Norwegian Water

Report

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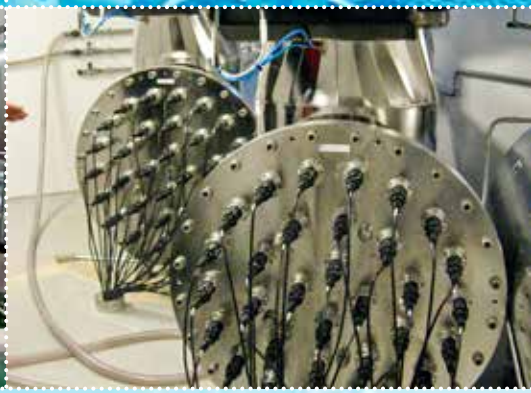
Microbial barrier analysis (MBA)

– a guideline



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About Norwegian Water

Norwegian Water is a special interest organisation representing Norway's water industry. It acts on behalf of the members, which are municipalities, companies owned by municipalities, municipal operational assistance organisations and some private water works. Norwegian Water in total represents 360 municipalities, with 95 % of the population. There are also nearly 100 affiliated members like consultants, producers, suppliers and institutions for research and education. Norwegian Water serves both as a special interest organisation and a competence building organisation for the members. The organisation works within the vision of "clean water – our future".

The Norwegian Water project system

Projects at a value of 10 million NOK (1.25 million EUR) are performed each year through the project system in Norwegian Water. The project system is financed by the members as a voluntary additional fee. The projects are proposed, approved and partly governed by the members, while specialists in the secretariat have the role as project managers. The best consultants in the marked are hired to perform the projects and write the reports and guidelines from the project system. Most of the projects are presented as a Norwegian Water report. The reports can be purchased from www.norskvann.no, and may be downloaded for free for the members taking part in the project system. The project system has so far produced more than 200 reports and guidelines for the members.

Norwegian Water

Norwegian Water BA, Vangsvegen 143, 2321 Hamar, Norway
Phone: +47 62 55 30 30 Email: post@norskvann.no
www.norskvann.no

Norwegian Water Report

Extract
In order to safeguard the public against waterborne diseases, water utilities must secure that multiple, microbial barriers (often referred to as hygienic barriers in Scandinavian languages) are provided for in their drinking water systems. In most water utilities disinfection of the water represents an important barrier against microbial contamination, but microbial barriers may also be achieved by actions taken in the catchment area and water source as well as in water treatment other than disinfection.

This report, that has been titled "Microbial Barrier Analysis" (MBA-Guideline), is intended to clarify the barrier concept and to help water utilities and their consultants determine what actions they should take to be sure that the microbial barriers in their systems are sufficient and the water is safe to drink.

A procedure is outlined for a numerical analysis of the barrier status of an existing or a proposed water system. The guideline also includes recommendations on calculation- and test-methods (the "tool-box") for disinfection actions that can be used to ensure that the inactivation (log-reduction) of microorganisms will be sufficient for the water system conditions

The report is the result of collaboration between the water and wastewater works associations in Norway (Norwegian Water), Sweden (Swedish Water) and Finland (Finnish Water Utilities Association).

Norwegian Water BA
Adress: Vangsveien 143, 2321 Hamar, Norway
Phone: +47 62 55 30 30
Email: post@norskvann.no
Web: norskvann.no

Title
Microbial barrier analysis (MBA) – a guideline

Author
Prof. emeritus Hallvard Ødegaard,
Scandinavian Environmental Technology,
Stein W. Østerhus,
Norwegian University of Science and Technology and
Britt-Marie Pott, Sydvatten AB.

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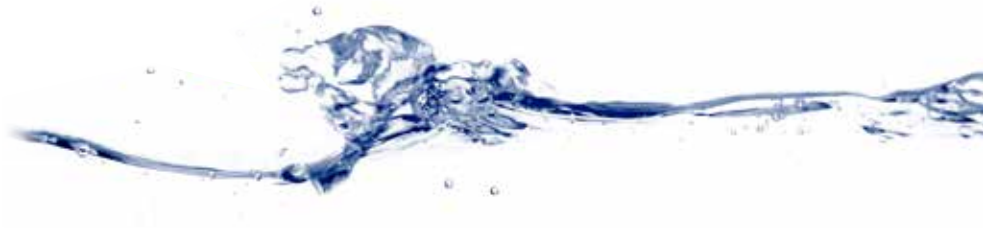
Preface



In order to safeguard the public against waterborne diseases, water utilities must secure that multiple, microbial barriers (often referred to as hygienic barriers in Scandinavian languages) are provided for in their drinking water systems. In most water utilities disinfection of the water represents an important barrier against microbial contamination, but microbial barriers may also be achieved by actions taken in the catchment area and water source as well as in water treatment other than disinfection.

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The initiative to prepare such a guideline report was taken by Norwegian Water in 2004 through the project "Optimal disinfection practice" (Ødegaard et al., 2007) with a follow-up report "Optimal disinfection practice phase 2" (Ødegaard et al., 2009a). These reports were the basis for the guideline report "Guideline to the determination of good disinfection practice" (Ødegaard et al., 2009b), co-financed with Swedish Water that also made a version in Swedish (Svenskt Vatten, 2013)

After having been used by water utilities, consultants and public health authorities in Norway and Sweden since 2009, it was decided to make a revision of the guideline as well as an international version written in English. This made the Finnish Water Utilities Association also join the project.

This report, the international version of the revised guideline, is basically a translation of the revised report written in Norwegian (Ødegaard et al., 2014). The content is a bit condensed, however and includes less "text-book" information about disinfection in general. All the information needed in order to evaluate the hygienic barrier status of the drinking water system is, however, included.

A calculation model in excel has also been produced and is available on the home pages of Norwegian Water (www.norskvann.no), Swedish Water (www.svensktvatten.se) and FIWA (www.vvy.fi)

The contract for producing the original as well as the revised versions of the guideline was assigned to Scandinavian Environmental Technology (dr.ing. Hallvard Ødegaard).

The first edition of the guideline (Ødegaard et al., 2009b), was written by a group connected to Department of Hydraulic and Environmental Engineering at Norwegian University of Science and Technology, consisting of prof. dr.ing. Hallvard Ødegaard (project leader), dr.ing. Stein Østerhus and dr.tekn. Esa Melin, with help from the master-students Arnulf Kalleberg, Marion Trøan and Solveig Fosse.

This report, the international version of the MBA-guideline, is written by Hallvard Ødegaard, with Stein W. Østerhus and Britt-Marie Pott as co-authors.

In the work with the revision of the Norwegian report as well as the present, international version, support has been given by a reference and a steering group consisting of experts from Norway, Sweden and Finland.

- From Norway: Asle Aasen (Multiconsult), Gunnar Mosevoll (Skien municipality), Jon Brandt (Asplan Viak), Lars Hem (Oslo municipality), Svein Forberg Liane (Sweco), Jens Erik Pettersen (Norwegian Institute of Public Health), Målfrid Storefjell (Hias) and Kjetil Furuberg (Norwegian Water)

- From Sweden: Britt.Marie Pott (Sydvatten), Olof Bergstedt (Göteborg Recycle and Water), Torbjørn Lindberg (National Food Agency) and Gullvy Hedenberg (Swedish Water).
- From Finland: Paivi Merilainen (National Institute for Health and Welfare) and Riina Liikanen (Finnish Water Utilities Association - FIWA).

The original project was financed by Norwegian Water, Swedish Water and Norwegian Food Safety Authority.

The revisions (2. edition as well as the international version) were financed by Norwegian Water, Swedish Water and FIWA.

Jerome B. Gilbert, Consulting Engineer, J. Gilbert, Inc., California, USA is acknowledged for his valuable contribution in reviewing the text and language of this English-written version of the guideline report.

Hamar, Stockholm and Helsinki, 20.12.2014

Kjetil Furuberg
Norsk Vann

Gullvy Hedenberg
Svenskt Vatten

Riina Liikanen
FIWA

Summary

In many water utilities disinfection of the water represents the most important barrier against microbial contamination, but hygienic barriers may also be achieved by actions taken in the catchment area and water source as well as in water treatment other than disinfection. According to the Norwegian Drinking Water Regulation, water utility should have at least two hygienic barriers to be approved by the Norwegian Food Safety Authority. For the water utility owners and their consultants, the notion "two hygienic barriers" has been difficult to relate to, without knowing exactly what barrier effect is required as a single hygienic barrier. Other countries also refer to hygienic barriers without specifying the number two, but expressing the goal that several (or multiple barriers) against microbial contamination shall prevail in the water system.
This guideline, that has been titled "Microbial Barrier Analysis" (MBA-Guideline), is intended to clarify the barrier concept and to help water utilities and their consultants determine what actions they should take to be sure that the public health barriers in their systems are sufficient and the water is safe to drink.

A procedure is outlined for a numerical analysis of the barrier status of an existing or a proposed water system.

Step	Determination of	Dependent on
1.	Raw water quality	• Historic data for raw water quality • New data from risk-based sampling program
2.	Barrier level required	• Raw water quality • Size of water supply system
3.	Catchment area and water source barriers	• Barrier actions in catchment area/water source • Surveillance of raw water quality
4.	Particle removal barriers	• Water treatment methods • Surveillance of water treatment
5.	Disinfection barriers	• Disinfection methods • Dosage in disinfection processes
6.	Overall barrier status (total protection provided)	• Barrier level requred ÷ barrier credits • Step 2 ÷ step 3 ÷ step 4 ÷ step 5

The steps of the MBA procedure

The procedure is based on the following steps (see the figure above):

1) Determination of **the raw water quality** – based on:
- Historical microbial raw water quality data
- New microbial raw water quality data if necessary, based on a risk-based sampling program

2) Determination of **the barrier level required** – based on:
- The microbial raw water quality conditions determined in step 1
- The size of the system as related to the risk

The barrier level required is expressed as the log-reduction of the different pathogen groups (bacteria, virus and parasites) that should be achieved in the whole system.

3) Determination of **the barrier in catchment area and water source** in terms of log-reductions of the different pathogen groups that can be credited to barrier actions in the catchment area and water source through:
- Source protection barrier actions taken in the catchment area and water source
- Surveillance of the raw water quality

4) Determination of **the removal barrier** in terms of log-reductions of the different pathogen groups, that can be credited to water treatment resulting in microbe removal through particle separation, based on:
- Type and extent of water treatment
- Operational monitoring of the treated water quality

5) Determination of **the disinfection barrier** in terms of log-reductions of the different pathogen groups that can be credited to the disinfection of the water based on:
- Type of disinfection method
- Design of the disinfection process

6) Determination of **the overall barrier status** which is determined by subtracting the log-credits found in step 3, 4 and 5 from the barrier level required of the different pathogen groups found in step 2.

If the final result gives negative log-values for all pathogen groups, the barrier status is satisfactory. If not, additional barrier actions are necessary.

The guideline also includes recommendations on calculation- and test-methods (the "tool-box") for disinfection actions that can be used to ensure that the inactivation (log-reduction) of microorganisms will be sufficient for the water system conditions. The tool-box can be used to:
- determine necessary dosage of disinfectants as well as the design of the contact tank in a design situation

- assure that the dosage used during operation is sufficient for the log reductions that are required

Detailed guidance for the use of the tool-box for various situations is included in the attachments to the guideline.

The MBA-Guideline is to be looked upon as a tool in the effort to make the water supply safe. It is not a substitute for other tools such as QMRA (quantitative, microbial, risk analysis) and HACCP (Hazard Analysis Critical Control Points). However, it is designed to supplement efforts to provide a safely functioning water system.

The MBA-Guideline has been designed to provide simple clear procedures. It does not require expert competence and extensive data collection, and is therefore especially suitable for small and medium-sized water utilities. It is being used by system owners as well as their consultants for all kind of systems in Scandinavia during the last 5 years.

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1. Introduction

In water management we can frequently encounter the term "multiple barriers" against contamination, indicating that actions to prevent the public from receiving contaminated water should be carried out through multiple, independent pollution preventing steps – so that if one of them should fail, another one would be sufficient to minimize the risk.

In this guideline on good disinfection practice the term "hygienic barrier" is defined as:

A natural or created physical or chemical measure to remove, render harmless or kill microbes (virus, bacteria, parasites etc.) to a level where they do not represent any health hazard (freely translated after the Norwegian Drinking Water Regulation).

The purpose of issuing such a guideline (referred to as the MBA-Guideline) is to:

1. help executive officers working with approval of utilities to determine which hygienic barrier actions that are necessary and sufficient – in dialogue with the systems owner and its consultants
2. help systems planners and consultants to propose which hygienic barrier actions are necessary and sufficient in a planned or existing system to provide the barrier level required
3. provide for the analysis, design, and construction of barrier measures that will ensure the acceptable, safe level of removal or inactivation of pathogenic microbes
4. provide knowledge about disinfection to the extent that the responsible for operation of systems can be aided in the operation of disinfections plants to ensure that the recommended levels of removal or inactivation of pathogenic microbes is achieved

This means that the MBA-Guideline is addressing all stakeholders in planning and operation of systems.

1.1. The hygienic barrier definition

Some countries have outlined a more detailed description in their legal framework. In Norway, for instance, the current Drinking Water Regulation includes the following expression (freely translated after the Norwegian Drinking Water Regulation):

In order to secure a safe drinking water, the owner of water utility that require approval (all systems > 100 persons connected) must through the choice of water source, source protection and water treatment, provide for at least 2 hygienic barriers[1)] altogether in the water supply system. One of these shall provide that the drinking water is disinfected or treated in any other way to ensure removal, render harmless or prevent infective diseases. The approving authority may, in case it can be shown that the total of barrier actions in the water source and the conditions underground are satisfactory altogether, decide that water from a groundwater source does not have to be disinfected or treated as described above.

Some other countries do not specify the number of barriers that are required, but recommend aiming to create "multiple microbial barriers". However, this requires that those responsible for approval, planning, construction and operation of water supply systems are familiar with the microbial barrier concept and how to determine whether or not a proposed action adequately protects public health. Similarly the microbial barrier effect of disinfection and various treatment methods must be known.

It is established practice that water utilities should prepare a Water Safety Plan (WSP) and use this plan for planning, design, and operation of its system. Water Safety Plans (WSP) provides a framework for proactive, systematic and effective management and surveillance of drinking water supplies based on a preventative risk-based approach. World Health Organization (WHO) has published a guideline report (WHO, 2005) on how to develop a WSP and how it can be used to provide safe drinking water to the public.

The Water Safety Portal (WSPortal) is a co-managed website by the International Water Association (IWA) and the World Health Organization (WHO). The Portal is intended for all those involved in the management of drinking water

1) The term "hygienic barrier" is translated directly from the term mostly used in Scandinavia. English speaking countries might have used the term "public health" or "microbial" barrier for the same.

supplies and provides practical guidance – in the form of case studies and tools – for those responsible for ensuring drinking water quality. Regional networks supporting WSP implementation are also hosted on this website. One may visit the website at http://www.wsportal.org.

Many countries are in the process of operationalizing the different tools that are required to implement WSP's and several are being developed, such as the risk analyses tool QMRA (quantitative, microbial, risk analysis) and HACCP (Hazard Analysis Critical Control Points) – a tool for determination of which check points that are needed to operate the water supply system in such a way that the probability of undesired events will occur.

The use of these tools requires extensive work and there is a danger that only the large water utility with a very competent staff will have the resources to perform analyses that are thorough enough to be of any value. In the Nordic countries there are a large number of small and medium-sized water utilities and a need was felt for a hygienic barrier analysis tool that was simple enough for anyone to use without compromising on the scientific level.

This guideline for microbial barrier analysis (MBA-Guideline) is such a tool. The MBA procedure that is described here can stand by itself or it can be used as a tool in the development of a Water Safety Plan. The implementation of QMRA and HACCP will improve the basis for the determination of the barrier level of the system that has to be determined in the use of the MBA. The MBA "tool-box" will help the user to design the disinfection measures that the MBA-procedure leads to, in a correct way.

1.2. Microorganisms

Most microorganisms are harmless and actually needed for the human well-being. Some microorganisms may cause disease (pathogenic microorganisms). The pathogenic microorganisms that we deal with in this guideline include viruses, bacteria and parasites. A very short description of the most common waterborne pathogens in the Nordic countries is given below.

1.2.1. Viruses

The virus group includes the smallest pathogenic microorganisms with typical sizes < 0,1 µm. They consist of genetic material enveloped in a protein coating and they require a host cell to multiply. In Scandinavia the group of Noroviruses is most frequently the cause of waterborne outbreaks (especially diarrhea), but many other viruses (Adenovirus, Rotavirus, Poliovirus, Hepatitis A virus etc.) may cause illness. The different viruses have very different resistances to being inactivated by the various disinfection methods. Adenovirus, for instance, is inactivated at low dosages of chemical disinfectants, such as chlorine and ozone, but can resist much higher dosages of UV irradiation than most other microorganisms of concern.

1.2.2. Bacteria

Bacteria consist of genetic material and cell machinery enveloped in a protein coating. There are numerous variants and they can multiply in a variety of conditions. Bacteria are bigger than viruses, typically ca. 1 µm. The bacteria that is most frequently the cause of illness in Scandinavia is *Campylobacter* that causes diarrhea. Other important pathogenic bacteria are certain strains of *Escherichia coli (E. coli), Salmonella, Yersinia and Legionalla*.

Some bacteria groups (for example *Bacillus* and *Clostridium*) create a survival form that is called "spores". These spores are very resistant to extreme conditions and to inactivation by disinfection.

1.2.3. Parasites

Parasites are larger than bacteria, typically 3 – 10 µm. In connection with drinking water it is mainly the protozoan *Giardia* and *Cryptosporidium* that is focused on. They can both be the cause of serious illness. Parasites need a host to multiply but the dormant stages outside the host are very stable and are very resistant to inactivation by chemical disinfection methods (especially chlorine). Over the last 10 years there have been several parasite outbreaks in Scandinavia. They are one of the primary reasons for the focus on hygienic barriers and disinfection through the MBA-Guideline.

1.2.4. Indicator organisms

It takes considerable effort to analyze for specific pathogenic microorganisms in drinking water. Random sampling is carried out and the chances of finding a specific microorganism are low – for several reasons. Therefore, it is necessary to rely on indicator organisms.

Indicator organisms should fulfill several criteria:

- They should be simple to detect with today's methods of analysis
- They should exist in quantities large enough for a fairly reliable detection
- They must give a fair indication of the risk of illness

All the commonly used indicators have weaknesses in meeting these criteria and the control of microbial quality of drinking water based on indicator organisms is far from perfect. The use of indicator organism for microbial quality control has, nevertheless, a great value since the result of the analysis will indicate whether or not there is any microbial contamination of the water - especially fecal contamination. When this information is combined with other (for instance physical/chemical) results of analysis, the reliability of the prediction of microbial water quality is strengthened.

According to the Scandinavian drinking water regulationss, routine analyses shall include the following indicators; Colony count (22 °C), Coliforms, *E. coli*, Intestinal Enterococchi and *Clostridium perfringens* (incl. spores).

E. coli is used as an indicator of fresh fecal contamination, and also as an indicator for the effect of disinfection processes. *E. coli* is, however not a reliable indicator for the presence of viruses and parasites (*Cryptosporidium* and *Giardia* (oo) cysts) in drinking water after disinfection. Neither is it a reliable indicator for presence of *Campylobacter* that is commonly caused by fecal contamination from birds.

Clostridium perfringens is used to indicate old fecal contamination as the spores of *Clostridum perfringens* can survive longer in the environment than *E. coli*. Since both viruses and parasites have a longer survival time than bacteria, *Clostridium perfringens* spores have been considered by some to be better as indicator for viruses and protozoa than *E. coli* for raw water. There is, however, a debate going on the suitability of *Clostridium perfringens* as an indicator and in the latest WHO guidelines for drinking water quality (WHO, 2011) *Clostridium perfringens* is not included as an indicator for routine analyses of consumer drinking water.

In the MBA-Guideline, however, *Clostridium perfringens* may be used as one of the indicators when determining the raw water quality level of a water source.

There is no requirement for analyses of viruses in Scandinavia, neither in raw water nor in treated water for consumption. Bacteriophages (especially coliphages) have been proposed as a human virus indicator. It is not implemented, however, since coliphages are not clear indicators of fecal contamination.

There is no tradition for routine control of parasites in neither raw water nor treated water for consumption. After the outbreaks in Sweden, Finland and Norway over the last 10 years, many utilities have started routine controls of parasites. Since parasites are critical for determination of the raw water quality objectives in this the MBA-Guideline, it is recommended that if fecal contamination over a certain level has been shown by routine analyses, a risk-based sampling program should be is carried out, including the control of parasites.

In the MBA-Guideline the presence of *E. coli* and *Clostridium perfringens* (if data is available) is used as the basis for determining the raw water quality level. If fecal contamination over a certain level has been indicated by routine analyses, a risk-based sampling program is to be carried out including analysis with respect to the parasites *Giardia* and *Cryptosporidium*. In situations where neither *E. coli* nor *Clostridium perfringens* have ever been detected (primarily in well protected ground water sources), it is recommended that a special evaluation of possible virus contamination (for instance by coliphage analysis and/or a risk assessment analysis) is considered.

1.3. Barrier actions

There are three principal ways of protecting the population against illness caused by waterborne pathogens:

- Prevent pathogens from reaching the system intake, by introducing barrier measures in the catchment area and/or in the water source
- Prevent pathogens from leaving the water treatment plant, by introducing removal of pathogens by particle separation methods and/or inactivation of pathogens by disinfection
- Prevent the treated water from being contaminated on its way to the consumer

In the MBA-Guideline, the two first of these are accounted for.

1.3.1. Barrier actions in catchment area and water source

Barrier actions that prevent contamination can be introduced in the catchment area and water source, for instance through restrictions in the exploitation and development of the watershed. There may also be barriers that reduce the probability of pathogens reaching the water intake, for instance through prolongation of residence time in the catchment area to enhance extinction of pathogens or through positioning of the intake where the water quality is better (e.g. at greater depth).

The effects of barrier actions in the catchment area or the water source are very difficult to quantify. Therefore the authorities in some countries (e.g. Sweden), do not accept actions in the catchment area or in the water source as sufficiently effective microbial barriers.

The results of such actions are only evident over time – as an improvement of the water quality in the water source. The procedure in the MBA-Guideline assumes that barrier actions that are already in place in an existing water utility, have already contributed to the water quality that prevails in the water source today. When establishing new systems or new barrier actions in existing water utilities, one may, however, improve the water quality and hence achieve an additional barrier effect of new barrier actions in the catchment area and the water source.

1.3.2. Barrier actions in the water treatment

Water treatment can bring about microbial barriers through removal of pathogens as particles as well as through inactivation of pathogens by disinfection.

Table 1.1 gives a rough qualitative overview of what may be expected from various particle separation methods for removal of the various microorganism groups

Table 1.1 *Qualitative efficiency with respect to microorganism removal of the most commonly used particle separation methods (assuming correctly designed and well-functioning processes)*

Particle removal method	Bacteria	Viruses	Parasites
Sand filtration (no coagulants)	Poor	Very poor	Poor
Coagulation/sand filtration	Good	Moderately good	Good
Membrane filtration[1)] RO and NF UF MF Coagulation/UF(MF)	 Very good Good Moderately good Very good	 Very good Moderately good Poor Good	 Very good Very good Good Very good

1) RO- reverse osmosis, NF-nanofiltration (< 5 nm), UF- ultrafiltration (< 40 nm), MF-microfiltration (< 100 nm)

Table 1.1 only is indicative, and chapter 2 (table 2.9), provides a more detailed quantification of efficiency in terms of expected log-reductions.

Disinfection has traditionally been the most important water treatment barrier measure in Scandinavia (Norway, Sweden and Finland). Earlier the most commonly used disinfectant was chlorine and to a far lesser extent ozone has been used. Lately, and especially because of the parasite outbreaks, UV-disinfection has been introduced – instead of or in addition to chemical disinfectants. Table 1.2 gives a rough overview of the efficiency of the most commonly used disinfection methods with respect to the three main categories of microorganisms.

Table 1.2 *Qualitative efficiency with respect to microorganism inactivation of the most commonly used disinfection methods (assuming correctly designed and well-functioning processes with sufficient disinfectant dose)*

Disinfection method	Bacteria	Viruses	Parasites
Chlorination	Very good	Good	Inadequate
Ozonation	Very good	Very good	Good/Inadequate[1)]
UV-disinfection	Very good	Good/Inadequate[2)]	Very good

1) Quite good with respect to Giardia, inadequate with respect to Cryptosporidium at ozone dosages normally used
2) Good with respect to most viruses in water of health related significance - inadequate with respect to Adenovirus at the UV-dosages normally used.

In chapter 3 of this MBA-Guideline it is demonstrated how the effectiveness of a disinfection method, given as log-reduction of the various microorganism groups, may be calculated based on the disinfection dosage and the water composition.

1.3.3. Operationalization of the "microbial barrier" concept

In the guidelines (Norwegian Food Safety Authority, 2005) of the Norwegian Drinking Water Regulation (Ministry of Health, 2001), the following expression can be found:

> *Any water treatment method ought to inactivate bacteria and viruses by a minimum of 99,9 % (3 log reduction) and possible parasites with 99 % (2 log reduction) to be considered as one hygienic barrier.*

The expression above could be used as a general definition of what one (1) microbial barrier must accomplish.

The MBA-Guideline provides for the quantification of the effectiveness of various barrier actions that have been chosen. It is based on the number of log-reductions of the various microorganism groups that the barrier actions can be calculated to provide, irrespective of whether a distinct number of barriers is required or if the more general notion of "multiple barriers" is used by the authorities.

Thus, the guideline user can follow the procedures recommended and determine whether or not the system has sufficient/acceptable hygienic barriers.

1.3.4. Independent barriers

The authorities normally require that each barrier is independent. This means that one barrier should function if another one fails or ceases to function as a barrier.

It means, for instance, that the particle separation barriers in the system must satisfy the water quality standard of the Drinking Water Regulation at all times, to be independent of a subsequent disinfection barrier, such as the one provided by UV which is dependent upon water quality (turbidity and color). The independent barrier objective requires that analysis of the treatment methods ensures that the barrier efficiency that has been assumed is actually achieved in each barrier step.

The robustness of multiple barriers can be enhanced by choosing different types of barrier actions in combination, for instance one (or several) based on actions in the catchment area/water source, one (or several) actions in the water treatment prior to final disinfection and one (or several) disinfection actions.

The issue of independent barriers is further discussed in chapter 4.

2. Procedure for the determination of hygienic barrier status

In this chapter a procedure is proposed for the determination of the overall microbial barrier status in a water system. The "tool-box" to be used for the calculations of the efficiency of the disinfection barriers is discussed in chapter 3 and applications of the "tool-box" are demonstrated in attachments 1 and 2.

2.1. The structure of the MBA-procedure

The procedure is carried out by determining the following (see figure 2.1):

1) Determination of **the raw water quality** – based on:
- Historical microbial raw water quality data
- New microbial raw water quality data if necessary, based on a risk-based sampling program

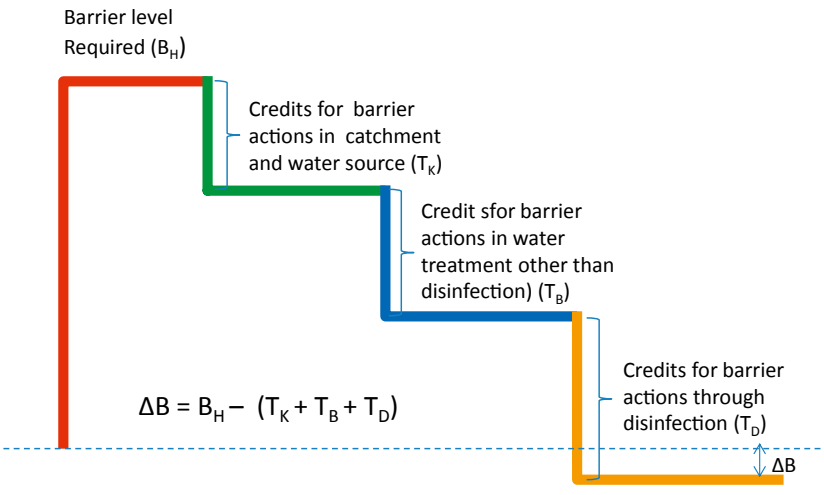
2) Determination of **the barrier level required** – based on:
- The microbial raw water quality conditions determined in step 1
- The size of the system as related to the risk

The barrier level required is expressed as the log-reduction of the different pathogen groups (bacteria, virus and parasites) that should be achieved in the whole system.

3) Determination of **the barrier in catchment area and water source** in terms of log-reductions of the different pathogen groups that can be credited to barrier actions in the catchment area and water source through:
- Source protection barrier actions taken in the catchment area and water source
- Surveillance of the raw water quality

4) Determination of **the removal barrier** in terms of log-reductions of the different pathogen groups, that can be credited to water treatment resulting in microbe removal through particle separation, based on:
- Type and extent of water treatment
- Operational monitoring of the treated water quality

Figure 2.1 *The MBA procedure*



If ΔB is negative in all microorganism groups, the overall hygienic barrier status is satisfactory

If ΔB is positive in any of the microorganism groups, additional barrier actions have to be implemented

5) Determination of **the disinfection barrier** in terms of log-reductions of the different pathogen groups that can be credited to the disinfection of the water based on:
- Type of disinfection method
- Design of the disinfection process

6) Determination of **the overall barrier status** which is determined by subtracting the log-credits found in step 3, 4 and 5 from the barrier level required of the different pathogen groups found in step 2.

If the final result gives *negative* log-values for *all* pathogen groups, the barrier status is satisfactory. If not, additional barrier actions are necessary.

2.2. Notions and definitions

The procedure utilizes the size of the water supply source (persons connected, pe) and the type of water source as criteria for the risk and vulnerability assessment of the system.

2.2.1. Water utility size

Three groups are used according to the number of people (p) connected to the water utility:
- < 1.000 p
- 1.000 – 10.000 p
- > 10.000 p

2.2.2. Type of water source

It is divided between surface water and ground water. Among surface water sources it is divided between lakes and rivers.

Among various types of groundwater it is divided between 1) groundwater in unconsolidated sediments (here referred to as groundwater in soil), 2) groundwater from boreholes in bedrock (here referred to as bedrock groundwater), 3) artificial recharged groundwater (produced through infiltration of surface water to the ground) and 4) surface water influenced groundwater.

Groundwater in unconsolidated sediments (groundwater in soil) is water that has been transported through the unsaturated and saturated zones of the soil for several days. It has been custom to indicate the residence time in the soil in days to indicate whether or not this flow route can be looked upon as a safe hygienic barrier.

Groundwater from boreholes in bedrock (groundwater in bedrock) is water from a drilled or blasted well in bedrock with or without any soil cover. When the soil cover is shallow (0 – 3 m) the groundwater may have a similar quality as that of the surface water that is supplying the well. When the soil cover is ≥ 3 m, the groundwater from bedrock may have a quality similar to groundwater in soil.

Artificially recharged groundwater is basically surface water that is pre-treated by passing the water through the soil. This type of groundwater may be handled in two different ways in the MBA guideline:
1. by taking the quality of the surface water as the basis, and give log-credit (see later) for the pretreatment that infiltration and passage through soil provides, or
2. by handling the artificial groundwater in the same way as groundwater from soils.

The latter option will require that the calculated residence time in the soil is minimum 3 days and the transported distance is minimum 10 m. If these criteria are not fulfilled, the water is to be considered surface water.

2.2.3. Raw water quality level

The procedure assumes raw water quality determination on two levels, based on:

1. a survey of the mandatory routine analysis over the last 3 years
2. an extended survey through a risk-based sampling program over 1 year

The duration of the surveys is a proposal. Each system must evaluate its data-base and use the data that is representing the raw water survey in the best possible way.

The result of the survey of the routine analyses will determine if it is necessary to implement the risk-based sampling survey. Water systems that have inadequate historical data on raw water quality will go directly for the risk-based sampling survey.

As indicators for microbial raw water quality the MBA-Guideline uses:

- *E. coli* (survey level 1 and 2)
- *Clostridium perfringens* (survey level 1, if data are available, and survey level 2)
- *Giardia* and *Cryptosporidium* (survey level 2)

The risk-based sampling program

The routine sampling programs for safe drinking water quality do not normally consider that the risk of contamination is larger in certain climatic situations than others. The raw water source is, however, exposed to more microbial contamination just after a heavy rain than after a long-lasting dry period. Microbial barriers must perform when necessary, irrespective of variations in climatic or other circumstances.

The risk-based sampling program should, therefore, show circumstances where the probability and the level of contamination are the highest and, as far as possible, include the following:

1. The spring circulation of the lake water (≤ 1/6 of the total amount of samples)
2. The autumn circulation of the lake water (≤ 1/6 of the total amount of samples)
3. A typical rainy day during the summer- and/or the winter season (≤ 1/6 of the total amount of samples)
4. A day with extreme rainfall during autumn and snowmelt during spring or autumn (≥ 3/6 of the total amount of samples)

The same should apply when surface influenced groundwater and artificially infiltrated groundwater are being considered. When it comes to groundwater from soils it is less likely that this water is influenced in the same way as surface water and that the routine water quality analysis should indicate the need for an extended, risk-based sampling program. With respect to rivers as raw water source, sampling-days should be chosen under items 2 and 3 above. The minimum number of sampling days in the risk-based program is proposed in table 2.1.

Table 2.1 *Minimum sampling days in the extended risk-based sampling program*

Size of water utility (persons connected)	Number of sampling days
< 1000 p	≥ 6
1000 – 10.000 p	≥ 12
> 10.000 p	≥ 24

The number of sampling days should preferably be higher than indicated in table 2.1. For most cases (medium-sized systems) the number of sampling days is recommended to be the double of the values indicated in table 2.1.

The utility is the best suited to determine when the risk for contamination is at its greatest and the risk-based sampling program should be adapted to the local situation and modified as circumstances change. Decisions on risk should be based on several years of representative samples as well as data from incidents over the years.

The samples from the risk-based sampling program are to be analyzed for *E. coli*, *Clostridium perfringens* and possibly (see figure 2.2 below) the parasites *Giardia* and *Cryptosporidium*. A thoroughly made risk assessment of the watershed may in some cases replace the analyses of parasites.

In the parasite analysis one should test for both *Giardia* and *Cryptosporidium* since it is not obvious that one is not present if the other one is not. It is the sum of the two that forms the basis for determining the water quality level.

It will strengthen the program if coliphages, as indicator of viruses, are included from time to time – even though this is not required for determination of the water quality level in the MBA guideline.

2.2.4. Barrier level required

Barrier level required is defined as the log-reduction in the three microorganism groups (bacteria, viruses and parasites) that has to be achieved through barrier actions in the water utility as a whole (in the catchment area and/or water source, in the treatment step(s) other than disinfection and in the disinfection step(s)). Statement of a barrier level required of 5b + 5v + 2p for instance, means that 5 log reduction of bacteria, 5 log reduction of viruses and 2 log reduction of parasites needs to be achieved in total, through various barrier actions throughout the system.

Barrier level required is made dependent on the size of the water utility and the water quality level of the water source (see table 2.2). The reason for making it dependent on water utility size is connected to risk. The epidemic consequences of contamination in a small water utility are smaller than in a large one.

2.2.5. Log-credit

The value of the barrier action that is implemented (in catchment/source as well as in treatment and disinfection) is given in terms of log-credits, i.e. log reduction of the various microorganism groups. 3b + 3v + 2p means for instance, 3 log reduction of bacteria, 3 log reduction of viruses and 2 log reduction of parasites. They are called log-credits because they will be deducted from the barrier level required to determine the overall barrier status (see figure 2.1).

By deducting the log-credits resulting from actions in catchment/source and treatment other than disinfection, one may calculate the log-reduction that is needed in the final disinfection step to arrive at final result that is acceptable to the utility.

In the tool-box chapter of the MBA guideline (chapter 3) supported by the roadmaps in the attachments, instructions are provided on the design and operation of disinfection methods to achieve the necessary disinfection log-reductions.

2.3. Implementation of the MBA-procedure

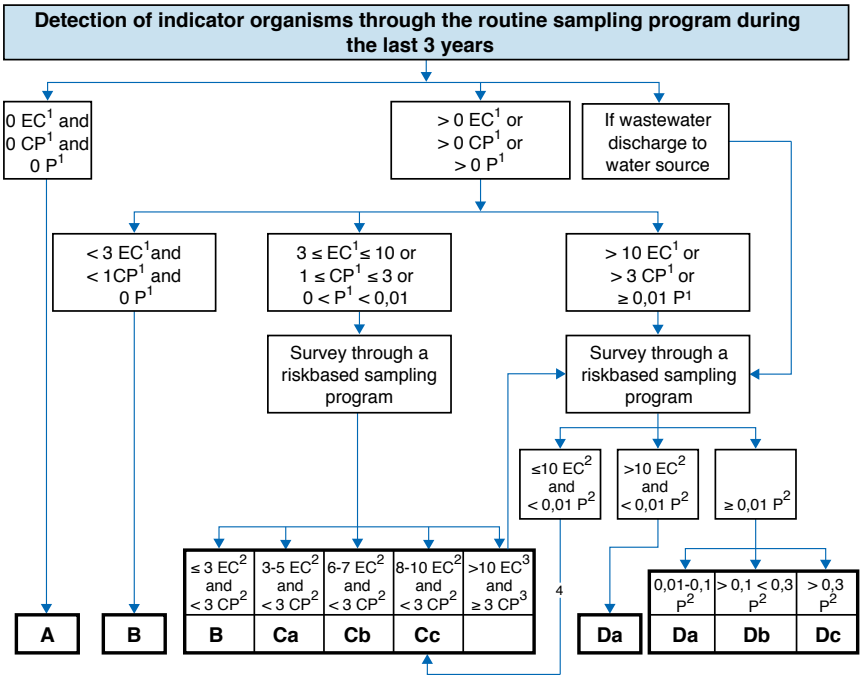
2.3.1. Determination of the water quality level

Figure 2.2 shows how the raw water quality level is to be determined. Two steps may have to be implemented:

1. Determination of the results from the routine sampling program for the indicators *E. coli* (EC) and (if available) *Clostridium perfringens* (CP) over the last 3 years. If data for CP do not exist or are scarce, the data for EC only are used.
2. Depending on the result of step 1, the raw water quality level may be determined directly (level A or B), or the extended risk-based sampling program has to be implemented. Depending on the result of the routine sampling program, the risk-based sampling program may be designed differently:
   - If the raw water quality determined by the routine sampling program is not too high (<10 *E. coli*/100 ml), the risk-based sampling program is directed towards *E. coli* and *Clostridium perfringens* (level C)
   - If the raw water quality determined by the routine sampling program is higher (≥10 *E. coli*/100 ml) and/or discharges of sewage (treated or untreated) to the raw water source exists, the risk-based sampling program is directed towards parasites (*Giardia* and *Cryptosporidium*) in addition to *E. coli* (level D)

One may avoid the need to use the extended risk-based sampling program of each category (a. or b.), if the worst possible raw water quality of that category is assumed (see below).

Figure 2.2 *Determination of raw water quality level*



[1] Detection of indicator [EC – *E.*Coli, CP – *Clostridum Perfringens*, P – parasites (if analyses available)] over indicated value (number/100 ml) one or several times during the last 3 years.

[2] Average concentration (number/100 ml) of indicator over the sampling period or detection of indicated level in more than 1/6 of the samples (16,7 %) over the period. For parasites it is sum of Giardia and Cryptosporidium/100 ml.

[3] Or > 20 EC/100 ml or > 6 CP in single samples.

[4] Only applicable if there is no wastewater discharge to water source and if < 3 CP can be demonstrated.

Following the arrows from the top in figure 2.2, the historic record of water quality through routine analyses over the last three years, determines the box to start the analysis. 0 EC means for example that no *E. coli* has ever been found in any sample during the last 3 years of routine sampling, while <3 EC means that *E. coli* have been found during this time, but none of the samples showed values above or equal to 3 *E. coli* per 100 ml.

- If neither *E. coli* (EC) or *Clostridium perfringens* (CP) or parasites (P) (in the case that CP- and/or P-data exist) have been found in the raw water through routine analysis over the last 3 years (indicated as 0 EC and 0 CP in figure 2.2), the water utility will be categorized as having the water quality level A.
- If *E. coli* or *Clostridium perfringens* is found in one or more samples over the last 3 years, the continued evaluation is dependent on that information. If in all samples < 3 *E. coli* per 100 ml have been found, and there are no *Clostridium perfringens* (CP) *or* parasites (P) (if data exist), the water quality level is B.
- Presence of > 3 but < 10 *E. coli* or > 1 but < 3 *Clostridum perfringens*, in any sample during the 3 year period, indicate that the water quality may be inferior from time to time and therefore the water quality must be investigated more thoroughly. The extended, risk-based sampling program (see 2.2.3 above) must be carried out focusing on *E. coli* and *Clostridum perfringens*. The average value and the frequency of detections of these indicators should be determined. Depending on the average value (between 3 and 10/100 ml) or frequency (> or < than detection in 1/6 or 16,7 % of the samples) the quality level will be B or Ca, Cb and Cc.
- If ≤ 10 *E. coli* or ≤ 3 *Clostridum perfringens* per 100 ml (on average) is detected, it is not required to include parasites in the analysis program (even though it would strengthen the determination of raw water quality level) and the water quality level (B or Ca, Cb and Cc) may be determined by the level of *E. coli* only.

- If there are wastewater discharges (treated or untreated) directly to the water source one should go directly to the D-category path whatever is the findings of *E. coli* and *Clostridium perfringens* from the routine analysis sampling program.
- If, the risk-based sampling program, results in the average values being >10 *E. coli* or > 3 *Clostridium perfringens*, or if one in single samples finds > 20 *E. coli* or > 6 *Clostridium perfringens,* parasites shall immediately be included as indicator in the sampling program – as indicated in figure 2.2.
- If the routine analysis program over the last 3 years shows > 10 *E. coli* or > 3 *Clostridium perfringens* in any sample, the danger of parasite contamination is considered probable, and a risk-based sampling program has to be implemented with parasite determination included.
  - If < 0,01 parasites (average sum of *Giardia* and *Cryptosporidium*) per 100 ml at the same time < 10 *E. coli* is found, the danger of parasite outbreak is considered low and the raw water quality is categorized as Cc
  - If the average parasite detection is >0,01 parasites per 100 ml (irrespective of *E. coli* detection), or the frequency of detection is higher than 1/6 (16,7 % of the samples), the water quality level falls into one of the categories Da, Db and Dc depending on how many parasites that are detected.
    - Low average parasite detection (< 0,01/100 ml) results in category Da
    - Higher parasite detection (> 0,01/100 ml) results in category Da, Db or Dc depending on how many parasites that are detected.

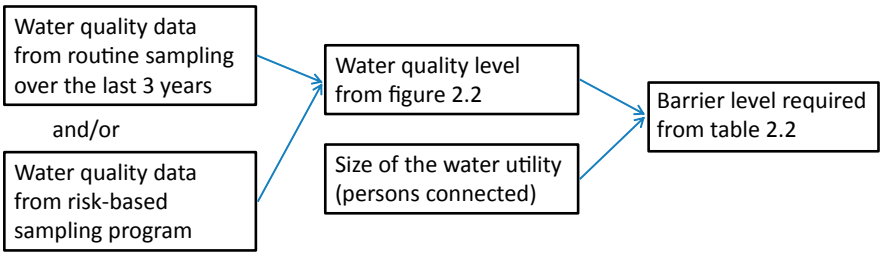
One may avoid the need to use the extended risk-based sampling program of each category, if one assumes the worst possible raw water quality of that category. i.e:
- **Level Cc in the case that one finds 3< EC< 10 and 1 < CP or 0<p<0,01**
- **Level Dc in the case that one finds > 10 EC and > 3 CP or > 0,01p**

Since the analysis for virus indicators is not normally included in the routine sampling, the absence of *E. coli* (EC) or *Clostridium perfringens* (CP) is not a guarantee of the absence of virus. If raw water quality level A is identified through the routine sampling program (i.e. 0 EC and 0 CP), one should make an assessment particularly directed towards the risk of virus contamination, for instance by carrying out coliphage analysis or making a special virus risk analysis before raw water quality level A is finally stated. If coliphages are found in any sample, without findings of EC or CP, it is recommended that the water quality level is changed from A to B.

2.3.2. Determination of barrier level required

When the raw water quality level has been determined, the next step in the MBA procedure is to determine the barrier level required according to figure 2.3.

Figure 2.3. *Determination of barrier level required*



The barrier level required is the set of log-reductions for the different microorganism groups that the water utility with a given water quality level has to handle, see table 2.2.

Table 2.2 *Barrier level required depending on size of systems and raw water quality level*

Size of water system		Raw water quality level			
		A	B	C	D
< 1000 persons connected	Barrier level required	3.0b + 3.0v + 2.0p	4.0b + 4.0v + 2.0p	a. 4.5b + 4.5v + 2.5p b. 4,5b + 4,5v + 2,75p c. 4,5b + 4,5v + 3,0p	a. 5.0b + 5.0v + 3.0p b. 5.0b + 5.0v + 3.5p c. 5.0b + 5.0v + 4.0p
1000 – 10.000 persons connected		3.5b + 3.5v + 2.5p	4.5b + 4.5v + 2.5p	a. 5,0b + 5,0v + 3,0p b. 5,0b + 5,0v + 3,25p c. 5,0b + 5,0v + 3,5p	a. 5.5b + 5.5v + 3.5p b. 5.5b + 5.5v + 4.0p c. 5.5b + 5.5v + 4.5p
> 10.000 persons connected		4.0b + 4.0v + 3.0p	5.0b + 5.0v + 3.0p	a. 5,5b + 5,5v + 3,5p b. 5,5b + 5,5v + 3,75p c. 5,5b + 5,5v + 4,0p	a. 6.0b + 6.0v + 4.0p b. 6.0b + 6.0v + 4.5p c. 6.0b + 6.0v + 5.0p

If, for instance, the system serving 7.000 persons where the routine analyses over the last 3 years has detected ≥ 3 *E. coli* while the extended risk-based sampling program revealed 5 *E. coli* (on average), the water quality level will be Ca (provided that >3 *Clostridium perfringens* (on average) or > 20 *E. coli* per 100 ml or ≥ 6 *Clostridium perfringens* in any single sample have been found).

From table 2.2 the barrier level required can be found to be: 5.0b + 5.0v + 3.0p

2.3.3. Determination of log-credits for barrier actions

Log credits may be given for the following barrier actions:

1. Barrier actions in the catchment area and in the water source
   - Physical barrier actions
   - Restrictions on the activity in the catchment area and water source
   - Improved raw water quality monitoring actions

2. Barrier actions in the water treatment plant
   - Particle separation
   - Disinfection
   - Improved monitoring and operation surveillance

There are, however, reasons to reserved judgment on awarding log-credits for barrier actions in the catchment area and the water source due to uncertainties about the efficiency of such actions.

In the planning phase of a system, log-credits may be given for planned barrier actions. For existing systems log-credits may only be given for barrier actions that are new in relation to those that were already there when the quality level of the water utility was established. There might, however, be "old" actions of the risk-reducing character that might not have any influence on the quality of the water. Old barrier actions of this nature may be awarded log-credits. Sound expert opinion should be relied upon in each case.

It is emphasized that in future years the utility should analyze the effect of the barrier measures implemented in the catchment area and source, and adjust the log-credit that is awarded according to the effect that is observed.

One may sum up various log-credits, but the total log-credit may not surpass certain limits for each category of barrier measures – as shown in table 2.3.

Table 2.3 *Maximum log-credit for various barrier actions*[1)]

Barrier action	Maximum log-credit
New actions in catchment area and water source – Lakes Maximum log-credit for physical and restrictive actions (see table 2.4), of which Maximum log-credit for raw water monitoring actions (see table 2.7)	**2.0b + 2.0v + 1.25 p** 0.75b + 0.75v + 0.5p
New actions in catchment area and water source – Groundwater Maximum log-credit for actions in various groundwater wells (see table 2.5 and, 2.6), of which Maximum log-credit for raw water monitoring actions (see table 2.7)	**2.0b + 2.0v + 1.25p** 0.75b + 0.75v + 0.5p
New actions in catchment area and water source – Rivers and brooks Maximum log-credit, for raw water monitoring actions only– provided automatic closing of raw water supply if exceeding limit of control parameter (see table 2.7)	**0.75b + 0.75v + 0.5p**
Water treatment actions other than final disinfection[2)] Maximum log-credit for individual, independent water treatment steps (see table 2.8) in the water treatment prior to final disinfection (before deduction caused by operation control monitoring defects, see table 2.9)	**3.0b**[3)] **+ 3.0v**[3)] **+ 3.0p**
Maximum log-reduction in final disinfection[4)] (before possible deduction for security defects, see table 3.7 and 3.10) Chemical disinfection methods, see chapter 3.8 UV-disinfection, see chapter 3.9 (table 3.9 and 3.10) Dose 40 mJ/cm^2 (biodosimetrically determined) Dose 30 mJ/cm^2 (biodosimetrically determined) Dose 25 mJ/cm^2 (biodosimetrically determined)	 **4.0b + 4.0v + 3.0p** **4.0b + 3.5v + 4.0p** 4.0b + 3.5v + 4.0p 3.5b + 3.0v + 3.5p 3.0b + 2.5v + 3.0p

1) For existing works the sum of the log-credits given for existing and new measures (including raw water surveillance actions) should not be set higher than the maximum value given in this table.
2) The log-credits are additive for individual, independent treatment steps in series and this may result in a higher log-credit in the water treatment (other than final disinfection) than what is indicated as maximum for individual steps.
3) If an oxidation method (for instance ozonation) constitutes a part of an independent treatment method, the maximum log-credit may be set at 4.0b +4.0v +3.0p – provided sufficiently high dose of oxidant (see chapter 3.7).
4) When analyzing new barrier measures for existing works that have UV-disinfection approved for an average UV-dose of 30 mJ/cm^2, maximum log-credit for the existing UV-disinfection should be set at 3.0b + 2.5v + 3.0p.

2.3.3.1 Log-credit for barrier actions in lakes and their catchment area

In table 2.4 the log-credits for physical and restrictive measures in the water a lake and its catchment area are indicated.

Table 2.4 *Log-credit for new physical and restrictive actions in lakes and catchment area*[1)]

Category of barrier action	Barrier actions in detail	Log-credit
Reduction of the pollution load to the water source	Closing of all sewage discharges directly to the water source and to river systems that leads directly to the source	0.75b + 0.75v + 0.5p
	Implementation of closed sewage systems (closed tank) for all sewage effluents in the catchment area, or watertight sewage systems bringing sewage out of the catchment area	0.5b + 0.5v + 0.25p
	Erecting fences for the prevention of farm animals, dogs etc. to come in direct contact with the source water and provision of garbage containers (including containers for dog feces) in the catchment area	0.25b + 0.25v + 0.15p
Restrictions in the activity allowed in the water source and the catchment area	Introducing a ban (or restrictions) on keeping grazing farm animals in the catchment area	0.75b + 0.75v + 0.5p
	Introducing a ban on potentially polluting activities in the catchment area, e.g. homes, cottages, motor traffic etc.	0.25b + 0.25v + 0.15p
	Introducing a ban (or restrictions) on the use of watersports, bathing or other types of recreation in the water source, e.g. motor traffic	0.25b + 0.25v + 0.15p
Measures connected to the water intake in the lake	Lowering or moving of the water intake to a depth that ensures that the intake is below the thermocline except in the circulation periods	0.5b + 0.5v + 0.25p
	Moving the raw water intake to such a position that it can be documented through hydraulic studies that fecal pollution from sewage and animals does not affect the water quality at the intake	0.25b + 0.25v + 0.15p
Absolut maximum summarized log-credit for barrier measures in water source and catchment		**2.0b + 2.0v + 1.25p**

1) The maximum of measures that can be awarded within each category of measures cannot be higher than what the most comprehensive measure is giving.

When analyzing a new system, the log-credit shall never be set higher than 2.0b+2.0v+1.25p. When analyzing existing water utility, the sum of log-credits for existing and new barrier actions shall never be set higher than 2.0b+2.0v+1.25p.

2.3.3.2 Log-credit for barrier actions in water utility based on ground water

Log-credit can primarily be given for barrier measures in the influence-area of the groundwater well. With respect to bedrock wells, so many deficiencies have been discovered that improvements of the design and construction of the well itself can be awarded a log-credit. Normally the protection zones around a ground water well are divided in:

Zone 0: The well zone. The area in a radius of 10 – 30 meter from the well point – for protection of installations at and in the well.

Zone 1: The close inflow area. The area from which the water drains to the well. The extent of this zone is normally given by that distance from the well from an area where the water requires 60 days to travel to the well at full pumping capacity.

Zone 2: The distant inflow area. The area outside the 60 days zone and from where water may reach the well and hence influence on the water quality.

Zone 3: The safety zone. Areas that might be part of the area of influence and hence may influence on the water quality in the well.

Log-credits for barrier actions connected to groundwater sources are given in table 2.5.

Table 2.5 *Log-credit for new barrier actions connected to groundwater sources*[1)]

Barrier actions in zone	Barrier actions in detail – that were not already implemented when the water quality level was determined	Maximum log-credit
Zone 0 The well zone	Fencing around and locking of gate to the well zone	0.25b + 0.25v + 0.25p
Zone 1 The close inflow zone (For groundwater in bedrock zone 1 extends to 100 m from the outer border of zone 0)	Introducing a ban on all forms of sewage installations in the zone. including sewage pipes, septic tanks, on-site infiltration systems etc., as well as spreading of sewage sludge	0.75b + 0.75v + 0.5p
	Introducing a ban on all form of agricultural activity including grass production, fertilizing, use of pesticides and use of the zone (or parts of it) as grazing land for farm animals	0,5b + 0,5v + 0,25p
	Introducing a ban on potentially polluting activities in the zone, e.g. homes, cottages, motor traffic etc. and all form of waste disposal sites	0.25b +0.25v + 0.15p
Zone 2 The distant inflow zone (For groundwater in bedrock zone 2 extends to 100 m from the outer border of zone 1)	Introducing a ban on all forms of sewage discharges to the ground, including effluents that are infiltrated in the ground, spreading of sewage sludge etc.	0.5b +0.5v + 0.25p
	Introducing a ban on all forms of agricultural activity in the zone, including grass production, fertilizing, use of pesticides and use of the zone (or parts of it) as grazing land for farm animals	0.25b + 0.25v + 0.15p
	Introducing a ban on potentially polluting activities in the zone, e.g. homes, cottages, motor traffic etc. and all form of waste disposal sites	0.25b + 0.25v + 0.15p
Improvement of well design and construction	Protection of the well with a well-house with water-tight floor and sealing around the well pipe	0.5b + 0.5v + 0.25p
	For groundwater in bedrock: Complete sealing between bushing-pipe and rock	0.5b + 0.5v + 0.25p
	Raising of the well pipe to at least 40 cm above ground including a water-tight lid	0.25b + 0.25v + 0.15p
Absolut maximum summarized log-credit for barrier actions implemented in connection with ground water		**2.0b + 2.0v + 1.25p**

1) The maximum of actions that can be awarded within each category of actions cannot be higher than what the most comprehensive actions is giving.

When analyzing new systems, the log-credit shall never be set higher than 2.0b+2.0v+1.25p. When analyzing an existing water system, the sum of log-credits for existing and new barrier actions shall never be set higher than 2.0b+2.0v+1.25p.

Artificial groundwater infiltration

When planning a system based on artificial groundwater infiltration (surface water that is infiltrated in the soil ground and taken out as groundwater), one may:

1. use the quality of the surface water to be infiltrated as the starting point for evaluating the necessary barrier and give log-credits for the artificial groundwater recharge (as a measure for improving the water quality)

or

2. use the water quality in the water taken from the ground as a starting point for evaluating the necessary barrier. In this case the source is treated as a soil groundwater source

If the raw water quality of the surface water is taken as the starting point, the log-credits given in table 2.6 may be used for the artificial groundwater recharge.

Table 2.6 *Log-credit for water quality improvement through artificial infiltration (surface water recharge to the ground or river bank infiltration)*

The residence time of the water in saturated and unsaturated zones	Maximum log-credit
> 60 days	3.0b + 2.5v + 3.0p
30 – 60 days	2.5b + 2.0v + 2.5p
15 – 30 days	2.0b + 1.5v + 2.0p
3 – 15 days	1.5b + 1.0v + 1.5p

It is assumed that the residence time in saturated and unsaturated zones may be predicted using hydrogeological investigations. Water from artificial groundwater infiltration with less than 3 days of residence time in the ground is not considered as soil groundwater but as surface water.

2.3.3.3 Log-credit for monitoring surveillance of raw water quality

Many systems have inadequate raw water quality monitoring. The primary monitoring efforts are usually spent on supplied water control (network control). Improved raw water quality monitoring provides better knowledge leading to enhanced security of the water quality. Such improvement deserves a log-credit if it results in a better preparedness for pathogen outbreaks.

Enhanced control of the raw water quality will, in itself, improve the preparedness since abnormalities can be discovered and corrected faster. It also helps predict how the water source reacts in threatening situations (heavy rainfall for instance). When such incidents are discovered through an improved monitoring of the raw water quality and coupled to barrier measures (for instance shutting off the water supplied) log-credit for such extended monitoring of raw water quality may be given, as shown in table 2.7.

Table 2.7 *Log-credit for improved surveillance of the raw water quality*[1)]

Category of barrier action	Raw water sampling and monitoring actions	Log-credit
Increased sampling frequency	Introduction of an extended microbial sampling and analysis program for raw water monitoring	
	• at least as comprehensive as the risk-based program	0.50b + 0.50v + 0.15p
	• at least as comprehensive as that used for net control	0.25b + 0.25v + 0.15 p
On-line monitoring of raw water quality	Introduction of on-line monitoring of raw water quality (turbidity, microbial activity or other parameters useful for monitoring the microbial quality) to be able to:	
	• automatically close raw water supply	0.50b + 0.50v + 0.15p
	• manually close raw water supply within an hour	0.25b + 0.25v + 0.15p
	• shift to another water source when exceeding the set point (alarm value)	0.25b + 0.25v + 0.15p
Absolut maximum summarized log-credit for improved sampling and on-line monitoring of raw water quality		**0.75b + 0.75v + 0.5p**

1) The maximum of actions that can be awarded within each category of actions cannot be higher than that of the most comprehensive action.

When analyzing new systems, the log-credit shall never be set higher than 0.75b+0.75v+0.5p. When analyzing an existing system, the sum of log-credits for existing and new barrier actions shall never be set higher than 0.75b+0.75v+0.5p.

2.3.3.4 Log-credit for particle separation measures in the water treatment

Table 2.8 shows log-credits that may be given to various water treatment processes that provide particle separation and resultant removal of microorganisms. The table is based on experiences in Norway and Sweden as well as on data from the literature (e.g. Hijnen and Medema, 2010).

Table 2.8 *Log-credit for particle separation processes in water treatment*

Particle separation method	Log-credit
Rapid sand filtration without coagulation (filtration rate < 7,5 m/h)[1)]	0.5b + 0.25v +0.5p
Membrane (MF) filtration[2)]	2.0b + 1.0v + 2.0p
Membrane (UF) filtration[3)]	2.5b + 2.0v + 2.5p
Membrane (NF) filtration[4)]	3.0b + 3.0v + 3.0p
Slow sand filtration (filtration rate < 0,5 m/h)	2.0b + 2.0v + 2.0p
Coagulation/direct filtration (media-filter)[5)]	2.25b + 1.5v + 2.25p
Coagulation/direct filtration (media-filter)[6)]	2.5b + 2.0v + 2.5p
Coagulation + sedimentation (or flotation) + filtration[5]	2.5b + 1.75v + 2.5p
Coagulation + sedimentation (or flotation) + filtration[6]	2.75b + 2.25v + 2.75p
Coagulation/membrane MF filtration[6)]	3.0b + 2.5v + 3.0p
Coagulation/membrane UF filtration[6)]	3.0b + 3.0v + 3.0p

1) Also valid for biofilters, ion exchange filters, activated carbon filters and calcium carbonate filters
2) Provided nominal membrane pore diameter < 100 nm
3) Provided nominal membrane pore diameter < 40 nm
4) Provided nominal membrane pore diameter < 5 nm
5) Provided turbidity in produced water < 0.2 NTU (on-line monitored)
6) Provided high coagulant dosage and operation control to ensure turbidity in water < 0.1 NTU (on-line monitored)

Table 2.10 includes filtration methods (sand filtration and membrane filtration with and without pre-coagulation). Filtration methods that are mainly use for other purposes that particle separation (such as ion exchange filters, activated carbon filters, calcium carbonate filters etc.) gives a modest separation of microorganisms – and are assumed to provide the same log-credit as rapid sand filter (without pre-coagulation) as long as the filtration rate is < 7.5 m/h. If it is above 7.5 m/h, no log-credit may be given.

The log-reduction that can be expected by the use of barrier coagulation/filtration is dependent on the particle separation effect. Therefore it is differentiated between a situation where the produced water turbidity is below 0.2 NTU and below 0.1 NTU. The later case normally requires enhanced coagulation, i.e. increased coagulant doses and pH-control. If the water contains NOM, the color reduction in enhanced coagulation should be >70 %.

Membranes may have become damaged and if so, the barrier effect may not be as good as indicated. Membrane filtration plants ought to be validated through membrane integrity tests and close monitoring of relevant parameters to discover any membrane damage.

In treatment plants based on ozonation/biofiltration, the ozonation gives the major log-reduction of microorganisms while the contribution from the filter is limited except for slow sand filters. For this method the log-credit for the ozonation step may be determined based on the Ct-values (se chapter 3.7), while the log-credit for the biofilter can be found in table 2.8 (equaling that of rapid sand filters). At the relatively high ozone dose that is used for NOM (color) removal (1 – 1.5 mg O_3/mg $TOC_{raw\ water}$), the calculated log reduction of bacteria and virus, as well as *Giardia*, may be high (> 3 log) but lower for *Cryptosporidium* (< 2 log).

2.3.3.5 Log-credit deduction for lack of operation control monitoring measures

The log-credits given in table 2.8 presuppose good operation that includes monitoring of water quality to reduce risk at unanticipated operational situations, for instance break-through of filters, dosing failure or power failure. If proper monitoring of treated water for operation control is inadequate, the log credits given in table 2.8 shall be reduced. Table 2.9 shows the log-credit deductions that are to be implemented when operational risk-reducing monitoring is absent.

Table 2.9 *Deduction of the log-credit given according to table 2.8 for lack of operationcontrol monitoring actions*

Category of barrier actions	Operation control monitoring (and follow-up) actions	Deduction in logcredit if monitoring measure is lacking
On-line monitoring of treated water quality with follow-up actions to comply with set limit values	**For on-line monitoring of treated water turbidity, color or other parameter suitable for process control:** • is lacking • is present, activating an alarm when over-shooting a set-point (alarm value)[1] leading to manual correction[2] of process conditions (e.g. adjustments of pH, coagulant dosage etc.) so that normal operation is restored • is present, activating an alarm when over-shooting a set-point (alarm value)[1] leading to manual closing[2] of raw water supply until the cause of abnormality is found and normal operation is restored • is present activating an automatic closing of raw water supply until the cause of abnormality is found and normal operation is restored	40% 20% 10% 0 %
Continuous monitoring of the electricity supply with follow-up actions at lapse of electricity supply	**If continuous monitoring and data transmitting to a control central of electricity supply data:** • is lacking • is present, activating an alarm at lapse of electricity supply, leading to manual closing[2] of raw water supply, until normal electricity supply is restored • is present, activating an automatic closing of raw water in case of supply failure of electricity supply, until normal electricity supply is restored • is present, activating an alarm leading to manual start-up[2] of emergency el-supply generator and/or UPS at failure of electricity supply • is present, activating automatic start-up of emergency el-supply generator and/or UPS at failure of electricity supply	40 % 20 % 0% 20% 0%

1) The set-point must be decided for the relevant parameter in each case
2) Within an hour

Example

A coagulation/direct filtration plant is achieving < 0.1 NTU in treated water. The log-credit (from table 2.8) is then 2.5b+2.0v+2.5p. The plant has the following monitoring equipment:

- Turbidity sensors are installed on the outlet of each filter. If the turbidity is passing 0.2 NTU, an alarm will go off and the operators will immediately correct operational controls manually so that 0.1 NTU is restored in the treated water. There is no automatic shut off of raw water supply.
- The plant is equipped with automatic start-up of emergency electricity generator when the normal supply is interrupted.

For this case the final log-credit for the plant will be:

Log-credit based on type of particle separation process:	2.5b + 2.0v + 2.5p
– Deduction because of:	
• lack of monitoring of treated water quality (20 %):	0.5b + 0.4v + 0.5p
• lack of electrical supply monitoring:	0.0b + 0.0v + 0.0p
Final log-credit for treatment:	2.0b + 1.6v + 2.0p

2.3.4. Determination of necessary log-reduction in the final disinfection step

When the barrier level required has been determined as well as the log-credits for barrier actions implemented in catchment area and source and in water treatment (other than disinfection), the log-reduction needed in the final disinfection step may be determined by subtraction of the log-credits from the barrier level required (see figure 2.4)

Barrier level required	$x_1\mathbf{b} + y_1\mathbf{v} + z_1\mathbf{p}$
Barriers in catchment area and water source	$x_2\mathbf{b} + y_2\mathbf{v} + z_2\mathbf{p}$
Particle seperation barriers in the water treatment	$x_3\mathbf{b} + y_3\mathbf{v} + z_3\mathbf{p}$
Disinfection barriers (log-reductions) required	$[x_1 - (x_2 + x_3)]\mathbf{b} + [y_1 - (y_2 + y_3)]\mathbf{v} + [z_1 - (z_2 + z_3)]\mathbf{p}$

Figure 2.4 *Determination of necessary log-reduction in the final disinfection step*

Chapter 3 explains how the level of the disinfection barrier (in terms of log-reductions) may be calculated. In existing system the result may be compared with the barrier level required determined as in figure 2.4 and the barrier situation of the whole systems (see chapter 4) may be determined.

In water utility under planning or design, the log-reductions required as determined from figure 2.4, constitutes the foundation for the design of the disinfection facilities.

3. Calculation- and test-methods ("tool-box") for disinfection

In this chapter a set of calculation- and test-methods ("tool box") will be presented that may be used in the planning as well as in design and operation of disinfection facilities.

1. In the system design, the tools may be used to determine necessary disinfection dose as well as design of the contact tank to achieve the necessary log-reduction that is shown to be necessary through the MBA-procedure.
2. In the operation the tools may be used for control of operation, for instance whether or not the disinfectant dosage is sufficient.

3.1. Basis for design and operation

There are especially three factors that form the basis for design and operation of disinfection facilities:

- The water flow (design flow in the planning situation)
- The composition of water to be disinfected (water quality) and temperature
- The Ct-values needed for various microorganisms to achieve a given log-reduction

3.1.1. Design flow

The design flow is set at maximum production flow on an hourly basis, i.e. $Q_{max\ hour}$. This definition must take into account maximum pumping capacity if the water is pumped into the disinfection facility so that $Q_{max\ hour}$ is set equal to maximum pump capacity.

3.1.2. Composition and temperature of the water to be disinfected

There are several parameters that may have an influence, but the three most important ones are:

- Organic matter content (represented by TOC or color in humic waters)
- Turbidity
- pH

The design basis for TOC (or color) and turbidity shall be the worst water quality that may be expected at the inlet of the disinfection facility. For existing plants, use the highest registered TOC/turbidity that is experienced during the last three years of operation, and analyze the data to determine if the highest TOC is coincides with the highest turbidity (this is not unusual). The design of the *dosing equipment* should consider the possibility to increase the dosage to the necessary level even if the organic matter removal step fails, and even though the disinfection as such is designed for a lower content of organic matter.

When using UV disinfection the situation must be somewhat different. A temporary failure of the TOC removal step may "knock out" the UV disinfection plant so that both barriers fail. This challenge is addressed by requiring a reduction of log-credit for UV-disinfection if the UV-transmission in the raw water to become lower than the UV-plant is designed for (see section 3.9.2).

The design pH is the pH at which the disinfection step is supposed to work. During chlorination, the pH has a very significant influence on the efficiency of disinfection.

The design temperature is dependent upon water source and if long-term data does not show differently, the design temperature in the MBA guideline (primarily to be used in the Nordic countries) should be:

- 0.5 °C for rivers and brooks
- 4 °C for lakes and for groundwater

In actual operations, the prevailing temperature should be evaluated. For the barrier evaluation the 90-percentile should be used, i.e. the temperature that is surpassed 90 % of the time (or possibly of registered measurements) since extreme temperatures could occur in short periods.

3.2. Ct-values for inactivation of various microorganisms

3.2.1. Generally about the Ct concept

The Ct concept is derived from a theoretical basis that couples inactivation (log-reduction) to the concentration, C, of disinfectant that the microorganisms have experienced over a certain time, t.

Based on experience and data from the literature it is possible to determine what Ct-value that is needed to achieve a given log-reduction of the various microorganism groups. This is discussed in section 3.2.
The challenge is to determine the correct C and t that are to be used in the calculation. This is discussed in section 3.3.

3.2.2. Design Ct-values

Based on the earlier work (Ødegaard et al., 2006, 2009a) and data from the literature (Guillot, E. and Loret, J-F., 2010), proposed design Ct-values are presented in table 3.1. And these values will form the basis for the analysis in the MBA guideline.

Table 3.1 *Required Ct-values (mg·min/l) for inactivation of bacteria, virus and parasites*

	Bacteria (3 log reduction)		**Viruses** (3 log reduction)		**Parasites of the Giardia group** (2 log reduction)		**Parasites of the Crypto-sporidium group** (2 log reduction)	
	4°C	0.5°C	4°C	0.5°C	4°C	0.5°C	4°C	0.5°C
Chlorine								
pH < 7	1.0	1.5	4.0	6.0	75	100	n.s.	n.s.
pH 7 – 8	1.5	2.0	6.0	9.0	100	150	n.s.	n.s.
pH > 8	2.0	3.0	8.0	12.0	175	250	n.s.	n.s.
Chloramine	100	200	1500	2000	1750	2500	n.s.	n.s.
Chlorine dioxide	1.0	1.5	10	15	20	30	>100	>150
Ozone	0.5	0.75	1.0	1.4	1.5	2.0	30	45

n.s. – not stated. The Ct-value is so high that it is of no interest for all practical purposes

The design temperature must be taken into account, and for chlorine pH is also taken into account. Ct-values > 100 require such high dosages (and/or long residence times) that they are not practical.

Since there is a direct connection between Ct and log reduction, the log reduction may be calculated for any Ct-value. When the required Ct-value is as shown in table 3.1, the calculated log-reduction ($n_{calculated}$) for any other Ct may be calculated as follows:

$$n_{calculated} / Ct_{calculated} = n_{required} / Ct_{required}$$

Example
Find the log reduction of virus to expect in ozone disinfection if the Ct-value is calculated to be 0.8 (mg•min/l) at 4 °C:

3/1.0 • 0.8 = 2.4 log – since $Ct_{required}$ = 1.0 for ozone at 4 °C for n_{log} = 3 log reduction

Likewise one may determine the $Ct_{required}$ for a certain log reduction (n) when the $Ct_{required}$ at another log reduction is known, through the formula:

$$Ct_n = Ct_{(n-1)} \cdot (n/n\text{-}1) = Ct_{(n+1)} \cdot (n/n+1)$$

Therefore it is sufficient to indicate only one $Ct_{required}$ for each disinfection situation, as shown in table 3.1, for 3 log reduction of bacteria and virus and 2 log reduction of parasites. By use of the formulas the necessary Ct for any other log reduction can easily be calculated.

3.3. Determination of Ct

The determination of C as well as t is important because:

- C varies over time as a result of consumption of the disinfectant
- t is dependent on the volume as well as the degree of mixing in the reactor (which is dependent on shape, division in chambers etc.).

The reactor in which the disinfectant (for instance chlorine) is brought in contact with the water for a certain time is normally referred to as the contact tank. It may consist of one or several contact tank segments. Also the water transmission pipe up to the first consumer may be included as a segment of the contact time.

3.3.1. Determination of t in the Ct-calculation

In contact tanks of different shapes there will be different amounts of mixing and different elements in the water will have different residence times in the tank. For the determination of the t (in the Ct-value) use the effective time, t_{eff}, as calculated by the equation below.

$$t_{eff} = (V/Q) \cdot F_h \cdot F_s$$

t_{eff} = effective residence time (min)
V = the volume of the contact tank (m^3)
Q = the design water flow (m^3/min)
T = V/Q = theoretical residence time (min)
F_h = hydraulic factor
F_s = serial factor

The values for the hydraulic factor and the serial factor are given in table 3.2. The time t_{10} is that when 90 % of the water elements are still in the tank (while 10 % has passed it) and t_m the time when 50 % of the water elements have passed it. These times may be determined through tracer experiments that may be very useful during operation of an existing system. In a planning and design situation, however, certain assumptions must be made to determine the mixing conditions (see table 3.2).

It is evident that the more plug-flow like the flow is the higher is the hydraulic factor. The ideal situation would be complete plug-flow. This is not possible in a mixed tank, however. By dividing the contact tank into several chambers in series, the flow regime for the whole contact tank approaches that of plug flow. That is the reason for the serial factor in the formula for $t_{eff.}$

Table 3.2 *Recommended values for hydraulic factor and serial factor at various mixing conditions*

Mixing condition (extent of plug flow (PF) in each chamber)	Hydraulic factor. Fh[1,2]		Description of each chamber in contact tank	Serial factor. Fs Chambers in series		
	t_{10}/T[1)]	t_m/T[2)]		1	2	3
No PF (complete mixing)	0.1	0.3	No baffles, agitated tank, high in- and out-velocities, low length/width ratio in tank (≦1)	1.0	2.0	2.5
Poor PF	0.3	0.4	No baffles inside tank, single inlets and outlets in tank, length/width ratio in tank >1	1.0	1.8	2.0
Average PF	0.5	0.5	Baffled inlet or outlet, some baffles inside tank and possibly multiple inlets and outlets. length/width ratio in tank >4	1.0	1.5	1.8
Quite good PF	0.7	0.7	Baffled inlet. serpentine baffles inside tank to increase length/width ratio to >6	1.0	1.3	1.4
Very good PF	0.9	0.9	Baffled inlet, serpentine or perforated plate baffles inside tank. High length/width ratio (>10)	1.0	1.1	1.1
Perfect PF	1.0	1.0	Very high length/width ratio (>20). Pipeline flow	1.0	1.0	1.0

1) To be used in Ct-calculation (see section 3.7.4)
2) To be used in calculation of k, Ci and Cout (see section 3.4.2 and section 3.7.2-3.7.3)

Example
If you have a contact tank consisting of 3 equally sized basins in series, each with a theoretical residence time of T (V/Q) = 10 min (i.e. total theoretical residence time = 30 min) and each basin has poor plug flow (single inlets and outlets and no baffles inside tank), i.e. hydraulic factor (t_{10}/T) of 0,3, the effective residence time (t_{eff}) for the whole contact tank will be:

$$teff = 0.3 \cdot 2.0 \cdot 30 \text{ min} = 18 \text{ min}$$

Later (section 3.4.3 and 3.7.4 and section 3.4.2 and section 3.7.2-3.7.3), it is shown how initial consumption (IF), degrading constants (k) and concentrations (C_i and C_{out}) may be calculated. For these calculations, t_m is more relevant than t_{10}, and the hydraulic factor t_m/T is to be used instead of t_{10}/T (see table 3.2). The table shows that the hydraulic factors are only different at poor plug-flow conditions.

When ozone is used, contact tanks may be designed as columns (i.e. pipeline shaped reactor with vertical flow). For such tanks the hydraulic factor values in table 3.2 are not particularly suitable. Then values in table 3.3 should therefore be used to determine the hydraulic factor in high, slender ozone contact tanks. When ozone contact tanks are shaped similar to chlorine contact tanks, the values in table 3.2 are to be used.

Gas bubbles that are present in the contact columns where the ozone is added can affect results, both through the fact that ozone is transferred from the bubbles and to the liquid and to the fact the mixing conditions are influenced. In gas/liquid contact tanks the flow regime may be improved considerably by using a packing medium in the tank. Table 3.3 also includes columns with packing.

Table 3.3 *Recommended values for hydraulic factor in high, slender ozone contact columns*

Contact system	Hydraulic factor, Fh[1,2]		Serial factor. Fs Columns in series		
	t_{10}/T[1)]	t_m/T[2)]	1	2	3
Open columns					
With gas bubbles present	0.5	0.55	1.0	1.5	1.8
Without gas bubbles present	0.7	0.75	1.0	1.3	1.4
Packed columns					
With bubbles present	0.85	0.85	1.0	1.1	1.1
Without gas bubbles present	0.95	0.95	1.0	1.0	1.0

1) To be used in Ct-calculation (see section 3.7.4)
2) To be used in calculation of k, Ci and Cout (see section 3.4.2 and section 3.7.2-3.7.3)

3.3.2. Determination of C in the Ct-calculation

The disinfectant concentration change in the contact tank depends on what type of disinfectant. The following chapters describe each chemical disinfectant separately, the calculation of the necessary dosage, as well at Ct.

3.4. Chlorine (chlorine gas and hypochlorite)

General information about (chlorine gas as well as hypochlorite) as a disinfectant is described in text-books and in Ødegaard et al.et al.(2006, 2009b, 2014). Whenever mentioning the concentration of chlorine in this guideline, the reference is to *free chlorine* (mg Cl_2/l) irrespective of the type chlorine product, or the form that it takes in the water.

3.4.1. The progress of concentration change in chlorine disinfection

When chlorine is added to water, a rapid consumption of chlorine will take place because of oxidation of various oxidiable compounds (organic as well as inorganic) in the water. This brings the chlorine concentration down to a level that we may call the initial concentration (C_i) with respect to disinfection. Then there will be a gradual slower degradation of chlorine down to a residual chlorine concentration after a given time. The residual concentration after passing the contact tank will be referred to as the outlet concentration (C_{out}), see figure 3.1.

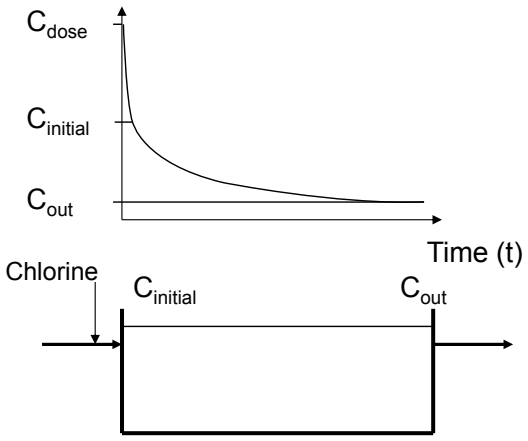


Figure 3.1 *Schematic of the concentration change in a chlorine contact tank*

The initial consumption of chlorine caused by oxidation is so rapid that it is difficult to determine its duration. In the MBA guideline we assume this is instantaneous and that the concentration progress can be described as shown in figure 3.2.

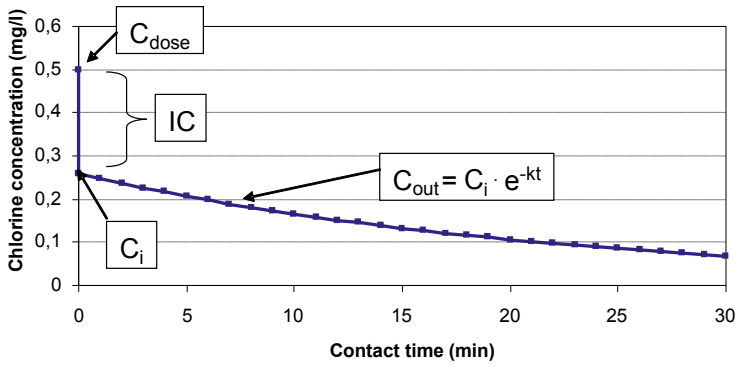


Figure 3.2. *Schematic description of initial consumption and chlorine degradation as a basis for the calculation of Ct*

This means that the relationship between dose (C_{dose}) and initial concentration (C_i) may be described as:

$$C_i = C_{dose} - IC$$

where IC is the initial chlorine consumption that takes place directly after dosage. It will be a function of water quality and the chlorine dosage.

The gradual reduction of the chlorine concentration over time from the initial concentration (C_i) to the residual concentration at the outlet (C_{out}) may be written as a first order degradation reaction, i.e.:

$$C_{out} = C_i \cdot e^{-kt}$$

where t is the residence time and k is the degradation constant for chlorine that is dependent on the water quality and the chlorine dosage.

The Ct-value will be represented by the area under the curve that describes concentration versus time in the contact time (see figure 3.2).

3.4.2. Initial consumption (IC) and degradation constant (k) for chlorine

There are several ways by which IC and k may be determined. In a plant in operation the most advantageous way is through measurements in the plant. Since this is not possible in planning and design, IC and k must be estimated either by laboratory experiments or by calculation based on knowledge of water composition.

The models presented below (section 3.4.2.2) that may be used for calculation of IC and k, are based on laboratory experiments over a wide range of water qualities (Ødegaard et al., 2009). Determination by experimental methods is also described.

3.4.2.1 Alternative 1: Determination of IC and k by measurements in a plant in operation

In operating plants the dose (C_{dose}) and the outlet concentration from the contact tank (C_{out}) may be known. If possible, one can measure the chlorine concentration in another well-defined place in the contact tank (for instance at the inlet to the contact tank, C_{in}) and calculate the degradation constant (k) based on measured concentration in these two locations.

The degradation constant may then be determined through the equation:

$$k = - [\ln(C_{out}/C_{in})] / t \qquad (t = t_{eff}, \text{ see section 3.3.1})$$

Thereafter the initial consumption may be determined by the equation:

$$IC = C_{dose} - C_i = C_{dose} - [C_{out} / e^{-k \cdot t}] \qquad (t = t_{eff}, \text{ see section 3.3.1})$$

3.4.2.2 Alternative 2: Determination of IC and k through model calculations

Experiments that were conducted, using the approach of Ødegaard et al.(2009), with different waters with a wide variety of compositions, lead to the following models for determination of IF and k:

$$IC_{chlorine} = 0.06 \cdot TOC + 0.36 \cdot C_{dose} + 0.08 \cdot (C_{dose}/TOC) - 0.12$$

$$k_{chlorine} = 0.013 \cdot TOC - 0.040 \cdot C_i - 0.010 \cdot C_i/TOC + 0.022$$

The chlorine model for IC is valid when:

- C_{dose} = 0.25 – 3.0 mg Cl_2/l
- TOC = 0.5 – 6.0 mg/l
- Calculated IC ≤ C_{dose} (at IC > C_{dose}, IC is to be set at IC = C_{dose})

The chlorine model for k is valid when:

- C_i = 0.25 – 3.0 mg Cl_2/l
- TOC = 0.5 – 6.0 mg/l
- Calculated IC < C_{dose}
- Calculated k > 0.005

3.4.2.3 Alternative 3: Determination of IC and k through a combination of measurements and calculations

If only the chlorine dose (C_{dose}) and the outlet concentration from the contact tank (C_{out}) is known, it is recommended that IC is first determined by use of the model given above, and that the initial concentration (C_i) is determined thereafter, through the equation:

$$C_i = C_{dose} - IC$$

Then the degradation constant (k) can be calculated, through the equation:

$$k = - [\ln(C_{out}/C_i)] / t \qquad (t = t_{eff}, \text{ see section 3.3.1})$$

The reason it is recommended that IC should be determined by the use of the model and not k, is that the uncertainty in the model determination of IC is estimated to be lower than that of k.

When neither the chlorine dose (C_{dose}) nor the outlet concentration (C_{out}) is known (typically when in the planning and design situation), both IC and k may be determined from the models. Since the values of IC and k are dependent on the chlorine dose, one has to assume a dose to be able to determine IC and k. If the assumed dose is not in agreement with the calculated dose, a new dose that gives new values for IC and k should be assumed, and recalculated until the assumed dose is in fair agreement with the calculated dose (see roadmaps in attachment 1).

3.4.3. Calculation of Ct

Since the Ct-value is given as the area under the curve for concentration progress (see figure 3.2), the Ct-value may be found through integration of the degradation equation and hence the equation for Ct is:

- When taking C_i as the starting point:

  $Ct = (C_i / k) (1 - e^{-k \cdot t})$

- When taking C_{out} as starting point:

  $Ct = (C_{out} / k) (e^{k \cdot t - 1)}$

In both equations the time (t) is the effective residence time (t_{eff}):

$t_{eff} = (V/Q) \cdot F_h \cdot F_s$ ($F_h = t_{10}/T$, see section 3.3.1)

3.4.4. Practical use of the tool-box – chlorine

The equations given above may be used in various applications. Detailed roadmaps for the practical use of the tool-box for different applications are presented in attachment 1, such as:

- Calculation of necessary chlorine dose when designing a chlorine disinfection facility (attachment V1.2)
- Calculation and use of Ct-value while operating or during design (attachment V1.3)
  - Use of Ct for documentation in the operation situation (attachment V1.3.1)
  - Use of Ct in a design situation (attachment V1.3.2)
  - Determination of necessary capacity of the chlorine dosing equipment (attachment V1.3.3)

This attachment also shows how the tool-box can be when the chlorine contact tank is divided in several segments (see attachment V1.1).

3.5. Chloramine

General information about use of chloramine as a disinfectant is described in in text-books or in Ødegaard et al. (2006, 2009b, 2014). When considering chloramination, it is the *total chloramine concentration* that is relevant, and presented in mg Cl_2/l.

3.5.1. The progress of concentration change in chloramine disinfection

When chloramination is used, rapid initial consumption does not take place as when chlorine is added as chlorine gas or as hypochlorite (compare figure 3.3 with figure 3.2). In the Ct-calculations for chloramination the initial concentration (C_i) is, therefore, set equal to the dose:

$$C_i = C_{dose}$$

where C_{dose} is the chloramine dose in mg Cl_2/l

The small amounts of free chlorine that may exist at low temperatures right after the dosage may be disregarded. Even though chloramine is significantly more stable than chlorine, it will degrade, but at a much slower rate. Since the degradation is slow and the disinfection power is relatively low, it is, for simplicity, assumed that the degradation of chloramine takes place in two phases (see figure 3.3):

1. A first phase with more rapid degradation that is dependent on water quality as well as auto-decomposition (self-decomposition)
2. A slower phase that is independent of water quality (provided that pH > 8 and Cl_2:NH3-N < 5:1) where primarily auto-decomposition takes place

The degradation in both phases may be approximated by a linear relationship between concentration and time, see figure 3.3.

The extent and duration of phase I may vary. For typical Scandinavian conditions (with respect to water quality and dose) the duration of phase I is typically around 5 hours.

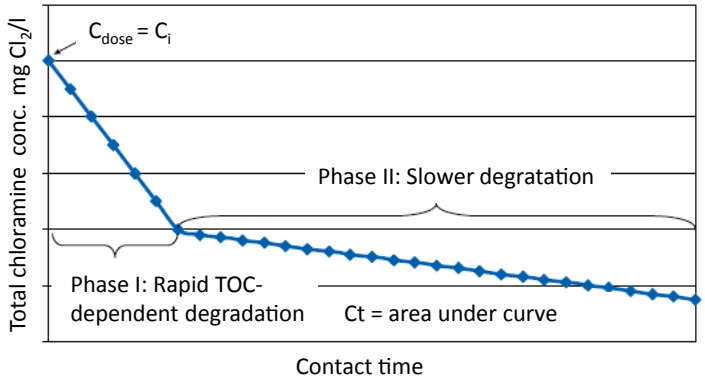


Figure 3.3 *Schematic presentation of the degradation of chloramine*

The concentration of chloramine after a given time (C_{time}) may be determined as:

$C_{time} = C_{dose} - [k_{phase\ I} \cdot t]$ for $t \leq 300$ min.

$C_{time} = C_{dose} - [k_{phase\ I} \cdot 300] - [k_{phase\ II} \cdot (t-300)]$ for $t > 300$ min.

$k_{phase\ I}$ and $k_{phase\ II}$ are the degradation constants for each phase respectively (see table 3.4).

Since there is very limited information about the degradation constants in the literature, the best way to estimate $k_{phase\ I}$ og $k_{phase\ II}$ is through experiments with the water to be treated. The simplest procedure is to measure chloramine concentration after certain time intervals for instance 2, 10 and 20 hours residence time. The constants, in terms of mg/(l • min), may then be calculated as:

$k_{phase\ I} = (C_{dose} - C_{t=2hrs}) / \Delta t = (C_{dose} - C_{t=2hrs}) / (2 \cdot 60)$

$k_{phase\ II} = (C_{t=10timer} - C_{t=20hrs}) / \Delta t = (C_{t=10hrs} - C_{t=20hrs}) / (10 \cdot 60)$

C_{2hrs}, C_{10hrs} and C_{20hrs} are the chloramine concentrations (mg Cl_2/l) after 2, 10 and 20 hours respectively, and Δt is the residence time difference (in minutes) between the two concentration measurements.

If experimental data from the water in question are not available, the values in table 3.4 may be used.

Table 3.4 *Proposed degradations constants for chloramine*

Degradation phases	Degradation constant	Value [mg/(l • min)]
Phase I	$k_{phase\ I}$	$3.3 \times 10^{-5} \cdot (1 + TOC)^{1)}$
Phase II	$k_{phase\ II}$	3.3×10^{-5}

1) TOC in mg/l

3.5.2. Calculation of Ct for chloramine

The effective residence time that is to be used in the Ct-calculations should be determined in the same way as for chlorine (se section 3.3.1).

The Ct for each of the two phases must be calculated and the total Ct-value will be the sum of the two.

$Ct_{Phase\ I} = [(C_{dose} + C_t)/2] \cdot t = [½\ (2C_{dose} - t \cdot k_{phase\ I})] \cdot t$ for $t \leq 300$ min

$Ct_{Phase\ II} = [½\ (C_{300\ min} + C_{time})] \cdot (t\text{-}300)$ for $t > 300$ min

$Ct_{total} = Ct_{phase\ I} + Ct_{phase\ II} = [½(2C_{dose} - 300k_{phase\ I})] \cdot 300 + [½(2C_{dose} - 600k_{phase\ I} - t \cdot k_{phase\ II} + 300k_{phase\ II})] \cdot (t\text{-}300)$

Since chloramine decomposes slower and a residual is desired in the network, the pipeline from the treatment plant to the first customer may also be used. Since the pipeline has close to perfect plug flow a hydraulic factor of $t_{10}/T=1.0$ should be used. The effective residence time is then equal to the theoretical residence time ($t_{eff} = V/Q$) when determining the Ct-value for a situation where the pipeline is used as the contact tank.
If there is supposed to be consumption of drinking water when the water leaves the plant, the use of the pipeline as contact tank is not possible, and the Ct-calculation must be based on effective residence time only in the contact tank as it is with chlorine disinfection.

3.6. Chlorine dioxide

General information about chlorine dioxide as a disinfectant may be found in text-books or in Ødegaard et al.(2006, 2009b, 2014).

The methods for calculation of Ct, effective residence time (t), progress in concentration change (C_{out}) and possible segmentation are the same for chlorine dioxide as they are for chlorine. The calculation of initial consumption (IC) and degradation constant (k) is, however, chlorine dioxide specific.

3.6.1. Initial consumption and degradation constant for chlorine dioxide

The models for the calculation of initial consumption (IC) and degradation constant (k) for chlorine dioxide are presented below, based on a limited number of data from literature. It is, recommended, however, that experiments be carried out on the water in question to produce more reliable data. The procedure of such experiments would be the same as for chlorine. In absence of such experimental data, the following models may be used:

$$IC_{chlorine\ dioxide} = 0.10 \cdot TOC + 0.61 \cdot [C_{dose}]^{0.2} + 0.14 \cdot (C_{dose} / TOC) - 0.20 / C_{dose}$$

valid if $C_{dose} > 0.25$ mg/l and $TOC \bullet C_{dose} > 1$ concurrently

$$k_{chlorine\ dioxide} = 0.01 \cdot [TOC]^{0.5} - 0.02 \cdot C_i + 0.015$$

If both chlorine and chlorine dioxide are present, $IC_{chlorine}$ and $IC_{chlorine\ dioxide}$ will both have to be adjusted (see section 3.6.2). This occurs because the initial consumption for one of the two oxidants also is reduced since easily oxidizable compounds are also oxidized by the other – and vice versa.

In such cases $IC_{chlorine}$ and $IC_{chlorine\ dioxide}$ is to be adjusted as follows:

$$IC_{chlorine\ dioxide,\ adjusted} = [C_{dose,\ chlorine\ dioxide}/(C_{dose\ chlorine\ dioxide} + C_{dose\ chlorine})] \cdot IC_{chlorine\ dioxide}$$

where $IC_{chlorine\ dioxide}$ is determined by the model above

$$IC_{chlorine,\ adjusted} = [C_{dose\ chlorine}/(C_{dose\ chlorine\ dioxide} + C_{dose\ chlorine})] \cdot IC_{chlorine}$$

where $IC_{chlorine}$ is determined by the model in section 3.4.2.

The degradation constants $k_{chlorine}$ and $k_{chlorine\ dioxide}$ are influenced indirectly since the initial concentrations $C_{i\text{-}Cl2}$ and $C_{i\text{-}ClO2}$ are influenced by the adjusted values for IC:

$$C_{i,\ chlorine\ dioxide} = C_{Dose\ chlorine\ dioxide} - IC_{chlorine\ dioxide,\ adjusted}$$

$$C_{i,\ chlorine} = C_{dose\ chlorine} - IC_{chlorine,\ adjusted}$$

This results in the following change of the degradation constants:

$$k_{chlorine\ dioxide} = 0.01 \cdot [TOC]^{0.5} - 0.02 \cdot C_{i\text{-}ClO2} + 0.015$$

$$k_{chlorine} = 0.013 \cdot TOC - 0.040 \cdot C_{i\text{-}Cl2} - 0.010 \cdot C_{i\text{-}Cl2} / TOC + 0.022$$

3.6.2. Calculation of Ct for chlorine dioxide

The procedures for calculating effective residence time, progress in concentration change, possible segmentation and Ct-value are the same for chlorine dioxide as for chlorine, taking into account the IC- and k-values calculated for chlorine dioxide (see 3.6.1).

If a combination of chlorine and chlorine dioxide is used, Ct is calculated separately for chlorine and chlorine dioxide with the adjusted values for IC and k for the two disinfectants respectively. Also the log-reduction calculations will have to be carried out separately and summarized to find the total log reduction (that might have to be corrected because of maximum log reduction limitations or safety breaches).

3.7. Ozone

General information about the use of ozone as a disinfectant can be found in text-books or in Ødegaard et al.(2006, 2009b, 2014).

3.7.1. Progress of concentration decay

In the use of ozone as a disinfectant, there are three processes involved:

1. The transfer of ozone from gas phase to water phase – which will increase the ozone concentration in the water
2. Oxidation processes with ozone as the oxidant – which will reduce the ozone concentration in the water
3. A decomposition of ozone (to oxygen) – which also reduces ozone concentration of ozone in the water

The three processes occur in parallel which makes it difficult to clearly describe the progress of the concentration change in the water. Ozone is much more reactive than chlorine and the reduction of ozone concentration from the concentration right after dosage to initial concentration takes place at a much higher rate than with chlorine, probably in a matter of seconds.

In figure 3.4 a simplified picture of the progress of concentration change is presented in which the different process phases are related to various tank segments in the ozone contact- and reaction facility.

The three phases of concentration change are:

1. A mixing phase that takes place in a dosing tank segment where the ozone is added (by a diffusor, injector, turbine etc.)
2. A ozone transfer phase in which ozone is transferred from gas to water in a contact tank segment, while at the same time the consumption of ozone occur because of its reaction with the compounds in the water.
3. A ozone consumption phase that takes place in a reaction tank where the ozone concentration is reduced because of decomposition

In practice it is difficult to separate the mixing phase from the transfer phase since the dosage often is done directly before or into the contact tank. In practical design, the contact tank should be considered to consist of the volume from the injection point to the outlet of the tank in which ozone bubbles are added (see figure 3.5).

In the calculations below, however, one is assuming separate mixing- and contact tanks, to take into account the difference in process progress of the mixing and the transfer phases.

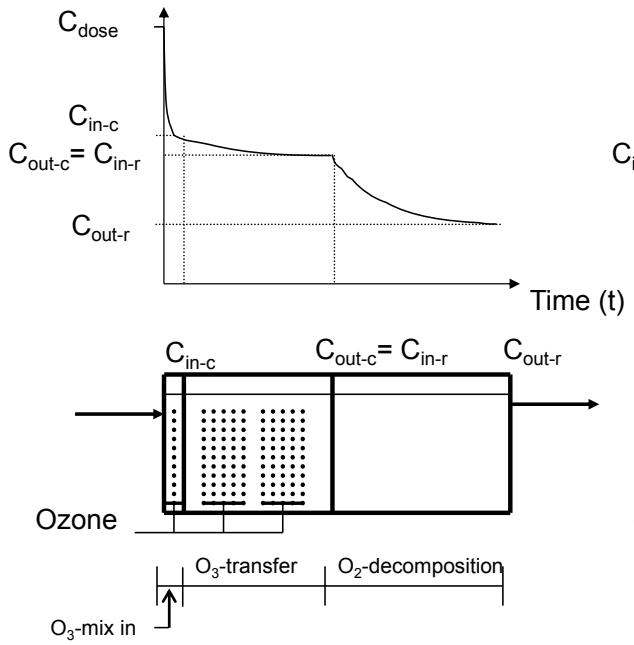


Figure 3.4 *Expected progress in concentration change in an ozone transfer system*

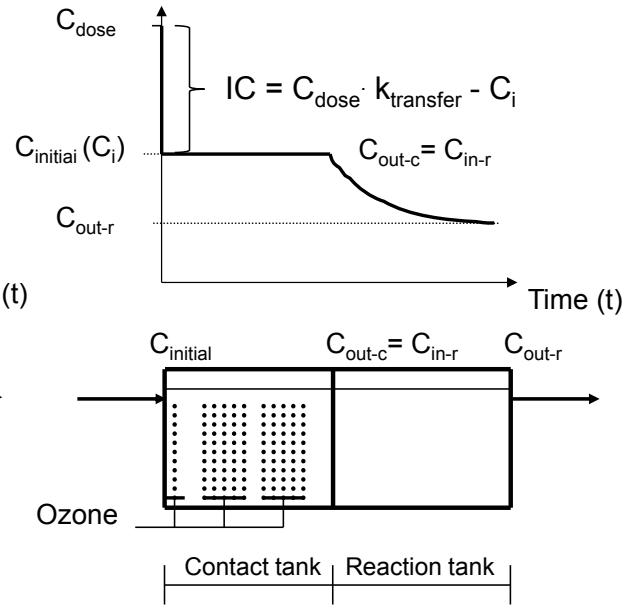


Figure 3.5 *Idealized progress in concentration change in Ct-calculation for ozone systems*

In figure 3.5 the concentration change progress is simplified to be able to calculate Ct. It is assumed that concentration in the water will drop momentarily from that of the dose (C_{dose}) down to an initial concentration (C_i) equaling the concentration that occurs after ozone transfer and oxidation of oxidisable compounds in the water.

The relationship between initial concentration and initial consumption (IC) will then be:

$C_i = (C_{dose} \cdot k_{transfer}) - IC$

where $k_{transfer}$ is the ozone transfer constant,

$k_{transfer}$ is an expression for the extent of ozone transfer to the water phase. At 100 % use of ozone (no loss) $k_{transfer}$ will be 1.0. At 10 % loss $k_{transfer}$ will be 0.9. The extent of transfer will be dependent on the shape of the contact tank. Table 3.5 indicates recommended values for $k_{transfer}$.

Table 3.5 *Recommended values for the ozone transfer constant, $k_{transfer}$.*

Contacting system	$k_{transfer}$
Diffuser/injector mixing, packed contact tank	0.90
Diffuser/injector mixing, contact tank without packing	0.75
Injector mixing in pipe proceeded by closed pipeline contact tank	0.99

C_i will equal the concentration that is entering the contact tank (C_{in-c}): $C_i = C_{in-c}$

IC is a function of water quality and ozone dose, and can be estimated by the use of the models that are presented in section 3.7.2.2.

Depending on the continued oxidation and the kinetics of the gas transfer, the concentration of ozone may both decrease and increase in the water on its passage through the contact tank. The decomposition of ozone concentration in the contact tank may, however, be expected to be of the first order, and hence

$$C_{out\text{-}c} = C_{in\text{-}c} \cdot e^{-kt} = C_{in\text{-}r} = C_i \cdot e^{-kt}$$

($t = t_{eff\text{-}c}$ see section 3.3.1)

where t is the effective residence time of the contact tank and k is the ozone degradation constant. Models for the calculation of k are given in section 3.7.2.2.

If the contact tank is segmented, $C_{eff\text{-}c}$ should be used in the Ct-calculation in each segment. $C_{eff\text{-}c}$ is assumed to be constant in each segment. The Ct for every segment is finally summarized to determine the Ct for the whole contact tank.

Table 3.6 *Determination of $C_{eff\text{-}c}$ in contact tank segments depending of reactor type*

Totally mixed reactor	Co-current reactor	Counter-current reactor
$C_{eff\text{-}c} = C_{out\text{-}c}$	$C_{eff\text{-}c} = C_{out\text{-}c}$ or ½ $(C_{in\text{-}c} + C_{out\text{-}c})^{1)}$	$C_{eff\text{-}c} = C_{out\text{-}c}/2$

1) If $C_{in\text{-}c}$ is to be included in the determination of $C_{eff\text{-}c}$ the $C_{in\text{-}c}$ must be determined by analysis and not by calculation.

In the reaction tank (which may consist of several segments) there are only consumption and no external supply of ozone. Therefore, the ozone concentration in the water coming from the contact tank may be assumed to be decomposed according to a 1. order reaction, i.e.:

$C_{out\text{-}r} = C_{in\text{-}r} \cdot e^{-k}$ ($t = t_{eff\text{-}r}$ see section 3.3.1)

and

$C_{in\text{-}r} = C_{out\text{-}c}$

where $C_{in\text{-}r}$ is the inlet concentration to the reaction tank and $C_{out\text{-}r}$ is the outlet concentration.

This means that the effective concentration for the reaction tank will not be constant, but a variable that will be determined by the ozone decomposition reaction; and hence the Ct-value may be determined as the area under the concentration against time curve.

3.7.2. Determination of initial ozone consumption and ozone degradation constant

Three alternative ways for the determination of ozone transfer constant ($k_{transfer}$), initial ozone consumption (IC) and ozone degradation constant (k) are outlined below. The user is reminded of the fact that the hydraulic factor $F_h = t_m/T$ (see table 3.3 and 3.2) should be used when determining the effective reactor residence time (t_r and t_c) below, when determining k, C_i and C_{out}.

3.7.2.1 Alternative 1: Determination of k by measurement in an existing plant

In an existing plant, the dose (C_{dose}), and the concentration at the outlet of the ozone contact tank ($C_{out\text{-}c}$) or the ozone reaction tank ($C_{out\text{-}r}$), are normally known. It is recommended that the ozone concentration is measured at minimum two well defined locations in the reaction tank and that these data are used to determine the degradation constant (k). Typical sampling spots are inlet ($C_{in\text{-}r}$) and outlet ($C_{out\text{-}r}$) of the reaction tank, or between two segments of the reaction tank (if segmented).

The degradation constant (k) may then be determined by the use of the equation:

$-k = [\ln(C_{out\text{-}r}/C_{in\text{-}r})] / t_r$

$C_{in\text{-}r}$ is equal to $C_{out\text{-}c}$ and t_r is the reaction tank effective residence time ($_{teff\text{-}r}$)

3.7.2.2 Alternative 2: Determination of IC and k by the use of models

If the dose is known but no ozone concentration measurements are available, one may use models for the determination of IC and k. The following models where presented in Norwegian Water report 169/2009 (Ødegaard et al., 2009a) based on experiments on water samples with a variety of compositions:

$IC_{ozone} = 0.14 \cdot TOC + 0.58 \cdot C_{dose} + 0.09 \cdot (C_{dose}/TOC) + 0.07 \cdot pH - 0.92$

$k_{ozone} = 0.050 \cdot TOC - 0.032 \cdot C_i - 0.017 \cdot C_i/TOC + 0.084 \cdot pH - 0.48$

The ozone model for IC is valid when:

- C_{dose} = 0.25 – 6.0 mg O_3/l
- TOC = 0.5 – 6.0 mg/l
- Specific dose. C_{dose} / TOC < 2.5 mg O_3 / mg TOC
- Calculated IC ≤ C_{dose} (if IC > C_{dose}, IC should be set at C_{dose})
- Calculated IC > 0.05 mg O_3/l

The ozone model for k is valid when:

- Initial concentration, C_i = 0.25 – 6.0 mg O_3/l
- TOC = 0.5 – 6.0 mg/l
- pH = 6.0 – 8.0
- Calculated IC < C_{dose}
- Calculated k > 0.005

The models may be used if data from laboratory testing of the water is not available. When neither the ozone dose (C_{dose}) nor the outlet concentration (C_{out}) are known, as in planning or design, one have to use calculated values (based on the models given above) for initial ozone consumption (IC) and ozone degradation constant (k) as well the estimated values for $k_{transfer}$ (from table 3.5)

Since the values of IC and k are dependent upon ozone dose, a dose must be assumed for the determination of IC and k. If this assumed dose turns out to be significantly different that the dose calculated later, a new dose, closer to the calculated one should be assumed and the procedure repeated until assumed dose is in agreement with calculated dose.

The alternative to determining IC and k through the use of the model calculations is to determine the values through laboratory experiments. A test procedure for such experiments is presented in Norwegian Water report 169/2009 (Ødegaard et al., 2009a).

3.7.3. Determination of initial ozone concentration

To be able to calculate the Ct-value (see 3.7.4) or to evaluate the accuracy of calculated k or IC, the initial concentration (C_i) should be known, and equal to the inlet concentration of the contact tank ($C_{in\text{-}c}$) from which the outlet concentration of the contact tank ($C_{out\text{-}c}$) and hence inlet concentration to the reaction tank ($C_{in\text{-}r}$) may be determined (see 3.7.1).

C_i may be calculated both based on the applied dose (C_{dose}) and from a measured inlet concentration to the ozone reaction tank. If possible both methods for the determination of C_i may be used to evaluate the accuracy of the values used for $k_{transfer}$ and calculated for IC.

Calculation of C_i based on the dose (C_{dose}) can be done by first determining $k_{transfer}$ from table 3.5 and IC from the model above (alt. 1):

Alt. 1: $C_i = (C_{dose} \cdot k_{transfer}) - IC$

or, alternatively (alt 2), based on contact tank outlet concentration (C_{out-c}):

Alt. 2: $C_i = C_{out-c} / e^{-k \cdot tc}$

It is to be expected that alt. 2 results in a higher value than alt. 1 because of the assumption in the calculation of C_i in alt. 2 that will overestimate C_i (see 3.7.1). If this is not the case, one should analyze the accuracy of the calculations closer.

3.7.4. Calculation of Ct in ozone systems

The Ct-calculation shall be carried out for the contact tank and reaction tank separately and then summarized. The user is reminded of the fact that the hydraulic factor $F_h = t_{10}/T$ (see table 3.2) should be used in the determination of effective reactor residence time (t_{eff-r} and t_{eff-c}) when calculating Ct.

Contact tank:
$(Ct)_c = C_{eff-c} \cdot t_{eff-c}$

Reaction tank:
$(Ct)_r = (C_{in-r} / k)(1 - e^{-k \cdot teff-r})$ (if based on C_{in-r})

or

$(Ct)_r = (C_{out-r} / k)(e^{k \cdot teff-r} - 1)$ (if based on C_{out-r})

where t_{eff-c} and t_{eff-r} are the effective residence times in the contact tank and reaction tank respectively.

The total Ct-value for the ozone system is then:

$(Ct)_{total} = (Ct)_c + (Ct)_r$

where t_c and t_r are the effective residence times (t_{eff-c} and t_{eff-r}) in the contact tank and reaction tank respectively.

3.7.5. Practical use of the tool-box – ozone

The equations that are presented above may now be used for different applications (see attachment 2) such as:

- Calculation of necessary ozone dose in the design of ozone systems (att. V2.2)
- Calculation and use of Ct in during operations and for planning/design (att. V2.3)
  - Calculation of Ct for documentation of barrier effect in an operation situation (att. V.2.3.1)
  - Calculation of Ct in connection with design of ozone systems (att. V2.3.2)
  - Design of the necessary capacity of ozone dosing equipment (att. V2.3.3)

Detailed roadmaps for each of these applications are shown in attachment 2. It also shows how the tool-box may be used when the contact- and/or reaction tank is segmented.

3.8. Determination of final log-reduction when using chemical disinfection methods

After calculation of Ct, that determines the calculated log-reductions, the maximum log-reduction applicable for chemical disinfection method have to be considered together with any safety shortcomings of the disinfection facility that would yield a lower level of log reductions.

Calculations of log-reduction for chemical disinfection facilities may result in very high log-reductions numbers at high dosages. In the MBA-Guideline a maximum log-credit level for various barrier actions is shown (see table 2.3). It is reasonable to apply such a maximum level also to the disinfection methods and hence:

Maximum log-reduction for chemical disinfection methods is set at: 4b + 4v + 3p

In table 3.7 safety measures that are normally used in chemical disinfection plants are listed. If one or several of these measures are not in place, a deduction shall be taken in Ct-calculated (or maximum) log-reduction.

The starting point is the Ct-calculated log-reduction. The deduction is to be taken after a possible correction of log-reduction for the maximum limitation. Thereafter the safety measures in the three main categories, A, B and C are assessed. Each of the main categories is given a maximum deduction in log-reduction (in %) (as compared to the Ct-calculated log-reduction, or possibly the maximum one that is applicable).

Then a log-credit is given in each of the main categories depending on the measure that is actually implemented. This reduction in deduction (i.e. the log-credit for measures implemented) can, of course, not exceed the values for maximum deduction within each main category, i.e. the minimal deduction in any category is 0 %.

The values in table 3.7 are recommendations, based on a certain degree of uncertainty and other values may be used if local conditions indicate this. If the situation is unknown, maximum deduction should be used. In chapter 5 examples are showing how table 3.7 is to be used.

Table 3.7 *Deduction (in %) of the Ct-calculated (or maximum) log-reduction because of safety breaches in chemical disinfection plants as well as credit (in % of log-reduction) for safety actions actually implemented.*

Main category	Risk-reducing security actions	Influence on logreduction[1)]
A) Action at temporary dosing failure	**Maximum deduction in category[2)]**	**- 10 %**
	1. Automatic shutdown of all water production[3)]	+ 10 %
	2. Alarm and automatic start of dosing equipment in reserve	+ 5 %
B) Action to reduce risk of dosing failure	**Maximum deduction in category[2)]**	**- 15 %**
	1. Back-up generator and/or UPS installed	+ 10 %
	2. Reserve dosing equipment installed	+ 5 %
	3. Equalization volume that may satisfy the water need when water production is stopped at dosing failures[4)]	+ 10 %
C) Other actions	**Maximum deduction in category[2)]**	**- 10 %**
	1. Satisfactory monitoring system installed (Residual chlorine/ozone)	+ 5 %
	2. Storage of critical reserve equipment[5)]	+ 5 %
	3. Satisfactory routines for cleaning, control and calibration of sensors for monitoring of residual chlorine or – ozone[6)]	+ 5 %
Measures summarized	**Total maximum deduction for security breaches in chemical oxidation facilities[2)]**	**- 35 %**

1) Credit for actions within each main category cannot exceed maximum deduction for that category
2) Minimum deduction in each category is 0 %
3) Requires sufficient equalization capacity/buffer volume in the system
4) Clean water tank, equalization tank or similar with a volume for at least 12 hours supply
5) Dosing- and circulation pumps, ozone generator parts, electrodes for monitoring equipment etc.
6) Minimum monthly controls/calibrations

3.9. UV disinfection

General information about UV-disinfection may be found in text-books or in Ødegaard et al.(2006, 2009b) or Eikebrokk et al.(2008). Since design and operation of UV facilities are quite different from those of chemical disinfection, UV disinfection has to be analyzed differently than the chemical disinfection methods.

3.9.1. UV-doses and inactivation

In principal the same concepts for concentration, contact time and Ct-value are also valid for UV-disinfection, except that the concentration is given as UV-intensity (I), contact time as irradiation time and Ct-value as UV-dose, the product of intensity and irradiation time.

The following concepts are used:

- Intensity, I (normally given as mW/cm^2)
  - Equivalent to concentration in chemical disinfection
- Irradiation time, t (normally given in seconds)
  - Equivalent to effective contact time in chemical disinfection and dependent on hydraulic conditions (residence
  - time distribution), but is for ideal (turbulent) plug flow equal to the volume of irradiation chamber divided by flow (V/Q)
- UV-dose, D (normally given as mWs/cm^2 or mJ/cm^2)
  - Equivalent to the Ct-value in chemical disinfection
  - $D = I \cdot t$
  - $1\ mWs/cm^2 = 1\ mJ/cm^2 = 10\ J/m^2$

Different microorganisms have different resistances to inactivation by UV irradiation. UV-disinfection is generally efficient for inactivation of all the main groups of microorganisms (bacteria, viruses and parasites) and compared to the chemical disinfection methods, it is especially efficient with regard to parasites. In the Nordic countries a UV-dose of 25 – 40 mJ/cm^2 is normally used.

It is normally referred to the "biodosimetric dose". It is the dose that is determined by comparing the log reduction achieved on a test organism in the type of UV reactor in question with a dose-response curve determined in the laboratory with the same organism. This dose value refers to a biodosimeter test validated by the Austrian (ÖNORM), German (DVGW) or American (USEPA) standards.

It is common that the authorities require a UV-dose of $\geq 30\ mJ/cm^2$ to safely inactivate bacteria, virus and parasites and $> 40\ mJ/cm^2$ to inactivate bacteria spores as well. Normally UV facilities are designed, therefore, for a biodosimetric dose of 40 mJ/cm^2, but lower or higher doses are also used. Some of the existing plants in Norway were approved by the authorities at an *average dose* of 30 mJ/cm^2. This was before the biodosimeter test was introduced as a requirement. The average dose was determined by calculation of intensity and theoretical residence time at different locations in the UV-reactor and integration of the product of the two to create an average dose.

UV disinfection is, relatively speaking, less efficient for inactivation of virus, and especially not very efficient for inactivation of *Adenovirus*. Table 3.8 (USEPA, 2006) shows the lowest dose that USEPA indicates for the inactivation of *Cryptosporidium*, *Giardia* and virus. It demonstrates that the dose requirement for virus is set very high in USA (143 mJ/cm^2 for 3 log reduction). This is due to the high resistance of Adenovirus.

Table 3.8. *Minimum UV-dose (mJ/cm²) for inactivation of Cryptosporidium, Giardia and virus according to USA rules (USEPA 2006).*

Log-inactivation	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	12	15	22
Giardia	1.5	2.1	3.0	5.2	7.7	11	15	22
Virus	39	58	79	100	121	143	163	186

The Norwegian Public Health Institute is of the opinion that the risk of being infected by Adenovirus through drinking water is not high enough to defend the economic and practical consequences of designing UV-facilities for a UV-dose high enough to inactivate Adenovirus. The institute is of the opinion that Norwegian children are exposed for such virus during their first years resulting in an uncomplicated course of sickness that gives good immunity.

The attitude regarding Adenovirus may be different in other countries and therefore the MBA-guideline will adapt the maximum log-reductions to whether or not Adenovirus shall constitute the basis for virus inactivation.

3.9.2. Determination of log-reduction in UV-disinfection

Provided that the UV facility is installed and operated in accordance with the requirements and specifications that are given by the approving authority and that the facility is approved by this authority, the maximum log-reductions for UV-disinfection at various UV-doses that shall be used in this guideline are shown in table 3.9.

Table 3.9 *Maximum log-reduction for approved UV plants at varying UV-dose*[1),2)]

Biodosimetric dose	Virus excl. Adenovirus	Virus based on Adenovirus
40 mJ/cm²	4.0b + 3.5v + 4.0p	4.0b + 1.25v + 4.0p
30 mJ/cm²	3.5b + 3.0v + 3.5p	3.5b + 1.0v + 3.5p
25 mJ/cm²	3.0b + 2.5v + 3.0p	3.0b + 0.75v + 3.0p

1) Provided that the UV-doses are biodosimetrically determined
2) When analyzing existing systems that have been approved with an average dose of 30 mJ/cm², the maximum log-reduction is 3,0b + 2,5v + 3,0p (3b + 0,75v + 3p when virus requirement is based on Adenovirus).

In the determination of the log-reduction for UV-disinfection in a given case, one takes the maximum log-reduction – as given in table 3.9 – as the starting point. Then the log-reductions are corrected (see table 3.10), where operational defects of the following main categories (A, B, C and D) are listed:

A Temporary lapse of – or reduced effect of the UV-plant (for instance because of power lapse)
B Reduction of risk for temporary lapse of – or reduced effect of the UV-plant
C Other design based issues
D Other operation based issues

If any of the measures mentioned in each of the main categories are missing, a deduction (see table 3.10) from the maximum log-reduction that is given in table 3.9 shall be made. The deduction is given in percent of the maximum log-reduction. For measures of category A, for instance, a maximum of 10% log reduction shall be made; that is: 0.4b+0.35v+0.4p for plants designed for a dose of 40 mJ/cm².

Table 3.10. *Deduction in log-credit for UV-disinfection (in % of maximum log-reduction) because of safety breaches for various main categories of barrier actions, as well as credit (in % of maximum log-reduction) for measures actually implemented in each category.*

Category of actions	Security actions for improving robustness of the UV-disinfection	Influence (%) on max. log-reduction (from table 3.9)[1]
A) Actions for temporary failure or reduced effect of UV-irradiation	**Maximum deduction in category A[2]**	**-10 %**
	1. Automatic shutting down of all water production (requires sufficient equalizing volume in the system)	+10 %
	2. Alarm and automatic start-up of reserve disinfection - for instance chlorination facility	+5 %
B) Actions to reduce the risk of temporary failure or reduced effect of UV-irradiation	**Maximum deduction in category B[2]**	**-20 %**
	1. UPS installed	+10 %
	2. Back-up generator installed	+10%
	3. Documentation of good and reliable power supply	+5 %
C) Other design related actions	**Maximum deduction in category C[2]**	**-30 %**
	1. Several UV-reactors designed and installed in such a way that full supply may be maintained at lapse of one[3]	+5 %
	2. Separate flow measurement for each UV-reactor to secure good hydraulic control	+10 %
	3. Control sensors (UV intensity, UV-transmission etc.) correctly located	+5 %
	4. Equalization volume located after UV-plant[4]	+10 %
	5. Reserve disinfection plant installed for instance chlorination facility	+5 %
D) Other operation related actions	**Maximum deduction in category D[2]**	**-30 %**
	1. A storage of critical reserve equipment[5]	+5 %
	2. Automatic shutting down of all water production in connection with start-up[6]	+10 %
	3. Good dose control[7]	+10 %
	4. Automatic shutting down of all water production if operation is outside validation range	+10 %
	5. Alarm if the operation is outside validation range	+5 %
	6. Satisfactory routines for cleaning, control and calibration of sensors[8]	+5 %
	7. Documentation of operation in terms of duration curves[9]	+5 %

1) The sum of log-credit within each category of measures cannot surpass maximum deduction because of the absence of measures that might be implemented to improve the robustness of the UV-disinfection facility
2) The minimum deduction in each category is 0 %
3) For instance 2 reactors á 100% at max flow, 3 reactors á 50% at max flow, etc.
4) Clearwater well, elevated reservoir or similar, with a volume for 12 hours supply - at least
5) Quartz-pipes, lamps, o-rings, wipers, wiper driving gear, ballasts, ballast fan, UV sensors, reference sensors and possibly UV-transmission sensors
6) Shutting down until full capacity is restored, see table V1.2.2 in attachment 1
7) Empirical equation for dose calculation based on UV intensity, flow, possibly UV transmission and number of lamps in operation
8) Monthly control and a minimum of yearly calibration of reference sensors
9) Duration curves: Curves that display calculated dose as a function of time (see Norwegian Water Report 164/2008). Such curves are very helpful in the evaluation of the probability of defects in the barrier function

Thereafter the credit would be given in each of the main categories depending on the barrier action that is actually being implemented. The deduction in log-reduction may not surpass the maximum deduction in each main category. The values for maximum deduction in each main category, as well as reduced deduction because of measures actually implemented, are given in table 3.10 – both in percent of maximum log-credit.

Chapter 5 contains examples on how the log-reduction for an actual plant can be determined based on this procedure.

To achieve independence of barriers, the performance of UV disinfection must be taken into account since the possibility that failure of a preceding treatment step could influence the UV-transmission. The log reduction in such a case will be dependent on raw water transmission as well as the designed UV-transmission.

Therefore, a percentage reduction of log-credit (possibly after deductions according to table 3.10) shall be taken as shown in figure 3.6

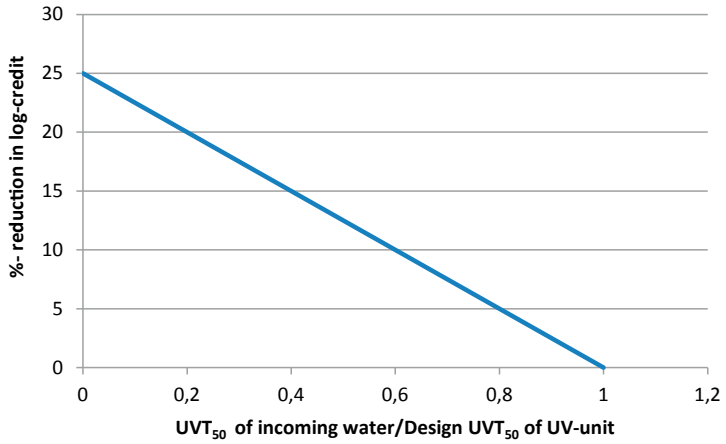


Figure 3.6 *Reduction (in %) of calculated log-credit for UV-disinfection (after possible deductions according to table 3.10) because of low UV-transmission in incoming water to UV plant and UV-transmission design*

When using figure 3.6:

- Incoming water is the water that is entering the UV-plant in a situation where the preceding treatment (that improves UVT) is failing for any reason. The incoming water will be equal to the raw water if there is only one UVT-improving step ahead of the UV-plant (which is often the case). If there is more than one UVT-improving steps ahead of the UV-plant, UVT_{50} in incoming water should be set at that value one will have if the most UVT-improving step fails.
- $UVT_{50mm\ raw\ water}$ shall not be set higher than the 10 percentile value for registered UVT50mm in raw water over the year – i.e. not more than 10 % of the registrations may have lower value
- Design UVT_{50mm} is at maximum water production

This reduction in log-credit may be avoided in cases a system is operated in such a way that the flow that is admitted to the UV-aggregate, is reduced so much that the increased dose results in a maintained log-reduction in those periods where the UVT-improving step is out of function.

If the water production is shut down automatically when the UV plant fails to be according to the certification, there should be no reduction in log credit.

4. Determination of the overall barrier status for the system

When the calculated log-reduction for an existing system has been determined, the barrier status for the overall water supply system may be determined, as demonstrated in figure 4.1.

Barrier level required	$x_1\mathbf{b} + y_1\mathbf{v} + z_1\mathbf{p}$
Catchment area and water source barriers	$x_2\mathbf{b} + y_2\mathbf{v} + z_2\mathbf{p}$
Particle removal barriers	$x_3\mathbf{b} + y_3\mathbf{v} + z_3\mathbf{p}$
Disinfection barriers	$x_4\mathbf{b} + y_4\mathbf{v} + z_4\mathbf{p}$
Overall barrier status	$[X_1 - (x_2 + x_3 + x_4)]\mathbf{b} + [y_1 - (y_2 + y_3 + y_4)]\mathbf{v} + [z_1 - (z_2 + z_3 + z_4)]\mathbf{p}$

Figure 4.1 *Determination of the overall barrier status for the water supply system*

If the final result shows *negative* log-values for all parameters (bacteria, viruses and parasites), the barrier status is satisfactory.

If one or more log-reduction values are positive, the barrier actions (in the catchment area and/or water source, or in the water treatment through improved particle separation and/or disinfection) must be strengthened sufficiently to make the overall result satisfactory (i.e. to give negative log-values in the final result).

When new barrier actions are implemented, the procedure has to be carried out again to verify the effect of the new barrier actions.

It is a goal that barriers in a water supply system are independent of each other, i.e. that the functioning of one barrier is not dependent of another one. It strengthens the overall barrier status when the system has barriers of different categories implemented, for instance barriers in the catchment area/water source as well as particle separation barriers and disinfection barriers. If there is more than one barrier acting within the same category, they should not be of the same kind, for instance two steps of chlorination. Two barrier measures of the same category, for instance two disinfection barriers like chlorination and UV-disinfection, may, however, be valuable because one method may be more efficient for inactivation of one group of microorganism than another one.

The Norwegian authorities have followed a regulation that requires at least two independent hygienic barriers in the system, by requiring at least one barrier in the catchment area/water source and water treatment, and the other one in a disinfection step. To achieve independent barriers the authorities recommend that the sum of log-reductions of the individual barrier actions in each of main categories which are:

- actions in catchment area/water source and water treatment (other than final disinfection)
- disinfection actions through chemical disinfection, UV-disinfection and good particle separation (e.g. membrane filtration)

should not be lower than **3b + 3v + 2p** to be considered as a complete hygienic barrier.

5. Examples on the use of the MBA guideline

This chapter discusses two examples. A theoretical system will be examined to demonstrate the use of the procedure and tool-box of the MBA-Guideline. The example will be a medium-sized utility with a lake as water source, where the existing water treatment is very limited, and barrier improvement is needed. This is a typical scenario in the Scandinavian countries. This chapter describes various development steps and alternative ways of preparing an acceptable barrier plan. The other example is a small water utility based on groundwater wells.

The examples are intended to cover a variety of situations, but of course not all. When a special procedure is analyzed, it is high-lighted by the use of headings or notification in the margin – so that it should be easy to go directly to the procedure of interest.

5.1. Waterlake water utility

Watertown municipality owns two systems. The largest one, Waterlake system, supplies water to 20600 persons from Waterlake that is a typical, deep Scandinavian lake containing soft and humic water.

The other system, for the village of Smalltown, supplies water to 5000 persons from two groundwater wells.

5.1.1. Barrier actions in catchment area and water source

In the catchment area there are several cattle farms, residences, cottages and roads. There have been restrictions on activities in the catchment in the past and some new restrictions are now to be implemented. There is already a ban on centralized sewage discharges, but there are a number of on-site discharges from scattered dwellings and cottages.

5.1.2. Raw water quality

Weekly samples have taken of the raw water and analyzed for indicator organisms, among them also *E. coli* and *Clostridium perfringens*. The survey of raw water quality has given the results shown in table 5.1.

Table 5.1 *Raw water data, Waterlake water utility, Watertown*

Year	Indicator organism	Number of samples	Number of positive samples	% positive	Average value number/100 ml	Highest value found number/100ml
2010	*E. coli* *Clostridium perfringens*	51 51	8 11	15.7 21.6	0.18 0.24	3 2
2011	*E. coli* *Clostridium perfringens*	52 6	13 2	25.0 33.3	1.10 0.67	14 3
2012	*E. coli* *Clostridium perfringens*	52 9	3 3	5.8 33.3	0.06 0.33	1 1
2013	*E. coli* *Clostridium perfringens*	45 10	2 2	4.4 20	0.04 0.2	1 1

5.1.3. Water treatment

The existing water utility has a very simple treatment process, consisting of:

1. Fine sieves (0.1 mm aperture/pore size)
2. Calcium-carbonate filters. Primarily for corrosion control with a filtration rate at maximum water production of 7.5 m/h
3. Chlorination for disinfection. By the addition of NaOCl
4. Clean water tank (clear well) that is also serving as chlorine contact tank is divided into two chambers with a total residence time of 30 min at maximum water production. Each of the chambers is rectangular and has baffles in the inlet and outlet but no baffles in each chamber.
5. The chlorine dosage is controlled to achieve the residual chlorine concentration at the outlet of the clean water tank of 0.05 mg Cl_2/l. At normal raw water quality the chlorine dosage is typically 0.5 – 0.7 mg Cl_2/l.

5.2. Description of planned barrier actions in Waterlake water utility

Watertown city is aware of the fact that the hygienic barrier situation of the water utility is unsatisfactory and has decided to make appropriate improvements. This work is to be based on the MBA-Guideline. Some barrier actions have already been implemented and a number of new ones are being planned.

5.2.1. New barrier actions in water catchment area and –source.

The following barrier actions, beyond those in operation already, will be put in place:

1. All on-site sewage discharges are terminated through the introduction of closed sewage tanks for all scattered dwellings and cottages.
2. A local regulation is implemented including a ban on recreational activities in the water source, such as boating, bathing and other recreational activity.
3. The raw water intake is moved to a location where tracer studies have shown to reduce the risk for short-circuiting of water from a brook in the catchment area (where cattle are allowed to feed) to the intake.

5.2.2. Implementation of a risk-based sampling program on raw water

An extended, risk-based sampling program on microbial raw water quality was carried out in 2013 with 24 samples over the year taken according to the recommendations in the MBA guideline (table 2.1). The results of these samplings and analyses are shown in table 5.2.

Table 5.2 *Results of the analyses from the risk-based sampling program in 2013*

Sample No	**E. coli** (no./100 ml)	**C.perfringens** (no./100 ml)	**Giardia** (no./100 ml)	**Cryptosporidum** (no./100 ml)	**Sum parasites** (no./100 ml)
1	2	0	0	0	0
2	4	0	0	0	0
3	3	0	0	0	0
4	5	2	0	0	0
5	29	8	0.05	0.02	0.07
6	27	7	0.02	0	0.02
7	3	1	0	0	0
8	4	1	0	0	0
9	3	0	0	0	0
10	0	0	0	0	0
11	15	6	0.01	0	0.01
12	11	2	0	0	0
13	2	1	0	0	0
14	0	0	0	0	0
15	4	0	0	0	0
16	19	7	0.08	0.03	0.11
17	16	11	0.04	0	0.04
18	4	0	0	0	0
19	5	1	0	0	0
20	0	0	0	0	0
21	1	0	0	0	0
22	19	12	0	0	0
23	25	8	0	0	0
24	21	6	0.04	0.01	0.05
Mean	9.25	3.04	0.0100	0.0025	0.0125
% > 10 EC	37.5				
% > 3 CP		33.3			
% > 0.01 P			20.8	16.7	25

5.2.3. Planned new water treatment actions

To create a good parasite barrier, it is decided to establish a new UV-disinfection facility. The chlorination facility may be maintained.

Since the color of the raw water has been increasing over the years and is approaching the standard in the Drinking Water Regulation (20 mg Pt/l), planning for improving the water treatment has started in which two different alternatives are considered:
Alt. 1: The calcium-carbonate filters are retrofitted to become three-media filters by addition of sand and anthracite on the top of the existing (but capped), calcium-carbonate filter and pre-coagulation are added.
Alt. 2: Ozone is added prior to the existing calcium-carbonate filters that will serve as a biofilter (and possibly still maintaining a certain corrosion control effect).

The MBA-Guideline is to be used to analyze which of the two alternatives is be preferred when the barrier effect is considered.

5.3. Evaluation of the barrier status in the existing Waterlake water utility

5.3.1. Determination of water quality level

Figure 2.2 is used to determine the water quality level.

The standard microbial water quality monitoring over the years (see table 5.1) shows:
1. > 0 EC and > 0 CP
2. > 10 EC and > 3 CP

According to figure 2.2 in the MBA-Guideline an extended survey through a risk-based sampling program was carried out in 2013. The results of this program are (see table 5.2):
1. 9.25 i.e. < 10 EC (E-coli/100 ml) is the mean concentration over the sampling period but > 10 EC in 37.5 % - i.e. more than 1/6 (16.7 %) of the samples
2. 0.0125 i.e. > 0.01 P (parasites/100 ml) is the mean concentration over the sampling period and > 0.01 P in 25 %, i.e. more than 1/6 (16.7 %) of the samples

By the use of figure 2.2 the water quality level can be determined to be **Da**.

5.3.2. Determination of barrier level required

With 20.600 persons connected to the water utility and source water quality level Da, the barrier level required, according to table 2.2 in the MBA-Guideline is: 6.0b + 6.0v + 4.0p.

5.3.3. Determination of log-credits in catchment area, water source and water treatment (other than disinfection)

There are no new actions when we are evaluating the existing plant.

For the planned up-grading of the new barrier actions in catchment area and water source, as well as calcium-carbonate filter, the following log-credits may be given:

Barrier action	**Log-credits**
Termination of on-site sewage discharges from scattered dwellings and cottages by introduction of closed tanks	0.75b + 0.75v + 0.50p
Introduction of local regulation on restrictions in public activity in the water source	0.25b + 0.25v + 0.15p
Changing location of the raw water intake	0.25b + 0.25v + 0.15p
Summarized log-credits in catchment area and water source	1.25b + 1.25v + 0.80p
Filtration through calcium-carbonate filter:	0.50b + 0.25v + 0.50p
Summarized log-credit for barrier actions ahead of disinfection:	**1.75b + 1.50v + 1.3p**

5.3.4. Determination of log-reduction for disinfection by chlorination

The log-reduction for the chlorination step may be calculated after the Ct of the chlorination facility is determined. For this the "tool-box" (see chapter 3, especially section 3.4) will be used. Security breaches in the chlorination facility have to be taken into account (see table 3.7) to determine the final log-reduction that can be credited to the final disinfection step in the existing plant.

5.3.4.1. Data basis

Since Waterlake is a medium-sized lake, the temperature is set at 4°C. pH is set at 8, since pH after the calcium-carbonate filter is 8,1. TOC in the raw water is on average 3.5 mg TOC/l and 3.0 mg/l after the calcium-carbonate filters.

According to table 3.1 in the MBA-Guideline, the design Ct-values at pH = 8.1 is:

- 2.0 mg min/l for 3 log reduction of bacteria
- 8.0 mg min/l for 3 log reduction of virus
- The log-reduction of parasites is so low that it is not included in table 3.1

5.3.4.2. Determination of the effective residence time (t_{eff}) in the chlorine contact tank

The clean water tank has a theoretical residence time (tank volume, V/flow, Q) of 30 min and is divided in two, rectangular shaped chambers with baffles in the inlet and outlet and some baffle walls in the chambers. According to table 3.2:

- Hydraulic factor, F_h (t_{10}/T): 0.5
- Serial factor, F_s: 1.5

For the Ct-calculation: $t_{eff} = (V/Q) \cdot F_h \cdot F_s = 30 \text{ min} \cdot 0.5 \cdot 1.5 = 22.5 \text{ min}$

5.3.4.3. Determination of initial consumption (IC) and degradation constant (k)

The TOC-content of the filtered water is 3 mg TOC/l (mean value) and the chlorine dose is normally 0.5 – 0.7 mg Cl_2/l. We shall use 0.6 mg Cl_2/l as the basis for determination of initial consumption (see section 3.4.2.2):

- Initial consumption. $IC = 0.06 \cdot TOC + 0.36 \cdot Dose + 0.08 \cdot C_{dose}/TOC - 0.12 =$
  $0.06 \cdot 3.0 + 0.36 \cdot 0.6 + 0.08 \cdot 0.6/3.0 - 0.12 = 0.29$ mg Cl_2/l
  - i.e.: $C_i = C_{dose} - IC = 0.6 - 0.29 = 0.31$ mg Cl_2/l
- Degradation constant. $k = 0.013 \cdot TOC - 0.040 \cdot C_i - 0.010 \cdot Ci/TOC + 0.029 =$
  $0.013 \cdot 3.0 - 0.040 \cdot 0.31 - 0.010 \cdot 0.31/3.0 + 0.029 = 0.055$

Since we in this case know the dose and can calculate C_i and since we know the residual chlorine concentration (0.05 mg Cl2/l), we may determine k with more certainty by using the formula:

- $k = - \ln (C_u/C_i)/t_{eff}$

When determining k (as well as IC) the t to use (t_{eff}) shall be based on the hydraulic factor t_m/T (see table 3.2) which, however, is the same as t_{10}/T (0.5) in this case, and hence t_{eff} for this calculation is the same as above (22.5 min):

- $k = - 1/22.5 \cdot \ln (0.05/0.31) = - 1/22.5 \cdot (-) 1.82 = 0.081$

Since this is considered to be a more accurate determination of k, compared to the theoretically based calculations from TOC above, we shall use this value in the determination of Ct.

5.3.4.4. The Ct-calculation

The Ct-calculation (see section 3.4.3) is based on $t = t_{eff} = 22,5$ min and a residual chlorine concentration of $C_{out} = 0.05$ mg Cl_2/l. The Ct-calculation may either be based on the outlet concentration or the initial concentration, C_i

a. Ct-calculation based on outlet concentration (C_{out}) and degradation constant (k)
(section 3.4.3):

- $Ct = (C_{out}/k)(e^{k \cdot t - 1}) = (0.05/0.081)(e^{0.081 \cdot 22.5 - 1}) = 3.8$ mg·min/l

Control:
b. Ct-calculation based on initial concentration (section 3.4.3):

- $Ct = (C_i/k)\,(1 - e^{-kt}) = (0.31/0.081)(1 - e^{-0.081*22.5}) = 3.2$ mg·min/l

We choose, conservatively, the lowest value, i.e. Ct = 3.2 mg·min/l

5.3.4.5. Determination of log-reduction

To calculate log-reduction, we use the following equation (see section 3.2.2):

$$n_{calculated} = n_{required} \cdot Ct_{calculated}/Ct_{required}$$

- Expected log-reduction of bacteria : $n_{calc.,\,bact.} = 3 \cdot 3.2/2 = 4.8$
- Expected log-reduction of virus : $n_{calc.,virus} = 3 \cdot 3.2/8 = 1.2$
- Expected log-reduction of parasites : ~ 0

There are a few security breaches of the chlorine dosage equipment and deductions in the log-reduction have to be considered. With respect to the safety actions in the chlorine disinfection equipment, the situation is as follows (with reference to table 3.7):

Category A	Category B	Category C
A1 – not in place A2 – in place	B1 – in place B2 – not in place B3 – in place	C1 – in place C2 – in place C3 – in place

The reduction is to be based on calculated or possibly maximum (if calculated is higher than maximum) log-reduction. The maximum log-reduction for chemical disinfection is: 4.0+4.0v+3.0p and hence the reduction calculations will be based on 4.0b+1.2v+0.0p.

Basis for calculated log-reduction		**= 4.0b + 1.2v + 0.0p**
Lack of A actions (max.)	**- 0.10 · [4.0b + 1.2v + 0.0p]**	
A1 actions: not in place		
A2 actions: in place	+ 0.05 · [4.0b + 1.20v + 0.0p]	
Sum A actions	- 0.05 · [4.0b + 1.2v + 0.0]	= - [0.20b + 0.05v + 0.0p]
Lack of B actions (max.)	**- 0.15 · [4.0b + 1.2v + 0.0p]**	
B1 actions: in place	+ 0.10 · [4.0b + 1.2v + 0.0p]	
B2 actions: not in place		
B3 actions: in place	+ 0.10 · [4.0b + 1.2v + 0.0p]	
Sum B actions	+ 0.20 · [4.0b + 1.2v + 0.0p]	= - [0.0b + 0.0v + 0.0p][1)]
Lack of C actions (max.)	**- 0.10 · [4.0b + 1.2v + 0.0p]**	
C1 actions: in place	+ 0.05 · [4.0b + 1.2v + 0.0]	
C2 actions: in place	+ 0.05 · [4.0b + 1.2v + 0.0]	
C3 actions: in place	+ 0.05 · [4.0b + 1.2v + 0.0]	
Sum C actions	+ 0.15 · [4.0b + 1.2v + 0.0p]	= - [0.0b + 0.0v + 0.0p][1)]
Final log-reduction for existing chlorination plant		= **3.8b + 1.15v + 0.0p**

1) The sum of credits for barrier actions implemented within one main category, cannot surpass the maximum log-reduction deduction of that category

5.3.5. Assessment of the barrier status of the existing water utility as well as the one planned for

The MBA procedure leads to the following with respect to the existing water utility:

Barrier level required:	+[6.00b + 6.00v + 4.00p]
- Log-credits for actions in catchment and source	- [0.00b + 0.00v + 0.00p][1)]
- Log-credits for water treatment actions	- [0.50b + 0.25v + 0.50p]
- Log-credits for disinfection actions (chlorination)	- [3.80b + 1.15v + 0.00p]
= Final result	**+ 1.70b + 4.60v + 3.50p**

If the new barrier actions in the catchment and source are implemented, the following barrier situation will prevail:

Barrier level required:	+[6.00b + 6.00v + 4.00p]
- Log-credits for actions in catchment and source	- [1.25b + 1.25v + 0.80p]
- Log-credits for water treatment actions	- [0.50b + 0.25v + 0.50p]
- Log-credits for disinfection actions (chlorination)	- [3.80b + 1.15v + 0.00p]
= Final result	**+ 0.45b + 3.35v + 2.70p**

1) Log-credits for actions in catchment and source can only be given for new actions as compared to the approach used when the water quality level was determined.

It is evident therefore that:

1. The existing water utility does not have sufficient hygienic barriers
2. Even if we introduce new restrictions on the public use of the water source, the system will not have sufficient barriers

One further action would be to improve disinfection by introducing UV disinfection in addition to the new restrictions for public use of the source for recreation. We may then calculate what the necessary log-reduction in the disinfection should be:

Barrier level required:	+[6.00b + 6.00v + 4.00p]
- Log-credits for actions in catchment and source	- [1.25b + 1.25v + 0.80p]
- Log-credits for water treatment actions	- [0.50b + 0.25v + 0.50p]
= Barrier level required in disinfection	**+ 4.25b + 4.50v + 2.70p**

The maximum log-reduction that can be given to UV-disinfection (provided a dose of 40 mJ/cm^2 – biodosimetrically determined), is 4.0b + 3.5v + 4.0p (see table 3.9). This means that it is not sufficient with UV-disinfection alone, but that the chlorination needs to be maintained, which would give the following barrier status for the whole system (if there were no safety breaches in the new UV-disinfection plant):

Barrier level required:	+[6.00b + 6.00v + 4.00p]
- Log-credits for actions in catchment and source	- [1.25b + 1.25v + 0.80p]
- Log-credits for water treatment actions	- [0.50b + 0.25v + 0.50p]
- Log-credits for UV-disinfection (maximum)	- [4.00b + 3.50v + 4.00p]
- Log-credits for chlorination	- [3.80b + 1.15v + 0.00p]
= Final result	**- 3.75b – 0.15v – 1.30p**

It is demonstrated, therefore, that if a new UV-disinfection plant is introduced with a dose of 40 MJ/cm^2 and with all possible monitoring and safety equipment installed (no deductions in log-reduction), the plant will have sufficient series of barriers. However, it is barely sufficient with respect to viruses, due in part to the design pH which is set at 8,1.

The cost of the UV-disinfection plant depends on how much safety and monitoring equipment that is included. A UV-facility has been proposed and the following is an analysis of the log-reductions that may be expected from the UV-facility.

5.4. Calculation of log-reductions to be expected from the UV- disinfection facility proposed for Waterlake water utility

The calculation of log-reductions for UV-disinfection is described in section 3.9.2.

The LP UV-plant is offered for a dose of 40 mJ/cm2 validated biodosimetrically according to ÖNORM with the following equipment and operation characteristics (see table 3.10):

Category A	Category B	Category C	Category D
A1 – in place A2 – not in place	B1 – not in place B2 – in place B3 – not in place	C1 – in place C2 – in place C3 – in place C4 – in place C5 – in place C6 – not in place	D1 – in place D2 – not in place D3 – in place D4 – not in place D5 – in place D6 – in place D7 – not in place

The calculated log-reduction for the UV-plant offered will then be as follows:

Maximum log-reduction		+[4.0b + 3.5v + 4.0p]
Lack of A actions (max.)	- 0.10 · [4.0b + 3.5v + 4.0p]	
A1 actions: in place	+ 0.10 · [4.0b + 3.5v + 4.0p]	
A2 actions: not in place		
Sum A actions	0.00 · [4.0b + 3.5v + 4.0p]:	- [0.0b + 0.0v + 0.0p]
Lack of B actions (max.)	- 0.20 · [4.0b + 3.5v + 4.0p]	
B1 actions: not in place		
B2 actions: in place	+ 0.10 · [4.0b + 3.5v + 4.0p]	
B3 actions: not in place		
Sum B actions	- 0.10 · [4.0b + 3.5v + 4.0p]:	-[0.4b + 0.35v + 0.4p]
Lack of C actions (max.)	- 0.30 · [4.0b + 3.5v + 4.0p]	
C1 actions: in place	+ 0.05 · [4.0b + 3.5v + 4.0p]	
C2 actions: in place	+ 0.10 · [4.0b + 3.5v + 4.0p]	
C3 actions: in place	+ 0.05 · [4.0b + 3.5v + 4.0p]	
C4 actions: in place	+ 0.10 · [4.0b + 3.5v + 4.0p]	
C5 actions: in place		
C6 actions: not in place	+ 0.05 · [4.0b + 3.5v + 4.0p]	
Sum C actions	+ 0.05 · [4.0b + 3.5v + 4.0p]:	+[0.0b + 0.0v+0.0p][1)]
Lack of D actions (max.)	- 0.30 · [4.0b + 3.5v + 4.0p]	
D1 actions: in place	+ 0.05 · [4.0b + 3.5v + 4.0p]	
D2 actions: not in place		
D3 actions: in place	+ 0.10 · [4.0b + 3.5v + 4.0p]	
D4 actions: not in place		
D5 actions: in place	+ 0.05 · [4.0b + 3.5v + 4.0p]	
D6 actions: in place	+ 0.05 · [4.0b + 3.5v + 4.0p]	
D7 actions: not in place		
Sum D actions	- 0.05 · [4.0b + 3.5v + 4.0p]:	- [0.2b + 0.15v + 0.2p]
Calculated log-reduction for the UV-plant proposed :		**+ 3.4b + 3.0v + 3.4p**

1) The sum of credits for barrier actions implemented within one main category cannot surpass the maximum log-reduction deduction of that category.

To secure independency of the UV-barrier from the coagulation/filtration barrier, a deduction must be made because of low UVT in the raw water (see figure 3.6). The plant proposed has been designed for an UVT_{50} of 50 % at maximum water production, while 10 % of the UVT_{50} registered in the raw water is below 30 % This means that $UVT_{50, raw\ water}$ / $UVT_{50, design}$ = 0.3/0.5 = 0.6 and that the reduction of log-credit should be 20 %, hence:

Final log-reduction for the UV-plant: (1-0.2) · (3.4b + 3.0v + 3.4p) = **2.7b + 2.4v + 2.7p.**

If the UV-disinfection plant proposed is installed without upgrading the water treatment in any other way, the barrier situation will be:

Barrier level required:	+[6.00b + 6.00v + 4.00p]
- Log-credits for actions in catchment and source	- [1.25b + 1.25v + 0.80p]
- Log-credits for water treatment actions	- [0.50b + 0.25v + 0.50p]
- Log-credits for UV-disinfection	- [2.70b + 2.40v + 2.70p]
- Log-credits for chlorination	- [3.80b + 1.15v + 0.00p]
= Final result	**- 2.25b + 0.85v – 0.00p**

This means that the UV plant is not sufficient even though chlorination is maintained. The barrier against virus is too low. Even if there were no safety breaches in the UV-plant, the virus barrier would not be good enough. However, the city has decided to improve color removal as well and it is decided to upgrade the water treatment plant.

5.5. Analysis of the alternative upgraded water treatment methods for Waterlake water utility

Two alternative processes are to be evaluated with respect to barrier effect:

1. The calcium-carbonate filters are retrofitted into three-media filters by the addition of sand and anthracite on the top of the existing, but capped, calcium-carbonate filter and pre-coagulation is introduced. Disinfection will consist of the UV-disinfection plant and chlorination may be maintained if necessary
2. Ozonation prior to the existing calcium-carbonate filters that are to serve as a biofilters (still giving a certain amount of corrosion control). Disinfection will consist of the UV-disinfection plant and chlorination may be maintained if necessary

5.5.1. Retrofitting into a coagulation – three media direct filtration plant

According to table 2.8 a log-credit of 2.25b + 1.5v + 2.25p is available if a turbidity of 0.2 NTU in the treated water is maintained and 2.5b + 2.0v + 2.5p if sufficient coagulant is added to maintain turbidity in the treated water of 0.1 NTU – provided that there are no deductions because of lack of operation control monitory actions. It is also recommended in the latter case that the color removal must be > 70 % reduction.

Since the raw water color is relatively low (even though it is approaching the standard of 20 mg Pt/l) and therefore 70 % removal might be difficult to achieve, the use of 2.25b + 1.5v + 2.25p as the log-credit for the coagulation process is recommended. We assume that operation control monitory measures are good, so there will be no deductions.

First we analyzed the situation without including the existing final chlorination:

Barrier level required:	+[6.00b + 6.00v + 4.00p]
- Log-credits for actions in catchment and source	- [1.25b + 1.25v + 0.80p]
- Log-credits for water treatment actions	- [2.25b + 1.50v + 2.25p]
- Log-credits for the UV-disinfection plant offered	- [2.70b + 2.40v + 2.70p]
= Final result	**- 0.20b + 0.85v – 1.75p**

The barriers against virus are too low with the UV-disinfection only and it is recommended to maintain the chlorination. The design-pH for chlorination will now be lower (7-8) and hence the log-reduction for chlorination will be:

- Expected log-reduction of bacteria : $n_{calc., bact} = 3 \cdot 3.2/1.5 = 6.4$
- Expected log-reduction of virus : $n_{calc.,virus} = 3 \cdot 3.2/6 = 1.6$
- Expected log-reduction of parasites : ~ 0

However, since the maximum log reduction for chemical disinfection methods is 4b+4v+3p, the log-reduction for the chlorination step in this plant will be: 3.8b + 1.6v + 0.0p if we assume the same reduction for breaches in the chlorination equipment as before. The barrier situation for the overall water utility will then be:

Barrier level required:	+[6.00b + 6.00v + 4.00p]
- Log-credits for actions in catchment and source	- [1.25b + 1.25v + 0.80p]
- Log-credits for water treatment actions	- [2.25b + 1.50v + 2.25p]
- Log-credits for the UV-disinfection plant offered	- [2.70b + 2.40v + 2.70p]
- Log-credits for chlorination	- [3.80b + 1.60v + 0.00p]
= Final result	**- 4.00b – 0.75v – 1.75p**

By introducing coagulation and retrofitting the filters, introducing the UV-plant proposed and maintaining the existing chlorination, the system will have an acceptable barrier status.

5.5.2. Retrofitting the water treatment plant into an ozonation/biofiltration plant

In this alternative an ozonation facility, i.e. ozone generator, contact columns, reactor tank etc., are established and put before the calcium-carbonate filters. The ozone added will ensure sufficient color removal. The filters are expected to have biofilm growing on the calcium-carbonate, turning the filter into a biofilter that will degrade the biodegradable organic matter that is created by the pre-ozonation.

An alternative would be to replace the calcium-carbonate with another granular media for biofilm growth; i.e., sand, expanded clay aggregates or granular activated carbon. In this evaluation we have assumed that the calcium carbonate perform adequately (even though it has to be discontinuously replaced because of dissolution) and that it may maintain a certain corrosion control effect, resulting in a pH after the filters in the range of 7-8.

The raw water TOC is 3.5 mg TOC/l and necessary ozone dose to achieve the color reduction aimed at is 1.2 mg O_3/mg TOC, i.e. 4.2 mg O_3/l. The raw waters
pH = 6.8.

The ozonation facility uses an ozone injector and a counter-current packed contact column with a theoretical residence time of 5 min and a co-current reaction tank (without any ozone addition and without packing) with a theoretical residence time of 10 min. The plant is to be operated with a residual ozone concentration out of the reaction tank of about 0.1 mg O_3/l.

The ozonation plant is equipped with the following control- and monitoring measures (with reference to table 3.7):

Category A	Category B	Category C
A1 – not in place A2 – in place	B1 – in place B2 – not in place B3 – in place	C1 – in place C2 – not in place C3 – not in place

The calculation of the Ct for ozonation plants follows the procedure in section 3.7. In a design situation, as here, we follow the roadmap given in attachment section V2.3.2 and use calculation based on ozone dose, since this is known (because of the performance needed for color reduction):

1. Ozone dose: 4.2 mg O_3/l
2. Ozone transfer coefficient (see table 3.5): 0.90
   (Contact tank: packed column with bubbles)
3. Initial consumption (IC) and degradation constant (k):
   IC_{ozone} = 0.14·TOC + 0.58·C_{dose} + 0.09·(C_{dose}/TOC) + 0.07·pH – 0.92
   = 0.14 · 3.5 + 0.58 · 4.2 + 0.09·(4.2/3.5) + 0.07·6.8 – 0.92
   = 2.6
   k_{ozone} = 0.050 · TOC - 0.032·Ci - 0.017· (Ci/TOC) + 0.084·pH – 0.48
   = 0.050 · 3.5 - 0.032·2.6 - 0.017· (2.6/3.5) + 0.084·6.8 – 0.48
   = 0.22
4. Number of segments in contact tank:
   Number of segments in reaction tank: 1
5. Volume contact tank = V_{CT} = Q (m^3/min)·5 min
   Volume reaction tank = V_{RT} = Q (m^3/min) ·10 min
6. Effective residence time in contact tank (see table 3.3): 5 min · 0.85 = 4.25 min
   Effective residence time in reaction tank (see table 3.3): 10 min · 0.70 = 7 min
7. Initial concentration:
   $C_i = (C_{dose} - IC)/k_{transfer.} = (4.2 - 2.6)/0.90 = 1.78$ mg O_3/l
8. Outlet concentration from contact tank:
   $C_{out\text{-}k} = C_i \cdot e^{-k \cdot tc} = 1.78 \cdot e^{-0.22 \cdot 4.25} = 0.70$ mg O_3/l
9. Inlet concentration to reaction tank:
   $C_{in\text{-}r} = C_{out\text{-}c} = 0.70$ mg O_3/l
10. Outlet concentration from reaction tank:
    $C_{out\text{-}r} = C_{in\text{-}r} \cdot e^{-k \cdot tr} = 0.70 \cdot e^{-0.22 \cdot 7} = 0.15$ mg O_3/l
11. Control: residual concentration ca 0.1 mg O_3/l – OK
12. Effective concentration in contact tank (see table 3.6)
    $C_{eff\text{-}c} = C_{out\text{-}c} = 0.70$ mg O_3/l
13. Ct-value for the contact tank:
    $Ct_c = C_{eff\text{-}c} \cdot t_c = 0.70 \cdot 4.25 = 2.98$ mg · min/l
14. Ct-value for the reaction tank:
    $Ct_r = (C_{in\text{-}r}/k)(1 - e^{-k \cdot tr}) = 0.70/0.22 \cdot (1 - e^{-0.22 \cdot 7}) = 2.50$ mg · min/l
15. Total Ct-value = 2.98 + 2.50 = 5.48 mg · min/l
16. Log-reduction: $n_{calculated} = n_{required} \cdot Ct_{calculated}/Ct_{required}$ (see section 3.2.2)

Log-reduction bacteria	: $n_{calc., bact.}$	= 3 · 5.48/0.5	= 32.9
Log-reduction virus	: $n_{calc., virus}$	= 3 · 5.48/1	= 16.4
Log-reduction *Giardia*	: $n_{calc., Giardia}$	= 2 · 5.48/1.5	= 7.3
Log-reduction *Cryptosporidium*	: $n_{calc., Crypto}$	= 2 · 5.48/30	=0.36

We see that the values for bacteria, virus and *Giardia* are far higher than the maximum credits for chemical disinfection, which are 4.0b + 4.0v + 3.0p.
The log-credit for the ozonation is therefore set at: 4.0b + 4.0v + 0.36p.

If, for any reason, only *Giardia* and not *Cryptosporidium* was of importance, a credit of 4.0b+4.0v+3.0p would be given.

Then it is necessary to take into account the lack of control and security measures taken for the ozonation plant offered, see section 3.8 and table 3.7.

Calculated (maximum) log-reduction		**= 4.0b + 4.0v + 0.36p**
Lack of A actions (max.)	**- 0.10 · [4.0b + 4.0v + 0.33p]**	
A1 actions: not in place		
A2 actions: in place	+ 0.05 · [4.0b + 4.0v + 0.33p]	
Sum A actions	- 0.05 · [4.0b + 4.0v + 0.33p]	= - [0.2b + 0.2v + 0.02p]
Lack of B actions (max.)	**- 0.15 · [4.0b + 4.0v + 0.33p]**	
B1 actions: in place	+ 0.10 · [4.0b + 4.0v + 0.33p]	
B2 actions: not		
B3 actions: in place	**+ 0.10 · [4.0b + 4.0v + 0.33p]**	
Sum B actions	+ 0.05 · [4.0b + 4.0v + 0.33p]	= - [0.0b + 0.0v + 0.00p][1)]
Lack of C actions (max.)	**- 0.10 · [4.0b + 4.0v + 0.33p]**	
C1 actions: in place	+ 0.05 · [4.0b + 4.0v + 0.33p]	
C2 actions: not in place		
C3 actions: not in place		
Sum C actions	- 0.05 · [4.0b + 4.0v + 0.33p]	= - [0.2b + 0.2v + 0.02p]
Calculated final log-reduction for the ozone facility		**= 3.60b + 3.60v + 0.32p**

1) The sum of credits for barrier actions implemented within one main category cannot surpass the maximum log-reduction deduction of that category.

If only *Giardia* and not *Cryptosporidium* had been of importance, the log-reduction would have been: 3.6 b + 3.6v + 2.7p.

The final barrier result with ozonation/biofiltration in the water treatment will then be:

Barrier level required:	+[6.00b + 6.00v + 4.00p]
- Log-credits for actions in catchment and source	- [1.25b + 1.25v + 0.80p]
- Log-credits for water treatment actions	
Ozonation	- [3.60b + 3.60v + 0.30p]
Biofiltration	- [0.50b + 0.25v + 0.50p]
- Log-credits for the UV-disinfection plant offered	- [2.70b + 2.40v + 2.70p]
- Log-credits for chlorination (pH = 7-8)	- [4.00b + 1.60v + 0.00p]
= Final result	**- 6.05b – 3.10v – 0.30p**

Without the final chlorination step the final result would be: - 2.05b – 1.30v – 0.30p

It is demonstrated that also this alternative will provide sufficient barriers in the system – even without the final chlorination. However, it is recommended, that chlorination be maintained to add an independent barrier.

5.6. Smalltown water utility

Smalltown water utility supplies water to 5000 persons in Smalltown from 2 groundwater wells in unconsolidated sediments.

There have been very limited barrier actions taken in connection with the wells, (fencing around and locking of gate to the well zone (zone 0)). It is planned to introduce some new barrier actions in the close inflow zone (zone 1).
There is no treatment whatsoever in the Smalltown system. Monthly samples have been taken and no registrations of *E. coli* or *Clostridium perfringens* have been made.

From figure 2.2 the water quality level is A, and from table 2.2 the barrier level required is 3.5b + 3.5v + 2.5p.

5.6.1. Planned barrier actions in the inflow zone (zone 1) of the groundwater wells in Smalltown water utility

In addition to existing barrier actions, it is planned to undertake new barrier actions that will give the following barrier effects in terms of log-credit:

Well zones	Barrier actions	Log-credit
Zone 1 The close inflow zone	Introducing a ban on all forms of sewage installations in the zone, including sewage pipes, septic tanks, on-site infiltration systems etc., as well as spreading of sewage sludge.	0.75b + 0.75v + 0.5p
	Introducing a ban on potentially polluting activities in the zone, e.g. homes, cottages, motor traffic etc. and all form of waste disposal sites.	0.25b + 0.25v + 0.15p
Summarized log-credit for barrier actions in the close inflow zone of the wells		**1.25b + 1.25v + 0.75p**

The total barrier effect of the actions planned in the inflow zone of the groundwater wells of Smalltown system of: **1.25b + 1.25v + 0.75p**, does not exceed the maximum value given in table 2.3.

5.6.2. Treatment barrier actions in Smalltown water utility

The actions in the close inflow zone of the wells are not sufficient to reach the barrier level required of 3.5b + 3.5v + 2.5p and since at least 1.75 log reduction of parasites is needed, UV-disinfection or a good particle separation is needed.

The UV-disinfection plant is identical to the one that was offered to Waterlake utility (i.e. has the same safety breaches). The difference is that the UVT_{50} of the raw water is very high compared to the design UVT_{50} ($UVT_{50,\ raw\ water}$ = 0.9 and $UVT_{50,\ design}$ = 0.5) and hence that there is no reduction of log-credit because of low UV-transmission and the log-reduction is therefore : 3.4b + 3.0v + 3.4p (see section 5.4).

5.6.3. Final result of barrier analysis - Smalltown utility

The final result of the Smalltown system after implementation of barrier actions in the inflow zone to the wells as well as instalment of the UV-plant is then:

Barrier level required:	+[3.50b + 3.50v + 2.50p]
- Log-credits for actions in catchment and source	- [1.25b + 1.25v + 0.75p]
- Log-credits for the UV-disinfection plant offered	- [3.40b + 3.00v + 3.40p]
= Final result	**- 1.15b - 0.75v - 1.65p**

Hence the barrier concept (plan) is satisfactory with the new barrier actions proposed.

If, instead of UV-disinfection, a UF membrane filtration plant had been implemented, the results would have been:

Barrier level required:	+ [3.50b + 3.50v + 2.50p]
- Log-credits for actions in catchment and source	- [1.25b + 1.25v + 0.75p]
- Log-credits for the UF-filtration plant offered	- [2.50b + 2.00v + 2.50p]
= Final result	**- 0.75b - 0.25v - 0.75p**

Both methods (UV-disinfection and UF-filtration) provide a satisfactory barrier status, but since the physical/chemical water quality is fine, it is decided to install a UV-disinfection facility.

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Attachment 1
Practical use of the toolbox – Chlorine

This attachment includes calculation road-maps for various purposes in either design or in operation when using chlorine as disinfectant. The basis for this tool-box attachment chapter is given in section 3.4 of the report.

The chlorine contact tank may be a single tank or divided in several chambers (segmented). In the following the road-maps for a single tank system is shown first and in section V1.3 it is demonstrated how to proceed if the contact tank is segmented.

V1.1 Roadmap for calculation of chlorine dose in the design of chlorine disinfection plants

In design the challenge is to determine the necessary chlorine dose, which is dependent on two conditions:

1. How large is the "chlorine demand", i.e. how much chlorine is consumed for oxidation
2. How large must the "chlorine residual" be, in order to be able to maintain a sufficiently high Ct-value during disinfection

At a given outlet concentration (residual chlorine concentration) one may "back-calculate" to the initial concentration that will be the same as the inlet concentration and hence the chlorine dose by determination of IC (see below).

The initial concentration (C_i) is given by:

$$C_i = C_{out} / e^{-k \cdot t}$$

When the initial concentration (C_i) is given, the chlorine dose can be found by adding the initial consumption (IC) that will take place right after dosage as described in section 3.4.1.:

$$C_{dose} = C_i + IC$$

The values of IC and k to be used in these calculations may be determined by the use of the models presented in section 3.4.2 of the report. Since, however, IC and k is not only dependent on the TOC of the water but also on the chlorine dose, it is necessary to iterate (using "trial and error") when the dose is calculated. Here the calculation "road-map" will be shown for a contact tank of one segment only, but the procedure is the same for several segments.

The "road-map" is as follows:

1. Assume a chlorine (or another chlorine) dose
2. Determine the initial chlorine consumption (IC) and the degradation constant for chlorine (k) from the models given in section 3.4.2 based on the TOC and chlorine dose assumed
3. Choose the residual chlorine concentration out of the contact tank (C_{out})
4. Calculate the initial concentration (C_i) by the use of: $C_i = C_{out} / e^{-k \cdot t\text{-eff}}$
5. Calculate the chlorine dose (C_{dose}) by the use of: $C_{dose} = C_i + IC$
6. Check if the calculated chlorine dose is in agreement with the assumed one (item 1)
7. If there is no agreement, a new dose, equal to the last calculated, is assumed and the "road-map" is repeated for this dose. The same is repeated until the assumed dose and the calculated dose is in agreement with each other.
8. The calculated C_{dose} is then the final result

V1.2 Roadmap for the calculation and use of Ct for a plant in operation as well as in design of a plant

The Ct-calculations will be different for a plant in operation, where it is possible to carry out measurements in the plant, and in the design of a new plant where no in-plant measurements are available. The purpose of the Ct-calculations will also be different. The two types of Ct-calculation are demonstrated below.

V1.2.1 Calculation and use of Ct for documentation at a plant in operation

At an operating treatment plant, the function of the chlorine installation may be documented through a Ct-calculation. For a plant consisting of a single chlorine contact tank, the following road map may be used for such documentation:

1. Measure the outlet concentration from the chlorine contact tank (C_{out}).
2. Determine effective residence time (t_{eff}) by the use of tracer studies for the determination of t_{10} (or tm), or by the use of hydraulic factor as shown in section 3.3.1.
3. Register the dose used, $C_{dose.}$
4. Measure the inlet concentration to the chlorine contact tank (C_{in}). This is preferable, but not absolutely necessary in order to carry out the documentation.
5. Determine initial consumption (IC) and degradation constant (k) as described in section 3.4.2. If a measured value for C_{in} is not available, go directly to item 7 in the road-map.
6. If measured values for C_{in} are available (in addition to knowledge about C_{dose}, C_{out} and t),:
   - Determine the degradation constant (k) by: $-k = [\ln(C_{out}/C_{in})] / t_{eff}$
   - Determine the initial consumption (IC) by: $IC = C_{dose} - C_i = C_{dose} - [C_{out} / e^{-k \cdot t\text{-}eff}]$

   Go to item 8 in this road-map
7. If measurement of C_{in} is not available, the initial consumption (IC) and the degradation constant (k) are determined as follows:
   - Determine IC from the model in section 3.4.2
   - Determine C_i by: $C_i = C_{dose} - IC$
   - Determine k by: $-k = [\ln(C_{out}/C_i)] / t_{eff}$
8. Calculation of Ct-value for the chlorine contact tank: $Ct = (C_{out} / k)(e^{k \cdot t\text{-}eff} - 1)$.
9. Compare the calculated Ct-value with the design Ct-value from table 3.1. and calculate the expected log-reduction for the plant by the use of the equations provided in section 3.2.2.

The analysis for a plant in operation should be carried out at different conditions (loadings, seasons, water qualities etc.) because changes in operational circumstances may influence the constants IC and k and hence the calculated Ct-value. By doing the analysis at several operational situations, a "library" of IC- and k-values for various circumstances may be established, that will be useful in dealing with future incidents and changes to the plant. It will also, of course, strengthen the accuracy of the values of IC and k as determined by the models and hence improve the basis for future design and operation.

V1.2.2 Roadmap for calculation and use of Ct for a plant under design

In a design situation both the contact tank volume and the necessary capacity of the dosing equipment must be determined. The calculations start at the outlet and continue back to the dosing point, or one may follow the water flow from the dosing point to the outlet. Irrespective of the starting point of the calculations, one will have to carry out an iterative calculation. The calculations shown below are for a contact tank with only one segment, but the roadmap may be used with as many segments as desired.

Calculation based on chosen outlet concentration

If the calculations are started at the outlet concentration, the roadmap for design of the contact tank reactor volume will be as follows:

1. Choose the outlet concentration (residual chlorine concentration), C_{out}.
2. Choose volume and shape of the contact tank.
3. Calculate the effective residence time for the contact tank based on section 3.3.1 and table 3.2.
4. Assume a dose.
5. Determine IC and k from the models (see section 3.4.2) based on the assumed dose and the TOC-concentration in the water.
6. Calculate the inlet concentration to the contact tank: $C_{in} = C_{out} / e^{-k \cdot t\text{-}eff}$
7. The inlet concentration (C_{in}) is equal to the initial concentration (C_i).
8. Calculate the dose: $C_{dose} = C_i + IC$
9. Compare the dose calculated with the dose assumed
   - If the calculated dose is not in agreement with the assumed dose, a new dose is to be assumed equal to the dose calculated previously. Return to item 5 in the roadmap and repeat the calculations. Continue like this until the calculated and the assumed dose are in agreement with each other
   - When there is agreement between assumed and calculated dose, continue to item 10 in the roadmap
10. Calculate the Ct-value for the contact tank: $Ct = (C_{out} / k)(e^{k \cdot t\text{-}eff} - 1)$
11. Compare the Ct-value calculated with the Ct-value required for the log-reduction aimed at according to table 3.1.
12. If there is agreement, the calculations are completed. If not the calculations have to be repeated with new choices in items 1 and 2.

Calculation based on chlorine dose

An alternative to starting with the outlet concentration is to start the calculation at the point of dosage and follow the water flow to the outlet. This alters the procedure and the roadmap will be as follows:

1. Choose the chlorine dose (C_{dose}).
2. Determine IC and k from the models in section 3.4.2.2 based on the dose chosen and the TOC concentration of the water.
3. Choose volume and shape of the contact tank.
4. Calculate the effective residence time in the contact tank based on section 3.3.1 and table 3.2.
5. Calculate the initial concentration: $C_i = C_{dose} - IC$
6. Calculate the outlet concentration from the contact tank: $C_{out} = C_i \cdot e^{-k \cdot t\text{-}eff}$
7. Compare the calculated outlet concentration (C_{out}) to that of the residual concentration aimed at;
   - If the calculated outlet concentration is not in agreement with the residual concentration aimed at, go back to item 1) and choose another chlorine dose (or alternatively another contact tank volume) and repeat the calculations.
   - If the calculated outlet concentration is in agreement with the residual concentration aimed at, continue to item 8.
8. Calculate the Ct-value for the contact tank: $Ct = (C_i / k)(1 - e^{-k \cdot t\text{-}eff})$
9. Compare the calculated Ct-value with the required Ct-value for the log-reductions aimed at according to table 3.1.
10. If there is agreement, the calculations are completed. If not the calculations have to be repeated with new choices in items 1 and 2.

V1.2.3 Design of the capacity of the dosing equipment

The roadmap for design of the dosing equipment will be a follow-up of the roadmap for design of the contact tank volume (as shown above) and will be as follows:

1. Choose an outlet concentration (residual chlorine concentration), C_{out}.
   - This may now be chosen to be higher than the one chosen for design of the contact tank in order to meet the water quality requirement in a situation of crisis (failure of water treatment plant)
2. Choose a water quality (TOC) that the dosing equipment is to be designed for;
   - This should be the worst water quality that may occur, possibly the raw water quality
3. Assume a dose.
4. Determine IC and k from the models given in section 3.4.2.2 based on the assumed dose and the design TOC.
5. Calculated the inlet concentration to the contact tank: $C_{in} = C_{out} / e^{-k \cdot t\text{-}eff}$
6. The inlet concentration (C_{in}) is equal to the initial concentration (C_i).
7. Calculate the dose: $C_{dose} = C_i + IC$
8. Compare the dose calculated with the dose assumed
   - If the calculated dose is not in agreement with the assumed dose, a new dose is to be assumed equal to the dose calculated previously. Return to item 4 in the roadmap and repeat the calculations. Continue until the calculated and the assumed dose are in agreement.
   - When there is agreement between assumed and calculated dose, continue to item 9 in the roadmap.
9. The calculated design dose, C_{dose} will determine the design of the chlorine dosing equipment
   - The purpose of this higher dose will be to secure a given residual chlorine concentration (chosen in item 1) at the worst water quality that may occur. Hence there is no need to carry out additional calculation of Ct-value

V1.3 Calculations when the chlorine contact tank is segmented

If the contact tank is composed of several chambers or segments, one may either carry out the calculations segment by segment, or one may use the total volume of the segmented tank, but take proper attention to the serial factor when determining the effective residence time (t_{eff}) – see section 3.3.1.

The hydraulic factor, F_h, is to be based on t_m/T when C_i, k and IC is to be determined and based on t_{10}/T when Ct is to be calculated.

V1.3.1 Calculations segment by segment

If there are several segments from the inlet to the outlet (for example segment 1, segment 2, segment 3 etc.), the initial concentration C_i will be the inlet concentration to segment 1. Assuming that there is no dosing of chlorine compounds between the segments and that the degradation constant is the same in all segments, the following relationship will prevail:

- $C_{out\text{-}1} = C_i \cdot e^{-k \cdot t1}$
- $C_{out\text{-}2} = C_{out\text{-}1} \cdot e^{-k \cdot t2} = C_i \cdot e^{-k \cdot (t1+t2)}$
- $C_{out\text{-}3} = C_{out\text{-}2} \cdot e^{-k \cdot t3} = C_i \cdot e^{-k \cdot (t1+t2+t3)}$

where $C_{out\text{-}1}$, $C_{out\text{-}2}$ and $C_{out\text{-}3}$ are the outlet concentrations from segment 1, 2 and 3 respectively, and t_1, t_2 and t_3 are the effective residence times in segment 1, 2 and 3 respectively.
The gradual reduction in chlorine concentration will follow the same progress through all the segments, which means that during operation the degradation constant, k, may be determined by measuring the concentrations between the various segments. For a contact tank consisting of the 3 segments 1, 2 and 3, the degradation constant k in each segment may therefore be determined independently by:

- $k = - [\ln(C_{out\text{-}3}/C_{out\text{-}2})] / t_3$
- $k = - [\ln(C_{out\text{-}2}/C_{out\text{-}1})] / t_2$
- $k = - [\ln(C_{out\text{-}1}/C_{in\text{-}1})] / t_1$

It should be pointed out that the residence time of a segment, for example segment 3, will in this case be $t_3 = t_m/T \bullet V_3/Q$ (see section 3.3.1) where V_3 is the volume of segment 3.

In order to calculate Ct (that must be based on hydraulic factor $F_h = t_{10}/T$), the t_{10}/T for all the segments must be summarized and then t_{eff} can be calculated as:

$$t_{eff} = [\Sigma_{\text{all segments}}(V_{segment}/Q) \bullet F_{h,\,segment}] \bullet F_s$$

V1.3.2 Calculations based on the overall residence time

One may, alternatively, use the summarized theoretical residence time for all the segments, especially when the segments are equally shaped. This will simplify the calculations to be the same as in the case with no segments, *except for the fact that the effective residence time has to be corrected*, taking into account the serial factor, F_s, that is relevant for the number of segment present (see table 3.2).

The effective residence time for a segmented contact tank will then be:

$$t_{eff} = V_{total}/Q \bullet F_h \bullet F_s$$

where F_h and F_s are taken from table 3.2 and V_{total} is the total volume of all the segments.

The overall Ct-value calculated from the initial concentration (C_i), will be:

$$Ct = [(C_i / k)\,(1 - e^{-k \cdot t\text{-}eff})]$$

An alternative expression for the overall Ct-value, based on a given outlet concentration in the last segment of the contact tank, is:

$$Ct = [(C_{out} / k)\,(e^{k \cdot t\text{-}eff} - 1)]$$

Attachment 2
Practical use of the toolbox – Ozone

This attachment includes calculation road-maps for various purposes in either design or in operation when using ozone as disinfectant. The basis for this tool-box attachment chapter is given in section 3.7 of the report.

The ozone contact tank as well as the reaction tank may be single tanks or divided in several chambers (segmented). In the following the road-maps for single tank systems are shown first and in section V2.3 it is demonstrated how to proceed if the contact tank is segmented.

V2.1 Roadmap for calculation of ozone dose in design of ozone plants

The necessary ozone dose is dependent on three conditions:

1. Gas transfer, i.e. the efficiency of the transfer of gas to water
2. Ozone consumption, i.e. how much ozone is to be consumed by oxidation and auto-decomposition
3. Ozone residual (or surplus) that has to be achieved to maintain a sufficiently high Ct-value to secure the desired log-reductions

At a given outlet concentration from the reaction tank the residual ozone concentration can be back-calculated to the inlet concentration of the reaction tank. If the ozone reaction tank consists of only one segment, the inlet concentration to the reaction tank, $C_{in\text{-}r,}$ (that is the same as the outlet concentration from the contact tank, $C_{out\text{-}c}$) is given by:

$$C_{in\text{-}r} = C_{out\text{-}c} = C_{out\text{-}r} / e^{-k \cdot teff\text{-}r}$$

The effective residence time of the reaction tank is then:

$$t_{eff\text{-}r} = V_{total,r} / Q \cdot F_{h,r} \cdot F_{s,r} \qquad (F_{h,r} = t_{m.r}/T_r)$$

In chapter 3.7.1 it was proposed that the effective concentration in the contact tank is given by the outlet concentration from the contact tank. The basis for this is that even if there is ozone consumption because of oxidation that should imply that the concentration is higher at the inlet than at the outlet, there is also a gas transfer taking place that will increase concentration from the inlet to the outlet. The net effect on the concentration changes through the contact tank is, therefore, difficult to predict. To be conservative in the $C_{eff\text{-}c}$ estimation, it is recommended to use the same $C_{eff\text{-}c}$ for the whole contact tank, when calculating Ct, and that this should be based on the outlet concentration, $C_{out\text{-}c}$, from the contact tank.

When calculating the necessary dose, however, one has to take the ozone consumption in the contact tank into consideration. This may be done by calculating a theoretical inlet concentration to the contact tank, $C_{in\text{-}c}$, in the same way as was done above for the reaction tank. It will not be the real inlet concentration, but a theoretical one that assumes that all gas transfer took place before the contact tank, and that the degradation constant for ozone had been the same as that in the reaction tank. If the contact tank consists of one segment only $C_{in\text{-}c}$, that is also initial concentration (C_i), is given by:

$$C_i = C_{in\text{-}c} = C_{out\text{-}c} / e^{-k \cdot teff\text{-}c}$$

where $t_{eff\text{-}c}$ is effective residence time in the contact tank and the other symbols are as given above.

When the initial concentration to the contact tank (that is set equal to the imaginary inlet concentration) is given, the necessary ozone dose is determined by the initial concentration (C_i) and the initial consumption (IC) as well as the extent of ozone transfer ($k_{transfer}$):

$$C_{dose} = (C_i + IC) / k_{transfer}$$

The determination of $k_{transfer}$ and IC is described in sections 3.7.1 and 3.7.2 respectively. Since both the initial consumption (IC) and the degradation constant (k) are not only dependent on the TOC and pH of the water, but on the ozone dose as well, it is necessary to iterate (by "trial and error") when the dose is to be calculated.

This roadmap will be as follows:

1. Choose the type of ozone injector and contact tank.
2. Determine the ozone transfer coefficient ($k_{transfer}$) based on item 1 and table 3.5.
3. Assume an ozone dose (C_{dose}).
4. Determine the initial consumption (IC) and the degradation constant for ozone (k) from the models (see section 3.7.2.2) based the TOC and pH of the water and the ozone dose.
5. Choose the residual ozone concentration aimed for at the outlet of the reaction tank ($C_{out\text{-}r}$).
6. Calculate the inlet concentration to the reaction tank: $C_{in\text{-}r} = C_{out\text{-}r} / e^{-k \cdot teff\text{-}r}$
   - The outlet concentration to the contact tank: $C_{out\text{-}c} = C_{in\text{-}r}$
7. Calculate the inlet concentration to the contact tank: $C_{in\text{-}c} = C_{out\text{-}c} / e^{-k \cdot teff\text{-}c}$
   - The initial concentration: $C_i = C_{in\text{-}c}$
8. Calculate the ozone dose: $C_{dose} = (C_i + IC) / k_{transfer}$
9. Compare if the calculated ozone dose (item 8) is in agreement with the assumed one (item 3)
   - If they are not in agreement, a new ozone dose is assumed equal to the one calculated, return to item 4 in the roadmap and continue calculations.
   - This is continued until the assumed dose and the calculated dose are in agreement with each other.
10. The dose, C_{dose}, thus determined is the final result.

V2.2 Roadmaps for calculation and use of Ct in a plant on operation as well as plant under design - ozone

As for chlorine, the Ct-calculations for a plant in operation, where it is possible to carry out measurements in the plant, will be different from a new plant under design or planning where no in-plant measurements are available.

V2.2.1 Roadmap for calculation of Ct for documentation in an operating plant – ozone

In assessing an existing in operation, the calculation of the Ct-value may be used to document whether or not the ozone plant is functioning according to the intention (i.e. giving the design log-reductions). For a plant consisting of one ozone contact tank and one ozone reaction tank (i.e. one segment in each tank), the roadmap will be as follows:

1. Measure the outlet concentration for the ozone reaction tank (residual ozone concentration, $C_{out\text{-}r}$).
2. Determine the effective residence time in the contact tank ($t_{eff\text{-}c}$) and in the reaction tank ($t_{eff\text{-}r}$). This may be done by the use of tracer studies (for determination of t_{10} or t_m) or based on hydraulic factors as shown in section 3.3.1 and table 3.2 and/or table 3.3.
3. Register the applied dose, C_{dose}.
4. Determine the gas transfer coefficient ($k_{transfer}$) and the initial consumption (IC) from table 3.5 and the calculation model for IC_{ozon} (see section 3.7.2.2) respectively
   - This is not absolutely necessary for the documentation of Ct-value, but is useful information in control calculations (see sections 3.7.1 and 3.7.2).
5. Measure the inlet concentration to the reaction tank ($C_{in\text{-}r}$) that is equal to the outlet concentration of the contact tank ($C_{out\text{-}c}$)
   - This is useful, but not absolutely necessary for the documentation exercise.
6. Determine the degradation constant (k) as described in section 3.7.2. If the measured value for $C_{out\text{-}c} = C_{in\text{-}r}$ is lacking, go directly to item 7 in the roadmap. If measured values for $C_{out\text{-}c} = C_{in\text{-}r}$ are available (in addition to knowledge about C_{dose}, $C_{out\text{-}r}$, $t_{eff\text{-}r}$ and $t_{eff\text{-}c}$), this will involve the following:
   - Determine the degradation constant (k) by: $-k = [\ln(C_{out\text{-}r}/C_{in\text{-}r})] / t_{eff\text{-}r}$
   - Go to item 8 in the roadmap
7. If measured values for $C_{out\text{-}c} = C_{in\text{-}r}$ are not available, the degradation constant (k) and outlet concentration from the contact tank ($C_{out\text{-}c}$) is determined as follows:
   - Determine k from calculation model (see section 3.7.2.2)
   - Determine $C_{out\text{-}c}$ as: $C_{out\text{-}c} = C_{in\text{-}r} = C_{out\text{-}r} / e^{-k \cdot teff\text{-}r}$
8. Determine the effective concentration in the contact tank ($C_{eff\text{-}c}$) based on the outlet concentration from the contact tank ($C_{out\text{-}c}$) and table 3.6.
9. Calculate the Ct-value for the ozone contact tank: $(Ct)_c = C_{eff\text{-}c} \cdot t_{eff\text{-}c}$
10. Calculate the Ct-value for the ozone reaction tank: $(Ct)_r = (C_{out\text{-}r} / k)(e^{k \cdot teff\text{-}r} - 1)$
11. Calculate the total Ct-value by summation of $(Ct)_c$ and $(C_t)_r$:
    - $Ct = [C_{eff\text{-}c} \cdot t_{eff\text{-}c}] + [(C_{out\text{-}r} / k)(e^{k \cdot teff\text{-}r} - 1)]$

12. Compare the calculated Ct-value with the required Ct-value for a given log-reduction in table 3.1, and calculate the log reduction in the plant by the use of the equations provided in section 3.2.2

The analysis for documentation of a plant in operation should be carried out under different operational conditions (loadings, seasons, water qualities etc.) because changes in operational circumstances may influence on the constants $k_{transfer}$, IC and k and hence on the calculated Ct-value. By carrying out the analysis at several operational situations, a "library" of IC- and k-values for various circumstances may be established, that will be useful to tackle various future incidents and changes on the plant. It will also strengthen the accuracy of the values of IC and k as determined by the models and hence improve the basis for future design and operation.

V2.2.2 Roadmap for the calculation of Ct to be used in planning and design of ozone plants

In planning and/or design there is a need for determining both the contact tank volume and the necessary capacity of the dosing equipment. The calculations should start from the outlet and calculate back to the dosing point, or follow the water flow from the dosing point to the outlet. Irrespective of the starting point of the calculation, one will have to carry out an iterative calculation.

As an illustration of the roadmap, a plant consisting of one ozone contact tank and one reaction tank have been chosen, but the same procedure may be used on as many segments (see section V2.3).

Calculation based on a chosen outlet ozone concentration (ozone residual concentration)

If the outlet concentration from the reaction tank is chosen as the starting point, the road map will be as follows for the design of the reactor volumes and the dose:

1. Choose the outlet concentration from the reaction tank ($C_{out\text{-}r}$).
2. Choose volume and shape of each tank.
3. Calculate the effective residence time in both the contact tank and the reaction tank based on the use of tracer studies (for determination of t_{10} or t_m) or based on hydraulic factors as shown in section 3.3.1 and table 3.2 and/or table 3.3
   - In this way the effective residence times $t_{eff\text{-}c}$ and $t_{eff\text{-}r}$ are determined
4. Assume a dose.
5. Determine the gas transfer coefficient ($k_{transfer}$) based on the type of ozone injector and table 3.4.
6. Determine the initial consumption (IC) and the degradation constant (k) by the use of the calculation models in section 3.7.2.2 based on assumed dose and the pH and TOC-concentration of the water.
7. Calculate the inlet concentration to the ozone reaction tank: $C_{in\text{-}r} = C_{out\text{-}r} / e^{-k \cdot teff\text{-}r}$
8. The inlet concentration to the ozone reaction tank ($C_{in\text{-}r}$) is equal to the outlet concentration of the ozone contact tank ($C_{out\text{-}c}$).
9. Calculate an imaginary initial concentration (C_i) that is equal to the inlet concentration of the contact tank: $C_i = C_{in\text{-}c} = C_{out\text{-}c} / e^{-k \cdot teff\text{-}c}$
10. Calculate the ozone dose: $C_{dose} = (C_i + IC) / k_{transfer}$
11. Compare the calculated dose with the assumed one
    - If the calculated dose is not in agreement with the assumed one, assume a new dose equal to the calculated one and go back to item 7 in the roadmap and repeat the calculations from there. Continue with this until it is agreement between calculated and assumed dose
    - When there is agreement, the dose is found and one can continue to item 13
12. Determine the effective concentration in the contact tank ($C_{eff\text{-}c}$) based on the outlet concentration from the contact tank ($C_{out\text{-}c}$) and table 3.6.
13. Calculate Ct-value for the contact tank: $(Ct)_c = C_{eff\text{-}c} \cdot t_{eff\text{-}c}$
14. Calculate Ct-value for the reaction tank: $(Ct)_r = (C_{out\text{-}r} / k)(e^{k \cdot teff\text{-}r} - 1)$
15. Calculate the total Ct-value as the sum of the two: $Ct = [C_{eff\text{-}c} \cdot t_{eff\text{-}c}] + [(C_{out\text{-}r} / k)(e^{k \cdot teff\text{-}r} - 1)]$
16. Compare the calculated Ct-value with the required Ct-value for a given log-reduction in table 3.1.
    - If the Ct-values are comparable, the calculations may end and the Ct is determined. If not the calculations should be repeated with new choices under items 1 and 2.

Calculation based on ozone dose

As an alternative to using the outlet concentration from the reaction tank as the starting point, one may start at the point of dosage and follow the water flow to the outlet. This requires a different procedure, however, that will be as follows:

1. Choose ozone dose (C_{dose}).
2. Determine the ozone transfer coefficient ($k_{transfer}$) based on type of ozone injector and table 3.5.
3. Determine the initial consumption (IC) and the degradation constant (k) for ozone by the use of the calculation models for IC and k (see section 3.7.2.2) based on the chosen ozone dose and the pH and TOC concentration of the water.
4. Choose volume and shape of each of the tanks
5. Calculate effective residence time in both the contact tank (t_{eff-c}) and the reaction tank (t_{eff-r}) based on the use of tracer studies (for determination of t_{10} or t_m) or based on the hydraulic factors as shown in section 3.3.1 and table 3.2 and/or table 3.3.
6. Calculate the imaginary initial concentration: $C_i = (C_{dose} - IC) / k_{transfer}$
7. Calculate the outlet concentration from the ozone contact tank: $C_{out-c}=C_i \cdot e^{-k \cdot teff-c}$
8. The inlet concentration to the reaction tank (C_{in-r}) is equal to the outlet concentration from the contact tank (C_{out-c}).
9. Calculate the outlet concentration from the ozone reaction tank: $C_{out-r}=C_{in-r} \cdot e^{-k \cdot teff-r}$
10. Control if the calculated outlet concentration from the reaction tank (C_{out-r}) is in agreement with the residual concentration planned for:
    - If calculated outlet concentration is not in agreement with the residual concentration planned for, go back to item 1 and choose another ozone dose (or possibly another reactor volume and repeat the calculations)
    - If the calculated outlet concentration is in agreement with the planned residual outlet concentration, continue to item 11.
11. Determine the effective concentration in the contact tank (C_{eff-c}) based on the outlet concentration from the contact tank (C_{out-c}) and table 3.6.
12. Calculate the Ct-value for the contact tank: $(Ct)_c = C_{eff-c} \cdot t_{eff-c}$
13. Calculate the Ct-value for the reaction tank: $(Ct)_r = (C_{in-r} / k) (1 - e^{-k \cdot teff-r})$
14. Calculate the total Ct-value as the sum of the Ct-value for the contact- and reaction tank: $Ct_{total} = [C_{eff-c} \cdot t_{eff-c}] + [(C_{in-r} / k) (1 - e^{-k \cdot teff-r})]$
15. Compare the calculated Ct-value with the required Ct-value for the log reduction planned for in table 3.1.
16. If the calculated Ct-value is in agreement with the required Ct-value, the final Ct-value is determined and the calculations are completed. If not, the calculations are repeated with new choices in items 1 and 2.

V2.2.3 Roadmap for the design of the capacity of the ozone dosing equipment

The roadmap for the design of the dosing equipment will be a follow-up of the roadmap for designing the reactor volume and will be as follows:

1. Choose the outlet concentration from the reaction tank (residual ozone concentration), C_{out-r}, to plan or design for
    - This may now be chosen to be higher than the one chosen for design of the contact tank in order to meet the water quality requirement in a situation of crisis (failure of water treatment plant).
2. Choose a design water quality (pH and TOC) for design of the dosing equipment
    - This should be the worst water quality that may occur, possibly the raw water quality.
3. Assume a dose.
4. Determine the ozone transfer coefficient ($k_{transfer}$) based on type of ozone injector and table 3.5.
5. Determine the initial consumption (IC) and the degradation constant (k) from the models (see section 3.7.2.2) based on assumed dose and TOC and pH of the water.
6. Calculate the inlet concentration to the reaction tank: $C_{in-r} = C_{out-r} / e^{-k \cdot teff-r}$
7. The outlet concentration from the contact tank (C_{out-c}) is equal to the inlet concentration of the reaction tank (C_{in-r}).
8. Calculate the imaginary inlet concentration to the contact tank: $C_{in-c} = C_{out-c} / e^{-k \cdot teff-c}$
9. The imaginary inlet concentration (C_{in-c}) is equal to an imaginary initial concentration (C_i).
10. Calculate the dose: $C_{dose} = (C_i + IC) / k_{transfer}$
11. Compare the calculated dose with the assumed one

- If the calculated dose is not in agreement with the assumed dose, assume a new dose equal to the one last calculated. Go then back to item 4 in the roadmap and repeat the calculations. Continue with iteration until there is agreement between calculated and assumed dose.
- When there is agreement between the calculated and the assumed dose, go to item 12 in the roadmap.

12. The dose finally determined, C_{dose}, is to be used for the design of the ozone dosing equipment
    - The purpose of determining this dose is to ensure that there is a certain residual ozone concentration /chosen under item 1 at the worst water quality designed for. As a result Ct-calculations are not needed for this case.

V2.3 Calculation of Ct-value if the contact tank is segmented – ozone

If the ozone contact tank and/or reaction tank is composed of several chambers or segments, one may either carry out the calculations segment by segment, or one may use the total volume of the segmented tank, but take proper attention to the serial factor when determining the effective residence time (t_{eff}) – see section 3.3.1.

The hydraulic factor, F_h, is to be based on t_m/T when C_i, C_{out}, k and IC is to be determined and based on t_{10}/T when Ct is to be calculated.

V2.3.1 Calculation segment by segment

If the ozone *contact tank* is composed of several chambers or segments (for example segment 1, segment 2, segment 3 etc.) from the inlet to the outlet, the initial concentration (C_i) will be the inlet concentration to segment 1 ($C_{in\text{-}c\text{-}1}$). These are all imaginary concentrations (used for dose calculation), assuming that all ozone is added in the first tank. Then the following relationship will prevail:

- $C_{out\text{-}c\text{-}1} = Ci \cdot e^{-k \cdot tc1}$
- $C_{out\text{-}c\text{-}2} = C_{out\text{-}c\text{-}1} \cdot e^{-k \cdot tc2} = C_i \cdot e^{-k \cdot (tc1+tc2)}$
- $C_{out\text{-}c\text{-}3} = C_{out\text{-}c\text{-}2} \cdot e^{-k \cdot tc3} = C_i \cdot e^{-k \cdot (tc1+tc2+tc3)}$

where $C_{out\text{-}c\text{-}1}$, $C_{out\text{-}c\text{-}2}$ and $C_{out\text{-}c\text{-}3}$ are the outlet concentrations from segment 1, 2 and 3 respectively, and t_{c1}, t_{c2} and t_{c3} are the effective residence times in segment 1, 2 and 3 respectively. All outlet concentrations are imaginary except the outlet concentration from the last step ($C_{out\text{-}c\text{-}3}$ in this case).

The effective concentration, $C_{eff\text{-}c}$, for all the segments is then determined by $C_{out\text{-}c\text{-}3}$ and table 3.6.

The Ct-value for the whole contact tank will then be:

$$(Ct)_c = C_{eff\text{-}c} \cdot (t_{c1} + t_{c2} + t_{c3})$$

In the same way, calculations segment by segment may be used for the reaction tank.
If the ozone *reaction* tank is composed of several chambers or segments (for example segment 1, segment 2, segment 3 etc.) from the inlet to the outlet, the outlet concentration of the last segment of the contact tank (for example $C_{out\text{-}c\text{-}3}$) will be the inlet concentration to segment 1 of the reaction tank ($C_{in\text{-}r\text{-}1}$). Provided that there is no dosing of ozone between the segments and that the degradation constant is the same in all segments, the following relationship will prevail:

- $C_{out\text{-}r\text{-}1} = C_{in\text{-}r\text{-}1} \cdot e^{-k \cdot tr1}$
- $C_{out\text{-}r\text{-}2} = C_{out\text{-}r\text{-}1} \cdot e^{-k \cdot tr2} = C_{in\text{-}r\text{-}1} \cdot e^{-k \cdot (tr1+tr2)}$
- $C_{out\text{-}r\text{-}3} = C_{out\text{-}r\text{-}2} \cdot e^{-k \cdot tr3} = C_{in\text{-}r\text{-}1} \cdot e^{-k \cdot (tr1+tr2+tr3)}$

where $C_{out\text{-}r\text{-}1}$, $C_{out\text{-}r\text{-}2}$ and $C_{out\text{-}r\text{-}3}$ are the outlet concentrations from segment 1, 2 and 3 of the reaction tank respectively, while t_{r1}, t_{r2} and t_{r3} are the effective residence times in segment 1, 2 and 3 of the reaction tank respectively.

This means that the gradual reduction in ozone concentration will follow the same progress through all the segments, which means that for a plant in in operation the degradation constant, k, may be determined by measuring the concentrations between the various segments. For a reaction tank consisting of the 3 segments 1, 2 and 3, the degradation constant k in each segment may therefore be determined independently of each by:

- $k = - [\ln(C_{out\text{-}r\text{-}3}/C_{out\text{-}r\text{-}2})] / t_{r3}$
- $k = - [\ln(C_{out\text{-}r\text{-}2}/C_{out\text{-}r\text{-}1})] / t_{r2}$
- $k = - [\ln(C_{out\text{-}r\text{-}1}/C_{in\text{-}r\text{-}1})] / t_{r1}$

It should be pointed out that the effective residence time of a segment, for example segment 3, would in this case be $t_{r3} = t_m/T \cdot V_3/Q$ (see section 3.3.1), where V_3 is the volume of segment 3.

In order to calculate Ct (that must be based on hydraulic factor $F_h = t_{10}/T$), the t_{10}/T for all the segments must be summarized and then t_{eff} can be calculated as:

$$t_{eff} = [\Sigma_{\text{all segments}}(V_{segment}/Q) \bullet F_{h,\,segment})] \bullet F_s$$

V2.3.2 Calculations based on the overall residence time

One may alternatively, when calculating Ct-value, use the summarized theoretical residence time for all the segments, especially when the segments are equally shaped. This will simplify the calculations to be the same as in the case with no segments, *except for the fact that the effective residence times for the contact and reaction tank have to be corrected*, taking into account the serial factor, F_s, that is relevant for the number of segment present (see table 3.2).

$$t_{eff\text{-}c} = V_{total,c}/Q \cdot F_{h,c} \bullet F_{s,c} \qquad (F_{h,c} = t_{10,c}/T_c)$$

and

$$t_{eff\text{-}r} = V_{total,r}/Q \cdot F_{h,r} \bullet F_{s,r} \qquad (F_{h,r} = t_{10,r}/T_r)$$

The Ct-value for the contact tank will then be:

$$(Ct)_c = C_{eff\text{-}c} \cdot t_{eff\text{-}c}$$

The Ct-value for the ozone reaction will be based on the inlet concentration ($C_{in\text{-}r\text{-}1}$):

$$(Ct)_r = [(C_{in\text{-}r\text{-}1} / k)\,(1 - e^{-k \cdot teff\text{-}r})]$$

The alternative equation, if a given outlet concentration in the last segment of the reaction tank ($C_{out\text{-}r}$) is used as the starting point, will be:

$$(Ct)_r = [(C_{out\text{-}r} / k)\,(e^{k \cdot teff\text{-}r} - 1)]$$

The total Ct-value for the overall system will then be the sum of the Ct-values for the contact tank and reaction tank respectively:

$$Ct = (Ct)_c + (Ct)_r$$

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Norwegian Water BA, Vangsvegen 143, 2321 Hamar, Norway
Phone: +47 62 55 30 30 Email: post@norskvann.no
www.norskvann.no