising mitigation measures within the system. Within a DWSP approach, this would normally be carried out for catchments, treatment, distribution and customer premises.

Table 8.1 Example frequency/consequence matrix from WHO Water Safety Plan Manual

	Severity or Consequence					
Likelihood or frequency		**Insignificant or no impact – Rating: 1**	**Minor compliance impact – Rating: 2**	**Moderate aesthetic impact – Rating: 3**	**Major regulatory impact – Rating: 4**	**Catastrophic public health impact – Rating: 5**
	Almost certain / once a day – Rating: 5	5	10	15	20	25
	Likely / Once a week – Rating: 4	4	8	12	16	20
	Moderate / Once a month – Rating: 3	3	5	9	12	15
	Unlikely / Once a year – Rating: 2	2	4	6	8	10
	Rare / Once every 5 years – Rating:1	1	2	3	4	5

Based on the rankings shown above, WHO categorise risk as:

- Low, <6
- Medium, 6-9
- High, 10-15
- Very High, >15

Risk factors relating to disinfection to be taken into account in developing DWSPs are listed in Appendix 1.1.

Appendix 1.1 sets out the hazards associated with the catchment, storage, treatment plant, distribution system and other hazards relating to the monitoring, management and control of disinfection systems.

9. GLOSSARY

Absorption:	The incorporation of light source or substance in one state into another substance or organism by molecular chemical or biochemical action
Activated Carbon:	Particles or granules of carbon processed to make them extremely porous and thus to have a very large surface area with a high capacity to selectively remove colour or impurities and chemical compounds from liquids and gases
Adsorption:	Attachment of a substance to the surface of another by molecular biological or chemical action
Algae:	Simple aquatic that may be attached or free floating and occur as single cells, colonies, branched or un-branched filaments in water.
Alkalinity:	The quantitative capacity of water to neutralize an acid; that is, the measure of how much acid can be added to a liquid without causing a significant change in pH. This capacity is caused by the amount of bicarbonate, carbonate, and hydroxide compounds present in the water Alkalinity is not the same as pH because water does not have to be strongly basic (high pH) to have high alkalinity. Alkalinity is usually measured as mg/l (milligrams per litre) of equivalent $CaCO_3$
Assimilable Organic Carbon: (AOC)	See Total Organic Carbon
Bacteria:	Microorganisms, often composed of single cells shaped like rods, spheres or spiral structures, which are ubiquitous in all habitats on Earth including water, and which range in size between 1-5 micrometers (μm).
Baffle.	A flat board or plate, wall, deflector, guide or similar device constructed or placed in flowing water to cause more uniform flow velocities, to absorb energy, and to divert, guide, or agitate water.
Barrier:	A treatment or disinfection process that constitutes an impediment to the transmission of waterborne pathogenic microorganisms or other contaminants to humans in drinking water. The term barrier encompasses treatment and disinfection processes that either remove or inactivate such microorganisms and contaminants.
Biodosimeter :	A surrogate (challenge) micro-organism with sufficient but similar sensitivity to UV as water transmittable microbial pathogens. *Bacillus subtilis* (bacterial spores) and MS2 coliphage (f-RNA virus) have frequently been used as biodosimeters for general UV reactor validation. Increasingly other biodosimeters, such as T1 phage, are being used for the validation of UV reactors used specifically for the inactivation of *Cryptosporidium*.
Biodegradeable Organic Carbon: (BDOC)	See Total Organic Carbon
Biodosimetry:	A procedure used to determine the reduction equivalent dose or fluence (RED or REF) of a UV reactor, involving - the inactivation measurement of a challenge microorganism after exposure to UV light in a UV reactor and - the comparison of the results with the known UV dose-response curve of the challenge microorganism (determined via bench-scale collimated beam testing)

Chlorination:	The process of adding chlorine, in either gaseous or liquid form to water which reacts to form a pH dependent equilibrium mixture of hypochlorite (OCl^-), hypochlorous acid (HOCl) and hydrochloric acid which is capable of inactivating microorganisms in water.
Chlorine residual:	
Free (available):	The amount of chlorine available as dissolved gas (Cl2), hypochlorous acid (HOCl), and hypochlorite ion (OCl–), that is not combined with ammonia (NH3) or other compounds in water. The three forms of free chlorine exist together in equilibrium, the relative portions of which are determined by the pH value and temperature. This is the parameter used which is monitored downstream of contact tank as C for calculation of the Ct value necessary for the verification of primary disinfection systems. Free chlorine residual is also monitored at the end of distribution networks to verify the ongoing efficacy of secondary disinfection systems
Combined:	The concentration of residual chlorine that is combined with ammonia **(**NH_3), organic nitrogen, or both in water as chloramine (or other chloro-derivatives), yet is still available to oxidize organic matter and act as a disinfectant. Combined chlorine can be accurately estimated as the difference between the measured total chlorine and measure or known free chlorine residual.
Total;	Total chlorine residual equal the sum of free chlorine residual and combined chlorine residual
Clarifier:	A large circular or rectangular treatment process tank through which water is passed upwards for a period of time, during which the heavier suspended solids or coagulated floc particles (including colloidal particles bound up therein) are removed from the water. Clarifiers are also called settling tanks and sedimentation tanks.
Coagulation:	The use of metallic salts (e.g, aluminium or iron) and or organic polyelectrolytes to aggregate suspended or colloidal particles, causing them to agglomerate into larger particulate flocs.
Colloidal:	A type of very small, finely divided particulate matter ranging in size from approximately 2 - 1,000 nm in diameter, which can be present in water. Colloids do not settle out rapidly and remain dispersed in a liquid for a long time due to their small size and electrical charge. Repulsion of similarly charged particles can prevent the particles from becoming heavier and settling out.
Colour:	Colour in water may result from a number of sources including metallic ions (iron and manganese), and particulate and dissolved organic material.
(Apparent):	Apparent colour is measured on the sample prior to any treatment and measures not only colour due to substances in solution (see true colour) but also colour due to suspended matter in the water
(True):	True colour, i.e. the colour of a sample from which turbidity has been removed by filtration
	The unit of colour measurement is based on a visual comparison of the colour of the sample to that of a series of standards, usually made with a platinum cobalt solution i.e. the Pt/Co scale
Conductivity:	A water quality parameter of the ability of water to conduct an electric charge and is related to the amount of total dissolved solids (TDS) in the water

Contact Time (t):	The hydraulic residence time, (determined by a tracer test or by a recognised calculation procedure), from the disinfectant dosage point or the disinfectant contact tank's point of entry to the point of exit from the tank.
Conventional Treatment:	A method of treating water which consists of the addition of coagulant chemicals, flash mixing, coagulation, flocculation (not necessarily in separate tanks or basins), clarification, by sedimentation or flotation and filtration, resulting in substantial particulate removal.
Ct:	The product of "residual disinfectant concentration" (C) in mg/l determined before or at the first customer, and the corresponding "disinfectant contact time" (t) in minutes, expressed in mg.min/l. This Ct value is widely utilised in international standards and guidance on disinfection practice for the establishment of target log inactivation for various pathogens and is used in practice to determine the disinfectant concentration" (C) necessary to achieve the target inactivation given the available contact arrangements.
Cryptosporidium:	A disease-causing protozoon widely found in surface water sources. *Cryptosporidium* is spread by the fecal-oral route as a dormant oocyst from human and animal faeces. In its dormant stage, *Cryptosporidium* is housed in a very small, hard-shelled oocyst form that is environmentally robust and very resistant to chlorine and chloramine disinfectants. When water containing these oocysts is ingested, the protozoa replicates within the intestinal tract of the host causing a severe gastrointestinal illness called cryptosporidiosis.
Cryptosporidiosis:	The gastrointestinal illness caused by infection with cryptosporidium.
Disinfectant	Any chemical oxidant, including but not limited to chlorine, chlorine dioxide, chloramines, and ozone which is added to water in any part of the treatment or distribution process and which is intended to kill or inactivate pathogenic microorganisms.
Disinfection	In water treatment, disinfection describes any physical, chemical or non chemical process which removes, kills or inactivates microorganisms in water including pathogens
Disinfection (DBPs):	Inorganic and organic compounds formed by the reaction of the **byproducts** disinfectant with natural organic matter and the bromide ion during water disinfection processes. Regulated DBPs include trihalomethanes, haloacetic acids, bromate, and chlorite
DPD:	A commonly used testing method for the determination of disinfectant levels in water samples based on the addition of DPD (i.e. **N,N Diethyl-1,4 Phenylenediamine).** The intensity of the reddish tint to the water formed in the sample relates directly to the amount of disinfectant such as free chlorine, chlorine dioxide and/or permanganate, present in the sample.
***E. coli*;**	Coliforms, specifically *Escherichia coli (E. coli),* are the universal indicator microorganisms of faecal contamination of water. These bacteria, which are of definite faecal origin (human and animal), are excreted in vast numbers and their presence in a water supply is proof that faecal contamination has occurred and is a definite indication that pathogens may be present.
Epidemiology:	The study of the occurrence and causes of health effects in human populations.
Filtration:	A treatment process for removing particulate matter from water by passage through porous media

Floc:	In drinking water treatment, floc refers to the fine cloud of spongy particles that form in water to which a coagulant has been added. The particles are largely hydroxides, commonly of aluminium or iron. They accelerate the settlement af suspended particles by adhering to' the particles and neutralizing such negative charges as may be present.
Flocculation:	A process to enhance agglomeration or collection of smaller floc particles into larger, more easily settleable particles through gentle stirring by hydraulic or mechanical means following chemical addition of aluminium or iron salts and polyelectrolytes.
Hardness:	Hardness in water, usually expressed in mg/l $CaCo_3$ is the measure of the concentration of dissolved calcium and magnesium salts, particularly carbonates and bicarbonates. There is no health risk associated with hard water, however, it can be difficult to lather and can cause scaling problems in hot water systems
Headloss:	The head, pressure or energy lost by water flowing in a pipe, in a channel or through a tank as a result of turbulence caused by the velocity of the flowing water and the roughness of the pipe, channel walls or restrictions caused fittings. Water flowing in a pipe or channel loses head, pressure or energy as a result of friction losses. The head loss through a filter is due to friction losses caused by material building up on the surface or in the interstices of the filter media.
Hydraulic Retention Time (HRT):	A measure of the average length of time that a liquid remains in a water retaining structure obtained by dividing the tank volume by the influent flowrate.
***Giardia lamblia*:**	Flagellated protozoa, shed with the feces of man and animals. When water containing these cysts is ingested by a new host, the protozoa cause a severe gastrointestinal illness called giardiasis.
Granular Activated Carbon:	The term refers to a) the highly porous adsorbent filter media which is produced by heating coal or wood in the absence of air prior to crushing the material into granulated form approximately 1mm in size b) the constituent element of a water treatment process by which treatment process water is passed through such media. Activated carbon is positively charged and therefore able to remove negative ions from the water such as chlorine and ozone and is recognised as an effective method of reducing dissolved organics and associated taste and odour problems in water by adsorption. Activated carbon must be replaced from time to time as it may become saturated and unable to adsorb
Haloacetic acids	The sum of the concentrations in milligrams per litre of the haloacetic **(HAA5):** acid compounds (monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid, and dibromoacetic acid).
Inactivation:	The effect that the application of a disinfectant has in destroying the cellular structure of pathogenic micro-organisms or in disrupting their metabolism, biosynthesis or ability to grow/reproduce, thereby inhibiting their ability to infect a host and cause human illness or disease.
Inorganic Materials:	Chemical substances of mineral origin, such as sand, salt, iron.
Immuno Compromised:	A person whose natural immunity to infection is not properly functioning due to pregnancy, certain cancers and genetic disorders, diseases such as HIV or AIDS, exposure to immuno-suppressant drugs as part of medical treatment or

	those undergoing chemotherapy or radiation therapy for cancer. Such persons are more prone to more serious infections and/or complications than healthy people.
Log inactivation:	A mathematical measure of microorganisms inactivation consequent to the application of a particular dosage by a given disinfection process, expressed as the log of the relative number of live organisms to unviable organisms remaining after exposure to the disinfection process Percentage reduction of viable organisms is expressed as $\mathbf{[100\text{-}10^{(2\text{-}x)}]\%}$ where x is the log inactivation value One log activation means that 90% of the microorganisms are no longer viable. Two log corresponds to 99%, three log is 99.9% and four log corresponds to 99.99%. Half log inactivation corresponds to a 68.4% inactivation.
Log removal:	The percentage of microorganisms physically removed by a given process.
Log reduction:	The percentage of microorganisms reduced through log removal added to the log inactivation
LP lamp:	Low pressure low output lamp. Such lamps operate at relatively low internal lamp temperatures and mercury vapour pressures, emitting predominantly monochromatic UV radiation at a wavelength of 253.7 nm (as well as in the visible wavelength region). LP lamps contain liquid elemental mercury.
LPHO lamp:	Low pressure high output lamp. Such lamps operate at moderately low internal lamp temperatures and mercury vapour pressures, emitting predominantly monochromatic UV radiation at a wavelength of 253.7 nm (as well as in the visible wavelength region). LPHO lamps contain alloys of mercury and other metals such as indium and gallium.
Micron:	A unit of length equal to one micrometer (µm) i.e. One millionth of a meter or one thousandth of a millimeter.
MP lamp:	Medium pressure lamp. Such lamps operate at relatively high internal lamp temperatures and mercury vapour pressures, emitting polychromatic UV radiation over the wavelength range from 200 to 400 nm (as well as in the visible wavelength region). MP lamps contain liquid elemental mercury.
Monochromatic:	Light output at only one wavelength, such as UV light generated by low-pressure and low-pressure high-output lamps.
NTU;	Nephelometric Turbidity Unit
O.E.L:	The Occupational Exposure Limit means the maximum permissible concentration, of a chemical agent in the air at the workplace to which workers may be exposed
Oxidant:	A substance that readily oxidizes (removes electrons from) something chemically. Common drinking water oxidants are chlorine, chlorine dioxide, ozone, and potassium permanganate.
Pathogens:	Microorganisms that can cause disease in humans, other organisms or animals and plants. They may be bacteria, viruses, or protozoa and are found in sewage, in runoff from animals, farms or rural areas populated with domestic and/or wild animals, and in water.

	There are many types of microorganisms which do not cause disease. These microorganisms are called non-pathogenic.
pH:	pH is an expression of the intensity of the basic or acid condition of a solution. Mathematically, pH is the negative logarithm (base 10) of the hydrogen ion concentration, [H+]. [pH = log (1/H+)]. The pH may range from 0 to 14, where 0 is most acidic, 14 most basic, and 7 neutral. Naturally occurring waters usually have a pH between 6.5 and 8.5.
Plug flow:	The travel of water through a tank, pipe, or treatment process unit in such a fashion that the entire mass or volume is discharged at exactly the theoretical detention time of the unit.
Photorepair:	A microbial repair process where enzymes in micro-organisms are activated by light in the near UV and visible range, thereby repairing UV induced damage. Photoreactivation requires the presence of light
Polychromatic:	Light energy output at several wavelengths such as with MP lamps
Primary Disinfection:	The treatment process element where a chemical or non-chemical disinfectant is used to achieve the necessary microbial inactivation of pathogenic microorganisms in water
Precursors: (to disinfection byproducts)	Organic and inorganic impurities that can be converted into disinfection by-products following addition of a disinfectant. For chlorination systems, precursors are constituents of natural organic matter, comprising suspended solids, turbidity, colour and dissolved organic carbon. In addition, for ozonation systems, the bromide ion (Br-) is a precursor material.
Reduction Equivalent Dose (or Fluence) (RED or REF):	The UV dose (fluence) derived by entering the log inactivation of the surrogate or challenge microorganism measured during full- scale reactor testing into the UV dose response curve that was derived for the microorganism through laboratory collimated beam testing.
Spp.	spp." Is an abbreviation used in biological classification meaning unspecified species (plural) of a genus.
Secondary Disinfection:	The application of a chemical disinfectant at the end of a treatment system or at some appropriate point along the distribution network to maintain the disinfection residual throughout the system to consumers.
Slow Sand Filtration:	A filter that consists of a bed of fine sand and relies on a biologically active layer on top of the sand, called *Schmutzdecke*, to filter out particles. The filtration rate is much slower (generally less than 0.4 m/h) than the rate used for rapid granular media filtration.
Solarization:	A change in the structure of a material due to exposure to UV light that increases light scattering and attenuation.
Specific ultra absorbance (SUVA):	SUVA is determined by dividing the measured UV absorption of the water violet at 254 nanometer (in m-1) by the measured DOC concentration of the water (in mg/L). SUVA analysis of water can indicate whether the organic matter in water is predominantly hydrophobic or hydrophilic and whether potential exists for the removal by coagulation processes of remaining natural organic matter in the water. Hydrophilic compounds have lower SUVA than hydrophobic compounds which are easier removed by coagulation processes

Sterilisation:	The removal or destruction of <u>all</u> microorganisms, including pathogenic and other bacteria, vegetative forms and spores
Surface water:	Surface water is defined as all water open to the atmosphere and produced by run-off of precipitation and by groundwater seeping through the top layers of soil. Surface water can be running (as in streams and rivers) or quiescent (as in lakes, reservoirs, impoundments and ponds).
Taxonomic:	Related to the practice and science of the biological classification of living organisms
Total Organic Carbon (TOC):	Total organic carbon (TOC) is used as a measure of the amount of natural organic matter (NOM) in a water sample and is important due to its role as a major precursor to disinfection by-products. Total organic carbon in source waters originates primarily from decaying natural organic matter (such as humic acids, fulvic acid, amines, and urea) but also from synthetic sources (such as fertilizers, herbicides, industrial chemicals, and chlorinated organics) TOC is measured using heat, oxygen, ultraviolet irradiation, chemical oxidants, or combinations of these oxidants that convert organic carbon to carbon dioxide Total organic carbon consists of two fractions: dissolved organic carbon (DOC) and particulate organic carbon (POC). DOC levels are determined in samples which have been passed through a 0.45 micron filter. Assimilable organic carbon (AOC) and biodegradable dissolved organic carbon (BDOC) are further subsets of DOC in water and are used as indicators of bacterial re-growth potential and disinfection by-product formation potential in water. In raw waters with DOC, the AOC and BDOC fractions are increased in water following oxidation processes such as ozone and require to be removed ahead of subsequent chlorination.
Total Trihalomethanes (TTHM):	The sum of the concentration in milligrams per litre of the trihalomethane compounds (trichloromethane [chloroform], dibromochloromethane, bromodichloromethane and tribromomethane [bromoform]).
Trihalomethane (THM):	One of the family of organic compounds, named as derivatives of methane, wherein three of the four hydrogen atoms in methane are each substituted by a halogen atom in the molecular structure.
Trihalomethane Formation Potential.	The measurement of THM formation potential of treated water indicates the maximum level of THMs that would occur following addition of chlorine. The test is conducted by adding chlorine to identical water samples at various dosage rates and measuring THMs formed. under similar site specific conditions (pH adjustment, retention time, temperature, etc.).
Tracer:	A foreign substance (such a dye) mixed with or attached to a given substance for subsequent determination of the location or distribution of the foreign substance.
Tracer study:	A study using a substance that can readily be identified in water (such as a dye) to determine the distribution and rate of flow in a tank, pipe, ground water, or stream channel.
Turbidimeter:	An instrument for measuring and comparing the turbidity of liquids by passing light through them and determining how much light is reflected by the suspended particulate matter in the liquid. The normal measuring range is 0 to 100 and is expressed as Nephelometric Turbidity Units (NTUs).
UV Absorbance (A):	A measure of the amount of UV light that is absorbed by a substance (e.g., water, microbial DNA, lamp envelope, quartz sleeve) at a specific wavelength

	(e.g., 254 nm). This measurement accounts for absorption and scattering in the medium (e.g., water).
UV Absorbance (UV_{254}):	A measure of the amount of UV light that is absorbed by a substance at **254 nm** 254 nm
UV Dose: (also UV Fluence)	The UV dose (fluence) is the UV energy per unit area incident on a surface. The dose received by a waterborne microorganism in a reactor vessel accounts for the effects on UV intensity of the absorbance of the water, absorbance of the quartz sleeves, reflection and refraction of light from the water surface and reactor walls, and the germicidal effectiveness of the UV wavelengths transmitted. UV dose (used in USEPA Guidance) is typically reported in units of mJ/cm^2 or J/m^2. UV fluence (used in European standards) is the product of the fluence rate (mW/cm^2) and exposure time (seconds), and commonly expressed in units of mJ/cm^2 or J/m^2 (where 1 mJ/cm^2 = 1 mWs/cm^2 = 10 J/m^2).
UV Intensity: (also called UV Fluence Rate)	The **term** UV intensity (fluence rate) is the power passing through a unit area perpendicular to the direction of propagation of UV light and in the operation of UV reactors is also the magnitude of UV light measured by UV sensors in a reactor .
UV Lamp Status:	A parameter that is monitored during validation testing and during long-term operation of UV reactors that indicates whether a particular UV lamp is on or off.
UV Light:	Light emitted with wavelengths from 200 to 400 nm.
UV Reactor:	the vessel or chamber where exposure to UV light takes place, consisting of UV lamps, quartz sleeves, UV sensors, quartz sleeve cleaning systems, and baffles or other hydraulic controls. The UV reactor also includes additional hardware for monitoring UV dose delivery; typically comprised of (but not limited to): UV sensors and UVT monitors
UV Reactor Validation:	Experimental testing to determine the operating conditions under which a UV reactor delivers the dose required for inactivation credit of bacteria, *Cryptosporidium*, *Giardia lamblia*, and viruses.
UV Sensor:	A photosensitive detector used to measure the UV intensity at a point within the UV reactor that converts the signal to units of milliamps (mA)
UV Transmittance	A measure of the fraction of incident light transmitted through a material (e.g., water sample or quartz sleeve). The UVT is usually reported for a **(UVT):** wavelength of 254 nm and a path length of 1 cm. UVT is often represented as a percentage and is related to the UV absorbance (A_{254}) by the following equation (for a 1-cm path length): % UVT = 100 x 10-^{A}
Vericytotoxinogenic E-coli (VTEC):	Verocytotoxigenic *E. coli* (VTEC) are so-called because of their ability to produce one or both of two verotoxins (VT1 and VT2) which results in severe illness requiring prompt public health action to prevent further transmission. VTEC cause a wide range of symptoms, from mild diarrhoea to hemorrhagic colitis with severe abdominal pain and bloody diarrhoea. Illness is usually self-limiting and resolves after about eight days. A proportion of patients however (approx. 9% of symptomatic Irish cases) develop haemolytic uraemic syndrome (HUS), a life-threatening complication. *E. coli* O157 was the first *E. coli* serogroup to be associated with this distinctive

illness but several other verotoxin-producing *E. coli* serogroups have been reported, including O26, O111, O103 and O145.

VTEC can also be transmitted through contaminated water, the environment, by direct contact with animal carriers or from person to person.

Water Hammer: The phenomenon of oscillations in the pressure of water in a closed conduit flowing full, which results from a too rapid acceleration or retardation of flow. Momentary pressures greatly in excess of the normal static or pumping pressure may be produced in a closed pipe from this phenomenon.