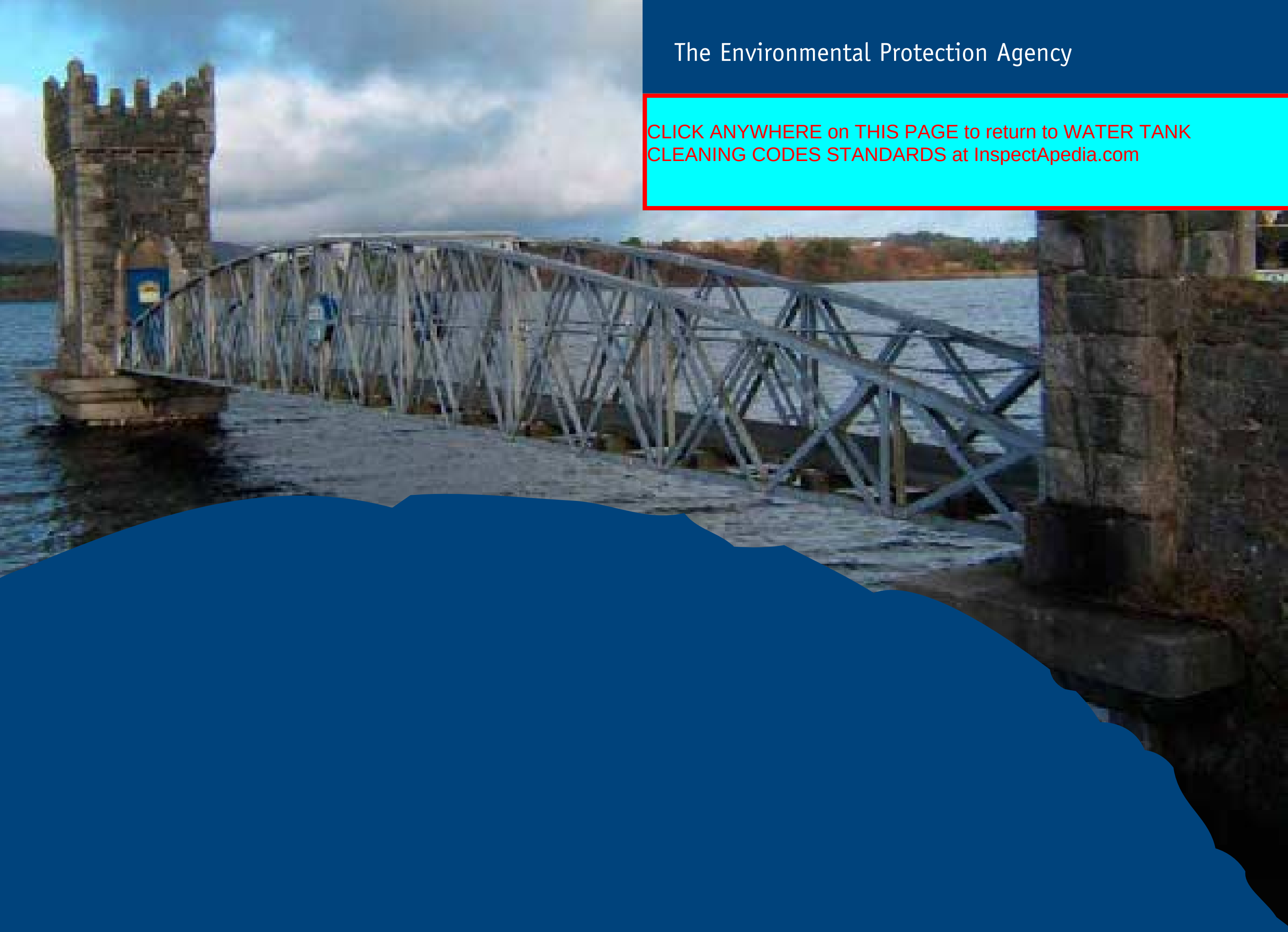

The Environmental Protection Agency

Water Treatment Manual: Disinfection

epa
Office of
Environmental
Enforcement

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.
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- 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.

MONITORING, ANALYSING AND REPORTING ON THE ENVIRONMENT

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- Providing guidance to the public and to industry on various environmental topics (including licence applications, waste prevention and environmental regulations).
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- 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.

Office of
Environmental
Enforcement

WATER TREATMENT MANUAL: DISINFECTION

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PREFACE

The Environmental Protection Agency was established in 1993 to licence, regulate and control activities for the purposes of environmental protection. In the Environmental Protection Agency Act, 1992 (Section 60), it is stated that "*the Agency may, and shall if so directed by the Minister, specify and publish criteria and procedures, which in the opinion of the Agency are reasonable and desirable for the purposes of environmental protection, in relation to the management, maintenance, supervision, operation or use of all or specified classes or plant, sewers or drainage pipes vested in or controlled or used by a sanitary authority for the treatment of drinking water….and a sanitary authority shall…have regard to such criteria and procedures".*

The EPA first published a Water Treatment Manual on Disinfection in 1998. Since the publication of this manual there have been significant developments both in terms of the technology and understanding of the disinfection of drinking water and in the supervisory role of the EPA in the drinking water area. This manual has been prepared to reflect best practice in drinking water disinfection.

The main changes to the manual include:

- Integration of the Water Safety Plan approach through-out the manual;
- A substantial revision of the UV chapter due to the latest research regarding its effectiveness in dealing with *Cryptosporidium*;
- A new chapter on Chlorine Dioxide;
- Updating of the chlorine, chloramination and ozone chapters to reflect current research;
- New appendices to give guidance on practical operational of disinfection systems including troubleshooting;
- A new Appendix on emergency disinfection.

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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 any 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.

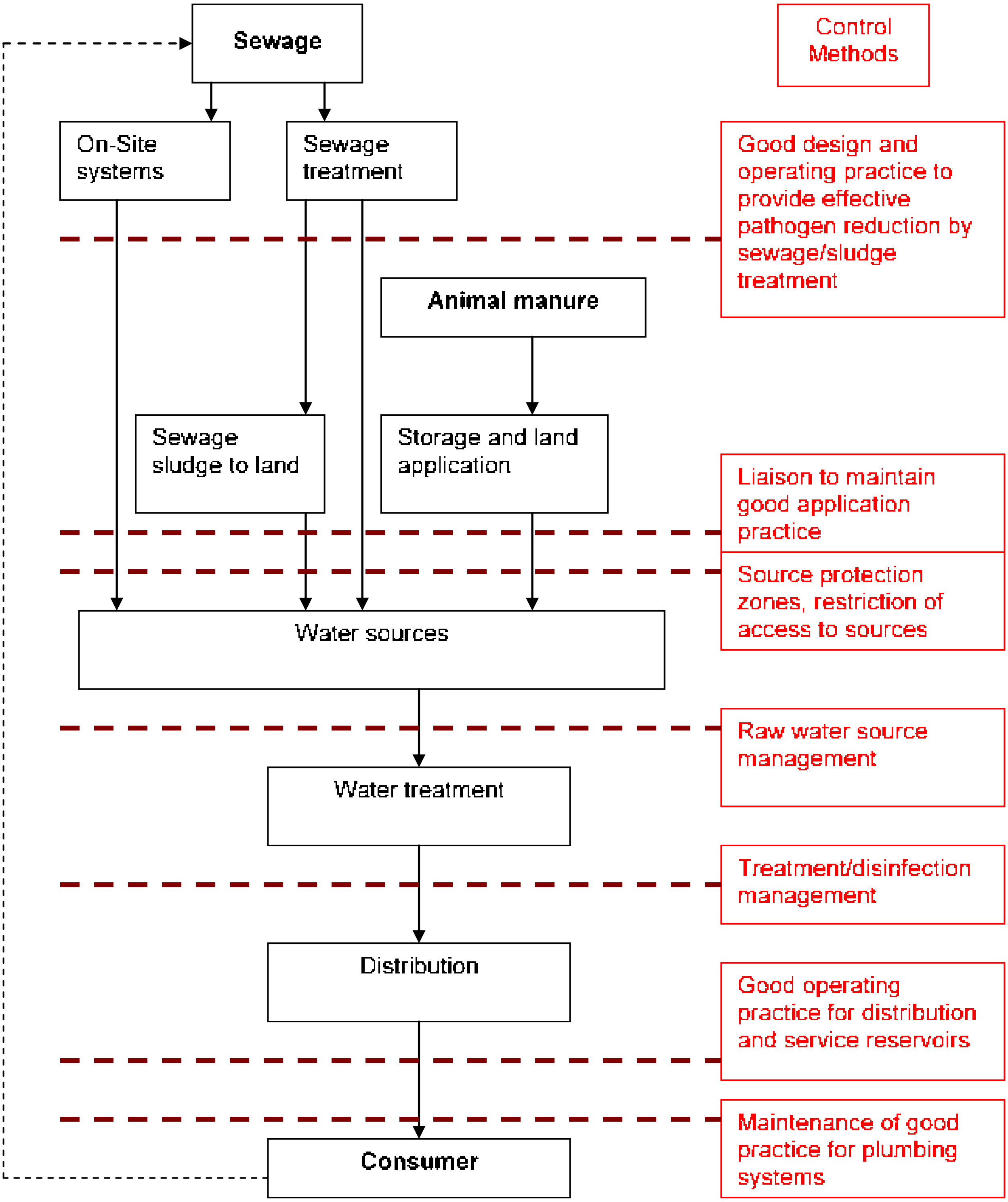

Figure 1.1 Sources and control of faecal contamination from source to tap

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

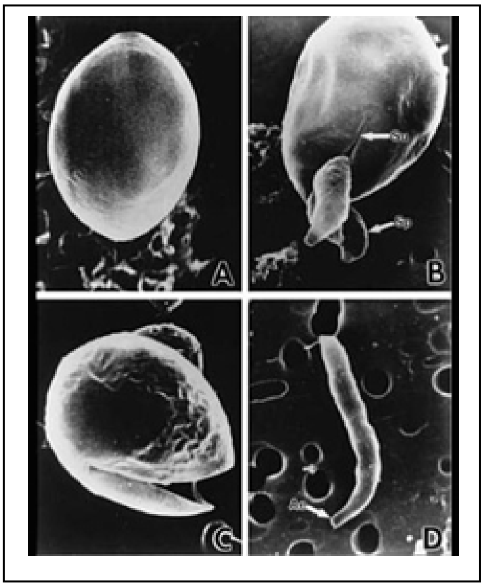

Plate 2.1 Excysting *Cryptosporidium* sporozoites

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).

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.

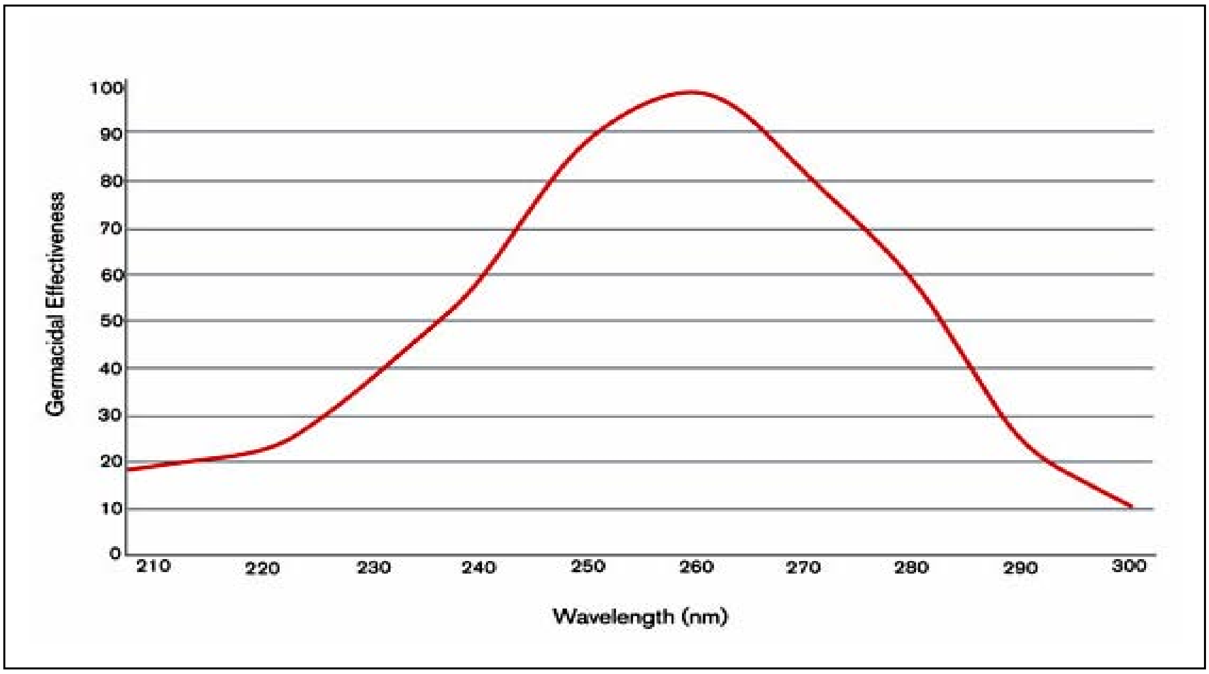

Fig 2.1 Germicidal Effectiveness of UV Light

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. Adenoviruses 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.

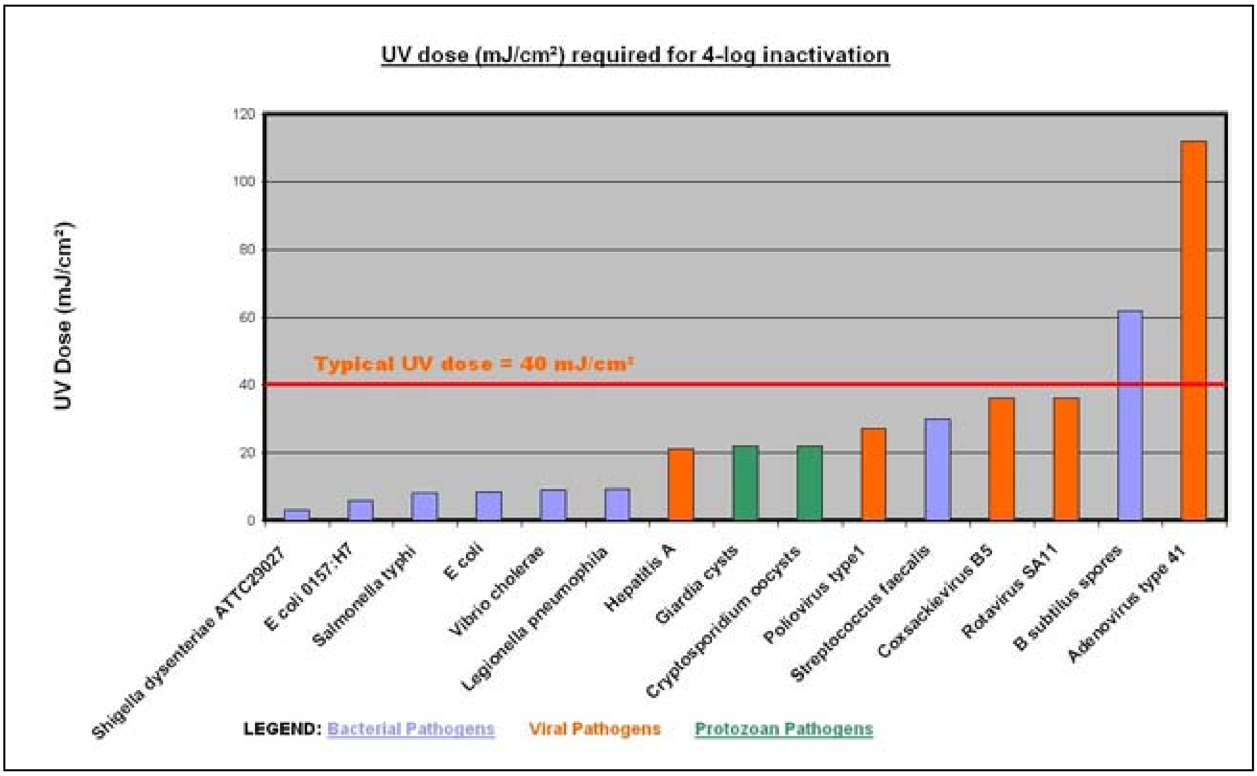

Fig 2.2 Required UV dose for 4-log inactivation of common waterborne pathogens

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):

$$k \quad k_0 e^{E/RT}$$ *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.

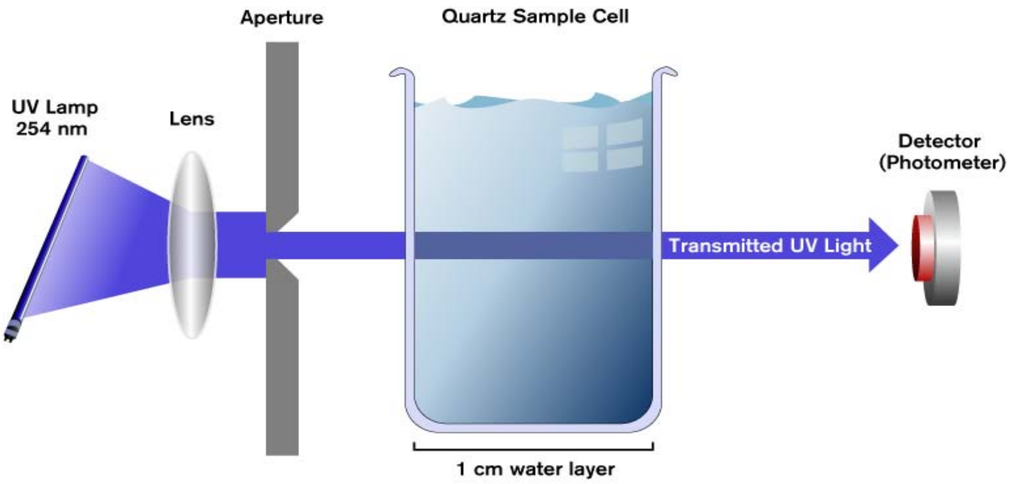

Figure 3.1. ***Schematic of UV transmittance measurement***

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.

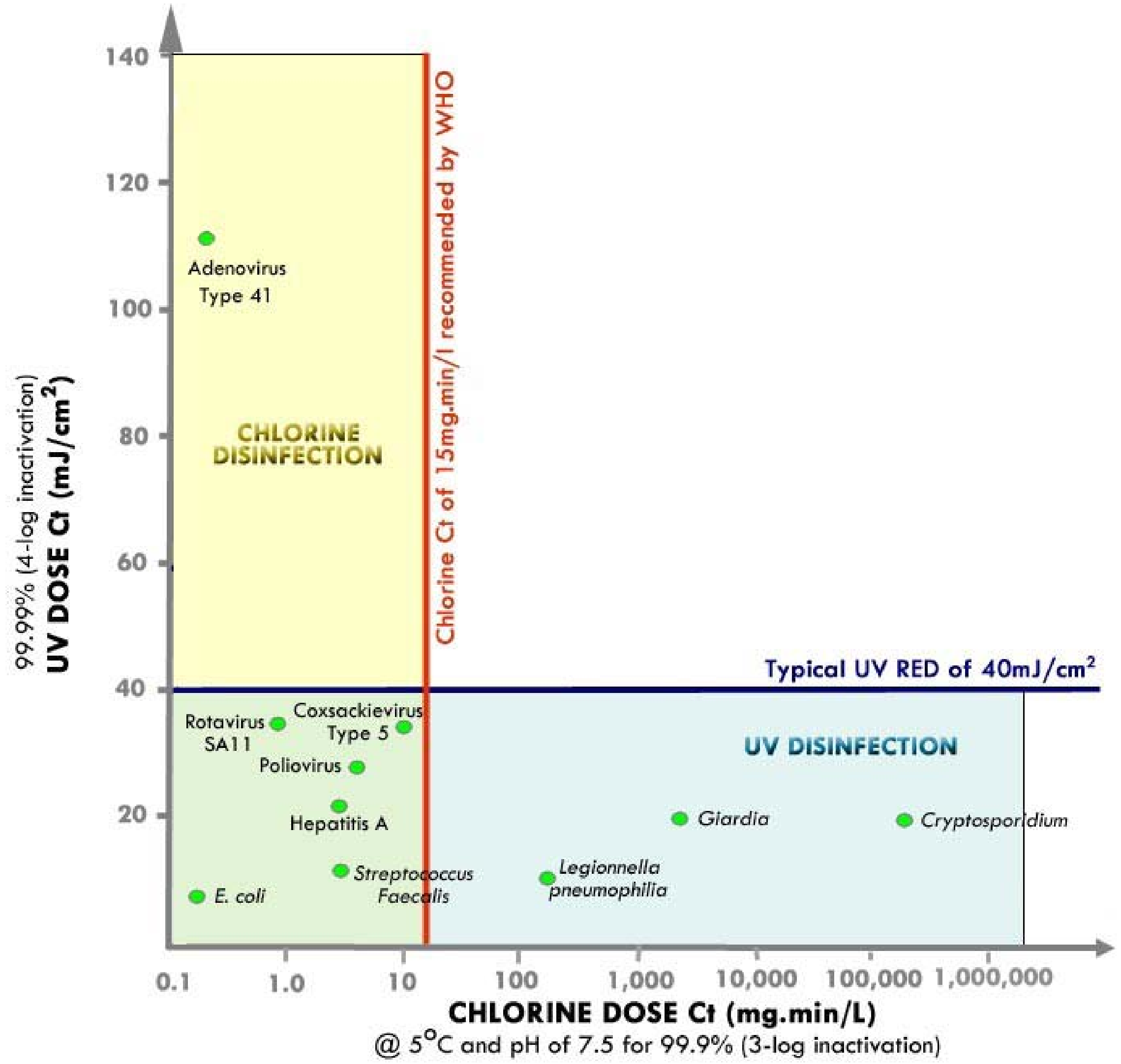

Figure 3.2 Synergistic uses of UV and chlorination disinfection systems

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.

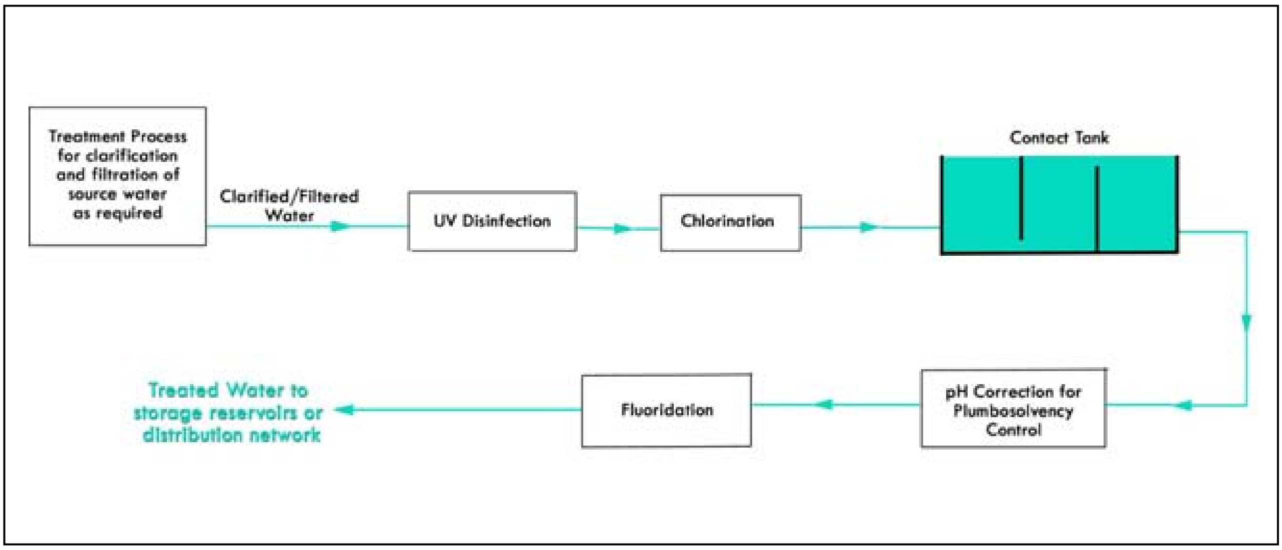


Figure 4.1 Suggested sequence of post treatment chemical dosing

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.

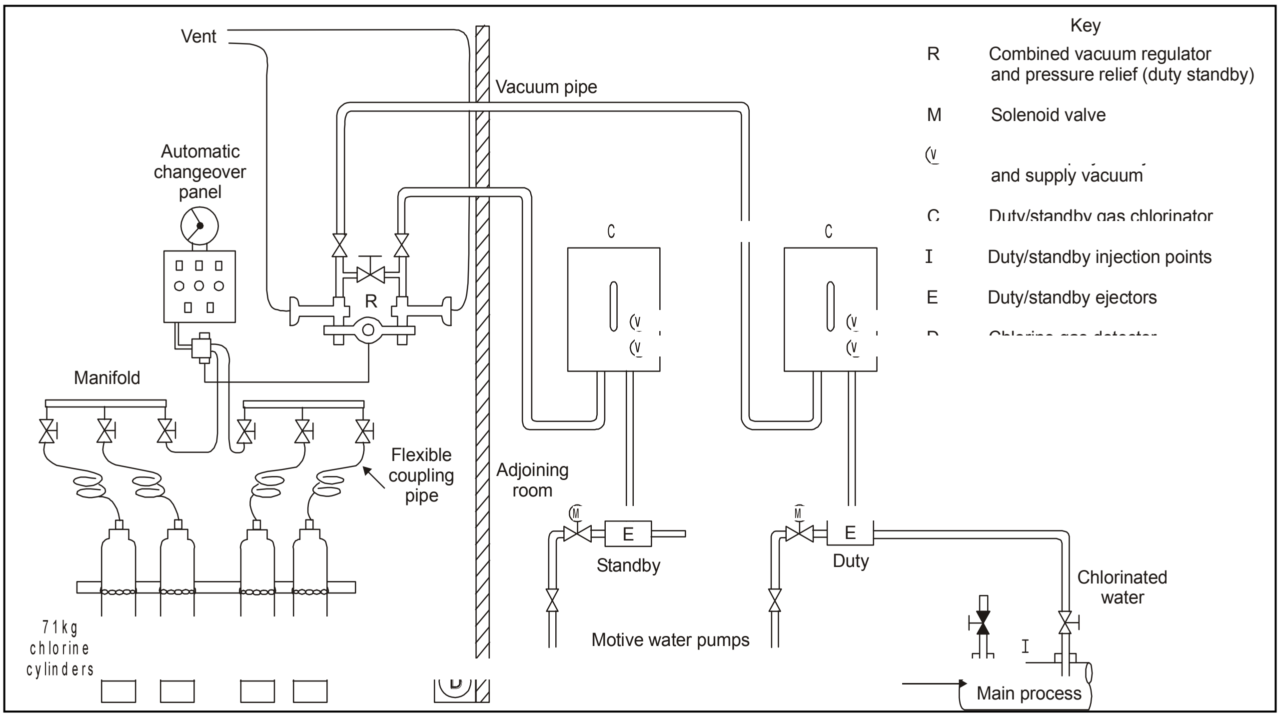


Figure 4.2 Chlorine gas system – example installation

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.

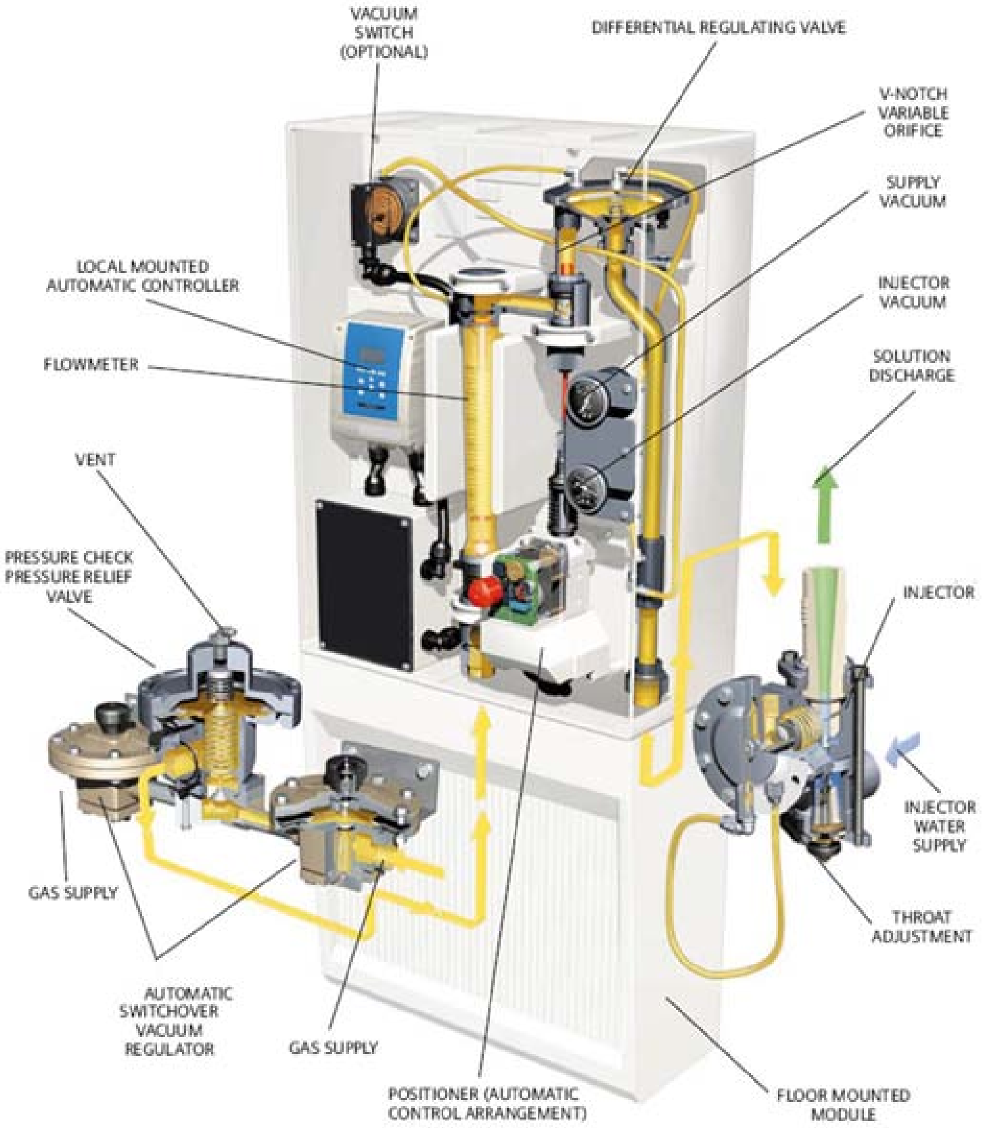


Figure 4.3 Typical Gas Chlorination equipment

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.

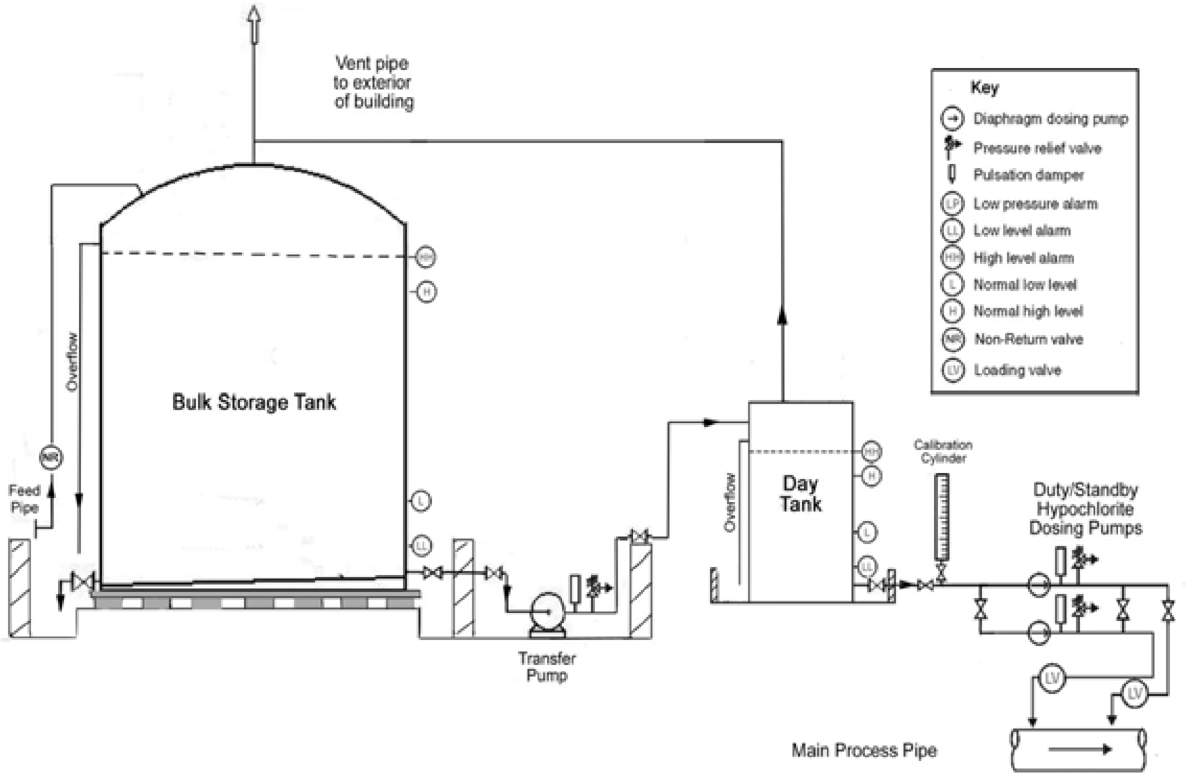


Figure 4.4 **Schematic of typical storage and dosing installation for bulk hypochlorite**

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 mg$CaCO_3$/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°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.

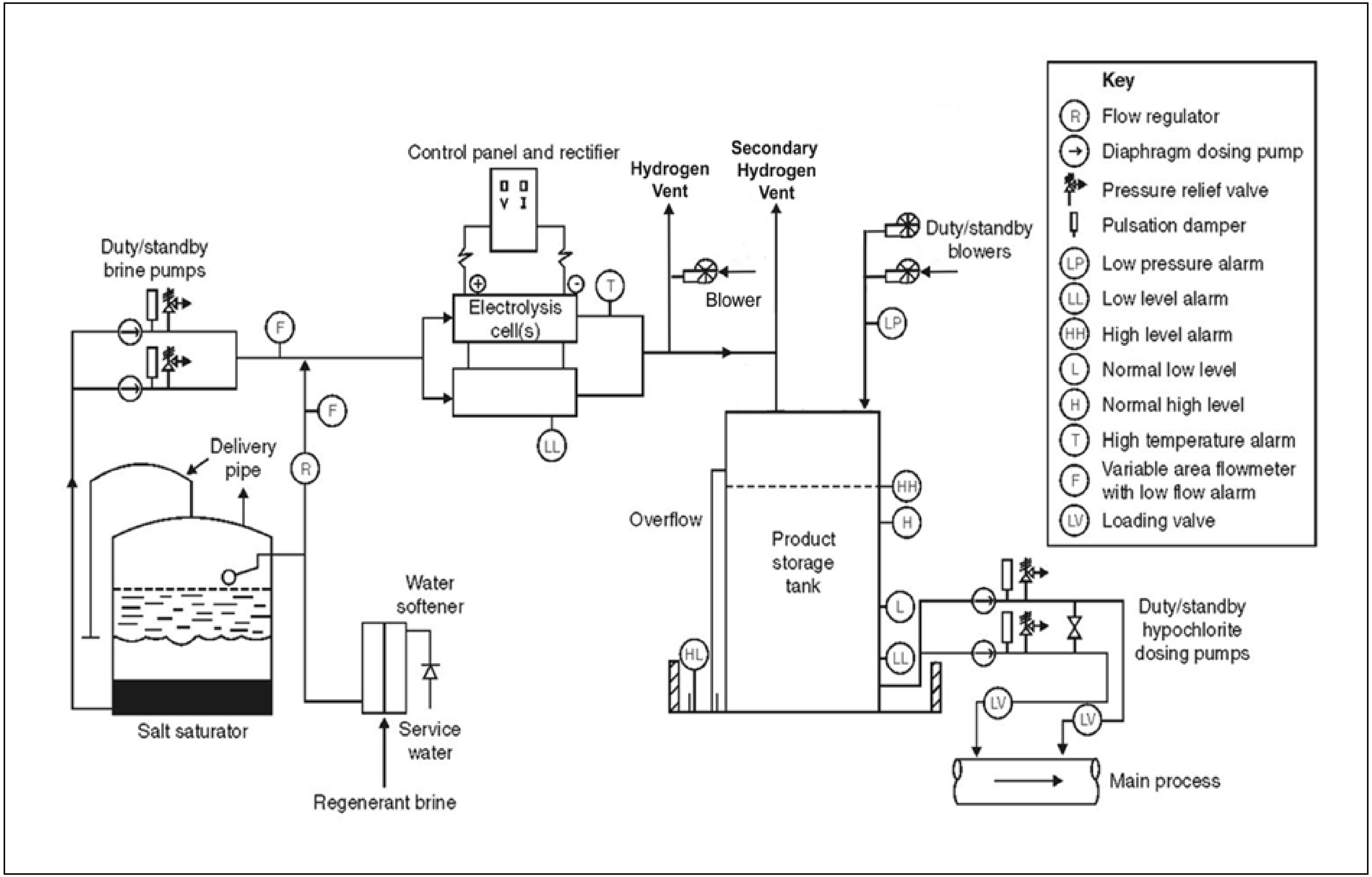


Figure 4.5 Example of on-site electrolytic chlorination installation

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.

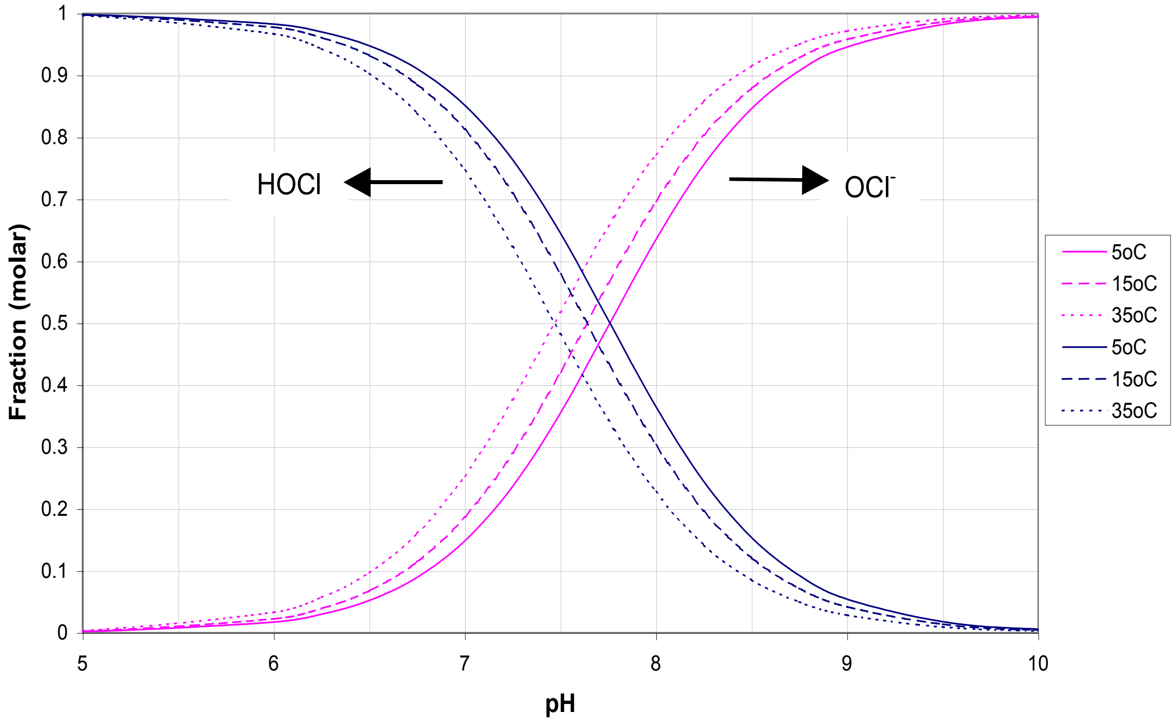


Figure 4.6 pH and temperature dependency of HOCl – OCl^- equilibrium

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:

$NH_3 + HOCl \rightarrow NH_2Cl + H_2O$ (monochloramine)

$NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O$ (dichloramine)

$NHCl_2 + HOCl \rightarrow NCl_3 + H_2O$ (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:

$$t_x = \left(\frac{t_x}{\tau}\right) \qquad \text{where } (t_x/\tau) = \text{correction factor.}$$

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.

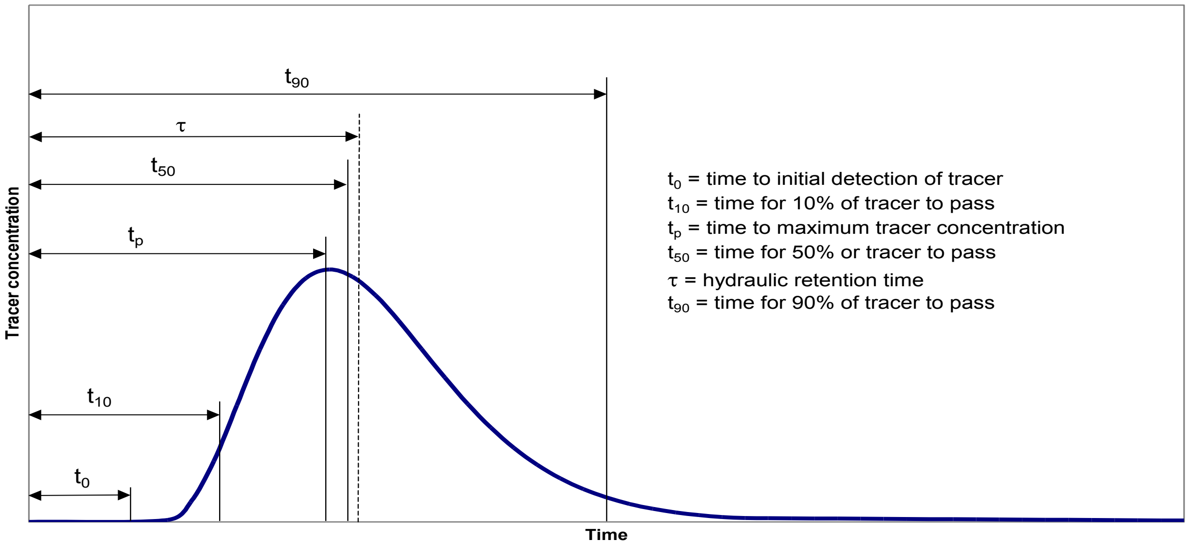


Figure 4.7 Illustration of tracer concentration at outlet after a “spike” test

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.

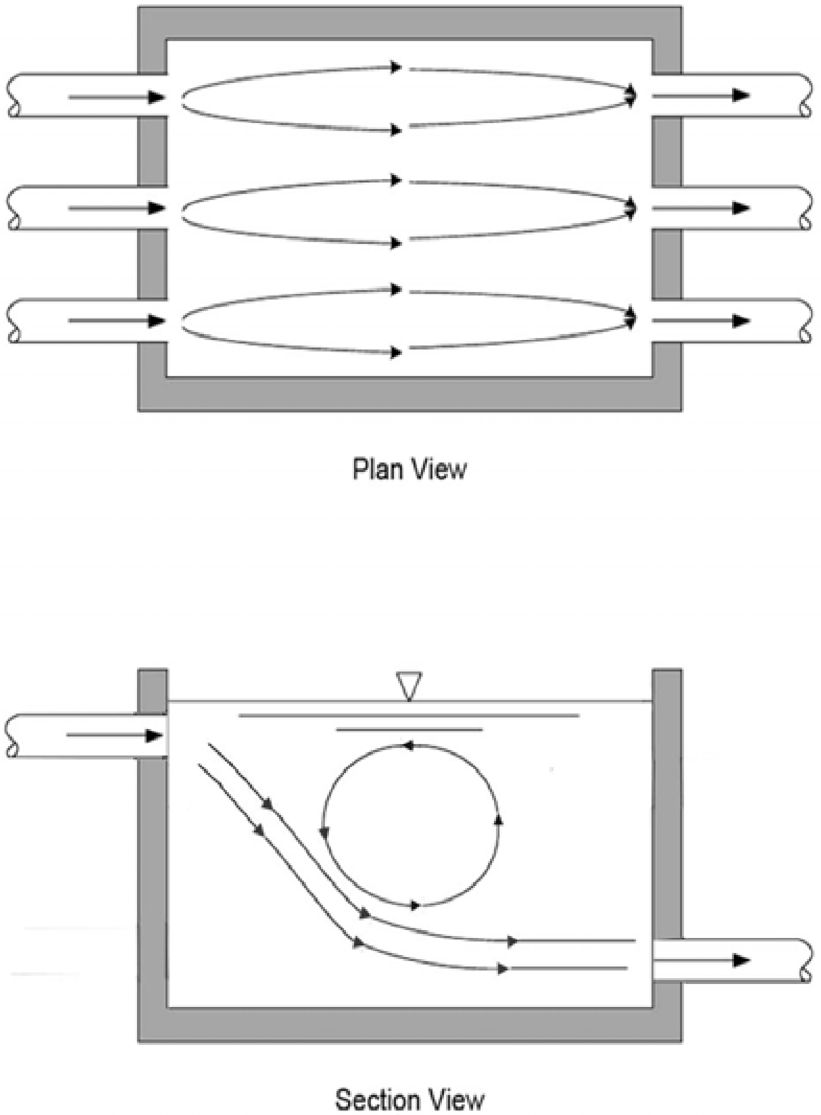
In the absence of tracer test data, an initial estimate of non-ideality can be made by consideration of the tank design, in particular provision of baffling.

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



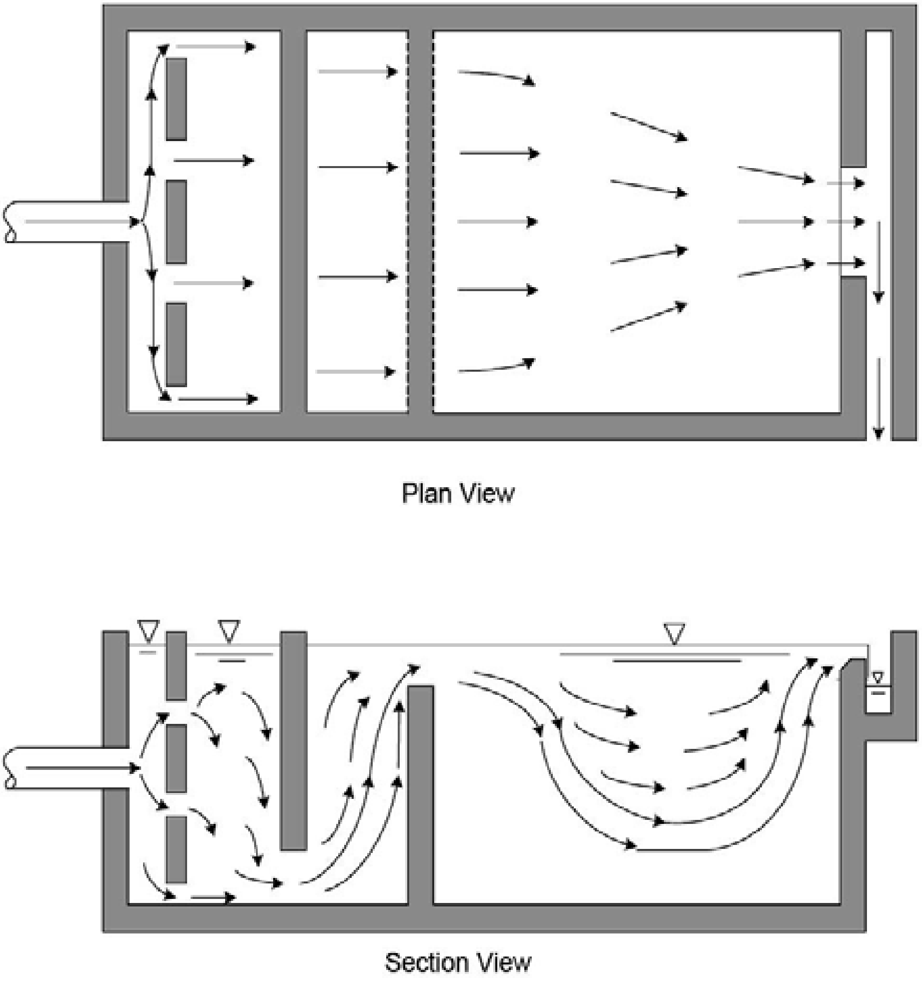
Source. US EPA (2003). LT1ESWTR disinfection profiling and benchmarking. Technical Guidance Manual

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

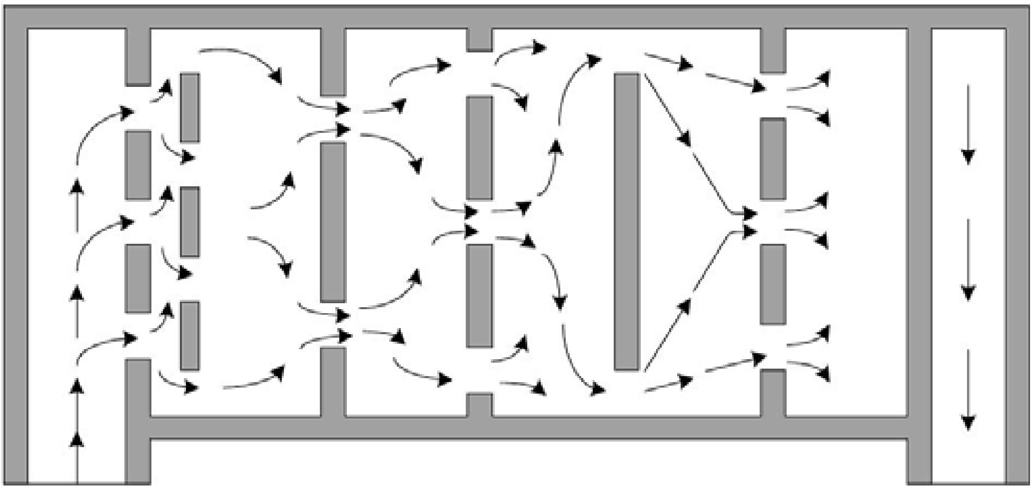
Figure 4.9 Average baffling arrangements in contact tank

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

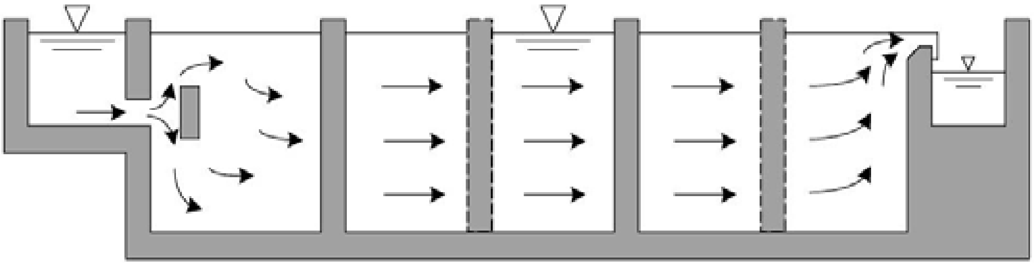
Features to be avoided include:

- 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.

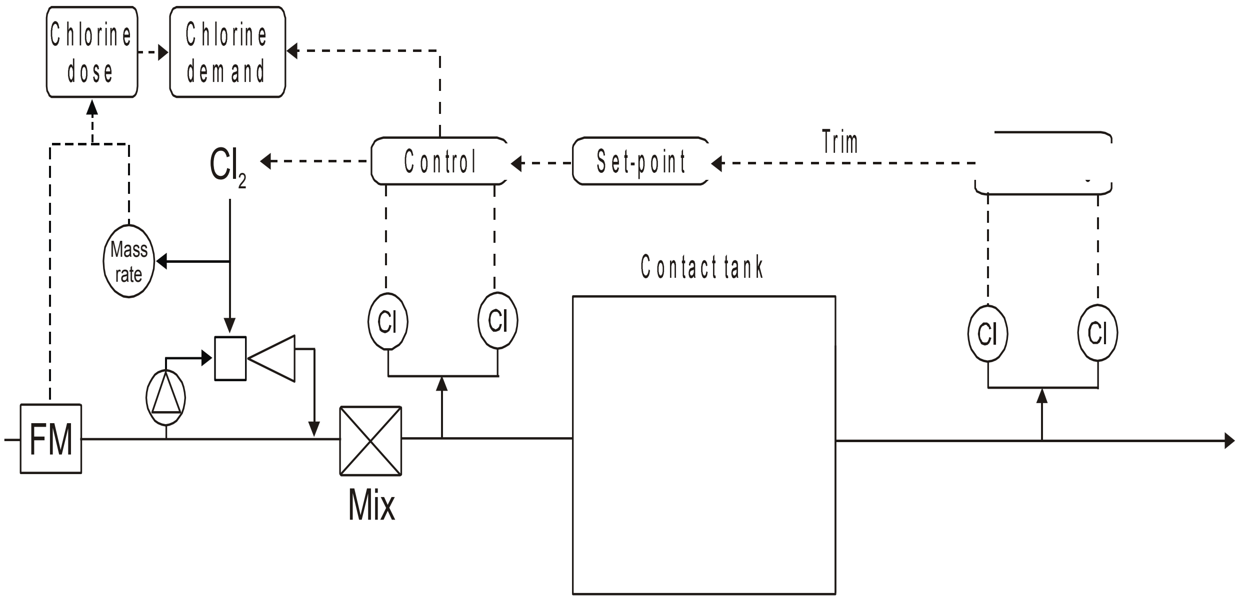


Figure 4.11 Schematic showing simple and cascade control of chlorine dosing prior to contact tank

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

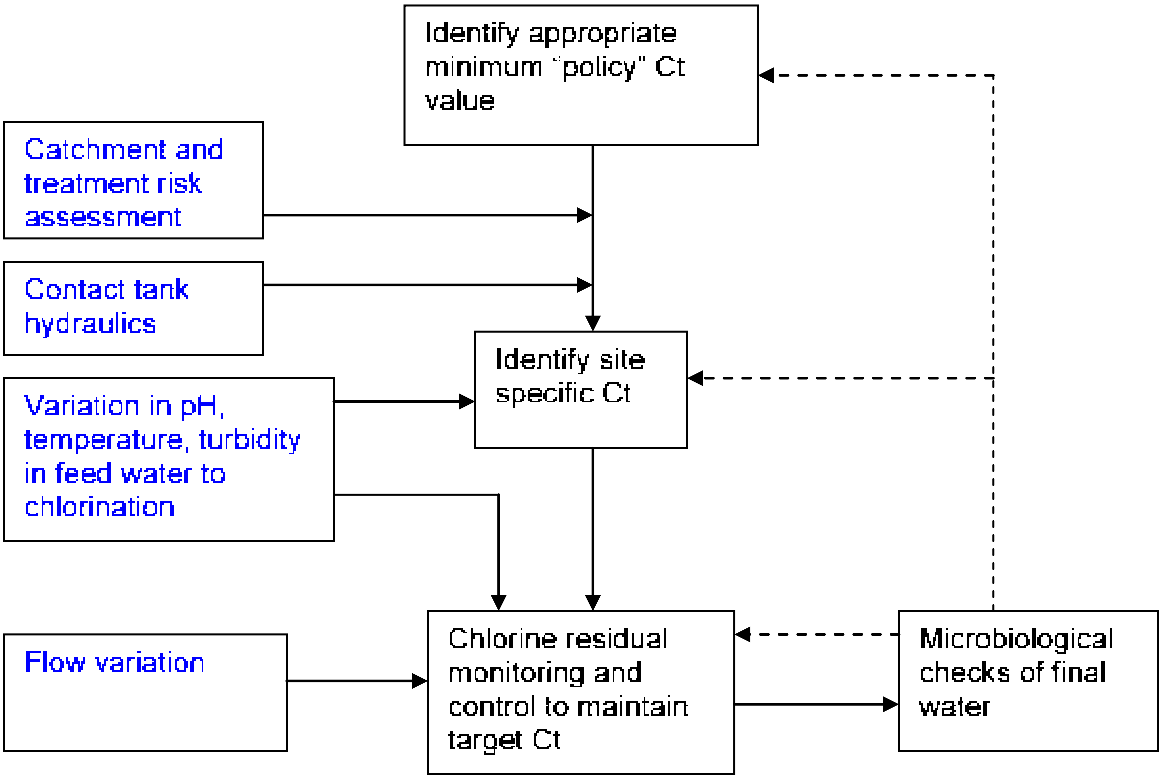


***Figure 4.12** Approach for implementing and maintaining chlorination conditions*

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

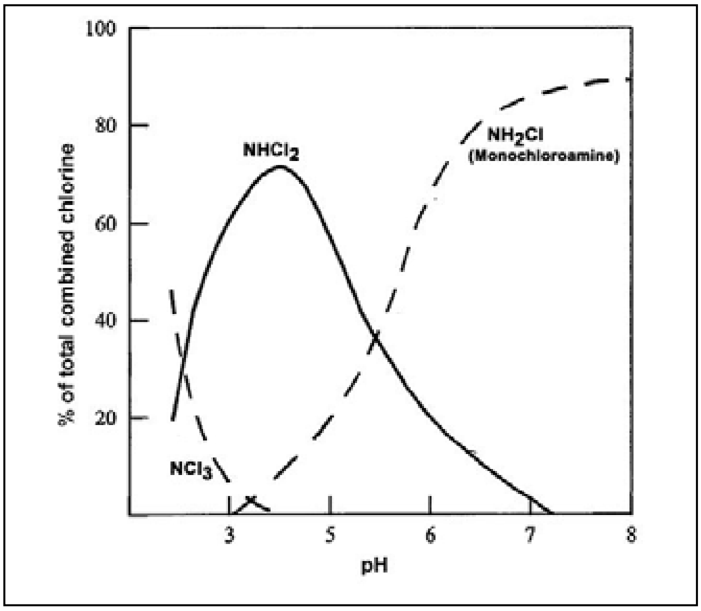


Figure 4.13. Distribution of chloramine formation with varying pH
(based on chlorine ammonia ratio of 5:1; Temp 20°C ; Contact time of 2 hours

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.

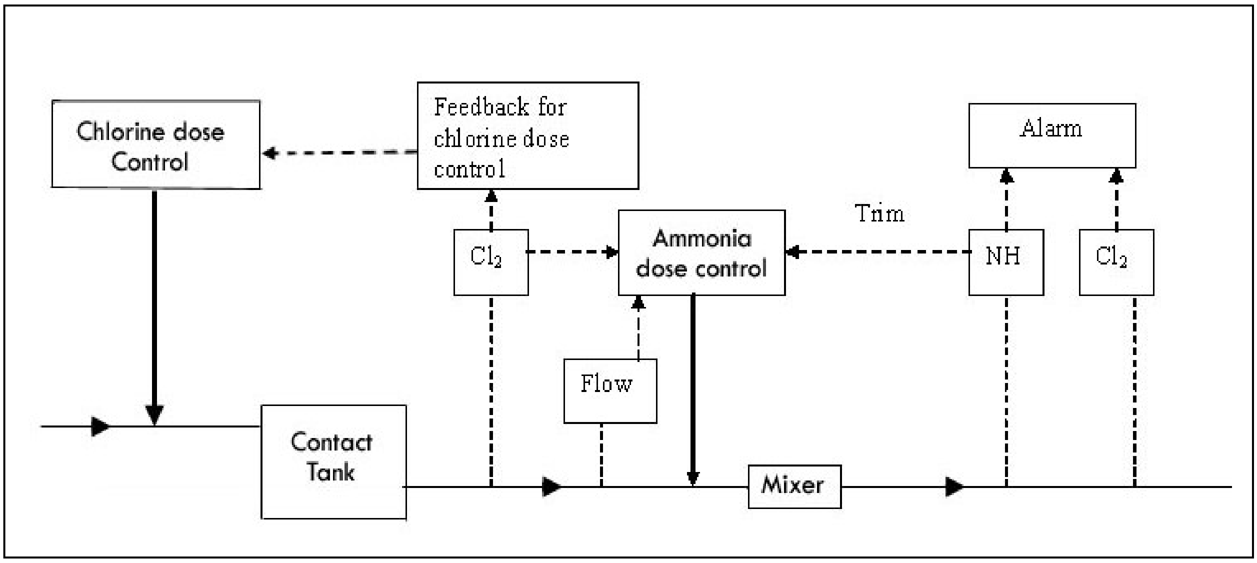


Figure 4.14 Example of chloramination control

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.

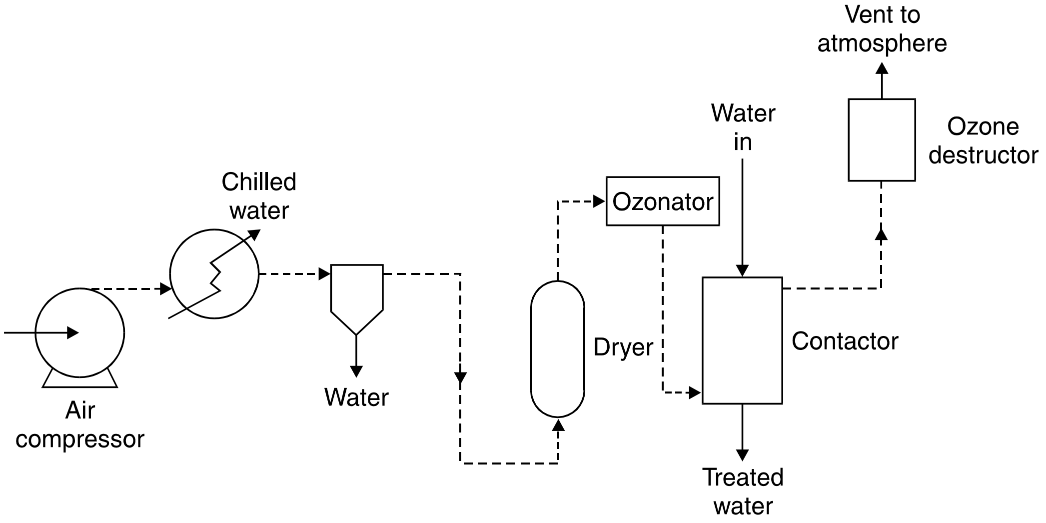

Figure 5.1 Schematic of air-fed ozonation system

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°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:

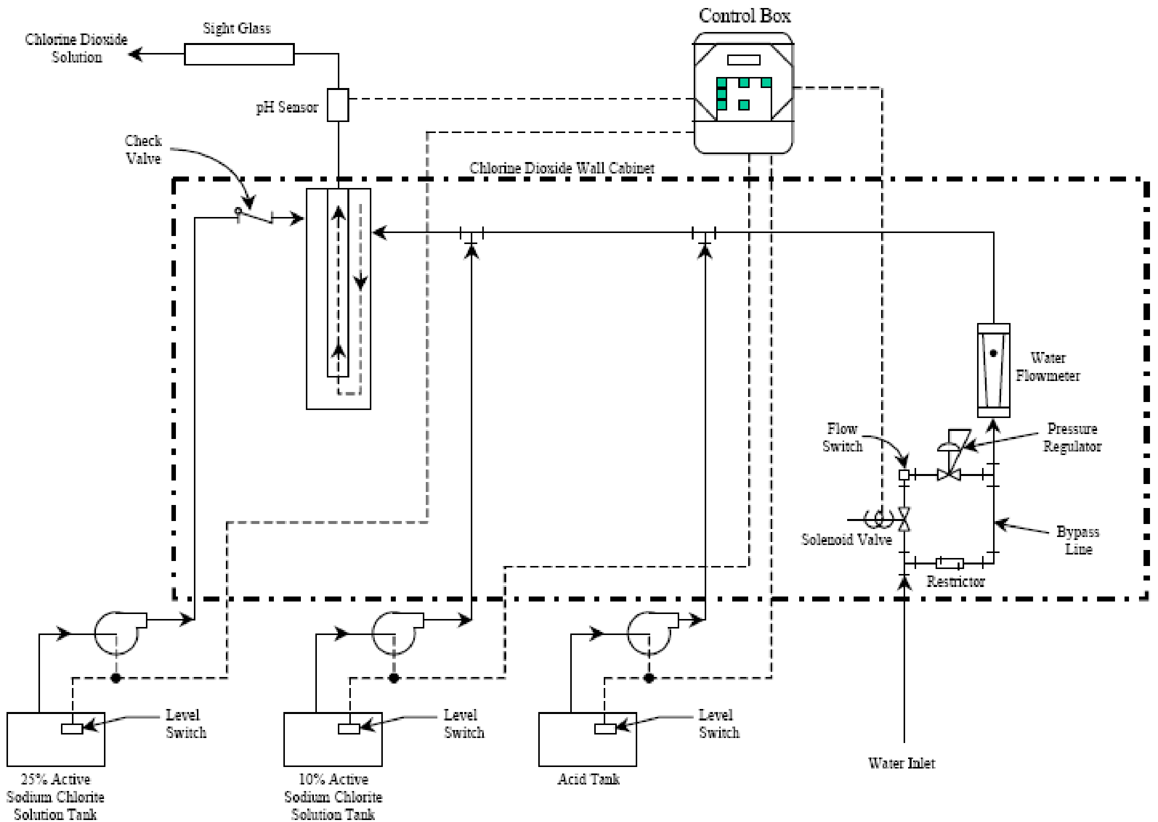
$5NaClO_2 + 4HCl \rightarrow 4ClO_2(aq) + 5NaCl + 2H_2O$ (acid:chlorite solution)

$2NaClO_2 + Cl_2(g) \rightarrow 2ClO_2 + 2NaCl$ (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.

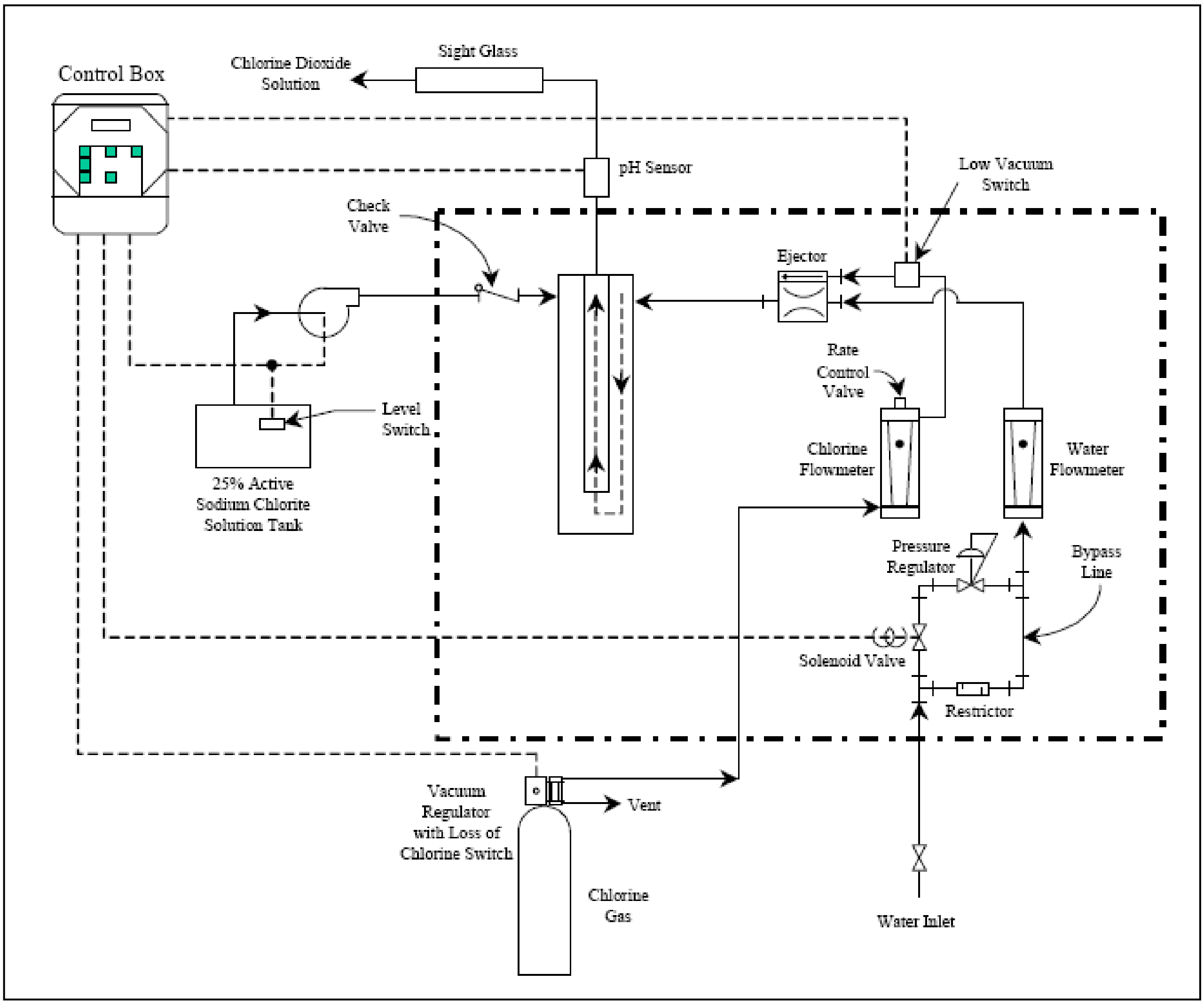


Fig 6.2 Chlorine Dioxide Generation using Chlorine gas: Chlorite solution method

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.

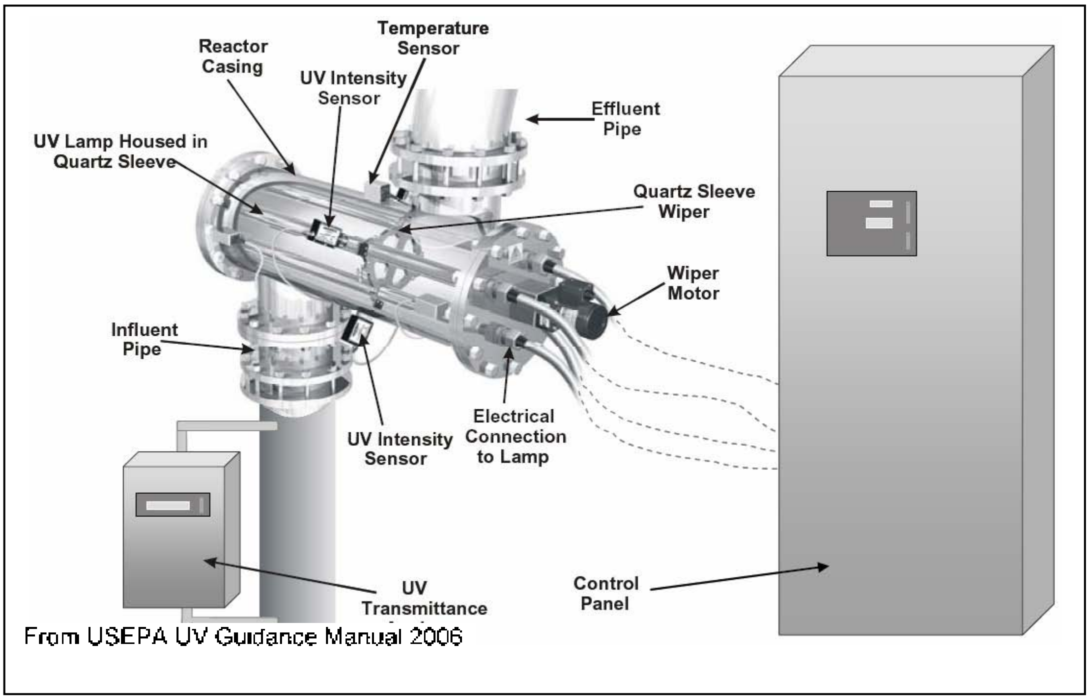
When ultraviolet (UV) radiation is absorbed by the cells of microorganisms, it damages the genetic material (DNA) within the cell in such a way that the organisms are no longer able to grow or reproduce, thus preventing the human illness cryptosporidiosis. DNA damage mainly results from irradiation at 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.



From USEPA UV Guidance Manual 2006

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).

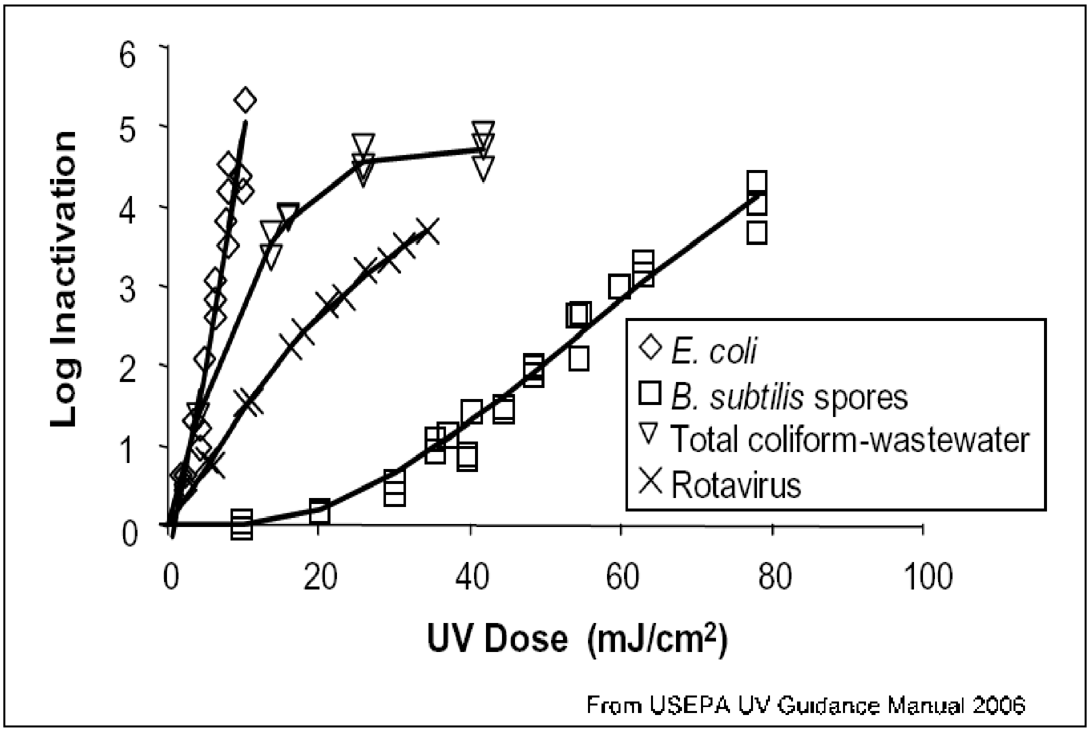
Photorepair is generally not of a concern in water treatment, because treated water is normally kept in the dark in pipes and reservoirs following UV disinfection. The USEPA UV Guidance Manual also reports that at dose rates quoted for protozoan inactivation, dark repair is not possible

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:

$$\mathrm{UVT} \quad 00\,\mathrm{x}\,10^{\;A}$$

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:

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

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:

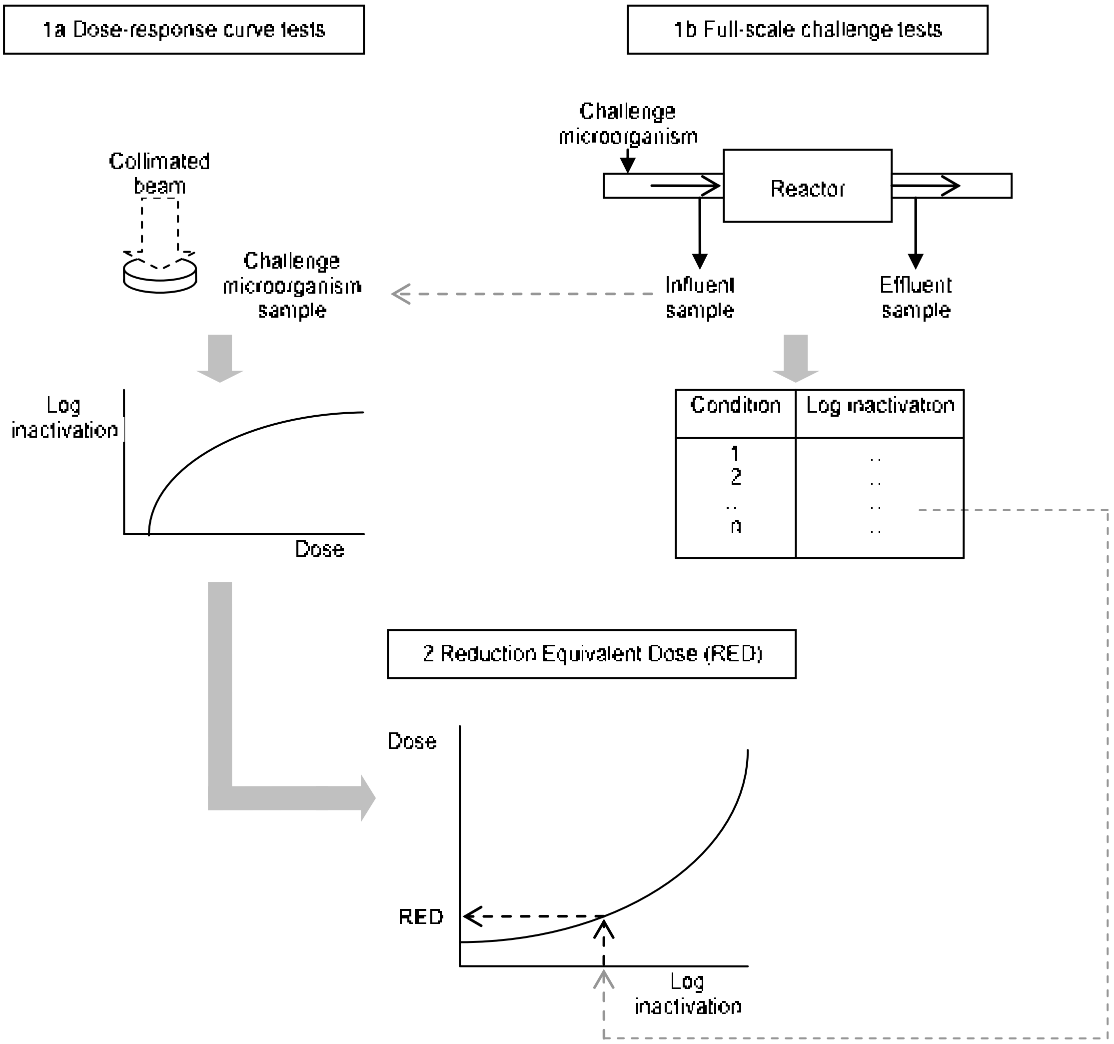


Figure 7.3 Principal steps of biodosimetry.

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.

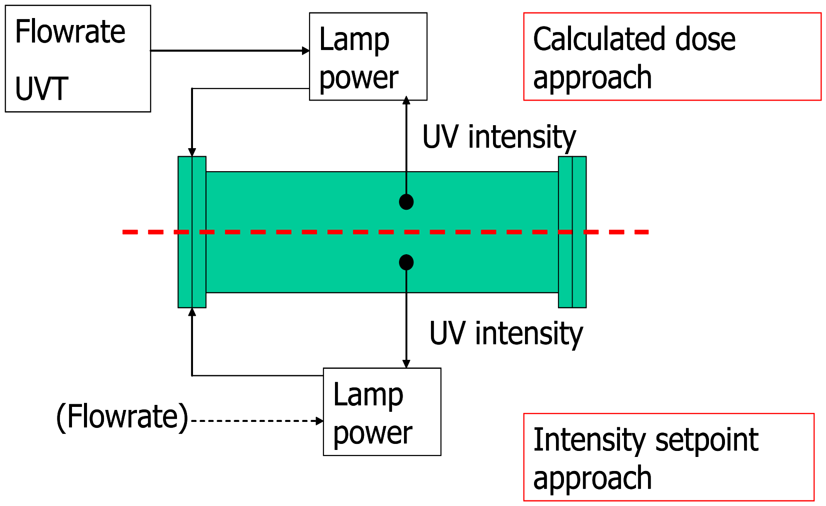


Figure 7.4 Approaches for UV dose control

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.

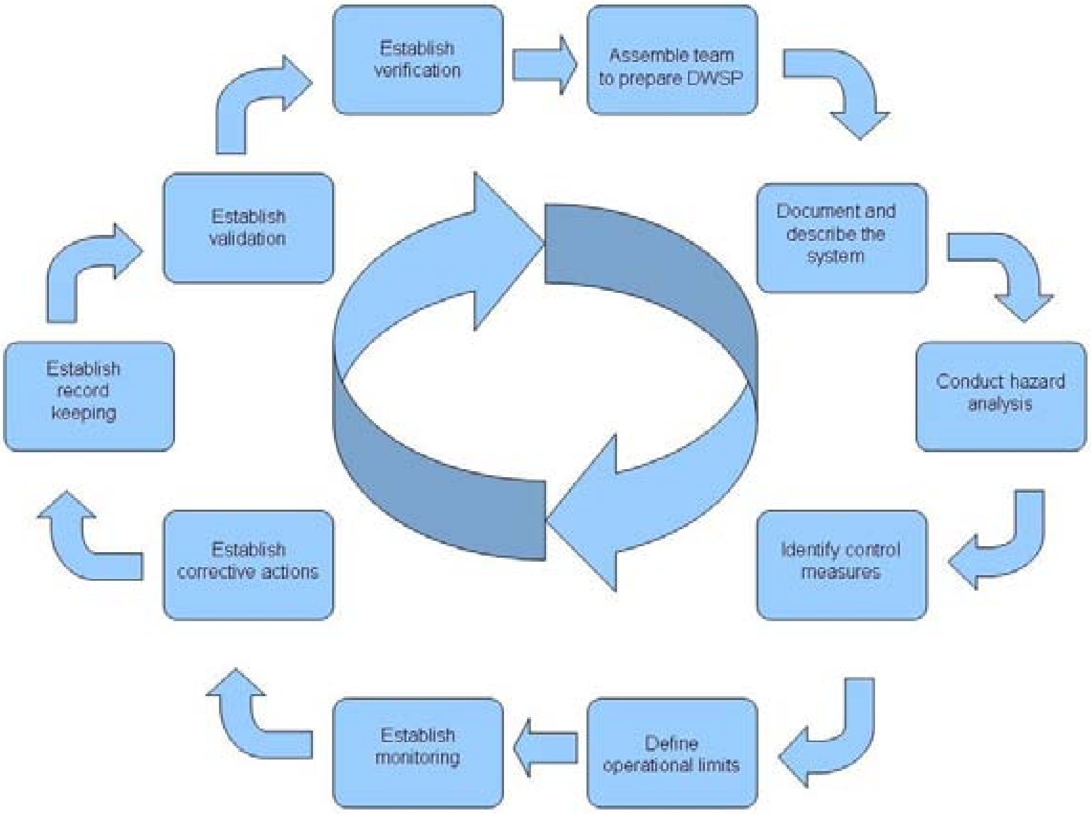


Figure 8.1 Drinking Water Safety Plan Methodology

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 **$[100\text{-}10^{(2\text{-}x)}]\%$** 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.

APPENDIX 1.1

TABLE OF HAZARDS AND CONTROL MEASURES ASSOCIATED WITH DISINFECTION

A) HAZARDS ASSOCIATED WITH SOURCE WATER

Catchment: Surface Water Supply

Hazard	**Control**
Flooding leading to rapid changes in water quality	Monitor raw water. Ability to shut off intake if raw water beyond acceptable limits. Appropriate treatment to deal with raw water.
Absence of characterisation of the raw water source	Conduct catchment risk assessment and/or establish monitoring programme.
Urban Waste Water discharge upstream with potential to cause microbial contamination	Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment.
Storm water overflow upstream with potential to cause microbial contamination	Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment. Raw water monitoring to identify times of higher risk.
On site systems/ septic tanks upstream with potential to cause microbial contamination	Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment.
Presence of Cryptosporidium in raw water	Liaison with stakeholders to prevent contamination of surface waters. *Cryptosporidium* monitoring programme. Appropriate treatment in place for *Cryptosporidium* removal/inactivation and consider additional treatment if needed. Turbidity monitoring of raw and treated water to identify periods of higher risk.
Agriculture - Microbial Contamination (e.g. from land spreading or storage of slurry or dung)	Liaison with stakeholder to prevent contamination of surface waters. Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment.
Industry, licensed or unlicensed (including IPPC/Section 4) - Microbial Contamination	Liaison with stakeholder to prevent contamination of surface waters. Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment.

Hazard	Control
Abattoirs - Organic and Microbial Contamination	Liaison with stakeholder to prevent contamination of surface waters. Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment.
Wildlife - Organic and Microbial Contamination	Consider additional fencing/security to prevent wildlife if possible. Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment.
Recreational use causing microbial contamination	Regulate or influence recreational use to prevent or reduce contamination. Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment.
Forestry felling causing increased sedimentation of the raw water and challenging disinfection	Turbidity monitor at intake, ability to shut off intake if raw water beyond acceptable limits. Liaison with stakeholder to prevent contamination of surface water.

Catchment: Ground Water Supply

Hazard	Control
Geology - swallow holes (surface water ingress) associated with raw water source	Turbidity monitoring to identify deterioration in quality, appropriate treatment to deal with source water. Consider closing intake or switching to other sources if raw water quality deteriorates.
Is the vulnerability classification a hazard for drinking water quality?	Review. Ensure appropriate treatment is in place.
Is the Aquifer Classification a hazard for drinking water quality?	Review. Ensure appropriate treatment is in place.
Well head casing incomplete or borehole unsealed causing intrusion of surface water or other contamination	Secure and maintain well head to prevent contamination.
Borehole not lined causing ingress of surface water	Line borehole to sufficient depth to prevent ingress.
Borehole or spring source influenced by surface water e.g. shallow borehole or well	Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment. Provide turbidity monitoring of raw water to identify times of high risk. Take out of supply if adequate treatment not in place.
Well head not secured against livestock access causing microbial	Protect well-head with appropriate cover.

Hazard	Control
contamination	
Infiltration gallery influenced by surface water causing microbial contamination	Monitor source water. Ensure appropriate treatment and robust disinfection system in place with appropriate monitors and alarms on key equipment.
Land drains causing preferential pathway for pollution of shallow well source	Re-route land drains.

Catchment: Surface Water or Groundwater Supply

Hazard	Control
Vandalism – deliberate contamination of source and unauthorised access	Appropriate security and alarm system for site. Lockable covers on all access points to water supply.

Raw Water Intake

Hazard	Control
Direct surface water abstraction causing variability in water quality	Change abstraction point to minimise variability in raw water. Ensure effective raw water monitoring available to take out of supply if needed. Provide bankside storage.
Intake not secured against livestock access causing microbial contamination	Install and maintain fencing in the vicinity of the intake.
Lake source intake point vulnerable to variation due to streams/ stratification/ algal blooms/ increased turbidity	Change abstraction point to minimise variability in raw water.
Sediment build up causing contamination	Regular programme for inspection of intake, clean as appropriate.

Raw Water Storage

Hazard	Control
Susceptible to flooding / contamination	Consider flood defences. Liaise with catchment stakeholders to minimise risk of contamination. Raw water contamination monitoring programme.
Unauthorised access resulting in deliberate contamination	Appropriate security and alarm system for site. Lockable covers on all

	access points to water supply.
Wildlife access to raw water tank causing contamination	Erect fencing or cover to prevent wildlife access.
Sludge build up in raw water tank causing contamination	Regular inspection and maintenance programme.
Leaking impounding reservoir causing ingress of contamination	Regular inspection and maintenance programme.

Raw Water Line

Hazard	**Control**
Pipe corroded or not watertight causing intrusion of Surface Water	Regular inspection and maintenance programme.
Raw water serving consumers without disinfection or other treatment	Ensure asset records are kept up to date and authorised connections refer to these records. Provide appropriate treatment for consumers or connect to treated water supply.

B) HAZARDS ASSOCIATED WITH TREATMENT PLANT

Plant Design

Hazard	**Control**
Appropriate treatment not in place to adequately treat the raw water	Ensure appropriate treatment is appropriate. Provide interim treatment in the short-term.
Treatment plant operating above design capacity	Ensure treatment plant is operating within acceptable limits. Plant data can be used to verify this
By-passing of any stage of treatment	Appropriate alarms to notify when individual processes are bypassed. By-pass valves locked-off.
Frequent and significant flow variations through the works	Consider intermediate storage to smooth out flow variations. Ensure processes are able to cope with fluctuations in flow. Verify with plant data

Coagulation/Flocculation/Clarification Stage

Hazard	**Control**
Chemicals delivered to incorrect storage vessel	Ensure chemical deliveries are overseen by competent treatment works personnel. Keep storage vessels locked to prevent unauthorised deliveries.
Floc carry over due to inappropriate/inadequate dosing regime	Regular dose optimisation. Verify with turbidity or metal concentration measurements.
Floc carry over due to overloading of the plant/ surge flows	Operate process within design parameters.
Floc carry over due to poor adjustment/maintenance/design of lamella plates	Regular inspection and maintenance programme
Floc carry over due to poor maintenance or flooding of settlement channels	Regular inspection and maintenance programme. Consider covering settlement channels if flooding a serious risk
Floc carry over due to variations in raw water characteristics	Regular inspection and dose optimisation
Floc carry over due to effects of weather condition	Regular inspection and maintenance programme. Consider covering clarifiers.
Floc carry over due to inadequate cleaning of clarifiers	Regular inspection and maintenance programme

Hazard	Control
Floc carryover due to poor settlement/ unstable sludge blanket	Regular inspection. Adjust sludge bleeds, dose or flow rate if necessary.
Floc carryover due to sludge float/ scraper not operating properly	Regular inspection and maintenance programme
Floc carryover due to sludge concentrators not operating properly	Regular inspection and maintenance programme
Floc carryover due to sludge bleeds not operating properly	Regular inspection and maintenance programme
Floc carryover due to insufficient sludge draw off	Regular inspection and maintenance programme
Chemicals used after expiration date – ineffective chemicals	Ensure chemicals are stored appropriately and used within expiry date
Inadequate storage areas for chemical stocks, risk of running out of treatment chemicals	Ensure storage is adequate for required chemical stockpile.
Chemical injection point vulnerable to potential damage	Regular inspection and maintenance programme. Consider moving dosing point
Inadequate cleaning regime in mixing tank	Regular inspection and maintenance programme
Algal or plant growth in clarifiers causing poor water quality and clogged filters	Regular inspection and maintenance programme
Poor structural integrity of clarifiers causing contamination due to ingress	Regular inspection and maintenance programme
Sludge recycled to head of works	Ensure sludge quality and quantity suitable for reuse. Appropriate monitoring in place.

Filtration stage

Hazard	Control
Inadequate pre-treatment (i.e. no clarification stage)	Review design, ensure appropriate treatment in place
Inadequate process control in place for filtration (e.g. lack of turbidity monitors)	Review design and monitoring requirements
Inadequate particle removal due to overloading of the filters	Run filters within design and operating limits. Assess with turbidity measurements or particle counts.
Inadequate particle removal due to blocked filters	Run filters within design and operating limits. Set and operate appropriate backwash programmes. Assess by measurement of head loss, flow rate and turbidity
Inadequate particle removal due to inadequate filter media depth	Check appropriate media depth for design of filter. Maintain filters as per EPA guidance and filter design.

Hazard	**Control**
Inadequate particle removal due to inadequate filter media type	Check appropriate media type for design of filter. Maintain filters as per EPA guidance and filter design.
Inadequate particle removal due to inadequate backwashing regime (e.g. inadequate cycle length, uneven scour, pump failure, loss of filter media)	Set and operate appropriate backwash programmes. Regular inspection of filters and maintenance of backwash equipment.
Inadequate particle removal due to poor filter maintenance (cracks, boils etc)	Regular inspection and maintenance programme. Replace filter media as appropriate.
Rapid gravity filters put back into operation without slow start	Use slow start, delayed start or run to waste on filter return to service. Assess with turbidity measurements. Provide appropriate turbidity alarms.
Slow sand filters put back into operation without ripening period causing inadequate particle removal	Check appropriate ripening regime in place. Assess with turbidity and coliform measurements.
Filtered Water – *Cryptosporidium* breakthrough	Ensure turbidity monitors on each filter routinely reviewed. Provide appropriate turbidity alarms.
Filtered Water – turbidity breakthrough greater than 0.2 NTU in sites where there is a risk of the presence of *Cryptosporidium* in the raw water	Run filters within design and operating limits. Assess with turbidity measurements, provide appropriate alarms.
Backwash water recycled to head of works causing increased turbidity	Monitor turbidity and flow rate on recycle flow line.

Disinfection

Hazard	**Control**
Disinfection system is not reliable	Ensure robust disinfection system in place with appropriate monitors and alarms on key equipment. Design and operate appropriately.
Inadequate contact time in place in accordance with WHO requirements	Increase contact tank capacity or reduce flow rate to achieve appropriate contact time. Consider alternative treatment.
UV system operating outside its validated range	Install appropriate alarms for intensity, turbidity and UVT. Consider run to waste if UV system operating outside design limits.
Chemicals used after expiration date – ineffective chemicals	Ensure chemical storage is appropriately sized. Regular inspection of chemicals to ensure expiry date has not been exceeded.

Other hazards associated with the treatment plant

Hazard	**Control**
Loss of Power Supply	Consider back up power supply e.g. standby generator.
Vandalism - loss of supply	Install appropriate alarms and security.
Instrumentation failure - loss of control e.g. set points for turbidity monitors	Install appropriate alarms with failsafe mechanisms e.g. the ability to run to waste
Telemetry - communication Failure	Install appropriate alarms and security
Flooding - loss or restriction of treatment works	Install appropriate alarms and security. Prepare response under Drinking Water Incident Response Plan (DWIRP).
Fire/Explosion - loss or restriction of treatment works	Ensure risks are minimised through good health and safety procedures. Prepare response under DWIRP.
Spill from unbunded chemical or oil storage tank causing contamination	Regular inspection and maintenance programme. Consider bunding chemical stores. Prepare response under DWIRP.
Chemical overdose due to poor process control	Regular calibration, inspection and maintenance programme.
Access to the plant - loss or restriction of access due to weather extremes or other event	Install appropriate alarms to warn of impending access restrictions. Prepare response under DWIRP.
Availability and continuity of supply of treatment chemicals	Consider long term arrangement with suppliers. Investigate alternative chemicals/ suppliers if critical e.g. single supplier
Electrical surge causing loss of communication and records	Install appropriate alarms with failsafe mechanisms e.g. the ability to run to waste.
Critical pump failure leading to loss of supply	Ensure spare capacity e.g. duty/standby arrangement. Prepare response under DWIRP.
Risk of fluorine overdose in treated water	Regular calibration, inspection and maintenance programme.
Poor quality batch of chemicals (e.g. low concentration) leading to inadequate treatment	Use approved suppliers. QA to trace batches of chemicals. Batch sample analysis.
Adverse weather conditions affecting treatment chemicals and/or processes	Install appropriate alarms with failsafe mechanisms e.g. the ability to run to waste.

C) HAZARDS ASSOCIATED WITH DISTRIBUTION

Hazard	**Control**
Risk of disinfection by-products in the network	Operate and control disinfection to minimise the risk of disinfection by-products. Optimise upstream processes to remove precursors for disinfection by-products.
Insufficient disinfection in distribution network causing microbial contamination	Provide secondary disinfection. Low level alarms set at appropriate limits.
Maintenance/ replacement of pipe work causing microbial contamination	Procedure for disinfection of mains after repair or replacement.
Backflow from industrial/ domestic premises or unregulated supply causing microbial contamination	Install adequate backflow prevention devices.
Scouring operations/ opening or closing valves causing disturbed deposits or introduction of stale water	Procedure for scouring operations/ opening or closing valves.
Open treated water reservoir causing contamination by wildlife	Cover reservoir. Secondary disinfection after reservoir.
Leaking Reservoir causing ingress of contamination	Regular inspection and maintenance programme.
Unprotected access covers and/or vents causing contamination	Lockable access covers, secure vents. .
Security/Vandalism to reservoir causing contamination	Appropriate security and alarm system for site. Lockable covers on all access points to water supply.
Lack of maintenance and cleaning of reservoirs causing contamination (sludge build-up in reservoirs, presence of dead vermin, etc)	Regular inspection and maintenance programme

D) HAZARDS ASSOCIATED WITH MANAGEMENT AND CONTROL

Hazard	**Control**
Lack of online monitors and alarms critical to disinfection	Ensure robust disinfection system in place with appropriate monitors and alarms on key equipment
Inadequate call-out facilities in place for caretakers, relief caretakers and technicians (electricians, plumbers etc)	Ensure adequate call-out facilities in place, with arrangements to cover leave.
Plant operator or relief caretaker not trained	Ensure all operators fully trained in respect of their duties.
Hygiene procedures not in place or plant operator manages waste water and	Appropriate procedures for plant operators in place.

drinking water treatment plants - risk of cross contamination	
Calibration/maintenance schedules not in place for key disinfection equipment including monitors and alarms	Put calibration/maintenance schedules in place. Service contracts for key equipment.
Lack of spare parts for key disinfection equipment e.g. UV bulbs	Ensure spare key disinfection equipment is in place

APPENDIX 2.1

PRACTICAL GUIDANCE FOR PLANT OPERATORS ON MEASURES TO ENSURE THE SECURITY AND VERIFICATION OF CHLORINATED WATER SUPPLIES

1. INTRODUCTION

Chlorination disinfection is the most widely used system for both the primary and secondary disinfection of water supplies worldwide due to the fact that chlorine forms a residual in the disinfected water. Such residuals are usually necessary to quality assure drinking water to the consumer tap and prevent recontamination of treated water during the subsequent distribution of drinking water through the reticulation network.

The Drinking Water Regulations SI 278 of 2007, under Regulation 13, requires Water Service Authorities or Private Water Suppliers to ensure that “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”.

Chlorination disinfection plants are often located within water treatment plants and are usually located downstream of any pre-treatment, oxidation, clarification and filtration stages of the process, so as to minimise the formation of halogenated disinfection by products (DBPs). Natural organic matter, as measured by colour, turbidity and total organic carbon, is the precursor of DBP formation in water. Secondary re-chlorination installations using chlorination can also be located remote from the plant.

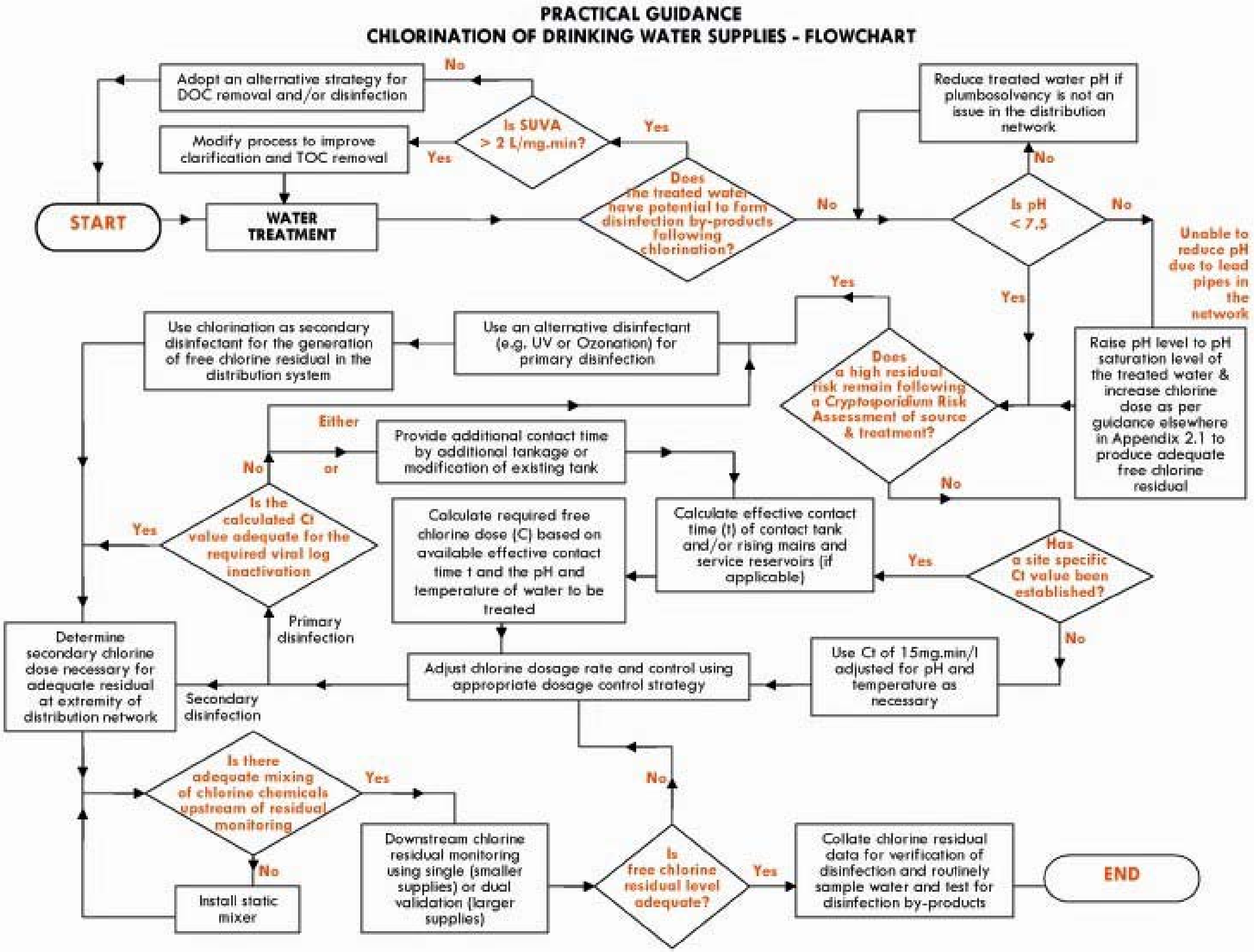
2. ACHIEVEMENT OF DISINFECTION GOALS BY PLANT OPERATORS

The operator of a chlorination installation, which is designed to provide a reliable disinfection barrier to pathogens, is required to safeguard the security of the drinking water supply and verify its continued operation.

The achievement of these goals will be best achieved by focussing on the following issues which are critical to the efficacy of disinfection and minimisation of DBPs:

- The proper operation of pre-treatment processes ahead of disinfection so as to minimise chlorination by-product formation
- Proper management of pH in water to be disinfected
- Identification and maintenance of appropriate Ct in contact tanks, rising mains and storage reservoirs ahead of residual monitoring and upstream of the first consumer
- The applicability of different dose strategies, the proper use of chlorine injection points, and the function of chorine residual monitoring for disinfection process control and verification
- Alarm generation and the provision of standby residual monitors and dosing pumps to ensure that only disinfected water enters the distribution network
- Management of distribution systems to prevent recontamination and excessive formation of by-products

The following flowchart sets out best practice in the use of chlorine as a disinfectant.


PRACTICAL GUIDANCE
CHLORINATION OF DRINKING WATER SUPPLIES - FLOWCHART
START
WATER TREATMENT
Does the treated water have potential to form disinfection by-products following chlorination?
Yes
Is SUVA > 2 L/mg.min?
No
Adopt an alternative strategy for DOC removal and/or disinfection
Yes
Modify process to improve clarification and TOC removal
No
Is pH < 7.5
No
Reduce treated water pH if plumbosolvency is not an issue in the distribution network
No
Unable to reduce pH due to lead pipes in the network
Yes
Raise pH level to pH saturation level of the treated water & increase chlorine dose as per guidance elsewhere in Appendix 2.1 to produce adequate free chlorine residual
Does a high residual risk remain following a Cryptosporidium Risk Assessment of source & treatment?
Yes
Use an alternative disinfectant (e.g. UV or Ozonation) for primary disinfection
Use chlorination as secondary disinfectant for the generation of free chlorine residual in the distribution system
No
Has a site specific Ct value been established?
Yes
Calculate effective contact time (t) of contact tank and/or rising mains and service reservoirs (if applicable)
Calculate required free chlorine dose (C) based on available effective contact time t and the pH and temperature of water to be treated
No
Use Ct of 15mg.min/l adjusted for pH and temperature as necessary
Adjust chlorine dosage rate and control using appropriate dosage control strategy
Primary disinfection
Is the calculated Ct value adequate for the required viral log inactivation
No
Either
Provide additional contact time by additional tankage or modification of existing tank
or
Yes
Secondary disinfection
Determine secondary chlorine dose necessary for adequate residual at extremity of distribution network
Is there adequate mixing of chlorine chemicals upstream of residual monitoring
No
Install static mixer
Yes
Downstream chlorine residual monitoring using single (smaller supplies) or dual validation (larger supplies)
Is free chlorine residual level adequate?
No
Yes
Collate chlorine residual data for verification of disinfection and routinely sample water and test for disinfection by-products
END

The following sections of this Appendix set out further guidance with respect to choices to be made by disinfection plant managers in the operation of the flowchart particularly in relation to the pretreatment of water, the application of chemical dosages and the monitoring and verification of chlorination systems These sections include reference to the main text of the manual where appropriate.

3. THE OPTIMISATION OF WATER QUALITY AND pH PRIOR TO DISINFECTION

As discussed in the Manual, the type of treatment to which water is subjected prior to primary disinfection, and the way that treatment is managed and operated, can have a very significant influence on the performance of disinfection and its verification under the Drinking Water Regulations with respect to inactivation of pathogen and minimisation of DBPs.

The effectiveness of chlorine disinfection is contingent on the pre-treatment process removing micro-organisms as well as ensuring the quality of water in terms of turbidity, natural organic material (commonly measured as TOC) and that pH is suitable for disinfection with chlorine.

The reduction of particulate, colloidal and dissolved organic carbon by oxidation/GAC adsorption, clarification and filtration processes results in less DBP precursors and less pathogenic micro-organisms in the water to be disinfected. The consequent reduction in chlorine demand will require a lower chlorine dose which will also contribute to less DBP formation.

Due to the predominance in Ireland of sources from surface waters and groundwaters influenced by surface waters, operators should strive.to establish the potential of the water for form disinfection by-products subsequent to the chlorination of treated water. This DBP formation potential can be determined by reference to historical sampling records, the determination of total organic carbon and the dissolved organic carbon fraction in treated water samples, and/or the laboratory testing of treated water samples following chlorine addition to determine the reactivity of the TOC in the water. Most of the organic carbon in drinking water supplies is typically dissolved.

Where there is a history of TTHM formation in post chlorinated treated water or potential for THM formation exists, a specific ultraviolet light absorbance (SUVA) analysis of the water should be undertaken, immediately upstream of chlorination points, to establish the hydrophilic (primarily humic acids) and hydrophobic fractions (primarily fulvic material) of the organic matter in the water.

SUVA is defined as the ratio between ultra violet absorbance at 254nm (UV_{254}) and the dissolved organic carbon (DOC) concentration in the water [i.e. SUVA = (UV absorbance/DOC) X100]. UV_{254} is regarded as a measure of the aromatic and unsaturated components of NOM and a good predictor of the tendency of source water to form TTHMs.

The ability of a coagulation clarification processes to remove remaining organic material from the water can also be determined by evaluating the SUVA of the water. Generally where the SUVA in L/(mg.min) exceeds 2.0, potential for process modification usually exists to further reduce organic matter in the water.

Section 4.4 of the Manual details the effect of pH on the formation of free chlorine and the availability of the more effective hypochlorous acid form in chlorinated water.

Chlorine disinfection dosing into waters with elevated pH levels above 7.5 can have the consequence of increased chlorine dosage due to the predominance of free chlorine in the form of the weaker hypochlorite ion. Larger chlorine dosages result in DBP formation where organic precursors have not been sufficiently removed prior to disinfection.

Separate control of pH is often used as part of a water treatment process and is usually controlled upstream of chlorination to diminish potential for plumbosolvency. Chlorination of treated water supplies above a pH of 7.5 can sometimes occur in low to moderate alkalinity treated water supplies where the pH has to be raised for plumbosolvency reasons. In the absence of pH control as part of treatment process, 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 chlorine residual in response to increasing pH. Such pH linked control of chlorine dose should only be considered on pristine groundwaters or on treated water supplies where TOC levels are low, thereby obviating the implications of related THM formation.

4. ESTIMATION OF APPROPRIATE Ct FOR DISINFECTION

4.1. Ct required

Table 4.3 of the Manual, reproduced below, details the Ct values recommended for the 2 log (99%) inactivation of bacteria and viruses and the Giardia protozoa and their dependence on the pH and temperature of water.

	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

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

As stated in the Manual, *Cryptosporidium* is highly resistant to chlorination which is totally ineffective for disinfection in sources with high *Cryptosporidium* risk. Where risk has been identified, following an assessment of catchment, source and treatment risks, treatment augmentation to remove oocysts or an alternative disinfection method capable of inactivation of *Cryptosporidium* should be employed ahead of secondary chlorination. This would also provide benefits for *Giardia* removal, and avoid the need for higher Ct to deal with *Giardia*.

The inactivation required should be identified from the Drinking Water Safety Plan risk assessment for individual works. For good quality, well protected groundwaters, 2 log inactivation should be sufficient, but for lowland surface waters a target of more than 3 log inactivation would be needed. The need for viral inactivation can be identified from the risk assessment. If risks from human sewage sources are identified in the catchment, requirements for viral inactivation would need to be taken into account, but if microbial risk was only from animal sources (e.g. cattle, sheep), bacterial inactivation may only need to be considered, provided that risks from *Giardia* (and *Cryptosporidium*) were covered by removal by treatment.

The World Health Organisation guidelines recommendation of 30 minutes contact time at a minimum of 0.5 mg/l free residual chlorine (i.e Ct value of 15mg.min/litre) must be achieved in all supplies before water is supplied to consumers. This Ct value is arrived at by multiplying the concentration C of 0.5mg/l by the effective contact time t value (30min) and in the absence of site specific Ct calculation. It is possible to achieve the same Ct by increasing C where t is inadequate and vice versa.

Where possible, a site specific cumulative calculation of effective contact time should be undertaken by the Water Services Authority or private water supplier, based on the Ct of chlorinated water retained in

- dedicated contact tanks within treatment plants,
- dedicated treated water rising mains (without consumer connection) up to but not including the downstream service reservoir, unless there is no dedicated contact tank at the treatment works.

Service reservoirs are not designed for providing efficient contact time (see Section 4.6 in the manual). This is taken into account below in the calculation of effective contact time for service reservoirs, by assuming poor flow characteristics.

In the absence of reliable site specific information to the contrary, a minimum effective Ct (see below) of 15 mg.min/l is recommended for all sites except:

Raw water type	**Recommended effective Ct**
Good quality groundwaters with no history of faecal indicator organisms in the raw water over the past 5 years	Minimum Ct 10 mg.min/l
Direct river abstraction surface waters where the source water quality can vary rapidly, or surface waters with faecal indicator organisms at >2000 cfu/100ml in any raw water sample taken over a 3 year period.	Minimum Ct 20 mg.min/l

Good quality groundwater (raw water) must be verified with at least 5 years of samples showing no faecal contamination in at least four samples in each year. Such data may be available from the WSAs own monitoring programme or through the EPA National Groundwater Monitoring Programme. In the absence of this data a minimum effective Ct of 15 mg.min/l must be applied. It is also necessary to demonstrate that the source is adequately protected, there are source protection plans in place and the borehole(s) meet best practice design criteria.

Modification of Ct for temperature and pH should be made as indicated in Section 7 of this Appendix.

4.2 Contact tanks

This calculation should have regard to Chapter 4 of this EPA *Water Treatment Manual: Disinfection* and in particular Table 4.3 and associated Figure 4.5, 4.6 and 4.7 with respect to the inclusion or otherwise of baffling arrangements within such contact tanks.

The effective contact time is related to both the volume of the contact tank and its design/structure (see Section 4.7of the Manual). In the absence of any tracer test data for the tank, the effective contact time can be estimated from:

$$\textit{Effective contact time (minutes)} = \textit{tank volume } (m^3) \times 60 \times D_f / \textit{flow } (m^3/h)$$

where:

tank volume = length x width x minimum depth

D_f is a factor related to the efficiency of the system to minimise short circuiting through the tank, as discussed in Section 4.7. Well designed tanks minimise short circuiting and have higher values for D_f.

Condition	**Description**	**D_f**
Unbaffled	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities.	0.1
Poor	Single or multiple unbaffled inlets and outlets, no intra-basin baffles.	0.3
Average	Baffled inlet or outlet with some intra-basin baffles.	0.5
Superior	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders.	0.7

The flow should be the maximum expected hourly flow. The tank volume should be the based on the minimum depth of water in the tank, for tanks where operating depth varies.

The effective Ct is the effective contact time multiplied by the target chlorine concentration after the tank.

Example calculation:

<table>
<tr><td>Tank volume</td><td colspan="3">10m long, 5m wide and with 3m minimum depth of water</td><td></td></tr>
<tr><td></td><td>L</td><td>W</td><td>D</td><td></td></tr>
<tr><td></td><td>10</td><td>5</td><td>3</td><td>Volume = 10 x 5 x 3 = 150 m^3</td></tr>
<tr><td>Tank design</td><td colspan="3">Assume “average”</td><td>D_f = 0.5</td></tr>
<tr><td>Flow</td><td colspan="3">150 m^3/h</td><td></td></tr>
<tr><td>Effective contact time (t)</td><td colspan="3">Tank volume (m^3) x 60 x D_f / flow (m^3/h)</td><td>150 x 60 x 0.5 / 150
= 30 minutes</td></tr>
<tr><td colspan="5">If the chlorine concentration in the water leaving the tank is 0.5 mg/l:
Effective Ct at outlet = 30 minutes x 0.5 mg/l = 15 mg.min/l</td></tr>
</table>

Calculation tool

Tank volume				**Flow (F)**	**Effective contact time (t)**
L	**W**	**D**	**D_f**	**m^3/h**	**t = L x W x D x 60 x D_f/F**
					t =
Chlorine concentration C (mg/l)					**Effective Ct = C x t =**

4.3 Distribution pipe

For sites where the effective contact time in the tank is insufficient to provide the required Ct, the contact time in the main from the works can be included in the Ct calculation, up to a service reservoir or the first customer connection, provided that the chlorine concentration at this point is stable and measured regularly, ideally using an on-line monitor. The available contact time in the main is calculated from:

Pipe volume = $\pi r^2 \times L$

where r = pipe radius (m) and L = pipe length (m).

Contact time (minutes) = Pipe volume x 60 / flow (m^3/h)

The flow should be the maximum expected hourly flow. Pipe sizes are usually quoted as diameter, which should be halved to provide the radius.

This calculation of contact time assumes the D_f for a pipe has a value of 1, i.e. perfect plug flow conditions.

Example calculation

Assuming a 1 km (1000 m) length of 0.3 m diameter pipe at a flow of 100 m^3/h, with a chlorine concentration at the end of the pipe of 0.3 mg/l.

Pipe volume	0.3 m diameter, 1000 m length		Pipe volume
	r	L	*πr^2 x L = 3.142 x 0.15 x 0.15 x 1000*
	0.15 m	1000 m	70.7 m^3
Contact time	Pipe volume x 60 / flow = 70.7 x 60 / 100 **= 42.4 minutes**		
Chlorine concentration **0.3 mg/l**			
Ct at outlet	Contact time x chlorine concentration = 42.24x 0.3 = **12.7 mg.min/l**		

Calculation tool

r	L	Flow (m^3/h)	Contact time	Chlorine concentration (mg/l)	Ct
			πr^2 x L x 60 / flow		Contact time x chlorine concentration

The service reservoir volume can be used in the Ct calculation if there is no dedicated contact tank at the treatment works. The effective contact time in the service reservoir is calculated as for a contact tank, assuming "Poor" design i.e. D_f = 0.3.

The total effective contact time is that for the pipe and service reservoir added together. The effective Ct is the total effective contact time multiplied by the chlorine concentration after the service reservoir.

Calculation tool for pipe plus service reservoir

Service reservoir volume				**Flow (F)**	**Effective contact time in service reservoir**
L	W	D	D_f	m^3/h	$= L \times W \times D \times 60 \times D_f/F$
			0.3		=
Pipe contact time calculated as above =					
Total contact time = Pipe contact time + service reservoir effective contact time					
Chlorine concentration after service reservoir (mg/l) =					
Effective Ct at outlet = Total contact time x chlorine concentration after service reservoir					

4.4 Other considerations

Chlorine residual readings downstream of each tank and pipeline for which effective contact time is claimed should be collated to permit the ongoing cumulative calculation of effective contact time based on decaying chlorine concentrations at different tanks and pipelines between the point of disinfection and the consumer. Consideration of source contamination risk, the targeted reduction in pathogens and the scheme specific decay profile in conjunction with the effective contact time of scheme headworks elements should inform decisions relating to the disinfectant dose.

The provision of adequate chlorine contact time before the water supply reaches the first consumers may be a particular problem in small water supplies and pumped distribution networks. Inadequate chlorine contact to inactivate bacteria and viruses may also exist in situations where existing site constraints do not permit the addition of adequate effective contact volumes in accordance with this manual.

Proper disinfectant mixing using static or mechanical mixers, correct pH control of water to be dosed and improved residual monitoring will all help to mitigate the risk to human health posed by insufficient chlorine contact. Where adequate contact volumes cannot be provided consideration should be given to the achievement of primary disinfection by pre-treatment using an alternative disinfectant (such as ozone or ClO_2) or UV disinfection. Refer to Section 7 of the Manual for details of UV disinfection and its synergistic use in conjunction with chlorination disinfection for broad spectrum inactivation of bacterial, viral and protozoan pathogens.

In the case of larger schemes with long distribution systems, the provision of adequate effective contact time is often not a problem due to the scale of the scheme headworks comprising treated clear water tank, the size of dedicated rising mains and storage tanks. By contrast, the chlorine dose to be applied at the treatment plant may be largely effected by issues other than adequate chlorine contact.

These issues may involve balancing the conflicting need to maintain adequate chlorine residual at the extremities of the large network while managing the taste and odour perception of consumers close to the scheme headworks. In this instance, the regular scouring of distribution mains in conjunction with the location of addition secondary chlorination systems on the network may be required to safeguard the health of consumers without creating the perception of excessive chlorination close to service reservoirs.

5. STRATEGIES FOR CHLORINE DOSING CONTROL

The common methods for controlling the addition of chlorine as part of a disinfection process include

- Feed forward dosing control where an operator set chlorine dosing rate is changed in proportion to the signal received from a process or pumped flowmeter
- Feed back dosing control where an operator set chlorine dosing rate is changed in proportion to the signal received from a residual chlorine monitor downstream of the dosing point.
- Cascade loop control involving feed forward control (in proportion to flow rate) and additional feedback control of dose rate (based on a chlorine residual monitor). The chlorine residual level downstream of mechanical mixing and/or chlorine contact time is compared with a desired residual set point value. A PLC based controller automatically adjusts the flow-proportional dose rate using the feedback residual chlorine signal to compensate for the difference. The PLC controller is usually programmed on a site specific basis to cater for each particular application

Depending on each specific disinfection application, there generally is an optimum choice for controlling the injection of either chlorine gas or sodium hypochlorite.

To determine the preferred strategy for their applications the operator needs an appreciation of the following

- the instrumentation required for each control strategy,
- the desired residual dosage and control
- the particular site constraints such as the availability and effectiveness of contact tank volumes and/or mixing devices, the range and variability of flowrates and chlorine demands
- the required routine maintenance required

Manual on-off control should never be used for chlorination of drinking water where waters originate from a surface water source or from a groundwater source subject to surface water contamination e,g. in areas with karst limestone geology. Exception may be made only where the flow is constant and there is a consistently low and stable chlorine demand such as from an unpolluted groundwater aquifer source.

Flow proportional control may be appropriate for booster chlorination application on pumped systems where a pre determined dose is required and where treated water quality is consistently good or chlorine demand is not variable. However if there is a long contact time prior to residual monitoring, feed back control may not provide a satisfactory response to variable water demand conditions. In addition when using bulk delivered hypochlorite (which can deteriorate over time) or particularly hypochlorite generated by on-site electrolytic technology (where chlorine content may vary depending on operating conditions at generation), flow proportional control without residual monitoring is not recommended.

Flow proportional control with residual monitoring feedback to adjust the dosing rate is suitable for systems where the water demand of the system at the point of dosage stays relatively constant but where the chlorine demand of the water or the chlorine content of the dosed solution is potentially variable. For most primary and secondary disinfection installations flow proportional dosing in tandem with residual monitoring control is the most common control strategy used.

Residual feedback control systems can also be used on inline chlorine booster stations but only where there is adequate mixing between the dosing point and the sampling point for the chlorine residual analyser. Homogeneous mixing of added chlorine is required to prevent inaccurate chemical dosage control due to inconsistently mixed chlorine solution at the sampling point. Where this mixing is not achievable hydraulically within the pipe manifold, static mixers should be used. Where such static mixers are used they should be accompanied by testing verification to prove that proper mixing is achievable to comply with any site installation constraints.

While flow proportional control of chlorine dose is an integral part of the most commonly used dosing strategies, it is important to consider the effects of flow variation on Ct and contact tank performance. In principle, a change in flow rate, with a consequent increase or decrease in contact time (t), should be accompanied by an inversely proportional change in chlorine residual (C) to maintain the target Ct.

However, the adjustment of chlorine concentration (C) to compensate for larger flows (i.e. smaller t value) may not be a viable approach for many disinfection installations, particularly at larger works, where operation to a fixed chlorine residual can be a more practical approach

6. RECORDING AND VERIFICATION OF CHLORINATION SYSTEMS

An appropriate regime for monitoring and control of chlorination dosing is necessary to ensure that the desired chlorine dose and residual concentration match the target for Ct under site specific conditions of flow, temperature and pH.

Another key issue relating to the provision of a reliable dosing and monitoring system as part of an appropriate dosing control strategy is the provision of backup dosing equipment. Duty and standby dosing arrangements should be in place at chlorine dosing points for primary or secondary disinfection at the treatment plant and at re-chlorination stations within the distribution network.

There should be automatic changeover of pumps in the event of malfunction of the duty pump and the automatic changeover facility should be checked on a regular basis by the water services authority or private water supplier to ensure it is operating adequately. Duty/assist dosing pump arrangements may also be acceptable provided that if either pump fails there is sufficient flexibility in the pump arrangements to ensure that the other pump automatically increases to compensate for the malfunctioning pump.

In addition to its use in controlling chlorine dosing, monitoring instrumentation and reliable storage of the chlorine residual data is necessary to ensure the validation of the disinfection system and its verification in the proper disinfection of drinking water.

A chlorine monitor must be installed at the appropriate location following disinfection (i.e. after the appropriate contact and mixing with water). The chlorine monitor must be a priority alarm with a dial out facility to ensure that an immediate response can be made in the event of inadequate levels of chlorine in the final water. Furthermore water services authorities and private water suppliers must ensure that the data from the chlorine monitor is archived and reviewed on a regular basis to observe any trends in chlorine demand. In this regard, the EPA have advised water services authorities to have regard to the EPA *Drinking Water Guidance Circular DW01/08 – Disinfection of Public Water Supplies*.

Validation of the monitoring and control regime will require routine checks on collated SCADA data that target residuals are being achieved, as well as frequent check sampling of drinking water for coliform analysis.

The monitoring of other water quality parameters may also 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 for the disinfection application.

At sites with sources subject to surface water contamination where colour and turbidity can be subject to significant and frequent variability, suitable alarms and/or control systems should be in place to prevent this impairing chlorination performance. It is best that such alarms should be priority alarms with dial out facility and/or system shut down if adequate treated water storage is available to facilitate an appropriate treatment and/or disinfection response by the operator.

Automatic control of chlorine residual to increase Ct in response to increased colour or turbidity changes is not recommended due to the risk of organic byproduct formation.

7. SUMMARY OF PRACTICAL GUIDANCE TO ENSURE SECURITY OF CHLORINATED WATER SUPPLY

The following list summarises the main issues which operators should take into account to ensure the security of chlorinated water supplies

- Reduce potential for DBP formation by optimising the clarity of the water to be disinfected by ensuring that where possible TOC levels are reduced to levels below 3mg/l
- Where plumbosolvency is not an issue in the distribution system, reduce the pH level of water to be disinfected to less than 7.5
- Ensure that secure and effective arrangements are in place for chlorine dosing and monitoring, with back-up and stand-by systems as needed, to maintain the desired dose and minimise the risk of non-disinfected water entering supply.
- Ensure that a site-specific Ct has been identified – a value of 15 mg.min/l should be used as a default if no site-specific factors suggest a higher value would be needed.
- Check that the “effective” contact time has been established based on consideration of the contact tank structure/design, or using tracer tests.
- Identify the target residual needed <u>after</u> the contact time, and set chlorine dosage rates and alarms appropriately.
- Ensure that allowance for temperature change and pH increase have been made for in establishing the Ct.
- If the Ct (and therefore the identified target residual chlorine) is not known to be based on minimum expected water temperature and highest expected pH, make adjustments to the target residual as indicated below:

  Assuming the target Ct is 15 mg.min/l, adjustments to Ct to allow for pH and temperature should be made as follows:

$$\text{Adjusted } Ct = 15 \times pH_d \times Temp_d$$

using the following temperature and pH correction factors:

Temperature (ºC)	$Temp_d$ factor
<5	1.5
5-10	1.2
>10	1

pH range	pH_d factor
8.26 – 8.50	1.4
8.01 – 8.25	1.3
7.76 – 8.00	1.2
7.50 – 7.75	1.1
<7.50	1.0

So for water temperature of 7ºC at pH 8.1, the Ct should be:

15 x 1.2 x 1.3 = 23.4 mg.min/l

- Regularly check the on-line chlorine monitor readings using a hand-held system – daily checks are recommended – and make adjustments to the monitor as appropriate (see Appendix 2.6).
- Maintain a record of chlorine residual monitoring data, and review routinely to ensure the system is secure.
- Implement a routine sampling regime for treated water to ensure microbiological compliance is being achieved, and disinfection by-product formation is not excessive in relation to the regulatory standards.

A suitable on-line chlorine residual monitor should be provided at an appropriate point in the system (i.e. after the defined contact period) to control the chlorine dose and/or provide an alarm in the event of the chlorine residual being higher or lower than the defined target value for the site. Low level alarms are critical in this respect, and a maximum of 0.1 mg/l below the target concentration for a maximum of 5 minutes would be recommended. A high level alarm is needed to prevent excess DBP formation and avoid customer complaints. A maximum of 0.2 mg/l above the target concentration is recommended.

Automatic shut down should be established if the chlorine concentration after the contact period falls below 0.2 mg/l below the target value for a maximum of 5 minutes.

For larger sites in particular, it may be advisable to provide shut down in the event of low chlorine before the contact tank, to avoid accumulation of non-disinfected water in the contact tank.

Clear guidance should be provided on dealing with alarms, which should include:

- Actions to be taken, and a checksheet to ensure the actions are carried out.
- Names and telephone details for the necessary contacts (primary contact and deputy.
- Names and telephone details for senior managers and health authority contacts, and guidance on when there could be health implications that would require these to be contacted.

Actions to be taken would be site specific, but could include for example:

- Check that the chlorine monitor is reading correctly by taking a manual measurement.
- Check chlorine dosing pumps and switch from duty to standby if appropriate.
- Check the integrity up upstream treatment (e.g. coagulation, filtration) and water quality within treatment.
- Check for changes in raw water quality that could have increased chlorine demand (ammonia, colour).
- Take works out of supply if this has not happened automatically and if the target residual cannot be restored.

APPENDIX 2.2

PRACTICAL GUIDANCE FOR PLANT OPERATORS ON THE OPERATION AND VERIFICATION OF UV DISINFECTION SYSTEMS IN USE

1. INTRODUCTION

UV disinfection plants can only be employed for the primary disinfection of water supplies due to the fact that such systems do not leave a residual in the disinfected water. Such residuals are usually necessary to prevent contamination of treated water during the subsequent distribution of drinking water to consumers and to quality assure its quality to the consumer.

UV disinfection plants are usually located within water treatment plant downstream of any pre-treatment, oxidation, clarification and filtration stages of the process, as determined necessary by the range of raw water quality parameters to be treated. Due to the de-chlorination effect of UV light, UV disinfection systems are also located upstream of chlorine disinfectants and other post treatment chemicals.

The Drinking Water Regulations SI 278 under Regulation 13 requires Water Service Authorities or Private Water Suppliers to ensure that “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”.

Verification of a UV disinfection system operation requires a plant operator to have;

- an understanding of the target goals of the UV system to be operated
- knowledge of the capability of the UV reactor(s) in operation, as determined by the validation certification of the particular reactor(s), including the dose monitoring strategy on which the certification is based
- knowledge of the functionality of the various elements of the reactor(s) and the associated instrumentation for the monitoring of key parameters to ensure correct UV system operation in accordance with its validation

In addition an operator will be required to demonstrate adherence to criteria recommended by the reactor manufacturer regarding the correct calibration of instrumentation and the required frequency for the replacement of system elements and instrumentation to ensure the continued efficacy of disinfection.

2. THE TARGETED GOALS OF THE UV SYSTEM

The goals of the designed UV system to be operated are usually determined by the system designer following a DWSP approach involving;

- 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 sampling to determine the extent of pathogen inactivation required of the UV disinfection system
- The determination, by the treatment process designer, of the pre-treatment process(es), necessary to ensure the required clarity of the water (with respect to colour, turbidity and TOC) and/or inorganic chemical removal, upstream of chosen reactor. The targeted goals of the pre-treatment, necessary to ensure the efficacy of the designer's chosen system and its ability to achieve the target pathogen inactivation levels established with respect to bacteria, viruses and protozoa.

It should also be clear to the plant operator whether the UV disinfection system is to be operated as

- a broad spectrum primary disinfection system to inactivate the full range of common waterborne bacterial, viral and protozoan pathogen with only secondary application of a residual forming disinfectant such as chlorine or chloramines
- targeted protozoan inactivation as part of a multi-barrier approach to primary disinfection in combination with another chemical disinfectants such as chlorine

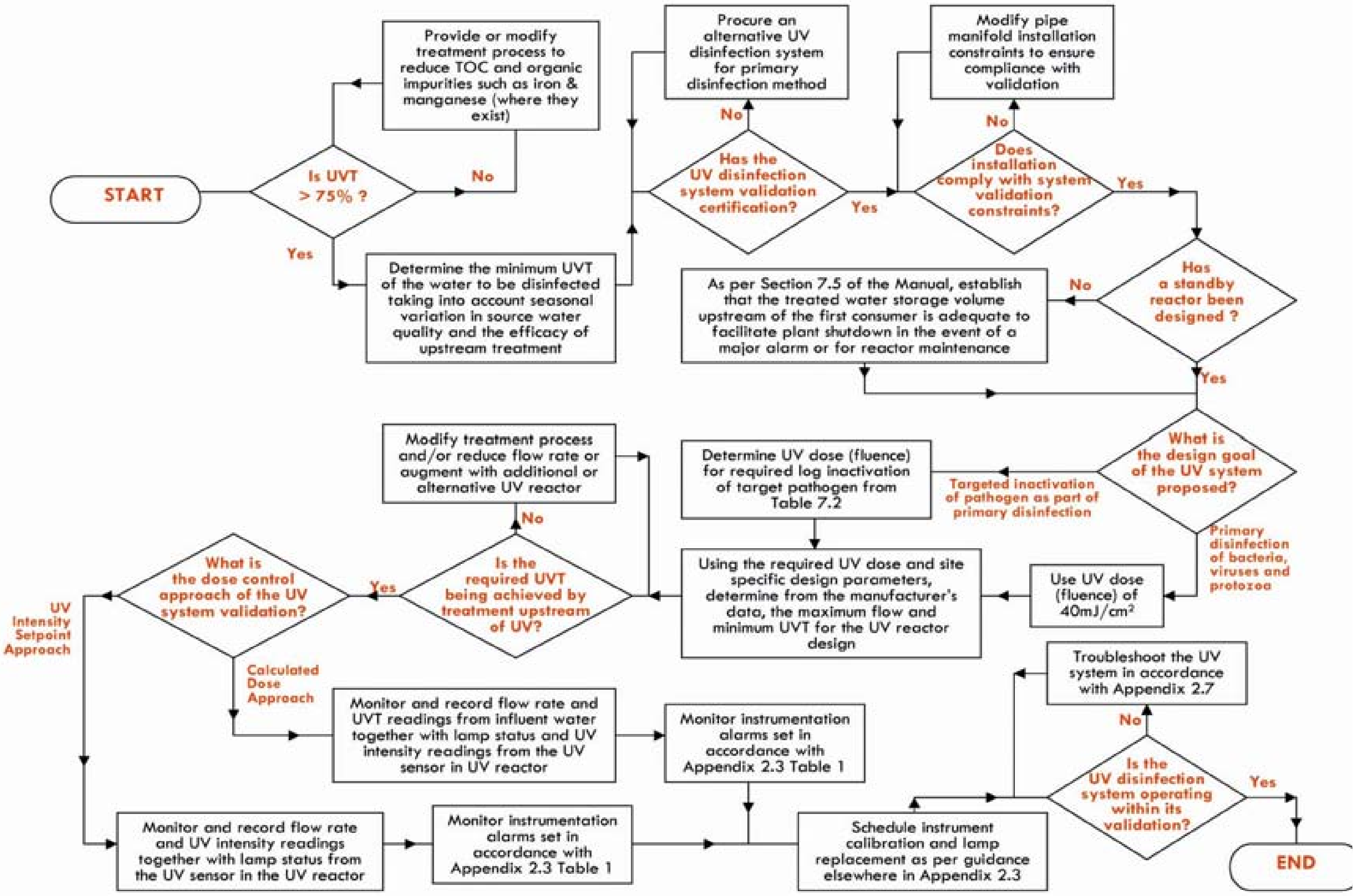
In the case of the former, it is usual that proprietary UV disinfection systems, to be used for broad spectrum UV disinfection, are required to have independent validation certification to deliver a 40 mJ/cm^2 at the particular design flow through the UV system. As set out in Table 7.2 of the Guidance Manual, this $40mJ/cm^2$ dose is required to deal with most waterborne viruses and spores while both common bacteria and protozoa are inactivated at lower doses.

In the case of the latter, the combination of UV disinfection with other chemical disinfectants for primary disinfection may require a lower UV dose than $40mJ/cm^2$, if UV disinfection is targeted to achieve only the inactivation of protozoan pathogen such as Cryptosporidium and Giardia. In this case the appropriate UV dose level will be determined by the required log activation to be achieved in the drinking water.

The following decision flowchart sets out practical guidance in the use of UV reactors for the primary disinfection of water supplies. In addition to system calibration and monitoring the flowchart also takes account of treatment risks likely to affect the efficacy of UV reactors in operation and the instrumentation parameters to be monitored by the plant operator to ensure verification of system operation in accordance with its validation certification.

The following sections of this guidance should be read in conjunction with the foregoing flowchart where clarification of the issues is required in relation to the decisions contained therein.

PRACTICAL GUIDANCE
UV DISINFECTION OF DRINKING WATER SUPPLIES – FLOWCHART



3. UV SYSTEM CAPABILTY AND VALIDATION CERTIFICATION

The Guidance Manual recommends that all UV systems used for the disinfection of drinking water should possess third party validation certification. This validation should be based on biodosimetry testing for the particular reactor from an independent third party testing facility undertaken in accordance with international standards and their validation protocols.

This validation certification will set out the capability of the UV reactor to apply a UV dose and deliver the targeted inactivation of pathogens under defined operating conditions including the following:

- the range of flow rates through the reactors
- the clarity of the water, as measured by the UVT transmittance of the water
- the UV intensity of the UV energy transmitted through the water as it passes through the reactor
- pipe installation criteria associated with the validation test
- the maximum number of hours since the lamps were last replaced

The operator shall ensure that

- the UV system is operated and maintained in accordance with the validation certification
- mercury lamps and other components are replaced after stipulated maximum usage periods
- associated monitoring instrumentation are calibrated and where necessary replaced at the frequency stipulated in the validation standards and in the manufacturers instructions

Such validation certification is usually based on either of two dose monitoring strategies namely the UV Intensity Setpoint approach and the Calculated Dose approach. Both of these strategies are described in the Guidance Manual.

The UV Intensity Setpoint approach is the system for the monitoring of UV systems validated in accordance with DVGW (German) and ONORM (Austrian) protocols. UV dose delivery is indicated by measured UV intensity from the UV sensors within the reactor which alters the dose in response to changes in flow rate and lamp aging. The minimum UV dose delivery is verified when the UV intensity is above a minimum setpoint value.

The Calculated Dose Approach is the system for the monitoring of UV systems validated in accordance with US EPA validation protocols Using this approach the UV dose is calculated using an equation dependent on flow rate, UV intensity, UVT and lamp status. The measured UV intensity sets the lamp power to sustain the required dose in reply to varying flow and UVT.

The main advantage of the UV Intensity Setpoint Approach compared to the Calculated Dose Approach is that

- UVT monitoring is not needed to confirm dose delivery. It is not required to monitor UVT for systems operated using the UV Intensity setpoint approach. As the UVT of the water decreases, the absorbance of the water will increase thereby reducing the UV Intensity reaching the UV sensor. This increased absorbance of UV light will reduce the intensity sensed to a level below the validated setpoint for 40mJ/cm^2 dose delivery, resulting in an generation of an off-specification alarm

- the UV Intensity Setpoint Approach is straightforward and simple to control with one operational setpoint and one maximum value for flow rate

- The UV Intensity Setpoint approach requires simpler tests to achieve validation than the Calculated Dose Approach.

This validation approach is used for small water systems which are usually operated on an on/off basis based on a fixed dose delivery of 40mJ/cm^2 dose.

The Calculated Dose Approach on the other hand facilitates a more flexible approach to UV disinfection as follows:

- the dosing of UV to achieve different log inactivation values and the specific targeting of pathogens as part of a multi-barrier approach to drinking water disinfection can be better accommodated using this approach.
- This approach enables UV dose pacing, which reduces operating costs and allows more energy efficient operation of larger UV reactor systems when water quality and flow rate varies When the UVT of the water rises and/or treated water flow rates fall, the power input necessary to achieve the required target dose can be lowered automatically by a control loop based on signals from a flowmeter, UVT monitor and the UV sensor(s) in the reactor. Similarly, when UVT of the water falls and/or treated water flow rate rises, the power can be automatically changed using the same control loop to increase the necessary absorbed power to maintain the targeted UV dose

The Calculated Dose Approach is also more intuitive in that the calculated dose can be compared to the required dose for the target pathogen and a required log inactivation.

A lower UV dose may be valid for such UV disinfection systems which are specifically used as a barrier to Cryptosporidium, when used for primary disinfection in combination with chlorination.

4. THE FUNCTION OF UV SYSTEM COMPONENTS AND INSTRUMENTATION

Operators of UV disinfection systems should consult the particular Operation and Maintenance Manual for their installation to ascertain drawings which should clearly demonstrate the various components and the location of monitoring/controlling instrumentation for the UV disinfection reactor(s). Such O&M manual should also contain data sheets in respect of the particular sensors used in the proprietary reactor and the UVT analyser where it is used for dose control under a reactor operated using a calculated dose approach

In addition, the process flow diagrams and functional design specification of the system and it's associated instrumentation should be consulted to ascertain the purpose of each reactor component and dose controlling instrument and sensor.

The verification of a UV process to the appropriate Supervisory Authority under the 2007 Drinking Water Regulations is dependent on the collation of operational data to demonstrate operation in compliance with its validation and the generation of system alarms to prevent and/or warn the operator when off-specification water is being produced.

Collation of operational data and alarm generation and the control of day to day operation is usually achieved by a microprocessor based PLC control system which continuously monitors and controls the UV reactor's system parameters in conjunction with an input flow signals from a flowmeter, the UV intensity sensors and a UVT sensor.

The UV system parameters commonly collated for record purposes and alarm generation are as follows

- Influent flow rate

- UV reactor and individual UV lamp status
- UV intensity
- UV Dose
- UV Transmittance
- Lamp cleaning cycle and history
- Absorbed Power level
- Specified Alarms
- Alarm History
- Accumulated run time for lamps or banks of lamps

The UV equipment is controlled by a central programmable logic controller (PLC) using either of the dose monitoring strategies described above, i.e. UV Intensity Setpoint or Calculated Dose approaches. A typical set of UV alarms and guidance on the functionality of such alarms for the various dosing strategies are set out overleaf.

ALARM SETPOINT	**ALARM TYPE**	**DOSE STRATEGY**	**PURPOSE**
Lamp Age	Minor alarm	Both	Run-time for lamp indicating end of defined operational lamp life which is different for LP, LPHO and MP lamps (refer to Table 7.1 Section 7.2.1 and manufacturers instructions regarding validated end of lamp life)
Calibration Check of UV sensor	Minor alarm	Both	UV sensor requiring calibration check based on operating time since last calibration.
Low UV Validated Dose	Major alarm	Needed for "Calculated Dose" approach only	Indicated validated UV dose (based on reactor parameters, i.e., flow rate, UV intensity, and UVT) falls below required UV dose.
Low UV Intensity	Major alarm	Both but the major control parameter for "UV Intensity Setpoint"	Intensity falls below validated conditions.
Low UVT	Major alarm	Needed for "Calculated Dose" but recommended for both	UVT falls below validated conditions when using "Calculated Dose" For "UV intensity approach" UVT is a useful indicator of decreasing water quality and a good surrogate instrument for high TOC levels in

			process water
High Flow	Major alarm	Both	Flow rate falls outside of validated operation range.
Mechanical Wiper Failure	Major alarm	Both	Lamp wipe function fails which uncorrected may compromise the efficacy of the system due to lamp fouling
Lamp Ballast failure	Major alarm	Both	Single lamp/ballast failure identified
	Critical alarm	Both	Multiple lamp/ballast failures identified.
Low Liquid Level	Critical alarm	Both	Liquid level within the UV reactor drops and potential for overheating increases.
High Temperature	Critical alarm	Both	Temperature within the UV reactor or ballast exceeds temperature setpoint

Appendix 2.3 Table 1 Typical alarm generation for UV disinfection systems

The design of a UV disinfection systems should ensure that the pipe manifold on which UV reactors are installed remain full of water even when flow through the system decreases to zero.

As set out in Section 7.5 of Manual, UV reactors may be required on a duty/standby basis to facilitate routine maintenance of the reactors and/or necessary component replacement without the unnecessary generation of off-specification water or the disruption of supply to consumers. Even if sufficient storage exists downstream of a UV reactor and upstream of the first consumer, the provision of a standby unit allows for automatic changeover of a reactor following alarm generation.

For larger UV Systems the power variability of MP lamps systems and associated ballasts panels between 30% and 100% of maximum power favours the use of MP lamps and “Calculated Dose” validation on systems designed to deal with a range of water flows and a variability of water quality above its minimum designed UVT. This ability to pace the UV dose in response to flow and UVT lends itself to the efficient operation of UV disinfection systems on larger flows where the potential for energy savings are greater

5. MONITORING REQUIREMENTS FOR UV DISINFECTION SYSTEM OPERATION

As set out in Section 3 and 4 above, the monitoring requirements of UV reactors will vary based on the type of UV reactor, its configuration and the dose-monitoring strategy used to ensure that it complies with its validation certification.

As set out in Table 1 above, UV reactors should also be regularly monitored to diagnose operating problems and determine when maintenance of equipment and key instrumentation replacement is necessary.

Monitoring of dosage using both dosage approaches must include UV intensity as measured by a UV sensor, flow rate and lamp status.

It is recommended that UV intensity, lamp status and flow be recorded at 4 hour intervals and where the dosing strategy uses the calculated dosage approach, the recording frequency of UVT and thus the calculated dose should similarly be at a recording frequency of 4 hours.

It is recommended that calibration of UV sensors be verified with respect to a replacement reference UV sensor at least monthly. It is best to calibrate sensors in both duty and standby units where they exist to ensure that both sensors are ready for use at any time. Where UV sensor calibration reveals that the reading measured on the duty sensor exceeds the reference unit by more than 20% the UV sensor should be replaced.

Because UVT is a critical parameter for the Calculated Dose Approach, calibration of UVT analyzers is necessary to determine if reactors are operating within validated conditions. It is recommended that if UVT is part of a dose monitoring strategy, on-line UVT analyzers should be evaluated at least weekly by comparing the on-line UVT measurements to UVT measurements using a bench-top spectrophotometer. Bench UVT reading should not vary from the reading recorded by the UVT analyzer by more than 2%.

It is recommended that off-specification events relative to validated parameters (UV Intensity, UVT, flow rate or lamp status) be monitored and alarmed and that the total off-specification monthly total volume be recorded where these parameters varied to the extent that the reactor operated outside its validated range. It is recommended that particular attention be paid to the minimising such off-specification events where the risk of a specific pathogen is high and where other parallel treatment and disinfection methods (where used) are incapable of removing or inactivating the particular pathogen. e.g. UV disinfection in high risk *Cryptosporidium* sources without adequate clarification treatment and with only chlorine as an augmenting or secondary disinfectant.

The USEPA UVDGM also contains useful flowcharts to assist in the management of off-specification events such as low UV intensity and UVT and low validated dose. Such flowcharts assist in necessary decision making surrounding instrumentation calibration, fouling of lamp sleeves and the necessity for lamp and sensor replacement.

APPENDIX 2.3

PRACTICAL GUIDANCE ON THE PREVENTION OF DISINFECTION SYSTEM PROBLEMS AND THE TROUBLESHOOTING OF SYSTEM MALFUNCTIONS

1. Introduction

In accordance with the Drinking Water Safety Plan risk-based approach to managing drinking water quality, “risk assessment and risk management …. in water supply from catchment to consumer” is key to the proper operation of water disinfection systems and the trouble shooting associated with their malfunction.

Operational procedures and consequent troubleshooting of disinfection systems will have to appreciate the influence of source risks and the efficacy of pre-treatment systems upstream of both primary disinfection and residual generation disinfection systems.

This Appendix provides guidance in relation to the management of source risks and the necessary pre-treatment issues in respect of each of the different disinfection technologies in common use in Ireland.

This guidance in respect of the prevention and mitigation of disinfection system malfunction is discussed as follows under the distinct headings of

- Appreciation of source risks to disinfection efficacy
- Management of treatment risks upstream of disinfection
- Maintenance of disinfection equipment and troubleshooting of system malfunctions.

This guidance does not seek replace the manufacturer’s manual relating to the operation and maintenance of disinfection equipment or the component instrumentation necessary to monitor and verify the various disinfection technologies. The following guidance shall be read in conjunction with the appropriate instrument manuals.

2. Appreciation of source risks to disinfection efficacy

The realisation of risks associated with raw water changes or seasonal variations in source waters is important in the Irish context, due to the heavy reliance in Ireland on surface water sources and on groundwater sources susceptible to surface water contamination.

Different catchment geology and land use within catchments can yield particular raw water quality challenges to treatment and subsequent disinfection such as

- a high risk of organic contaminants as evidenced by spikes in colour, turbidity and TOC, associated pathogens
- Excessively high or low levels of hardness
- other inorganic impurities such as iron and manganese

The natural variation in the organic content, pH and temperature of surface water sources waters can also, in different ways and to a varying extent, all affect the efficacy of disinfection systems. These variations may require treatment systems and alarmed monitoring instrumentation upstream of disinfection systems themselves to be designed to cope with changes in key water quality parameters affecting their operation.

Less source risk and variation in raw water quality parameters is associated with groundwaters from deep aquifers although groundwaters abstracted in areas with shallow soils over an underlying karstified limestone can demonstrate surface water risks

3. Management of treatment risks upstream of disinfection

As discussed in the various sections of the Guidance Manual referring to the common disinfectants used in Ireland, the type of treatment that water is subjected prior to primary disinfection, and the way that treatment is managed and operated, can have a very significant influence on the performance of disinfection systems and their verification in use under the Drinking Water Regulations.

In this regard, it is important that the role of treatment processes upstream of disinfection is understood by plant operators in providing:

- Control of water quality parameters such as natural organic matter (as measured by TOC) and other inorganic impurities in water that can affect the efficacy of both chemical and non chemical disinfection systems used for primary and residual generation disinfection systems
- Additional removal barriers to pathogens ahead of disinfection as a means of augmenting the subsequent inactivation of pathogens by disinfection
- Control of water quality parameters which are precursors to by-product formation in final treated water

In addition, the Manual also details how the storage and generation of oxidants for treatment and/or subsequent disinfection of water can result in the formation of inorganic by-products in drinking water. The chapters of the Manual and the practical guidance Appendices, relating to various chemical and non-chemical disinfectants used for primary disinfection, details which water quality parameters affect the efficacy of the various disinfection systems.

In the case where chemical are used as primary disinfectants, the Ct tables set out in the manual for each disinfectant detail the adverse effect of low temperatures (in the case of ozone and chlorine dioxide) and high pH and temperature variations in the case of chlorine.

The Manual also details the risks associated with different chemical disinfectants with respect to both organic and inorganic disinfection by-product formation. While the risks are summarised as follows, operators should refer to the Manual and the particular practical guidance appendices for more detail.

Chlorination:	Organic THM and HAA by-products consequent to the presence of excessive natural organic matter in treated water comprising particulate or colloidal organic carbon such as colour and turbidity and/or dissolved organic carbon. The presence of inorganic by-products such as chlorate (consequent to the decay in the concentration of bulk sodium hypochlorite) or bromate (from the onsite generation of hypochlorite from salt with a high bromide content)
Ozonation:	Organic by-products formed consequent to inadequate removal of the biodegradeable organic carbon fraction which is increased by ozonation The potential for bromate formation – an inorganic disinfection by-product

Chlorine Dioxide:	The potential for the formation of the inorganic disinfection by-products chlorite and chlorate

The effectiveness of chlorine disinfection for residual generation in distribution networks is contingent on a treatment process removing micro-organisms as well as ensuring that the quality of final water in terms of turbidity and natural organic material (commonly measured as TOC) and pH is suitable for disinfection with chlorine.

4. Troubleshooting of disinfection system malfunctions

4.1 Chlorination

Chlorination is used primarily to disinfect drinking water supplies but can also use to oxidise both organic (natural organic material) and inorganic contaminants (iron and manganese) as part of drinking water treatment upstream of disinfection.

Chapter 4 of this Manual details the use and efficacy of chlorination in various forms (gas, bulk delivered hypochlorite or on site generated hypochlorite) as either a primary disinfectant following treatment or a secondary disinfectant (in combination with another disinfectant) or at a chlorine booster station on the distribution network.

A malfunction in chlorination disinfection systems usually results in one or more of the following:

- Insufficient free chlorine residual in drinking water to consumers at various points in the distribution network
- Excessive free chlorine residual in water with the possible consequent effects of consumer unacceptability due to taste and odour and DBP formation potential
- The presence of high concentrations of chloro-organic DBPs and other inorganic DBPs in drinking water

The following Tables explore the possible causes for each of the foregoing chlorination malfunctions. In the case of each possible cause it sets out what the likely symptoms of malfunction and the remedial action to be taken together with possible preventative operational practices or maintenance to be taken

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Insufficient chlorine residual	*Dosing Pump malfunction due to incorrect calibration or faulty pump controller*	Pathogens detected in supply? Is free chlorine concentration less than target level for adequate chlorination at consumers? Incomplete maintenance record? Date of last pump calibration curve?	Routine maintenance of dosing pump, regular calibration of pump delivery curve and checking of pump dose-controller. A low set-point alarm on chlorine residual monitor	Analyse fault and repair Manually dose reservoir with chlorine pending pump re-calibration and controller repair or replacement if necessary.
Insufficient chlorine residual	*Calculated Chlorine dose incorrect leaving Treatment Plant*	Pathogens detected in supply? Is free chlorine concentration less than target level for adequate chlorination at consumers? Is dose controller operating properly? Is the calculated dose adequate for required target Ct value? Is the chosen control strategy adequate or operating properly?	Scheduled sampling and testing for residual chlorine on surface water affected sources following heavy rainfall. Supervisor review of dose calculation following changes of water quality Digital display of dose rate in addition to SCADA logging	Change dose controller settings, if operating correctly. Recalculate dosage rate and check for adequate Ct. Implement feedback control of dosing using residual monitoring Supplement operator training.
Insufficient chlorine residual	*Flow proportional dose control not working properly*	Pathogens detected in supply? Is the chlorine demand variable? Is contact time to residual monitoring overly long? Is possible hypochlorite decay taken account of in dose?	Setpoint alarm generation on colour or turbidity Regular check on flow meter calibration Regular monitoring of hypochlorite concentrations	Consider additional feedback control linked to residual monitoring.
Insufficient chlorine residual	*Feedback dose control at re-chlorination stations not working properly*	Pathogens detected in supply? Is the chlorine demand variable? Is chlorine properly mixed at residual monitoring? Is possible hypochlorite decay taken account of in dose?	Regular flushing of mains. Regular monitoring of hypochlorite concentrations Proper mixing at residual sampling point	Increase dose pending corrective action Consider relative positions of dosing and residual sampling points Consider use of static mixer
Insufficient chlorine residual	*Dose controller not calibrated properly*	Pathogens detected in supply? Is pump calibration curve used to programme the controller still valid?	Regular checking of calibration	Increase dose pending corrective action. Programme the controller based on revised calibration

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Insufficient chlorine residual	*High or variable chlorine demand.*	Pathogens detected in supply? Is chlorine residual less than target level at disinfection point for adequate chlorination of water to consumers? Is chlorination equipment adequate when chlorine demand is highest? Is chorine demand due to particulate or dissolved organic carbon?	Adequate treatment of water to remove colour, turbidity and TOC upstream of chlorine disinfection. Use of a dose control strategy capable of reacting to raw water quality changes with feedback control of chlorine dose linked to chlorine residual A properly designed chlorination dosing system to cater for expected range of organics in the water	Implement changes to upstream water clarification process to control the reasons for high chlorine demand during periods of poor water quality. Replace chlorinator and/or dosing pumps to cater for variations in required dose Manual monitoring and manual chlorine control during poor water quality episodes.
Insufficient chlorine residual	*Dose correct but pH level too high*	Is chlorine residual less than target level at disinfection point for adequate chlorination of water to consumers? Is water subject to variable pH? Has pH drifted above 7.5? What is pH saturation of water?	High level set point on a pH monitor to detect drift in pH	Increase chlorine dose pending further action and testing waters for DBPs Lower pH as part of treatment process if plumbosolvency is not a water distribution network issue (i.e. lead pipes and services)
Insufficient chlorine residual	*Chlorine gas or hypochlorite solution runs out*	Pathogens detected in supply? Is chlorine residual less than target level at disinfection point for adequate chlorination of water to consumers?	Provision of adequate spare cylinders or level monitoring on bulk hypochlorite with low tank level set-point alarm or OSE malfunction	Emergency dosing using Appendix 3.1 pending delivery or generation of chlorine chemicals Fit alarm system if not supplied
Insufficient chlorine residual	*Lower % Sodium Hypochlorite solution than expected*	Is chlorine residual less than target level at disinfection point for adequate chlorination of water to consumers? What are the solution strength and storage conditions of hypochlorite on site? On what strength solution is the dosing calibration and calculated dose based? Is it the hypochlorite exposed to sunlight? Check quality of salt delivery for OSE	Properly sized storage facilities for hypochlorite and OSE to control age of dosed solution and its exposure to light Recording of percentage solution of bulk hypochlorite deliveries to ensure that chemical strength and consequent stroke of dosing umps are correct Monitoring and recording of ongoing hypochlorite testing	Increase the hypochlorite dose pending a new delivery Decrease the percentage solution of hypochlorite ordered as decay is less at lower solutions Facilitate the testing and recording of hypochlorite solutions dosed

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Insufficient chlorine residual	*Faults/blockages in dosing lines and injectors*	Is chlorine residual less than target level at disinfection point for adequate chlorination of water to consumers? Are dosing pumps operating properly? Check filters on solution dosing lines for blockages In the case of gas chlorinators was maintenance recently undertaken on gas lines and is chlorinator and storage room temperature controlled? In electrolytic system what is the purity of the salt used?	Regular maintenance of dosing pumps and filters on small bore dosing lines Order only high purity salt with optimal precipitating impurities Dry chlorine gas lines following maintenance Temperature control of chlorination and chlorine storage areas to minimum 15°C Adequate pressure at chlorine solution injection point	Correct reason for pump malfunction if appropriate. Unblock or replace filters on dosing lines to exclude impurities in dosing solution Dry out chlorine gas lines Regulate temperature in chlorine storage and dosing areas if appropriate. Change salt for electrolytic generation to higher purity
Chlorine dose and residual too high	*Dosing Pump malfunction due to incorrect calibration or faulty pump controller*	How high is free chlorine concentration at consumers? Incomplete maintenance record? DBPs detected in supply? Date of last pump calibration curve?	Routine maintenance of dosing pump, regular calibration of pump delivery curve and checking of pump dose-controller. A high set-point alarm on chlorine residual monitor	Analyse fault and repair Lower chlorine dose pending pump re-calibration or controller reset or replacement if necessary.
Chlorine dose and residual too high	*Calculated Chlorine dose incorrect*	How high is free chlorine concentration at consumers? DBPs detected in supply? Is dose controller operating properly? Is the calculated dose too high for required target Ct value? Is the chosen dose control strategy adequate or operating properly?	Scheduled sampling and testing for residual chlorine on surface water affected sources of variable quality Supervisor review of dose calculation following changes of water quality Digital display of dose rate in addition to SCADA logging	Change dose controller settings, if operating correctly. Recalculate dosage rate and check for adequate Ct. Implement feedback control of flow proportional dosing using residual monitoring Supplement operator training.

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Chlorine residual too high	*Higher % Sodium Hypochlorite solution than expected*	How high is free chlorine concentration at consumers? DBPs detected in supply? On what strength solution is the dosing calibration and calculated dose based? Was a higher strength solution transferred to the solution tank?	Recording of percentage solution of bulk hypochlorite deliveries to ensure that correct dose calculation is used to control dosing pumps Monitoring and recording of ongoing hypochlorite testing	Lower the hypochlorite dose pending a investigation of solution strength Facilitate the ongoing testing and recording of hypochlorite solutions dosed Provide operator training in the preparation of chlorine solutions
Disinfection by-products detected in water	*Significant change in TOC or colour & turbidity of source water after heavy rainfall*	Check rainfall records and gauging stations on influent rivers from catchment Scope extent of change in raw water quality parameters including pH and alkalinity Check UV transmittance as a short term surrogate parameter to full TOC analysis Is the groundwater source subject to surface water intrusions at raised water table levels	Adequate treatment of water to remove colour, turbidity and TOC upstream of chlorine disinfection. Regularly monitor TOC levels (and UVT as surrogate parameter to warn of TOC variation)	Undertake jar testing for existing treatment to reduce incoming TOC. Identify whether possible adjustment of pH or alkalinity changes are necessary Perform more frequent TOC monitoring & scope changes in treatment if required for TOC removal
Disinfection by-products detected in water	*Significant change in TOC levels in source water after dry weather*	Is there evidence of algal bloom in source water? If groundwater, has water changed due to borehole or well level depletion? If close to the sea, is there evidence of slight salt water intrusion? Check bromide levels in source water?	Adequate treatment of water to remove colour turbidity and TOC upstream of chlorine disinfection.	Undertake jar testing for existing treatment to reduce incoming TOC. If high algal concentrations in source waters, consider if necessary to include drum screen on abstraction or oxidant such as ozone or alternative source location.

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Disinfection by-products detected in water	*Change in DBPs due to upset in coagulation settling tanks operation at the treatment plant*	Is excess sludge build up in settling basin causing resolublisation of TOC in the water? Check sludge blanket to determine if carryover has occurred. Has carry over of organic solids occurred & is it combining with chlorine forming DBPs? Has increased flow rate decreased the amount of TOC removed in the tank.	Operate flow proportion coagulant dose with pre-dose pH or alkalinity boosting as required complete with alarmed dosing pump status, low set points on coagulant dosing tank levels and required pH range for optimal coagulation	Verify proper coagulant operation and provide/change alarmed set points as required to obviate re-occurrence of process upset In the case of carryover occurrence lower the sludge blanket and clean lamella plates or tube settlers as required
Disinfection by-products detected in water	*Significant change in TOC and/or turbidity levels due to sub-optimal operation of filters at the treatment plant*	Check filter turbidity monitoring for colloidal breakthrough associated with long filter runs or during filter ripening. Check length of filters runs, turbidity & head loss at backwash. Check for hydraulic filter overloading. Has a filter has been taken off-line resulting in overloading a high flow rates? If chlorine is being added ahead as an treatment oxidant ahead of GAC filter, is the activated carbon exhausted?	Operate filters with a post backwash settling period or wasting of first flush filtrate during ripening period following backwash Regularly monitor and record the adsorptive capacity of GAC filters if chlorine pre-treatment is used to improve removal efficiency of biodegradable organic carbon Regular monitoring of GAC filters and recording of carbon replacement intervals	Verify proper filter backwash headloss operation &optimal filter runs, adjust backwash cycle as needed. Make clarification process control adjustments as required. Replace or reactivate carbon on GAC filters if appropriate
Disinfection by-products detected in water	*Significant change in TOC or turbidity levels in water leaving the clear water tank or reservoirs at the treatment plant*	Is there evidence of sediment deposition in tanks and if so when it was last cleaned out? Are there dead zones in the tank?	Record maintenance of sediment removal from tanks Adequate baffling in clear water tanks to prevent dead zones	Clean sediment from tank. Consider tracer test on tank to establish if dead zones exist If tanks are twin celled consider reducing effective volume if adequate Ct is available

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Disinfection by-products detected in water	*Presence of inorganic by-products such as chlorate or bromates*	In bulk hypochlorite disinfection facilities what is the strength, age and storage conditions of the delivered hypochlorite? In OSE installations what is the purity of the salt product used for hypochlorite generation?	The proper design of storage facilities to allow for the timely use of bulk delivered hypochlorite	Ensure that hypochlorite storage drums tanks and dosing facilities exclude light exposure The use of low bromide salt for hypochlorite generation in OSE installations especially where chlorination is undertaken downstream of ozonation which can also form bromate by-products.
Disinfection by-products detected in water	*Change in DBPs due to bio growth or changes within the distribution system*	In larger distribution systems is water age excessive allowing reaction between free chlorine & TOC remaining in the water following treatment? Is bio growth in the distribution system concentrating organic materials that are reacting with free chlorine producing DBPs? Is there evidence of tuberculation upstream in the pipe network? Are the DBPs present downstream of storage reservoirs and if so are there sediment deposits in the tanks? Have reservoir levels with history of sediment deposition been severely lowered due to hydraulic demand? Have flow patterns changed resulting in transport of sediment within the network consequent to pipe flushing or repair? Was excess chlorine added to water network following new pipe commissioning or repair of existing pipe?	Provision of treatment process upstream of disinfection and distribution which lowers levels of TOC Regular flushing of distribution mains and reservoirs Co-ordination of pipeline/reservoir maintenance and repair with treatment and disinfection of water	In the case of network extremities and dead ends initiate corrective flushing programme. Mains with bio-growth may need to be superchlorinated and consideration should given to using chloramination as secondary disinfectant Tuberculation should be removed by pigging of pipes More regular flushing of reservoirs Monitor efficiency of previous mains scouring and redo using unidirectional flushing techniques where scouring is undertaken systematically from the centre of the scheme headworks while ensuring a chlorine residual is verified in scoured water.

4.2 Ozone

Ozonation is used primarily to oxidise colloidal organic compounds, for colour removal and for the reduction in levels of organic carbon as subsequent chlorination DBP precursors. Ozone as a powerful oxidant is also used for remove/reduction of inorganic contaminants (such as iron and manganese), algae and compounds that produce taste and odour, phenolic compounds and some pesticides as part of drinking water treatment process, upstream of disinfection. In conjunction with its oxidation role, it can be used for primary disinfection of drinking water supplies.

Due to the fact that ozonation residual are short lived as part of the oxidation/treatment process, chlorination is usually used following ozonation for residual generation to quality assure water within the distribution network to consumers

Chapter 5 of this Manual details the use and efficacy of ozonation as either as an oxidant or a primary disinfectant ahead of a secondary disinfection using a residual generating disinfectant. Ozone is generated on site by electrical corona discharge from dry air or oxygen. As a disinfectant, the performance of ozone is dependent on the ozone Ct (based on the ozone concentration during exposure to water in a contactor of designed hydraulic retention), temperature, pH and the turbidity and TOC levels in water to be treated. Section 5.3 of the manual details the Ct values required for different log inactivation of waterborne pathogens and the extent of its dependence on temperature.

A malfunction in ozonation disinfection systems usually results in one or more of the following:

- Low ozone residual during the disinfection process
- The presence of high concentrations of chloro-organic DBPs and inorganic DBPs in drinking water consequent to the non-removal of organic precursors ahead of subsequent chlorination and
- the formation of bromates at higher ozone dose rates.

The following Tables explore the possible causes for each of the foregoing ozonation malfunctions. In the case of each possible cause, it sets out what the likely symptoms of malfunction and the remedial action to be taken together with possible preventative operational practices or maintenance to be taken

Malfunction:	**Possible Cause**	**Fault Analysis**	**Possible prevention**	**Corrective action**
Low Ozone residual in contactor	*Dose controller not operating properly or applied dose rate incorrect*	What is ozone residual after contactor? Is the air drier operating properly? Check maintenance record for the most recent calibration of ozone sensor Is the water vapour content of air above manufacturer's instructions? Check preventative maintenance log Check records of dose calculation	Regular maintenance and re-calibration of ozone sensor and dose controller Ensure operating staff is adequately trained on complex nature of equipment operation, monitoring and its dependency on temperature. Checking of dose calculation by supervisory personnel	Increase the ozone dose manually or dose supply with chlorine pending rectification. Adjust recalibrate or replace the ozone controller as appropriate. Maintain air drier to ensure dry air is added to ozonator Train staff in the correct method for dose calculations
Low Ozone residual in contactor	*Inadequate equipment design*	What is ozone residual after contactor? Is the ozonator and contactor suitably sized to maintain the required log inactivation of targeted waterborne pathogens at the lowest expected temperature within its seasonal range.	Obtain proof that the contactor as designed has been effective in operation in similar water quality applications.	Process redesign to assess the most cost effective way to increase the required design Ct – usually by contactor modification
Low Ozone residual in contactor	*High Ozone demand due to variability in water quality*	Is ozone residual after contactor only low during periods of poor water quality? Is colour and TOC high in the water? If very high - is the ozone generator able to produce sufficient ozone during these poor water quality episodes	A properly designed and optimised pre-treatment process upstream of ozonation to control high ozone demand Dose control strategy with feedback control of ozone dose linked to ozone residual sensor.	Turn up ozone dose manually pending resolution of problem Process redesign to assess the most cost effective way to reduce ozone demand e.g. pre-treatment optimisation or screening/filtration to reduce particulate organic content Consider use dose control inversely proportional to temperature with feedback control linked to ozone residual

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Low Ozone residual in contactor	*Rapid rate of ozone decay due to high pH*	What is ozone residual after contactor? Is the pH above 7.5?	pH control as part of pretreatment process	Analyse the record of water quality monitoring to establish the need or otherwise for the inclusion of pH control
High level of organic DBPs following subsequent chlorination	*High level of TOC in the water for ozonation*	Are organic DBPs evident in n the drinking water downstream of secondary chlorination disinfection? Has GAC filtration been included following ozonation? When was the GAC last replenished? Is there evidence of downstream biological re-growth in the network?	Upstream treatment processes to reduce TOC levels in the water Provision of GAC filters following ozonation to remove the increased fraction of biodegradable organic carbon formed in the water by ozonation	Optimise upstream pre- treatment for reduction of TOC Evaluate subsequent filtration and introduce or replace GAC in the filter as required to reduce TOC and the increase biodegradable fraction going to supply following ozonation.
High level of bromate formation	*High level of bromide in the water for ozonation*	Establish bromide ion content of water to be ozonated Is ozonation being undertaken in combination with chlorination using electrolytic hypochlorite generated by OSE	Ozonation of water at low pH to minimise bromate formation.	Optimise upstream pre- treatment for reduction of DOC Lower the ozone dose. Lowering of pH and alkalinity levels in water may also help reduce bromate formation If OSE is use low bromide salt for hypochlorite generation.

4.3 Chlorine dioxide

Chlorine dioxide (ClO_2) is used as a disinfectant to inactivate waterborne pathogens and also as an oxidation to remove/reduce inorganic contaminants (such as iron and manganese) compounds that produce taste and odour, destruction of phenolic compounds and for zebra mussel control. It is also used for primary disinfection of drinking water supplies.

As ClO_2 cannot be compressed or stored commercially as a gas because it is explosive under pressure, chlorine dioxide requires to be generated on site using a variety of generation methods, which are set out in Section 6.2 of the Manual. As stated in section 1.1 of the Manual, the heath and safety risks associated with ClO_2 generation are not addressed in this manual as these risks are covered under current Health and Safety legislation.

ClO_2 generates a residual which is used for the calculation of Ct as a measure of disinfection performance. While the use of ClO_2 to provide a disinfectant residual in waters with low TOC and a low ClO_2 demand can result in residuals that can last for days, its use is somewhat limited in waters with moderate to high TOC.

Chapter 6 of this Manual details the use and efficacy of chlorine dioxide as either as an oxidant or a primary disinfectant which is often followed by chlorine as a residual generating secondary disinfection.

As a disinfectant, ClO_2 can inactivate most waterborne microorganisms over a wide pH range between 5 and 10. The disinfection performance of ClO_2 is dependent on its Ct (based on the ClO_2 residual concentration in water during contact time exposure) and the turbidity and TOC levels in water to be treated. Section 6.3 of the manual details the Ct values required for different log inactivation of waterborne pathogens which is generally independent of temperature. The Ct values for the inactivation of protozoa are generally much higher than ozone.

However due to the formation of chemically stable chlorate by-product in water dosed with ClO_2, dose rates are limited by regulation internationally. Although there is currently not a chlorate limit in Irish Drinking Water Regulations, the US EPA recommends a maximum dose of 1.4 mg/l chlorine dioxide to maintain chlorite below 1 mg/l and a maximum residual disinfection level of 0.8 mg/l for ClO_2. Further information on chlorite and chlorate by-product formation and on the possibility of halogenated by-product formation consequent to downstream secondary chlorine disinfection are detailed in section 6.4 of the Manual

A malfunction in chlorine dioxide disinfection systems usually results in one or more of the following:

- Low ClO_2 residual during the disinfection process
- High ClO_2 residuals in water which in excess of a modest dose readily form excessive chlorates especially in combination with subsequent dosing of sodium hypochlorite
- The presence of high concentrations of inorganic DBPs i.e. chlorites and chlorites in drinking water and also indirectly halogenated organic DBPs formation consequent to the non-removal of organic precursors ahead of subsequent chlorination

The following Tables explore the possible causes for each of the foregoing chlorine dioxide malfunctions. In the case of each possible cause, it sets out what the likely symptoms of malfunction and the remedial action to be taken together with possible preventative operational practices or maintenance to be taken

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Low ClO_2 residual	*Dose controller not operating properly or applied dose rate incorrect*	What is ClO_2 residual? Check maintenance record for the most recent calibration of ClO_2 sensor & controller? Is the water vapour content of air above manufacturer's instructions? Check preventative maintenance log Check records of dose calculation – are frequent errors recorded?	Regular maintenance and re-calibration of ClO_2 sensor and dose control calibration Ensure operating staff is adequately trained. Monitoring of ClO_2 residuals particularly following water quality variability Checking of dose calculation by supervisory personnel	Increase the ClO_2 dose manually or dose supply with chlorine pending rectification. Recalibrate, adjust, or replace the ClO_2 sensor or controller as appropriate. Train staff in the correct method for dose calculations Recalculate dose rates and alter controller settings
Low ClO_2 residual	*Inadequate equipment design*	What is ClO_2 residual following dosage? Is the ClO_2 system suitably sized to maintain the required log inactivation of targeted waterborne pathogens especially protozoa and *Cryptosporidium* in particular? Can the required disinfection inactivation be achieved given the internationally recommended maximum dose rates? Can the generator deliver the maximum recommended dose rate at the highest ClO_2 demand?	Obtain proof from suppliers that the system as designed has been effective in operation in similar water quality applications especially for sources with high risk of *Cryptosporidium* .	Use alternative or larger ClO_2 generator to increase the required design Ct
Low ClO_2 residual	*No ClO_2 from generation system*	Low ClO_2 residual? Check levels of remaining constituent generation chemicals. Is ClO_2 usage high?	Low level set point alarms on constituent generation chemicals A log of chemical deliveries and expected replacement dates. Adequate spare chemical deliveries	Dose supply with chlorine pending rectification. Install low set point alarms on stored chemicals alarm

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Low ClO_2 residual	*ClO_2 generation system malfunction*	Check deliver record for ClO_2 generation chemical concentrations i.e Chlorite, Hydrochloric acid, chlorine solutions Examine chemical supplier's certificate of chemical analysis Check that chemical dose rates are correct for delivered concentrations.	Comprehensive commissioning tests to determine the optimum ratios of constituent chemicals for ClO_2 generation Inspection logging and correct labeling of chemical deliveries by plant operator Adhere to planned preventative maintenance and keep record	Train staff in the correct chemical feed rate calculations Increase the ClO_2 generation chemical feed rates or manually dose water supply with chlorine pending rectification
Low ClO_2 residual	*Insufficient ClO_2 solution being dosed*	Check ClO_2 residual levels Is pump capacity sufficient to meet maximum ClO_2 demand Is malfunction due to scaling in dosing lines or injectors?	Adhere to planned preventative maintenance of pump and keep record	Increase the ClO_2 generation chemical feed rates or manually dose water supply with chlorine pending rectification Replace pump if deficient If scaling of dosing lines or injectors is a problem consider softening of sodium chlorite make-up water
Low ClO_2 residual	*High ClO_2 demand due inadequate dose control at times of variability in water quality*	Is ClO_2 residual in disinfected water only low during periods of poor water quality? Is colour and TOC high in the water? If very high - is the ClO_2 generator able to produce sufficient ClO_2 during these poor water quality episodes	A properly designed and optimised pre-treatment process upstream of disinfection dose to control high ClO_2 demand Dose control strategy with feedback control of dose linked to ClO_2 residual sensor.	Turn up ClO_2 dose manually pending resolution of problem Process redesign to assess the most cost effective way to reduce ClO_2 demand e.g. pre-treatment optimisation or screening/filtration to reduce particulate organic content Consider use of dose control with feedback control linked to the maintenance of ClO_2 residual

Low ClO_2 residual	*ClO_2 solution decay due exposure to sunlight*	What is ClO_2 concentration in solution tank?	Tank from which ClO_2 solution is dosed should be such that it excludes sunlight	Ensure dosing and mixing of dose occurs within pipes and closed tanks
High ClO_2 residual	*Dosing Pump malfunction due to incorrect calibration or faulty pump controller*	How high is ClO_2 residual in disinfected water– is it in excess of 0.8mg/l? Incomplete pump maintenance record? Has chlorite or chlorate been detected in water supply? Date of last pump calibration curve?	Routine maintenance of dosing pump, regular calibration of pump delivery curve and checking of pump dose-controller. A high set-point alarm on ClO_2 residual monitor	Analyse fault and repair Lower ClO_2 dose pending pump re-calibration or controller reset or replacement if necessary.
High ClO_2 residual	*Calculated ClO_2 dose incorrect*	How high is ClO_2 residual in disinfected water– is it in excess of 0.8mg/l? Has chlorite or chlorate been detected in water supply? Is dose controller operating properly? Is the calculated ClO_2 dose >1.4mg/l ? Is the chosen dose control strategy adequate or operating properly?	Scheduled sampling and testing for ClO_2 on surface water affected sources of variable quality Supervisor review of dose calculation following changes of water quality Digital display of dose rate in addition to SCADA logging	Change dose controller settings Recalculate dosage rate and check for adequate Ct. Implement feedback control of flow proportional dosing using residual monitoring Supplement operator training.
High ClO_2 residual	*% ClO_2 solution generated is higher than expected*	How high is ClO_2 residual in disinfected water– is it in excess of 0.8mg/l? Has chlorite or chlorate been detected in water supply? On what strength ClO_2 solution is the dosing calibration and calculated dose based?	Verify measured solution strength against the system commissioning tests for percentage solution generated based on new constituent chemicals of known concentration Monitoring and recording of ongoing ClO_2 solution testing	Lower the ClO_2 dose pending a investigation of solution strength Facilitate the ongoing testing and recording of ClO_2 solutions dosed Provide operator training in the preparation of ClO_2 solutions

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
High level of inorganic DBPs chlorite and chlorate	*By-products consequent to incorrect ClO_2 generation*	How high ClO_2 is residual in disinfected water– is it in excess of 0.8mg/l? Has chlorite or chlorate been detected in water supply to consumers? Is the calculated ClO_2 dose >1.4mg/l? Is the ratio of chemicals for ClO_2 generation correct? Is there perceived taste and odour in the water? If hypochlorite chlorination is used downstream as secondary disinfection is there chlorate content therein from decaying bulk hypochlorite?	Comprehensive commissioning tests to determine the optimum ratios of constituent chemicals for ClO_2 generation Inspection logging and correct labeling of chemical deliveries by plant operator Comprehensive operator training in chosen method of ClO_2 generation.	Change chemical generation chemical ratios to optimise correct ClO_2 generation Evaluate subsequent filtration and introduce or replace GAC in the filter as required to reduce TOC and the increase biodegradable fraction going to supply following ozonation. Supplement staff training as required? If hypochlorite decay is contributing chlorite lower the NaOCl bulk delivered concentration and expedite chemical turnover
High level of inorganic DBPs chlorite and chlorate	*Chlorination of TOC in the water resulting in reduction of ClO_2 to chlorites*	Are TOC levels in the water high prior to application of ClO_2 Is ClO_2 dosing being undertaken in combination with secondary chlorination using chlorine?		Optimise upstream pre- treatment for reduction of TOC Lower the ClO_2 dose If hypochlorite decay is contributing chlorite lower the NaOCl bulk delivered concentration and expedite chemical turnover

4.4 UV Disinfection

Because UV disinfection does not leave a residual in drinking water supplies water, it is used primarily to for primary disinfectant following treatment of water. UV disinfection plants are usually located within water treatment plant downstream of any pre-treatment, oxidation, clarification and filtration stages of the process, as determined necessary by the range of raw water quality parameters to be treated.

Disinfection only takes places during the passage of water through the UV reactor. In order to ensure that the requisite dose to effect inactivation of the targeted waterborne pathogens are delivered, the Guidance Manual recommends that all UV systems used for the disinfection of drinking water should possess third party validation certification. This validation should be based on biodosimetry testing for the particular reactor from an independent third party testing facility undertaken in accordance with international standards and their validation protocols. Details of these validation protocols (primarily DVGW (German), ONORM (Austrian) or US EPA) and the advantages and limitations of validation certification to these different standards are detailed in Chapter 7. Such validation is required to ensure that UV disinfection systems are verifiable in use in accordance with Regulation 13 of the Drinking Water Regulations SI 278 of 2007.

The target UV dose to be delivered by UV reactors will depend on the particular application, but a dose of 40mJ/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*. Appendix 2.3, which sets out practical guidance on UV disinfection systems, details further the use of UV disinfection for either broad spectrum primary disinfection or the targeted use of UV disinfection in combination with another disinfectant. The Manual and Appendix 2.3 also detail the UV dose approach which is the basis of the different European and US validation protocols.

In an Irish context, where over 90% of water sources are either from surface waters or surface affected ground waters, chlorination usually follows UV disinfection for residual generation and the quality assurance of disinfection in the distribution system

Chapter 7 of this Manual details the use and efficacy of UV disinfection systems in the inactivation of waterborne pathogens and the effects of certain water quality issues on the performance of UV disinfection systems. Section 7.3 of the manual details the UV dose required for different log inactivation of waterborne pathogens. The Manual and Appendix 2.3 detail the function of various monitoring instrumentation vital to ensuring UV systems are operated and that preventative maintenance is undertaken in accordance with system validation certification.

UV disinfection system malfunctions can occur results in one or more of the following:

- Low UV intensity or UV dose due to impedance by low UVT in water consequent to organic material as measured by colour, turbidity and TOC and inorganic impurities such as iron, manganese and hardness
- Failure to undertake maintenance in accordance with manufacturer's system validation

The following Tables explore the possible causes for each of the foregoing UV malfunctions. In the case of each possible cause, it sets out what the likely symptoms of malfunction and the remedial action to be taken together with possible preventative operational practices or maintenance to be taken.

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Low UV Intensity or UV Dose	*UV intensity lower than validated UV dose for target inactivation due to malfunction of UV reactor components*	Have pathogens been detected in the water? Was a low UV intensity alarm activated? (as per both European and US EPA validation protocols) What is the UVT of the water? If UVT monitoring is included as part of UV dose control (US EPA protocols) was a low UVT alarm activated Is there scale formation on the UV lamp sleeves? What are the age of the lamps with respect to hours run? Is there a standby UV reactor and if so is there automatic changeover on low UV intensity alarm? Has water penetrated through seals of quartz sleeve enclosing lamps? Check the maintenance record of the UV system with respect to UV sensor calibration (German and Austrian protocols) Check the maintenance record of the UVT monitor calibration if provided as part of a calculated dose approach validation (US EPA protocols)	Use only UV reactors which hare validation certification capable of verification for targeted inactivation of pathogens Routine cleaning and maintenance schedule for lamp sleeves or provision of mechanical and/or chemical quartz sleeve wipe systems as part of UV reactor Regular UV sensor calibration. Replacement of UV lamps in accordance with manufacturer's instruction and validated end of lamp life. Alarm UV sensor to warn of inadequate UV intensity and link alarm to duty UV reactor changeover if redundancy is provided or shut down off water flow if storage of properly disinfected water downstream is adequate to give response time Include UVT monitoring on system to facilitate further alarm generation of inferior water quality and help differentiation between reactor and water quality malfunction Auditing of plant operation and maintenance records	Reduce water flow until UV irradiation dose exceeds 40 mJ/cm^2 (European validation) or target dose (USEPA validation) Manually disinfect treated water storage tank (chlorine) until satisfactory water quality can be restored if cryptosporidium risk is low Clean quartz sleeve and sensor lens if fouling is evident within the reactor Replace UV lamp if in excess of end of lamp life (EOLL) set our in validation. Recalibrate sensor and if still not operating properly replace unit If UVT monitoring is part of dose control (US EPA protocols) recalibrate the UVT monitor Lubricate sleeve seal if quartz sleeve is leaking. Consider use of mechanical wiper system on UV reactor or a new UV reactor if inorganic fouling is excessive, pending pre treatment of water to remove same Instigate a planned calibration and maintenance schedule for monitoring instrumentation

Malfunction:	Possible Cause	Fault Analysis	Possible prevention	Corrective action
Low UV Intensity or UV Dose	*UV intensity lower than validated UV dose for target inactivation due to deterioration of water quality*	Have pathogens been detected in the water? Was a low UV intensity alarm activated? (as per both European and US EPA validation protocols) What is the UVT of the water? If UVT monitoring is included as part of UV dose control (US EPA protocols) was a low UVT alarm activated Is the flow rate within the envelope of the UV reactor validation certification? Check colour, turbidity and TOC levels in water? Is there excessive scale formation on the UV lamp sleeves? If so check iron, manganese and hardness levels	Ensure that the design criteria for the UV disinfection system is based on adequate water sampling record which should adequately capture the seasonal variation of water quality. A baseline database of UVT testing will best inform the appropriateness of UV disinfection as a primary disinfection method. Routine maintenance and calibration checks on flow rate controller. Use only UV reactors which have validation certification capable of verification for the targeted inactivation of pathogens Routine cleaning and maintenance schedule for lamp sleeves or provision of mechanical and/or chemical quartz sleeve wipe systems as part of UV reactor As part of the system, alarm UV sensor to warn of inadequate UV intensity and link alarm to duty UV reactor changeover, if redundancy is provided. Ensure upstream treatment has alarmed turbidity and/or preferably UVT monitoring on system to facilitate further alarm generation of inferior water quality and which help differentiation between reactor and water quality malfunction	Reduce water flow until UV irradiation dose exceeds 40 mJ/cm^2 (European validation) or target dose (USEPA validation) Shut off water flow if storage of properly disinfected water downstream is adequate to give response time If colour turbidity & TOC are high and UVT is low in the water, optimise treatment ahead of UV disinfection to reduce organics in the water If inorganic impurities such as iron, manganese or hardness are high in the water and if mechanical and/or regular chemical sleeve cleaning is not capable of reducing sleeve fouling to facilitate acceptable operation. Optimise treatment or add a pre-treatment oxidation system. If pre-treatment to remove natural organic matter is required, reappraise the use of UV disinfection as part of the revised process to remove organics, to effect primary disinfection of treated water and need for an alternative secondary disinfection within the distribution system. Supplement staff training.

Malfunction:	**Possible Cause**	**Fault Analysis**	**Possible prevention**	**Corrective action**
Re-infection of water in distribution system	*UV systems' inability to generate residual*	Have pathogens been detected in the water? Does monitoring of the UV disinfection system show that the water treated by UV disinfection was by reactors operated within the hydraulic and UV dose constraints of their validation certification	Use of chemical disinfection such as chlorination or chloramination as a secondary disinfection system downstream to generate a residual.	Arrange for scouring of distribution mains. Implement secondary disinfection if there is no secondary disinfection downstream of UV

APPENDIX 2.4

DAILY LOG SHEETS FOR OPERATORS OF DISINFECTION EQUIPMENT FOR THE VERIFICATION OF PRIMARY DISINFECTIONSYSTEM OPERATION

1. Introduction

Regulation 13 of the Drinking Water Regulations sets out the obligations of Water Service Authorities and regulated Private Water Suppliers with respect to the monitoring and verification of disinfection systems.

Verification of primary disinfection systems involving approved chemical disinfectants requires that data is monitored and collated to demonstrate that that the necessary Ct value has been consistently maintained during drinking water disinfection.

Verification of primary disinfection systems means ensuring that the actual Ct achieved is consistently greater than the Ct value, established in the Manual for the particular chemical in order to achieve the level of particular pathogen inactivation required, based on the risk assessment of catchment and treatment risk using the Drinking Water Safety Plan (DWSP) approach.

For primary disinfection, using the commonest form of primary disinfection (i.e. chlorination), a Ct value of 15mg/l.min is recommended by the World Health Organisation to establish that the necessary level of inactivation of residual pathogens (other than protozoan cysts *such as Cryptosporidium*) is achieved in the final drinking water following treatment.

Operators will be required to collate records of the following data to establish the consistent efficacy of chlorination as a primary disinfectant

- the establishment of t (effective chlorine contact time) in minutes between the point of application of the chlorine dose and the chlorine residual monitor closest to the first consumer following chlorination, based on day to day flow records, This calculation of effective t should take account of Section 4.6 of the Manual.
- recorded free chlorine residual levels following this contact time collated from monitoring instrumentation and hand held check monitoring in water
- pH levels of water to be chlorinated to verify the formation of hypochlorous acid formation following dosing
- Temperature of water to be chlorinated

The verification of chlorination as a secondary disinfectant requires only the measurement of pH levels of water to be chlorinated and the recording of free chlorine residual at the periphery of the distribution system downstream to verify disinfection to the consumer tap.

As non chemical disinfection systems, such as UV, do not leave a residual in the water which can be used for disinfection process verification, another form of process verification is needed to confirm the proper operation of UV disinfection systems in use in accordance with SI 278 of 2007. For UV systems, this alternative method of process verification is based on validation certification of UV reactors.

The Manual in Chapter 7 sets out details the different validation certification for systems using the UV setpoint intensity approach (the Austrian ONORM or German DVGW protocols) or the calculated dose approach (US EPA protocols) to UV dose control.

These reactors are subjected to independent third part testing by manufacturers to determine the following parameters necessary for monitoring of validation compliance and hence process verification:

- the maximum flow;
- the minimum UV transmittance (UVT) of the water to be disinfected;
- minimum UV dose as measured in the reactor by UV Intensity(UVI);
- the hydraulic installation constraints assumed in the validation testing for delivery of the UV dose
- the required frequency of necessary lamp replacement
- the recommended frequency of calibration of instrumentation such as .UV intensity sensors

In order to demonstrate UV system verification, Water Service Authorities and private water suppliers should retain at the plant a copy of the system validation certification plus a record of the flow rates, UV dose measured by the reactor(s), UVT of the water (where the Calculated dose approach is used), plus details of the lamp replacement, accumulated run time for lamps or banks of lamps in use, records of UVI sensor and UVT monitor calibration and the alarm history

The following sheets in respect of chlorination and UV disinfection are included as guidance only for plant operators representing best practice with respect to the type of information that may be looked for during an audit of public or private water supplies.

The form can be adapted to mirror site specific requirements of each particular disinfection station and can be built up over a period of time.

DAILY OPERATOR LOG FOR VERIFICATION OF CHLORINATION SYSTEM PERFORMANCE

Supply Name:

Supply Code:

Month and Year:

Disinfection station location:

Raw Water Source

Target TOC of water to be disinfected:

Upstream Treatment Process:

Primary or secondary disinfection function of chlorination station: log

Target viral log reduction determined by risk assessment to DWSP: mg.min /l

Reqd Ct level based on DWSP risk assessment (for primary disinfection only):

Target Free chlorine levels at periphery of distribution network mg/l

		A	*A(today)- A(yesterday)*			C	D	E	F	G		H = (C*F)	J =(C*G)	Is J >15mg.min/l?			
						(Primary Disinfection only)			Data collated by SCADA from on line chlorine monitor at disinfection station		Hand held residual chlorine readings	(Primary Disinfection only)	(Primary Disinfection only)	(Primary Disinfection only)	Secondary Disinfection for residual generation)		
Day	**Hours run**	**Meter Reading**	**Total Daily throughput**	**Water Temperature**	**pH of Water**	**Effective Contact Time upstream of residual monitor ****	**Maximum Chlorine dose**	**Minimum Chlorine dose**	**Maximum Free Chlorine residual**	**Minimum Free Chlorine residual**	**Minimum Chlorine residual**	**Maximum Actual C t achieved**	**Minimum Actual C t achieved**	**Is minimum actual C t >Reqd C t**	**Residual readings at periphery of**	**Operator's Note on disinfection system malfunctions and corrective actions taken**	**Operators Initials**
	hours	m³	m³	°C	Scale 0-14	min	mg/l	mg/l	mg/l	mg/l	mg/l	mg.min /l	mg.min /l	Yes or No	mg/l		
1																	
2																	
3																	
4																	
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* **Refer to Table 4.3 of the Manual for reqd Ct based on risk assessement of catchment and treatment risk using the DWSP approach**

** **Refer to Section 4.6 of the Manual and Appendix 2.1 for details of Effective Ct calculation**

🟦	**Generic information recommended for both primary and secondary chlorination**
🟧	**Column to be completed in respect of primary chlorination installations only**
🟩	**Column to be completed when chlorination has a secondary disinfection role**

DAILY OPERATOR LOG FOR VERIFICATION OF UV DISINFECTION SYSTEM PERFORMANCE - UV SETPOINT INTENSITY APPROACH

Supply Name:
Supply Code:
Month and Year:
UV disinfection system location:
Raw Water Source
Upstream Treatment Process:
Type of UV reactor:
Target UVT to be achieved by pre-treatment processes:

Maximum validated flow rate for UV reactor m³/hour
Minimum validated UVT of reactor %
UV Intensity setpoint determined by validation for delivery of 40mJ/cm² at max flow and min UVT W/m²
Recommended frequency of UV lamp replacement hours
Date of last replacement of UV lamps days
Recommended frequency of UV sensors calibration: days
Date of last calibration of UV sensors

						A			**B**	**is B> A**			
Day	**Hours run**	**Total Daily Production**	**Maximum hourly flow**	**Average hourly flow**	**Minimum hourly flow**	**Validated minimum UV Intensity setpoint ***	**Is time since last calibration of UV sensor in accordance with manufacturers**	**Date for next replacement of UV lamps**	**Minimum Daily UV intensity reading**	**Is minimum daily UV intensity>minimum UV Intensity setpoint**	**Off specification volume *****	**Operator's Note on disinfection system malfunctions and corrective actions taken**	**Operators Initials**
	hours	m³	m³/hr	m³/hr	m³/hr	W/m²	Yes or No	Date	mg.min /l	Yes or No	if answer is No		
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* Target UVT of water following treatment and maximum flow rate are used only to choose the reactor. Ongoing UVT monitoring during operation is not necessary for system verification

** The Manual recommends that **calibration of UV sensors** be verified with a reference UV sensor

*** Off-specification operation occurs when the UV facility operates outside of the validated limit if a UV sensor is not in calibration or the UV valiated dose is less than the required .

DAILY OPERATOR LOG FOR VERIFICATION OF UV DISINFECTION SYSTEM PERFORMANCE - CALCULATED DOSE APPROACH

Supply Name:
Supply Code:
Month and Year:
UV disinfection system location:
Raw Water Source
Upstream Treatment Process:
Type of UV reactor: %
Target UVT to be achieved by pre-treatment processes:
Target pathogen:

Maximum validated flow rate for UV reactor at target UVT: m^3/hour
Minimum validated UVT of reactor at design flow rate: %
Required UV dose to achieve log inactivation of target pathogen: mJ/cm^2
Recommended frequency of UV lamp replacement: hours
Date of last replacement of UV lamps: days
Recommended frequency of UV sensors calibration: days
Date of last calibration of UV sensors
Validation Factor as per the reactor validation certification:
Date of last calibration of UVT monitors

			B			D				E	F	is F > B	A		
Day	**Hours Run**	**Total Daily Production**	**Required UV Dose**	**Flow Rate**	**Measured UVT of Water**	**Calculated UV Dose ***	**Is time since last calibration of UV reactor sensor > recommended time interval ****	**Is the operated life of UV lamps > maximum lamp life as per manufacturer**	**Is time since last evaluation of system UVT monitor > recommended time interval *****	**Validation Factor**	**Daily minimum Validated UV Dose i.e D/E**	**Is the Validated UV Dose> Required UV Dose**	**Off specification volume ******	**Operator's Note on disinfection system malfunctions and corrective actions taken**	**Operators Initials**
	hours	m^3	mJ/cm^2	l/s	%	mJ/cm^2	Yes or No	Yes or No	Yes or No		mJ/cm^2	Yes or No	if previous answer is No		
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Note:

* **Calculated UV Dose**, which is caclulated by the PLC algorithm in the SCADA system, is based on measured UVT, flow rate and UV sensor reading

** US EPA UV Guidance Manual recommends that **calibration of UV sensors** be verified with a reference UV sensor **at least monthly**

*** US EPA UV Guidance Manual recommends that o**n-line UVT analyzers be evaluated at least weekly** by comparingthe on-line UVT measurements to UVT measurements using a bench-top spectrophotometer

**** Off-specification operation occurs when the UV facility operates outside of the validatedlimit, a UV sensor is not in calibration, the system UVT monitor is notin calibration or the UV valiated dose is less than the required .

APPENDIX 2.5

PRACTICAL GUIDANCE ON DISINFECTION CHEMICAL STORAGE, HYGIENE AND HOUSEKEEPING AT TREATMENT PLANTS

1. Introduction

Practical guidance relating to the delivery and storage of chemicals for disinfection at treatment plants, secondary disinfection points and re-chlorination stations are typically confined to those used chemicals for chlorination purposes. Other less common disinfection chemicals, i.e. chlorine dioxide and ozone are generated on site.

The various forms of chlorine chemicals which are used in the Irish context are as follows:

- Chlorine gas delivered in pressurized containers in a liquid form
- Bulk delivered sodium hypochlorite in different concentrations ranging from 5-15% solutions
- Sodium hypochlorite generated by OSE technology on site from a brine solution as required and stored on site for more immediate use at a much lower concentrations than bulk delivered sodium hypochlorite

And less frequently

- Calcium hypochlorite usually delivered to site in granular or tablet form for dilution on site prior to dosing

Because chlorine in its various forms is a toxic, corrosive material, it can cause irritation when workers breathe it or their skin is exposed to it. At very high concentrations, chlorine gas exposure can cause death after just a few breaths. In addition chlorine in its various forms is very reactive with other process chemicals stored within treatment plants.

Because of the danger of respiratory damage, chemical burns, and death, operators need to be trained to use, store and handle chlorine chemicals properly and ensure that associated operational work practices, safety and emergency procedures are adhered to, maintained and updated.

These practical guidance notes do not purport to deal with the hazards posed by the storage, generation or use of these chemicals in water treatment or disinfection, the interaction of these chemicals or the associated hazards for plant operators managing the production of drinking water for water service authorities or private drinking water suppliers.

The Health Safety and Welfare Act 2005 addresses the responsibilities of water service authorities and private suppliers in the management of these operator risks. This guidance is only intended to supplement site specific operating procedures and the specific material safety data sheets for the various chemicals.

Users of the Manual should also consult current EPA Guidance entitled ‘IPC Guidance Note on Storage and Transfer of Materials for Scheduled Activities’ available on the EPA website

http://www.epa.ie/downloads/advice/general/Materials%20storage.pdf

2. Chlorine Gas

2.1 Chemical reactivity

Chlorine is a very reactive chemical which reacts violently with hydrogen, acetylene gases and solvents. These reactions create heat by exothermic reactions. The reaction of chlorine with ammonia can create explosive compounds and gases that are toxic to breathe. Chlorine reacts with metals and heat. In the presence of water, chlorine can create a highly corrosive and dangerous acid mist.

Consequently

- Never store chlorine gas and ammonia in the same building or area.
- Keep chlorine isolated and in different rooms from the chemicals that it reacts with.
- Store chlorine away from all sources of water to avoid creating acid mists. Keep chlorine equipment moisture-free. Do not use water to clean up chlorine leaks or spills.

Because of chlorine reactivity, the production of standard operating procedures for its storage and handling are very important.

2.2 Chlorination storage and dosing areas

The following special storage and handling features, which are typically provided at treatment plants and disinfection stations using chlorine gas, should be utilized and maintained during plant operation.

- Chlorine storage and equipment rooms equipped with doors, opening outward to the outdoors complete with panic hardware.
- Viewing window into chlorine storage and equipment rooms for operator security
- Visual and audible emergency alarms at the chlorine room entrance.
- Exhaust fans with a typical rating to air changeover every minute
- A chlorine gas leak detector to generate alarms and attendant ammonia bottle to help locate a leak
- An emergency kit to repair leaking containers.
- Hand trucks with chains for cylinders or properly rated electric hoist for chlorine drums

Chlorine storage areas, storage containers and process equipment and lines should be properly labelled and appropriate hazard warning should be posted in accordance with site specific operating procedures.

Gas containers should be stored in separate or divided rooms separately from flammable materials and other chemicals such as ammonia and sulphur dioxide, if used elsewhere in the installation.

Containers should be stored and used above ground level and always in a vertical position. Chlorine gas containers should be stored in marked areas shielded from external heat sources. The protective hood should be kept secure on all unused containers and should only be taken off when the container is being used. All containers in use should be secured in position by chains or other methods as appropriate. Gas containers should only be lifted with suitably rated and tested equipment and never by their protective hoods. Empty cylinders should be clearly marked and segregated from unused cylinders.

When discharging liquid to a common manifold, the containers must have a separate vacuum regulator manifold. Whenever possible use vacuum gas delivery rather than pressure delivery. Vacuum lines should be polyethylene, PVC pipe or similar materials resistant to moist gas. Routing tubing through external unventilated conduit is not advised. Where plastic connections are used, vacuum connections must not be over-tightened. Pressure lines, where necessary, should be seamless carbon steel

All pipe, valves, and fittings must be thoroughly cleaned of all oils and foreign matter (grease, pipe chips, dirt, etc.) prior to assembly or reassembly. Failure to properly clean may result in undesirable chemical reactions and non-warrantable equipment failure.

Vents from chlorine gas installations should be discharged to atmosphere in a suitable open location where the risk to personnel has been risk assessed. The termination point must be open, pointing downward and should covered with a fine mesh screening. Vent pipes from the system should be separately routed and should never be discharged via a manifold with other vented lines.

2.3 Personnel training and safe work procedures

Written safe work practices should be compiled on a site specific basis to prevent chlorine leaks and spills and promote safety of all site personnel and site visitors. These safe work practices should form the basis of on-site training for all plant operatives and supervisory personnel in exposure control, first aid, PPE, and emergency response. This training should be documented and upgraded during ongoing operation.

Current material safety data sheets, warning signs and other proprietary chlorine wall charts should be visible for use by site personnel and visitors. In particular written operating procedures should be followed by operators that address the appropriate steps for evacuating and filling chlorine containers. Operators should wear appropriate personal protection equipment (PPE) consisting of rubber gloves, apron and face shield or goggles, when changing cylinders.

Similarly, a site specific inspection and maintenance schedule should be created for all chlorine storage and handling equipment and associated safety equipment. Equipment and chlorine containers should be regularly monitored for leaks using ammonia leak detection kits. Line repair kits should be available. Site operatives should never repair a leak alone. Leaks should be repaired using site specific emergency response procedures and involve more than one person.

In addition, chlorine detection instrumentation, safety showers eyewash stations and personal protection equipment (PPE) should be regularly inspected for proper operation. Chlorine detection instruments in storage and dosing areas should be interfaced into an alarm system with appropriate alarm set points for detection.

Where chlorine gas installations are located in confined sites or in built up areas, close to the public, consideration should be given to perimeter chlorine monitoring or air scrubbing equipment.

2.4 Emergency procedures and PPE

Preparation is key to the management of emergencies. Chlorine monitoring alarms monitor work areas for accidental leaks or spills. Automatic or remote shut-down capability allows the operator to control of the situation from a distance.

A written site specific emergency plan should be prepared for each chlorine gas installation by Water Service Authorities. Plant managers and operators should be trained in any of the procedures that require their involvement. Periodic drills should be performed by site personnel to test the plan and the readiness of warning instrumentation, necessary PPE and communication protocols with external agencies. Responses to the plan should be documented and the plan should be regularly updated to take account of such responses.

Sufficient multiple sets of personal protective equipment (PPE) such as splash goggles, face shields, gloves, overalls, and leather boots should be available for all plant personnel working around chlorine gas installations.

A positive pressure demand type Self-Contained Breathing Apparatus (SCBA) with a full face piece, and containing a minimum 30 minute air supply, should be located in close proximity at all installations to protect operators from breathing in chlorine fumes. Such SCBA should be kept remote from the chlorine dosing or storage room to ensure workers can put the equipment on safely. The SCBA equipment should be approved and the operators must be adequately trained by a competent person in the use and maintenance of SCBA through induction training and periodic courses.

Any worker who is required to enter an atmosphere potentially dangerous to life shall ensure that a second worker, suitably equipped with SCBA also, is present and in communication at all times with another person who is trained in handling chemical emergencies and the use of respiratory protective equipment. With this, a provision is made for rescuing the endangered worker immediately if his respiratory device fails or he becomes incapacitated for any reason.

In case of an accidental exposure, move exposed personnel to a well-ventilated area and seek medical assistance.

3. Bulk Delivered Hypochlorite

3.1. Chemical reactivity and incompatibility

Sodium Hypochlorite, or bleach, is produced by adding elemental chlorine to sodium hydroxide and is a strong oxidant It a clear, slightly yellowish solution with a characteristic odor and a relative density of is 1.1 – 1.2. Sodium Hypochlorite is normally supplied as a 14% w/v solution

Commercial product varies from 5% sodium hypochlorite (I.e. domestic grade bleach, which is an irritant with a pH of around 11). At higher concentrations (10-15%) sodium hypochlorite (with a pH of around 13) burns and is corrosive. Commercial solutions are less hazardous and easier to handle than elemental chlorine. The pH of sodium hypochlorite is high because sodium hydroxide is used in its manufacture to increase stability of the product.

Incompatible chemicals include acids and compounds with ammonia. Accidental mixing causes release of chlorine gas. Mixing of hypochlorite with certain organic based cleaning compounds may also result in the emission of explosive gasses. Piping and material handling equipment containing stainless steel, aluminum, carbon steel or other metals such as copper, nickel and cobalt should also be avoided as they accelerate the rate of decomposition.

A standard operating procedure and MSDS for hypochlorite must be posted in a protective shop envelope on the wall of storage and dosage installation for the use of the operator and other personnel of water suppliers.

3.2. The stability of stored sodium hypochlorite

Sodium hypochlorite at higher concentrations becomes increasingly unstable and degrades to chlorate thereby affecting the storage life and decreasing concentrations with time. This degradation accelerates in higher temperatures and in the presence of sunlight. Dilution greatly reduces degradation, especially for solutions delivered in concentrations less than 7% to 8%. Degradation also happens when sodium hypochlorite comes in contact with acids, certain metals and chlorine gas. These characteristics must be kept in mind during transport, storage and use of sodium hypochlorite.

Storage containers or tanks should be sited out of sunlight in a cool area and should be vented to the outside of the building.

Sodium hypochlorite storage procedures should be arranged to minimize this slow natural decomposition. The lower the concentration the less the decomposition rate is. Where existing storage volumes of 15% hypochlorite are greater than 28 days, consideration should be given to lowering the concentration of product delivered to 10% or lower in order to extend the product shelf life, reduce the rate of degradation and the consequent formation of chlorates.

Dosage rates must be adjusted by operator in accordance with an operating procedure to compensate for progressive loss in chlorine content due to the storage age of chemical.

3.3. Hypochlorite storage and dosing installations

The design of storage installations should pay particular attention to spill containment including containment for 110% contents of the largest tank, no uncontrolled floor drains, an overflow from chemical storage tanks that discharges to the containment area and separate containment areas for incompatible chemicals should be provided.

Fibre reinforced plastic (FRP), PVC, polyethylene, polytetrafluoroethylene (PTFE) and Polyvinylidene Fluoride (PVDF) are generally accepted materials for contact with sodium hypochlorite. Where fiberglass is used for reinforcement in tank walls, the fibres must be protected from the sodium hypochlorite with a sufficient depth of coating. PVC piping that is exposed to sunlight requires a protective paint coat to assure an adequate service life

The filling of storage and dosing tanks with hypochlorite should be covered in site specific safe working practices due to

- the hazards to persons associated with accidental spillage as set out in 3.1 above
- The different type and size of installations, ranging from large municipal schemes (with tankered bulk delivery) to small supplies using hypochlorite in IBCs and small drums

As with all stored hazardous chemicals, bulk storage tanks and valved fill stations should be clearly labelled with the chemical name, its 4 digit UN number and its chemical formula.

Vent(s) from bulk tanks should be sized at 100-150% of fill pipe diameter to prevent excess pressures or vacuum during filling and should be terminated at a suitable external location, remote from air intakes, doors, windows, and parked vehicles, in a downward aspect with a fine corrosion resistant mesh to prevent contamination.

Fill points should be located directly over containment area and provision should be also made for a ball shut off valve to prevent backflow of chemical when hose is disconnected, and to guard against any unauthorized filling without the presence of appropriate site personnel. A liquid sensor that activates audible and visual alarms, at a high level set point, should be provided on bulk storage tanks. The alarms must be mounted at locations that will alert both the treatment system operator and tank truck delivery driver to prevent overfilling of bulk tank(s). Emergency overflows from tanks should discharge to the containment area at a level of typically 300mm from floor level.

A pair of rubber gloves, an apron or other protective clothing, splash goggles, and a facemask should be provided for each operator as per Material Safety Data Sheets (MSDS). To cater for accidental splashes of hypochlorite chemicals on the skin or in the eyes, emergency eye washes and showers should be provided between the location of the hazard and the nearest means of egress. These drench showers and eyewashes should be located throughout the facility following on-site risk assessment of accidental exposure. Flush eyes and skin for at least 15 minutes and seek medical treatment after exposures.

Where drums are used, provisions should be made for disposing of drums in accordance with a site-specific procedure which will prohibit rinsing out of drums, prevent their exposed to internal contamination and minimize personal and environmental exposure to chemicals.

As with all hazardous chemicals, feed lines should be ideally routed overground along cable trays through readily accessible floor ducting. Underground buried ducting should be avoided unless secondary contained within a sealed sleeve. Feed lines should be color-coded yellow, labelled with chemical name, and show arrows to indicate direction of flow.

3.4. Control of gasfication

Operators should be aware, when taking delivery of Sodium Hypochlorite that the solution is active particularly at higher concentration and will release a large proportion of gas in solution and during subsequent degradation during subsequent storage. The release of gas from the solution temporarily affects the dosing system by creating a gas lock in the dosing system resulting in a loss of prime and a lower applied chlorine dose for that period.

After receiving a delivery of sodium hypochlorite, it should be allowed to stand for a few hours or over night, before utilizing the chemical to liberate much of the gas contained within the liquid. The concentration of bulk sodium hypochlorite deliveries should be monitored relative to specification particularly following a new delivery but also on an ongoing basis, as the stocks of hypochlorite ages, so that chlorine dosing can be adjusted accordingly.

The most common dosing systems use diaphragm metering pumps with a pulsation damper, a pressure relief valve, a calibration cylinder and a loading valve.

Some dosing pump suppliers offer auto-degas valves systems as part the dosing system design. Gas is typically removed from the suction line through a vent valve and directed back to the storage tank with a small amount of liquid.

As set out in Section 4.3.3 and Figure 4.4 of the Manual, suction connections between the bulk Sodium Hypochlorite storage tank and the metering pump should be designed to minimise formation of gas pockets. Bulk hypochlorite dosing systems should be installed with a flooded suction to aid in the prevention of gasification. Pump suction lines should be always below the minimum tank liquid level and be installed downwards from the tank to the pump.

Delivery lines should slope upward from the metering pump without loops or pipe configurations which will trap sodium hypochlorite between two closed valves and be fitted with anti-siphon valves.

4. On site generation of sodium hypochlorite

In recent years many water service authorities and some private group scheme water suppliers have installed on-site electrolytic (OSE) hypochlorite generators that produce weak hypochlorite solutions (~0.8% NaOCl) using an electrolytic cell and a saturated solution of salt water.

4.1. Comparison of installations dosing bulk delivered hypochlorite vis-à-vis OSE product

The weaker sodium hypochlorite solution (typically 0.8%) generated on site, falls below the 1.0% threshold for hazardous materials.

Relative to commercial sodium hypochlorite (5-15%) it is less hazardous and also a more stable chemical compound. The batch manufacture of hypochlorite, inherent in OSE system design, for use over a relatively short period of time means that product decomposition concerns associated with commercial bulk delivered product and the consequent generation of chlorates is greatly reduced.

Issues highlighted in Section 3 above relating to incompatible chemicals and the exposure of hypochlorite to metallic compounds similarly applies to OSE generated product. Like commercial hypochlorite, storage tanks are usually made from PVC, polyethylene, FRP, PTFE or PVDF.

However the weaker hypochlorite solutions from OSE installations require larger chemical dosing equipment than for bulk delivered product. Although similar instrumentation and control features for the monitoring, storage, dosing and disinfection verification apply to OSE product, additional issues surrounding

- Salt quality and the consequent risk of bromate byproducts generation in the OSE product solution (refer to Section 4 of the Guidance Manual)
- The ongoing management of systems to vacate hydrogen gas generated by electrolytic cells and from above OSE stored product which are specific to site generated hypochlorite installations.

4.2. Environmental conditions for hypochlorite generation and storage

0.8% sodium hypochlorite has a freezing point of approximately 30°F (-1°C). The sensitivity of the electrolytic cells utilized to generate the sodium hypochlorite, the system must be placed in an environment which assures:

- No direct sunlight
- Room air temperature between 45°F & 100°F (7°C- 38°C)

Because of the foregoing and the need to minimize the degradation effects of temperature and UV exposure on both the hypochlorite solution and plastic tank commonly used, product tanks are best located indoors

However operators should take cognisance of minimum air temperatures to prevent freezing of the stored sodium hypochlorite and freezing of the hydrogen dilution blower air flow & pressure switch devices on OSE generation equipment.

4.3 Management of ventilation systems at OSE installations

Hypochlorite generation processes create a small amount of hydrogen gas as a normal byproduct. Systems are usually fully sealed and subject to internal forced ventilation which quickly dilutes the hydrogen generated by the electrolytic cell and from the OSE product tank. Most proprietary systems also possess automatic safeguards which shut down the system if a fault is detected. Gas leak from OSE equipment usually result from accidental damage to part of the system.Consequently a parallel room ventilation system will assure the hydrogen gas is quickly dispersed. As hydrogen will rise to the ceiling, the room ventilation system should be designed to provide for exhaust air to exit near the ceiling.

It is also suggested that where possible room ventilation systems should be interlocked with the operation of OSE product generation and in larger installations consideration should be given to internal hydrogen detection and alarm generation to progressively activate the room ventilation system, generate visible alarms and ultimately the cessation of product production.

All tanks should be vented. The vent should exceed the size of the tank's largest inlet or outlet nozzle by two inches. The vents should have a vinyl insect screen attached to the end to keep debris or insects out of the tank.

The most common cause of damage to FRP and plastic tanks is lack of venting during filling or emptying operations. Every atmospheric pressure rated tank must be protected at all times by properly sized vent pipes in order to prevent build-up of pressure or vacuum conditions. This includes not only the ingress of air and egress of gasses when emptying and filling the product tank, but is also required under normal conditions when changes can occurs in the temperature to the contents of the product tank consequent to the elevation of temperature newly generated OSE product when discharged to the tank.

All hypochlorite storage tanks must be considered a confined space. Operators should never remove an access hatch or work on the storage tank until the requirements of a site specific operating procedure has been complied with.

5. Calcium Hypochlorite

Calcium hypochlorite is another chlorinating chemical used infrequently in an Irish context. It is used primarily in smaller water supply disinfection applications and in swimming pools. It is a white, dry solid containing approximately 65% chlorine, and is commercially available in granular and tablet form.

Calcium hypochlorite is particularly reactive in the solid form with associated fire or explosive hazard if handled improperly. All forms of calcium hypochlorite should be properly stored in accordance with manufacturer's instructions in a cool, dark, dry place in closed corrosion resistant containers. Calcium hypochlorite should be stored away from heat and organic materials that can be readily oxidized. Improperly stored calcium hypochlorite has caused spontaneous combustion fires in the past

Granular calcium hypochlorite, if stored out of closed containers can lose about 18% of its initial available chlorine in 40 days. Consequently stocks should be dated and controlled and used in rotation so as to minimise deterioration in storage.

Solutions should be prepared on a batch basis for use following mixing and special provision for the separation of diluted calcium hypochlorite from inert materials 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

6. Hygiene and good housekeeping at treatment/disinfection installations

Due to the importance of water as a food product, the importance of good hygiene practices by operators and the elimination of the potential public health hazard posed by uncontrolled ingress by vermin at water treatment works cannot be overstated as a means of limiting disease transfer to drinking water supplies.

Section 11 of the EPA - EC Drinking Water Regulations 2007 - Public Water Supplies Handbook sets out the following guidance for operators with respect to the need to operate good hygiene practices at treatment plant

*"All operators, maintenance staff and samplers (and any contractors and sub-contractors) working at the treatment works where they could come into contact with partially or fully treated drinking water or come into contact with equipment that is in contact with drinking water, should have been **fully trained in hygienic practices** commensurate with their duties. Where appropriate, this training should include the actions required if one of these personnel has an illness (for example gastroenteritis or Hepatitis A) that could pose a risk of contamination of the drinking water supply or spread of the illness to other personnel. Hygienic practices are particularly important for multifunctional personnel who may work on both water supply and sewage.*

*As an example, in the UK there is a national water hygiene training scheme that all operators and contractors are required to pass to obtain the "National Water Hygiene Card" before they can work on a water treatment works (operation, repair and maintenance).This scheme consists of completing a health questionnaire, receiving comprehensive water hygiene training and successfully passing a multi-choice test paper. The scheme is operated by Energy and Utility Skills Register (EUSR) on behalf of the UK water industry (*http://www.eusr.co.uk/eusr/the-eusr-card/the-national-water-hygienecard*)*

The EPA recommends that WSAs develop, through the Water Services Training Group (WSTG), a hygiene training course for operators, contractors and others (such as samplers) working on water treatment works and distribution networks."

With respect to control of vermin at treatment and disinfection plants, the Water Service Authority or private water supplier shall ensure that the following precautionary measures are taken and maintained at installations

1. All buildings and storage areas shall be kept and maintained in a clean and sanitary condition. No rubbish or other waste shall be permitted to accumulate or to remain in any area which may afford food, refuge or a breeding place for rodents.
2. All equipment, drums and other material stored placed on pallets elevated above the ground or floor, with a clear clean space beneath.
3. Where repairs or alterations are made to the installation, ensure such alterations are undertaken and made rodent-proof by the proper use of impervious materials.
4. All wall or ventilator openings at or near foundation level shall be covered for their entire height and width with perforated sheet metal plates, expanded sheet metal or iron grilles or gratings with openings therein shall not exceed 12 mm in least dimension.
5. Openings due to deteriorated walls or broken masonry or concrete, shall be protected against the ingress of rodents by the closing of such openings with cement mortar, concrete, or masonry.
6. All exposed edges of wooden doors and jambs shall be protected against the ingress of rodents by covering said doors and jambs with solid sheet metal. All such doors on which metal plates have been fitted shall, when closed, fit snugly so that the maximum clearance between any door and the door jamb and sill shall not exceed 10mm.
7. All reservoir roof ventilators and access manhole openings shall similarly all be fitted with removable anti-vermin mesh screens to prevent birds, animals or insects from entering the storage tanks or reservoirs.

8. All openings which are accessible to rodents by way of exposed pipes, wires, conduits and other appurtenances, shall be covered with a mesh not larger than 12mm) Such mesh guards shall be fitted snugly around pipes, wires, conduits or other appurtenances and be fastened securely to the exterior wall and shall extend a minimum distance of 300mm beyond and on either side of said pipe, wire, conduit, or appurtenance.

APPENDIX 2.6

PRACTICAL GUIDANCE ON CALIBRATION AND MAINTENANCE OF ON-LINE AND PORTABLE MONITORING EQUIPMENT

These guidance notes are intended to supplement the manufacturer's instructions for calibration and maintenance, which should be followed.

Chlorine in water samples is quite volatile, and so the calibration of online instruments is normally carried out by comparing the online instrument reading with the result of analysis on a handheld instrument at the analyser. Points to bear in mind with this procedure are:

- It is important that the analyser sampling system has a suitable point at the analyser for withdrawing a sample which is representative of the instrument sample.
- Instrument readings must be stable for calibration to take place. If online instruments are 'hunting', subject to rapidly changing process conditions or poor mixing, then calibration should not be undertaken.
- Sample cells for the chlorine handheld tests should be scrupulously clean and not used for other samples which may have a chlorine demand. Separate cells should be used for free chlorine and total chlorine analysis.
- The handheld instrument analysis must be carried out immediately.
- The analysis should be duplicated.
- A good quality handheld colourimetric monitor such as the Hach pocket colourimeter with the correct DPD reagents should be used.
- The sample must not be shaken vigorously, as chlorine will be lost.
- If the online reading has not changed since the sample was taken, then the reading is trimmed so that it agrees with the test kit reading. If the online reading has changed, then it should be trimmed to correct the percentage error detected by the test kit.

Zero checks for online analysers should follow the manufacturer's instructions. A number of different methods are used to produce a zero free chlorine sample. These include:

- Passing process water through an activated carbon filter to remove chlorine before passing it to the instrument. Some manufacturers supply such a filter as part of the instrument.
- Dechlorination of the sample by using a filter packed with calcium sulphite
- Irradiation of the sample with ultraviolet lamps to decompose hypochlorous acid to hydrochloric acid
- Halting the sample flow so that the chlorine in the flowcell is consumed.
- Feeding the instrument with unchlorinated sample water.

Calibration needs to be undertaken on a monthly basis as a minimum and may need to be undertaken on a weekly basis, or every few days if demanded by the application and analyser drift. Records should be kept of the corrections applied at calibration and the frequency adjusted so that the corrections are maintained within the accuracy required for the application.

It is recommended that frequent checks of analyser readings are carried out between calibrations to provide assurance that this key measurement is within the accuracy expected. These may be daily or even every shift. If the discrepancy between online and handheld is within the accuracy required, then no trimming is needed. If not, then a proper calibration should be carried out with duplicate samples and the result recorded.

Using the above calibration procedure, the online reading is entirely dependent upon the handheld unit for its accuracy. Analytical Quality Control (AQC) would then require that the handheld unit itself is calibrated against the laboratory DPD or another method which can be calibrated by a stable standard solution such as potassium permanganate. Alternatively, suppliers will offer a service for this purpose and their recommendations for frequency of calibration should be followed.

Good sampling practice must be followed with online chlorine instruments. Sample tubes should be replaced or cleaned on a regular basis. Suitable materials are opaque PVC, nylon or stainless steel. Copper or clear plastic pipes should not be used. Pipe bores of 6-8mm are normally sufficient, larger diameters may be needed to avoid blockage on unfiltered samples. Problems sometimes arise where the sample loses chlorine between process and analyser. Common reasons for this are:

- Chlorine demand due to dirt or incorrect sampling pipework material;
- Excessive delay between sample and analyser due to long distance and insufficient flow. A good flow velocity is 0.8 metres per second.
- Turbulence due to excessively high flow velocity.

It is good practice to include a sampling point at the process and analyser ends of the sampling system so that checks can be carried out on the integrity of the sample delivered to the analyser.

Analyser maintenance

As noted above, the manufacturer’s directions should be followed. The main tasks for amperometric analysers are:

- Periodic flowcell cleaning;
- Replacement of buffer reagents;
- Maintenance of reagent pumps, typically this will be peristaltic tubing replacement.
- Replacement of membranes

The commonest failure modes with respect to chlorine analysers are buffer pump failure membrane failure, sample blockages. Manufacturer’s directions should be followed with regard to electrode cleaning/replacement. Reference electrodes may need periodic replacement of electrolyte.

APPENDIX 3.1

PRACTICAL GUIDANCE ON THE EMERGENCY DISINFECTION OF DRINKING WATER SUPPLIES

1. Drinking Water Incident Response Plan

A drinking water incident or emergency is defined in recent Guidance on preparing and implementing a Drinking Water Response Plan (DWIRP) as

"*any event detected by routine compliance monitoring or routine operational monitoring, or any other event that was not necessarily detected by the routine compliance or operational monitoring and has occurred because of something that has happened in the catchment, at the treatment works or in the distribution system. That*

- *appears to have caused illness in the community as a result of the quality of the water supplied (reports of illness in the community that could possibly be caused by the water supply); or*
- *because of its effect, or likely effect, on the sufficiency or quality of the water supplied, gives rise to, or is likely to give rise to, a significant risk to health of the persons to whom the water is supplied; or*
- *has caused, or is likely to cause, significant concern to persons to whom the water is supplied; or*
- *has attracted, or is likely to attract, significant local or national publicity.*"

The necessity for the instigation of an emergency response to drinking water disinfection may result from incidents affecting drinking water supply on either a scheme wide basis or on a particular section of scheme headworks or distribution network, such as;

- Contamination of surface water source consequent to a natural event such as flooding which can adversely effect the water quality or the ability of treatment disinfection system to function at all or to function within the design criteria of the treatment/disinfection plant
- The serious pollution of a groundwater source from which water is abstracted for supply (the treatment before supply may only consist of disinfection);
- The failure or malfunction of the primary or secondary disinfection system;
- Significant number of complaints of discoloured water or water with an abnormal or offensive taste/odour within a few hours from a particular area of the supply area;
- Extended power outages or failure of power distribution within a plant which can affect the ability of the treatment/disinfection plant to operate properly
- Contamination due to inappropriate or incorrect dosing of chemicals as part of the treatment/disinfection process
- Contamination of water supplies consequent to the system maintenance or repairs to the distribution system
- Contamination due to backflow or back-siphonage from a cross-connection event
- Loss of pressure and water supply in distribution mains for any reason.

Emergency response to a drinking water incident will take place under the overarching Framework for Major Emergency Management which is in place for the administrative areas of Water Service Authorities in Ireland. As part of this framework, planned arrangements for response to contamination threats and incidents should be mobilised although it is envisaged that most DWIRPs will not activate the Major Emergency Plan.

Circular L4/09 requires Water Services Authorities to prepare a Drinking Water Incident Response Plan (DWIRP) setting out the "strategy and protocols for responding to contamination incidents or other emergencies impacting on water supply in their own areas, irrespective of whether they themselves are the water suppliers or whether the water is provided by public or private group schemes or through DBO contractors".

The compilation of a DWIRP by the Water Service Authority will usually deal with

- A flexible framework for specific site sampling, data collection and laboratory analysis to determine the contamination threat - bearing in mind that the water may contain an unknown contaminant
- The identification, selection and implementation of the most appropriate containment option.
- The co-ordination where appropriate with adjoining Water Services Authorities in relation to water supplies that traverse administrative boundaries.
- The co-ordination of a public health response to the incident designed to minimise public exposure to contaminated water by issuing of notices, dissemination of information to consumers and to comply with protocols for interaction with the HSE and EPA for dealing with such drinking water incidents.
- The planning and implementation of remedial works to eliminate the source and effects of contamination or treatment/disinfection failure that caused the incident.
- The monitoring and verification of recovery of the supply scheme or elemental part of the headworks or distribution network where the incident occurred, prior to a return to normal operations.

Users of this Manual are referred to Section 8 of the aforementioned EPA handbooks for further guidance on the preparation of a DWIRP.

This Appendix will subsequently deal only with the issues surrounding options for disinfection remedies involved in the protection of human health or the provision of an alternate potable drinking water supply during remediation activities following a drinking water incident.

2. Alternative drinking water supply during remedial works to treatment works or distribution system following a drinking water incident

Although the average daily water use per consumer in Ireland is 130-140 litres per day only a small fraction, less than 5 litres/head/day is typically consumed or used in food preparation.

During a drinking water incident or emergency, it should be borne in mind that, in most instances, mains water can continue to be used for sanitary purposes unless the risk posed by the contaminant poses a health and safety risk to consumers.

Having established the chemical and/or pathogenic nature of the contaminant in the water, the site specific DWIRP will determine whether the emergency incident warrants the placing of the following notice or not, as dictated by the particular circumstances of each incident:

- A "boil water notice" may be invoked where the contaminant is pathogenic bacteria, viruses or protozoa and where boiling would render water potable.

- A "do not drink notice" may be invoked where the contaminant is chemical in nature and where ingestion poses a health risk to consumers and where boiling or disinfection may not render the water potable.

- A "do not use notice" may be invoked where the contaminant in the water poses a risk to human health through inhalation or dermal exposure.

Where applicable, consumers should be advised as to which of the following options for alternative supply of drinking water is proposed in the DWIRP for the management of the drinking water incident.

a) Where alternative treated water supplies can be diverted:

- Where the infrastructure exists and level of unaccounted for water in the distribution system allow, the scheme supply area affected by the incident can be compartmentalised and an alternative treated water can be diverted via an interconnection pipe from an adjacent supply scheme or water service authority

b) Where the contaminant is bacteriological or biological in nature

- The use of bottled water to be purchased from local retailers.
- The boiling of water supplied to the consumers tap prior to drinking or use for oral hygiene purposes.
- Where protozoan contaminants such as *Cryptosporidium* are not suspected in the water the disinfection of water supplied to the consumers tap prior to drinking or use for oral hygiene purposes, using various forms of chlorination.

c) Where a “do not drink” or “do not use” notice is required

- The use of bottled water to be purchased from local retailers or provided by the Water Service Authority in certain cases such as elderly or infirm consumers.
- The boiling of bulk water deliveries hauled to distribution centres by certified water hauliers.
- The disinfection of bulk water deliveries hauled to distribution centres by certified water hauliers

In cases where consumers cannot access either mains supplies or distribution centres for alternative bulk delivered supplies,

- the disinfection of untreated water which may also require basic clarification and/or filtration prior to application of a suitable disinfectant.

Containers to be used for the haulage of bulk delivered waters should preferably be:

- manufactured from a grade of stainless steel included in Annex 5 of the UK DWI Advice Sheet 5 – “Approval of products made from recognised materials and from metals” or
- bowsers and tanks approved for emergency use in the conveyance of water as set out in Part B3.2 of the UK DWI List of Approved Products or similar approved

If not made from stainless steel or approved materials for use in contact with water for human consumption, the container should be made from a material designated a “food grade”.

The appropriateness of the container shall take into account the chemical properties of the water that will be in contact with the metallic product, e.g. chlorine content, dissolved oxygen, pH value, hardness, alkalinity, and naturally occurring organic matter.

Container surfaces to be used for the haulage of drinking water should be cleaned and thoroughly disinfected before filling with drinking water, following which, samples of the drinking water have been shown to maintain chlorine residual and comply with Drinking Water Regulations in respect to taste and odour, colour and turbidity.

It should always be borne in mind that consumers using bulk delivered water from distribution centres should always be advised to boil water prior to drinking. Although water delivered may have a verifiable chlorine residual at the distribution centre, the container in which the consumer collects the water may reintroduce contamination or the chlorine residual may dissipate depending on the duration of storage prior to use.

3. Emergency disinfection of alternative water supplies and contaminated infrastructural elements during a drinking water incident

In an emergency situation, no disinfection method is ideal given the usually limited treatment resources available. The best disinfection methodology is very much site specific and dependent on the quality of water to be disinfected and the nature of the identified contaminant.

Chemical disinfectants particularly chlorine are less effective in water with excessive levels of natural organic matter manifested as suspended matter, turbidity or colour. The addition of chlorine directly to highly coloured or turbid water may result in poor disinfection and the excessive formation of disinfection by-products.

In water scheme or household situations where a UV disinfection reactor is available, its installation and use upstream and in combination with chemical disinfection may reduce the potential for by-product formation by reducing the chemical disinfectant dosage necessary to achieve the requisite pathogen inactivation in the water to be disinfected.

In the case of emergency disinfection, it is the responsibility of the Water Service Authority or private water supplier to choose the emergency disinfectant based on a specific risk assessment which takes into account the safety of the disinfectant, any potential health risks to consumers and the effectiveness of the disinfectant in control of pathogenic microorganisms in the water and the practicalities of the use of the different types of disinfectants.

In general, disinfection products which are routinely in use by Water Service Authorities and private water suppliers at the plant or disinfection station should also be employed for emergency use.

For emergency disinfection applications such as

- the sterilisation of water supply infrastructural elements such as wells, process tanks, storage reservoirs and distribution pipelines which may be the source of the contamination or which may have come in contact with the contaminant.
- the disinfection of alternative drinking water supplies during an incident.

the most commonly used disinfectants usually involve the following forms of chlorination;

- Sodium hypochlorite (NaOCl), in accordance with IS EN901: 2007, commercially available in dry form containing 30%–35% chlorine and liquid form at concentrations of between 5% and 15% chlorine
- Calcium hypochlorite ($Ca(OCl)_2$) in accordance with IS EN900:2007, available commercially in granular, powdered or tablet form, dissolves readily in water and contains 70%–75% chlorine.

Users should refer to sections 4.3.3 and 4.3.5 of the Manual for further details relating to the storage, stability and shelf life of the foregoing chemicals and their use as disinfectants for drinking water.

For verification of the emergency chlorination of water for alternative drinking water supply, the World Health Organisation recommends that water should be consumed following the measurement of residual free chlorine of 3 mg/L after at least 50 minutes contact with the water.

Other forms of temporary emergency disinfection used are;

- Sodium dichloroisocyanurate (NaDCC) 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 production of 1.0mg/l of free available chlorine typically requires dosage rates of 1.55mg/l of NaDCC

- Proprietary mobile disinfection units which are designed to dose sodium hypochlorite or chlorine dioxide disinfectant from a small associated tank. Such units are equipped with a dosing pump, a micro processor and an optional flow meter. Such associated control systems are capable of achieving preprogrammed dosing rates and system fault monitoring. Depending on circumstances, these portable systems can be powered by an internal battery, a 220V mains source, a solar source or a generator.

Where Water Service Authorities or private water suppliers propose to use a disinfection product other than those disinfectants in routine use at the particular treatment/disinfection plant, the Water Service Authority or private water supplier shall undertake a site specific risk assessment as part of the DWIRP taking the following into account;

a) The risks associated with the health hazard or other water quality problems requiring attention.

b) The risks associated with the proposed solution.

c) The reasons that routine disinfection methods cannot be used.

d) The likely duration of emergency disinfection and dose level, the maximum values for duration and dose and the method of disinfection verification to mitigate risks to all consumers from the organisms requiring the use of emergency disinfection.

g) The actions to be taken to mitigate the risks to all consumers from the use of the emergency disinfectant proposed, including full consideration of vulnerable groups and individuals at specific risk, e.g. renal dialysis patients (both home and hospital based), children under the age of 1 year, etc.

h) The contingency actions to be taken if emergency disinfection proves ineffective or impractical.

4. Emergency disinfection of alternative water supplies by consumers during a drinking water incident

Where alternative supplies other than raw untreated waters are not available to consumers, suspended matter in the raw water should be allowed to settle out and where possible water should be filtered before clear and clean water is drawn off for emergency disinfection. In a household situation, this filtration may be achieved by passing water through a lean cloth prior to disinfection.

Given that contamination of untreated or alternative water supplies during an incident may contain non-bacteriological contaminants such as *Cryptosporidium* or other protozoa, boiling is the only universally safe method recommendable to consumers for the emergency disinfection of;

- inadequately treated or disinfected water.
- bulk delivered alternative water supplies.
- settled and clarified untreated raw water.

Boiling of water for a period of three minutes is 100% effective at killing all waterborne pathogens in water including protozoan pathogens and is even effective for turbid waters.

Following boiling, water should be allowed to cool in a clean container prior to drinking. The flat taste of the boiled water can be improved by aeration of the water which is readily achievable by pouring it back and forth between two clean receptacles prior to drinking.

The use of chlorine compounds or iodine by consumers as emergency disinfectants can only be used where the contaminant is known to be only bacteriological or viral in nature.

Where the known contaminant can be inactivated using chlorine disinfectants, the emergency disinfection of small batch volumes of water for drinking water purposes can be effected using the two commonly available chlorine compounds i.e. sodium hypochlorite (NaOCl) and calcium hypochlorite ($Ca(OCl)_2$).

Users should refer to sections 4.3.3 and 4.3.5 of the Manual for further details, relating to the storage, stability and shelf life of the foregoing chemicals and their use as a disinfectant for drinking water.

The World Health Organisation (WHO) recommends that a stock 1% solution of the foregoing chlorination chemicals should be prepared prior to disinfection of water. This 1% solution can be made up for the various available chemical forms as follows:

a) *Chlorine bleaching powder i.e. calcium hypochlorite at 30%–35 % available chlorine, also commonly known as chlorinated lime or chloride of lime*

   - 35 g of bleaching powder mixed into 1 litre of water.

b) Powder or granular form high test calcium hypochlorite containing 70%–75% chlorine
   - 15 g mixed into 1 litre of water

c) *Unscented household bleach solutions of sodium or calcium hypochlorite – 3.5% solution*

   - Mix 1 part chemical solution to 5 parts water

d) *Unscented household bleach solutions of sodium or calcium hypochlorite – 5% solution*

   - Mix 1 part chemical solution to 4 parts water

For the batch emergency disinfection of drinking water, the WHO recommends that 6 ml of the 1% stock solution should be added and mixed with 10 litres of water. It is also recommended that the water is safe to drink only if there is evidence of a slight smell of chlorine after 30 minutes.

It should however be borne in mind in cases, where the contaminant is chemical rather than pathogenic in nature, that the foregoing emergency disinfection methods will not necessarily remove or mitigate chemical or heavy metal contaminants where they exist in water.

Where emergency disinfection has taken place it is essential that an increased operational monitoring programme is undertaken to verify the effectiveness of the emergency disinfection. The WSA should identify points within the distribution network downstream of the point of emergency disinfection and carry out additional monitoring for free residual chlorine. The purpose of this is to verify that the levels of chlorine in distribution network are adequate and that the emergency disinfection has dealt with the cause of the absence of or low levels of disinfectant previously in the distribution system. This monitoring should take place at the extremities of the distribution network as well as vulnerable points within the network (e.g. areas with a history of low residual chlorine levels). If it is found that the emergency disinfection measures have not had the desired effect in some or all of the distribution network the WSA should immediately consult with the HSE to determine whether consumers need to be advised regarding the safety of the water. In tandem with this the WSA should examine the effectiveness of the emergency disinfection measures and should examine whether further issues in the distribution network are contributing to the problem (e.g. ingress).

References:

American Water Works Association (2002) Disinfection of Water-Storage Facilities

AWWA Report C652-02

DoEHLG (2009) Circular L04/09 - Drinking Water Incident Response Plans

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DWI (2010) List of Approved Products for use in Public Water Supply in the United Kingdom. Updated May 2010 and available at http://www.dwi.gov.uk/drinking-water-products/approved-products/soslistcurrent.pdf

EPA (2010) European Communities (Drinking Water) (No. 2) Regulations 2007 A handbook on the Implementation of the Regulations for Water Service Authorities for Public Water Supplies

USEPA (2004) Response Protocol Toolbox: Planning for and Responding to Drinking Water Contamination Threats and Incidents Module 5: Public Health Response Guide April 2004

WHO (2004) Guide to promotion of Drinking-Water disinfection in emergencies

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomhnithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil, Pobal agus Rialtais Áitiúil.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail;
- scardadh dramhuisce.

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

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