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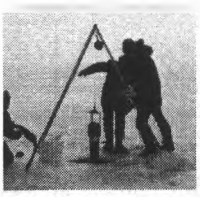
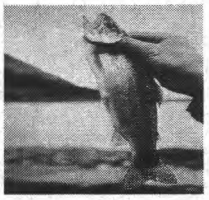
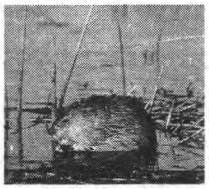
Northern River Basins Study



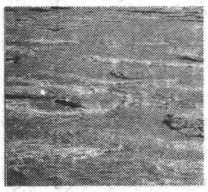




NORTHERN RIVER BASINS STUDY PROJECT REPORT NO. 139

A REVIEW OF LITERATURE ON THE REMOVAL OF MICROBIAL CONTAMINANTS FROM DRINKING WATER



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by

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PREFACE:

The Northern River Basins Study was initiated through the "Canada-Alberta-Northwest Territories Agreement Respecting the Peace-Athabasca-Slave River Basin Study, Phase II - Technical Studies" which was signed September 27, 1991. The purpose of the Study is to understand and characterize the cumulative effects of development on the water and aquatic environment of the Study Area by coordinating with existing programs and undertaking appropriate new technical studies.

This publication reports the method and findings of particular work conducted as part of the Northern River Basins Study. As such, the work was governed by a specific terms of reference and is expected to contribute information about the Study Area within the context of the overall study as described by the Study Final Report. This report has been reviewed by the Study Science Advisory Committee in regards to scientific content and has been approved by the Study Board of Directors for public release.

It is explicit in the objectives of the Study to report the results of technical work regularly to the public. This objective is served by distributing project reports to an extensive network of libraries, agencies, organizations and interested individuals and by granting universal permission to reproduce the material.

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Whereas the above publication is the result of a project conducted under the Northern River Basins Study and the terms of reference for that project are deemed to be fulfilled,
IT IS THEREFORE REQUESTED BY THE STUDY OFFICE THAT;
this publication be subjected to proper and responsible review and be considered for release to the public.

(Dr. Fred J. Wrona, Science Director) — (Date) 14 May 96

Whereas it is an explicit term of reference of the Science Advisory Committee "to review, for scientific content, material for publication by the Board",
IT IS HERE ADVISED BY THE SCIENCE ADVISORY COMMITTEE THAT;
this publication has been reviewed for scientific content and that the scientific practices represented in the report are acceptable given the specific purposes of the project and subject to the field conditions encountered.
SUPPLEMENTAL COMMENTARY HAS BEEN ADDED TO THIS PUBLICATION: [ ] Yes [ ] No

(Dr. P. A. Larkin, Ph.D., Chair) — (Date) 24 May 96

Whereas the Study Board is satisfied that this publication has been reviewed for scientific content and for immediate health implications,
IT IS HERE APPROVED BY THE BOARD OF DIRECTORS THAT;
this publication be released to the public, and that this publication be designated for: **[ ] STANDARD AVAILABILITY [ ] EXPANDED AVAILABILITY**

(Lucille Partington, Co-chair) — (Date) May 29/96

(Robert McLeod, Co-chair) — (Date) May 21/96

A REVIEW OF LITERATURE ON THE REMOVAL OF MICROBIAL CONTAMINANTS FROM DRINKING WATER

STUDY PERSPECTIVE

Water is essential to life and it can be an important vector for conveying contaminants into humans. To assist the Northern River Basins Study (NRBS) Board in making recommendations about the safety of drinking water supplies, the Drinking Water component designed a five-step program of studies. The steps included:

1. synthesis of existing data on water use and water quality;
2. investigation of odour in water and tainting in fish;
3. review of health records for water borne diseases;
4. assessment of conventionally treated and non-conventional water; and
5. preparation of a synthesis report.

Related Study Questions

2) What is the current state of water quality in the Peace, Athabasca and Slave River basins, including the Peace-Athabasca Delta?

8) Recognizing that people drink water and eat fish from these river systems, what is the current concentration of contaminants in water and edible fish tissue and how are these levels changing through time and by location?

This report deals with step four and provides a literature review of the occurrence and health impacts of: microorganisms, drinking water regulations from Alberta, the US and the World Health Organization (WHO), and approaches to controlling microbial contamination in drinking water. Microbial contaminants include: bacteria, viruses, protozoa, fungi and helminths (parasitic worms). The review concluded that contamination from microbial sources is probably the most important challenge for drinking water quality in the study area and echoes a similar conclusion by WHO for other areas of the globe. There is strong evidence that drinking water regulations will become increasingly more strict and small communities are likely to face the biggest challenge in meeting the regulations. Limited operating expertise, inadequate plant design and inadequate funding are some problems likely to be encountered by these communities.

The available literature continues to identify a combination of filtration and disinfection as the best technology for the removal of microorganisms. Proper filtration of water is stressed not only to make the disinfection process more effective but to minimize the protection afforded by particles left in the water. These particles in protecting microorganisms from disinfection allow the microbial material to stimulate regrowth in the water distribution systems. New processes are identified to deal with chlorination resistant microorganism such as *Giardia* and *Crytosporidium.* Although disinfectants exhibit variation in eradicating different organisms, the relative efficiencies of disinfectants in descending order are ozone, chlorine dioxide, chlorine and chloramine. Some microorganisms

Information from this project and its companion surveys, "A Review of Literature on the removal of Organic Chemicals from Drinking Water", and "A Review of Literature on the Removal of Inorganic Contaminants from Drinking" (NRBS Report Numbers 87 and 88) provide an overview of the current state of knowledge in drinking water treatment. These and other drinking water projects will form the basis for the Drinking Water Synthesis report. This report will also support a companion study, "Human Health Monitoring Program" that will be examining human health issues in Northern Alberta.

REPORT SUMMARY

In 1992, the Northern River Basin Study (NRBS) was established to address a number of environmental concerns raised from the northern river basins communities. After extensively analyzing the existing information with respect to the physical, chemical, biological and aesthetic characteristics of water treatment facilities in the study area, the study (Prince et al., 1995) found that a majority of water quality violations in the NRBS area resulted from the microbial related contamination. Analysis of health records showed that the incidences of giardiasis appeared to be higher in the NRBS area than the provincial average (Emde et al., 1994). Coincidentally, the World Health Organization (WHO, 1993) concluded that the microbial quality continues to be the most important for safe drinking water in order to protect public health. Consequently, microbial control must always be of paramount importance and must never be compromised.

This report reviews the various water treatment technologies available to remove the microorganisms from raw water supplies. Discussion of each technology included the process overview, performance, design consideration, operating and maintenance aspects, costs and status of technology development. Specific considerations were taken to those technologies applicable for small community systems located in the NRBS area. Also, the impacts of important microorganisms and relevant regulations were examined to highlight the significance and requirements of removing microorganisms from water treatment processes. The following conclusions were made:

1. Among various pathogens, particular attention should be directed to control newly recognized waterborne microorganisms such as *Giardia*, *Cryptosporidium* and viruses. These microorganisms are often widespread in nature, have a low infectious dose, cause high incidences of waterborne diseases, and are resistant to chlorination.

2. The use of coliforms as an indicator organism presently remains the most sensitive and specific way to detect microbial contamination and assess treatment efficiency. However, one must realize their limitations in predicting the protozoan and viral contamination. It would be desirable to include the particle size distribution determination for performance monitoring.

3. To safeguard against the contamination of waterborne pathogens, a multiple barrier approach should be exercised whenever possible. With this approach, controlling of microbial contamination starts from the collection of all wastes for treatment at specified sites, followed by the use of natural self-purification capacity. In water treatment, the multiple barrier approach involves the use of multiple water treatment processes in ensure a safe public water supply.

4. The best available technologies for the removal of microorganisms in water treatment include both filtration and disinfection. Disinfection alone using chlorine and its derivatives as the only treatment for surface water is ineffective to prevent waterborne giardiasis and cryptosporidiosis. An adequate pretreatment and filtration in addition to disinfection should be implemented for all surface waters.

5. Pretreatment by coagulation and flocculation is necessary to obtain high microorganism removals in filtration. It can also remove a significant portion of the organic materials that interfere with disinfection.

6. The filtration processes, combined with pretreatment, can remove *Giardia* cysts and *Cryptosporidium* oocysts 99 percent or more providing that an optimum dosage of chemical coagulant is used. The efficiency of removing viruses is over 90 percent, dependent on the type of filtration. However, the filter ripening and turbidity breakthrough can substantially deteriorate the effluent microbiological quality. The water treatment plants should keep the effluent turbidity as low as possible, preferably less than 0.2 NTU.

7. Provided that the raw water quality is adequate, slow sand filters, diatomaceous earth filtration, membrane filtration and package plants are the most applicable filtration technologies to small community systems.

8. The addition of filtration aids is essential for successful removal of microorganisms by rapid rate filtration and direct filtration. The proper dosages should reflect the seasonal variations in filter influent quality. The mechanisms underlying the flocculation and filtration of microorganisms closely follows the same principles as the elimination of colloidal and finely dispersed substances.

9. Different disinfectants exhibit wide variations in the inactivation of microorganisms. In general, their relative efficiency in descending order are ozone, chlorine dioxide, chlorine, and chloramines. Due to their weak disinfection potential, chloramines are most frequently used as secondary disinfectants.

10. Different types of microorganisms have different resistance to the disinfectants. It appears that among the concerned pathogens, the *cryptosporidium* oocysts and *Giardia* cysts are the most resistant to disinfection, followed by viruses. Bacteria are usually the most sensitive to disinfection.

11. Disinfection efficiency is strongly affected by the turbidity, pH, temperature, disinfectant demand causing materials and initial mixing. To ensure adequate disinfection, it is critical to maintain the disinfectant residual and achieve sufficient contact between microorganisms and disinfectant molecules.

12. Most disinfectants will react with various substances in water to form the disinfection by-products. The strategies for controlling the disinfection by-products include the source control, precursor removal, alternative disinfectant and air striping.

13. At present, none of disinfectants employed in practice could solve all the problems the water utilities are facing. The chlorination, in combination with the optimization of coagulation and filtration, remains the most technically effective and economically feasible approach for controlling the microorganisms from water treatment processes. When the disinfection by-products become concerned, the alternative disinfectants such as ozone should be considered.

ACKNOWLEDGMENT

This report was financially supported by the Northern River Basin Study (NRBS) through the Grant Contract to Dr. Daniel W. Smith and Stephen J. Stanley. The authors wish to thank the guidance and technical reviews by the NRBS Advisory Board.

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1.0 INTRODUCTION

In 1992, the Northern River Basin Study (NRBS) was established to address a number of environmental concerns raised by the northern river basin communities. Under this umbrella, the drinking water component was commissioned to assess the drinking water quality in the region, identify problems to be solved, and provide recommendations for improving the drinking water quality if necessary.

After extensively analyzing existing information with respect to the physical, chemical, biological and aesthetic characteristics of 189 water treatment facilities, Prince et al. (1995) found that a majority of water quality violations in the NRBS area resulted from microbial related contamination. Several sites violated or had poor bacterial quality more than 10% of the time. However, this problem was found not unique. Similar situations occurred in the North America and the rest of world (Goodrich et al., 1992). The World Health Organization (WHO, 1993) concluded that the microbial quality continues to be the most important for safe drinking water in order to protect public health. Consequently, the control of microbial water quality must always be of paramount importance and should never be compromised.

Another water quality parameter closely related to the microbiological quality of drinking water is turbidity. The study by Prince et al. (1995) showed that a number of water treatment plants have difficulties in meeting the turbidity standard adopted by Alberta Environment from the "Guidelines for Canadian Drinking Water Quality". Although turbidity itself may not necessarily have adverse health impacts on the human being, it has been used to measure the effectiveness of water treatment processes in the removal of particulate matter, in turn, to indicate the potential escape of microorganisms from the water treatment facilities. It was also concluded that high levels of turbidity can protect microorganisms from disinfection and can stimulate bacterial regrowth in water distribution systems. Thus, the turbidity should be lowered as much as possible to reduce microbial contamination.

According to the Terms of Reference outlined by the NRBS (see Appendix A), the subject of this report is to review and compile the technologies available for the removal of microbial contaminants via employing proper water treatment processes. Considering that most of the communities in the NRBS area are small in scale, an emphasis will be placed on the technologies applicable for the small water treatment systems. The primary purpose of this report is to provide information to public water system engineers, plant operators and decision-makers so that they can understand the importance of microorganism control. Furthermore, design concepts, process effectiveness, operational considerations and costs associated with the proper selection and implementation of various technologies are also explained.

2.0 OCCURRENCE AND HEALTH IMPACTS OF MICROBIAL CONTAMINANTS

This section presents a brief review of the occurrence of pathogenic microorganisms in drinking water and their impacts on the public health. Emphasis has been placed on the sources of waterborne diseases to substantiate the water treatment requirements and the factors affecting the selection of proper control methods. Relevant information can be found in separate NRBS reports (Emde et al., 1994; Prince et al., 1995).

2.1 OCCURRENCE OF PATHOGENIC MICROORGANISMS

Pathogenic microorganisms are those which can overcome the natural defense of the human body, thereby, causing diseases. In drinking water, they mostly originate from the discharges of human and animal feces through the surface runoff over the ground during storms, failures in septic or sewer systems, and sewage treatment plant effluents (Geldreich, 1986). The contamination can also occur after water leaves the treatment plant through cross-connection between the safe drinking water and a source of contamination, backflow in a water supply line, or regrowth of microorganisms in water distribution systems. Although microbial contamination occurs most often in surface water, it can also occur in ground water because of their migration in the natural environment and inflow into improperly placed or sealed wells (US EPA, 1990b).

Important properties that distinguish microbial contaminants from chemical pollutants include (WHO, 1993):

1. pathogens are discrete and not in solution;
2. pathogens are often clumped or adherent to suspended solids in water, so that the likelihood of acquiring an infective dose cannot be predicted from their concentration in water;
3. the infective dose of a pathogen depends on the invasiveness and virulence of the pathogen, and the immunity of the individual;
4. after infection, pathogens multiply in their host;
5. dose response of pathogens is not cumulative.

Table 1 lists some of pathogenic microorganisms that might be found in the NRBS area drinking water supplies, together with their significance of health risk, persistence in water bodies and important sources. The list is similar to microbial contaminants that have been identified in other regions as well (WHO, 1993; Craun, 1988). It must be pointed out that this list is not exhaustive for all potential pathogenic microorganisms in drinking water. Others may cause diseases which either have not been identified or have low public health impact worldwide. With the advance in analytical protocols and the increasing awareness of waterborne diseases, it can be expected that the number of waterborne microorganisms will continue to grow.

Table 1. Some Waterborne Pathogens in Water Supplies[a]

Pathogen	Health Significance	Persistence in Water Supplies[b]	Resistance to Chlorine[c]	Relative Infective Dose[d]	Important Animal Reservoir
Bacteria					
Campylobacter jejuni, C. coli	High	Moderate	Low	Moderate	Yes
Pathogenic E. coli	High	Moderate	Low	High	Yes
Salmonella typhi	High	Moderate	Low	High[e]	No
Other salmonellae	High	Long	Low	High	Yes
Shigella spp.	High	Short	Low	Moderate	No
Vibrio cholerae	High	Short	Low	High	No
Yersinia enterocolitica	High	Long	Low	High(?)[g]	Yes
Pseudomonas aeruginosa[f]	Moderate	May multiply	Moderate	High(?)	No
Aeromonas spp.	Moderate	May multiply	Low	High(?)	No
Viruses					
Adenoviruses	High	?	Moderate	Low	No
Enteroviruses	High	Long	Moderate	Low	No
Hepatitis A	High	?	Moderate	Low	No
Entericall transmitted non-A, non-B hepatitis viruses, hepatitis E	High	?	?	Low	No
Norwalk Virus	High	?	?	Low	No
Rotavirus	High	?	?	Moderate	No(?)
Small round viruses	Moderate	?	?	Low(?)	No
Protozoa					
Entamoeba histolytica	High	Moderate	High	Low	No
Giardia intestinalis	High	Moderate	High	Low	Yes
Cryptosporidium parvum	High	Long	High	Low	Yes
Helminths					
Dracunculus medinensis	High	Moderate	Moderate	Low	Yes

[a] Source: WHO, (1993).

[b] Detection period for infective stage in water 20 C: short, up to 1 week; moderate, 1 week to 1 month; long, over 1 month.

[c] When the infective stage is freely suspended in water treated at conventional doses and contact times. Resistance moderate, agent may not be completely destroyed; resistance low, agent completely destroyed.

[d] Dose required to cause infection in 50% of healthy adult volunteers; may be as little as one infective unit for some viruses.

[e] From experiments with human volunteers

[f] Main route of infection is by skin contact, but can infect immunosuppressed or cancer patients orally.

[g] - not known or uncertain

It is significant to note that some microbial contaminants, for example, *Giardia*, can also come from animals which serve as the reservoirs of infection for humans (Rose, 1988). These organisms have high health significance, are persistent in natural waters and have relatively low infective doses. Geldreich (1972) warned that the risks caused by these microorganisms tend to be more significant in remote areas than in areas more colonized by humans.

The microbial contaminants include the bacteria, viruses, protozoan, fungi and helminths (see Table 1). Historically, bacteria were recognized as the main waterborne microorganism in drinking water. With improvements in sewage disposal practices, development and protection of water sources and the wide use of chlorination, their health impacts have been dramatically reduced. Recently, considerable amount of attention has been directed to control the waterborne protozoan, notably, *Giardia and Cryptosporidium* (Rose et al., 1991). They are in the size range of a few micrometers and are very resistant to chlorination. However, as low as 1 cyst or oocyst may cause an infection.

2.2 OUTBREAKS OF WATERBORNE DISEASES

An outbreak of waterborne disease has been defined as an incident where two or more persons have a similar illness after the consumption or use of water and if epidemiological evidence can implicate the water as the source of illness (Craun, 1986). They were not fully understood until the development of the germ theory of disease in the nineteenth century. Several factors may affect the outbreaks of waterborne diseases: the fate of microorganisms, infectious dose, human susceptibility, water treatment effectiveness (WHO, 1993).

The occurrences of diseases that may have been waterborne in the NRBS area were examined by Emde et al. (1995). Table 2 is a compilation of the noticeable disease statistics for potentially waterborne and/or foodborne diseases during the period of 1985 to 1990. However, these records did not allow to distinguish the incidences with respect to whether water was the vehicle of transmission. Also, the reported incidences may not reflect the actual diseases due to the limitations of the database quality and completeness, and the low population of the study area. Regardless, it did provide the information that the waterborne diseases may occur in the NRBS area. Giadiasis, salmonellosis, shigellosis and hepatitis A were identified as the most frequently occurring diseases in this category.

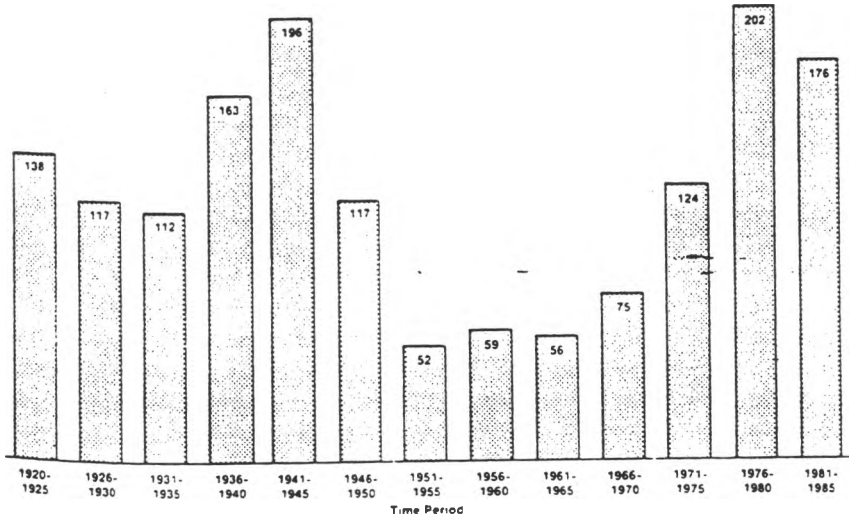
A similar observation was reported in the United States by Craun et al. (1992). Figure 1 shows annual occurrences of outbreaks of waterborne-diseases from 1920 to 1985, along with the etiologic agents. It indicates a general decline from 1946 to 1966, but a rapid rise from less than 10 outbreaks to 50 in 1980. Since then, the outbreaks continue to occur, numbered from 15 to 20 per year. This does not imply that the waterborne disease control has not been improved. Instead, the increased occurrences of annual outbreaks are probably due to both more active data collection, more aggressive incidence investigation and more types of waterborne diseases being recognized (Craun et al., 1992). Thus, the most recent data appear more representative of actual outbreaks than data collected before. As noted by Moore et al. (1994), however, the recent data may still lack accuracy due to the absence of mandatory surveillance for all states and the limited knowledge about identified diseases.

Table 2. Noticeable Diseases for Potentially Waterborne and/or Foodborne Pathogens: 1985 - 1990[a, b]

Disease	Amebiasis	Giardiasis	Salmonellosis	Shigellosis	Cryptosporidiosis	Typhoid	Legionellosis	Hepatitis A	Unspecified Diarrhea
1985	4.8	64.5	31.4	8.3	4.5	0.4	0.2	1.8	NA
1986	4.8	68.5	32.2	6.3	2.9	4.7	0.3	13.1	17.5
1987	4.7	63.3	40.0	8.7	4.7	4.7	0.6	6.0	17.4
1988	6.0	62.3	40.3	11.1	6.0	0.3	0.3	8.8	16.3
1989	5.5	58.4	41.3	6.6	1.4	0.3	0.2	8.7	18.3
1990	5.8	59.8	35.1	5.1	0.7	0.3	0.4	12.1	23.9

[a] Source: Emde et al., (1995).
[b] Reported as incidences per 10,000 population, based on the information available.

Figure 1. Annual Waterborne Disease Outbreaks for 1920 - 1985 (Source: Craun, 1986)



The incidences of waterborne diseases in the United States population has declined gradually since 1950. There are about 8 cases of illness reported per 100,000 person-years during 1920-40 to 4 cases per 100,000 person-years during 1971-80. The average number of incidences per outbreak has decreased from 572 during 1926-30 and 681 during 1961-65 to 185 incidences per outbreak during 1981-85 (see Figure 2). This is because the reported outbreaks tend to occur in small communities, affecting fewer people.

Efforts have been made to identify the etiologic agents responsible for these waterborne outbreaks. Among them, protozoa parasites are currently the most frequently identified etiologic agents (Moore et al., 1994). From 1971 to 1985, *Giardia* was the most commonly implicated pathogen (see Table 3). There were in total 452 outbreaks associated with the waterborne diseases in ground water and surface water, causing over 110,000 cases of illness. Among them, 92 outbreaks were identified by *Giardia*, which accounted for around 22 % of the cases of waterborne diseases. In the surface water alone, *Giardia* caused 52 % of total 123 outbreaks. A significant portion of waterborne disease outbreaks were caused by the Hepatitis A and gastrointestinal viruses. They produced 43 outbreaks, but only 7 % of the cases of illness. In addition, the waterborne bacterial agents continue to pose adverse health impacts in both ground water and surface water. It was shown that *Shigella*, *Campylobacte* and *Salmonella* are the most common etiologic agents.

Figure 2. **Average Number of Incidences per Waterborne Outbreaks for 1920 - 1985 (Source: Craun, 1986)**

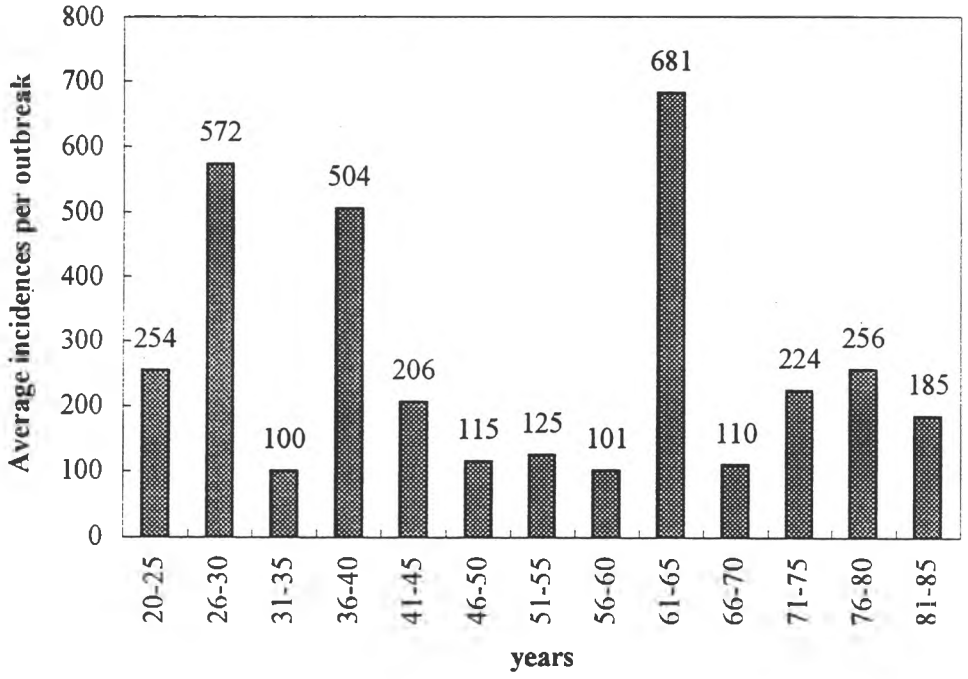


Table 3. **Total Waterborne Diseases in Ground Water and Surface Water:1971-1985**[a]

Illness	Number of outbreaks	Cases of illness
Gastroenteritis, undefined	251	61478
Giardiasis	92	24365
Chemical poisoning	50	3774
Shigellosis	33	5783
Hepatitis A	23	737
Gastroenteriris, viral	20	6524
Camppylobacterosis	11	4983
Salmonellosis	10	2300
Typhoid	5	282
Yersiniosis	2	103
Gastroenteritis, toxigenic E. coli	1	1000
Cryptosporidiosis	1	117
Cholera	1	17
Dematitis	1	31
Amebiasis	1	4
Total	502	111228

[a] Source: Craun, 1986.

Similar trend has been reported by more recent statistics from the Center for Disease Control and the US EPA. However, with the improvement in analytical procedures, the new waterborne disease agents and their significance have been realized, particularly for *Cryptosporidium*. In 1992, the same numbers of outbreaks of giardiasis and cryptosporidiosis were reported. This increased incidence of cryptosporidiosis may be contributed to the increased public awareness that the organism may cause the waterborne diseases. However, Moore et al. (1994) warned that the outbreaks associated with *Cryptosporidium* are probably still underscored because the detection procedure for this organism by certain local laboratories was not standardized. In the spring of 1993, the *Cryptosporidium* outbreak in Milwaukee, Wisconsin sounded a national alarm that waterborne diseases are a continuing threat to public health. An estimated 403,000 people had watery diarrhea. That event became the largest waterborne disease outbreak in the history of United States (Bolden and Farrell, 1994).

More than half of both the number of outbreaks and the causes of illness were reported as the unidentified AGI. This fact indicates the current difficulty with procedures permitting rapid detection of waterborne diseases, as well as the diagnosis and identification. It also signals the limitations of current technologies to control microbial contamination.

2.3 INDICATOR ORGANISMS

Because pathogens in water are usually low in concentration and a wide variety could be present, it is infeasible both economically and technologically for many water systems to isolate and determine them in routine water analysis (Metcalf and Eddy, 1991). This leads to the wide use of indicator organisms to provide indirect evidence of water contamination. An ideal indicator organism should be universally present in high numbers in the feces of humans and warm-blooded animals, and readily detectable by simple methods. It should not multiplicate in natural water. Furthermore, their persistence in water and their degree of removal in treatment of water should be similar to those of waterborne pathogens (WHO, 1993). Unfortunately, none of the indicator organisms has been able to fulfill all of these requirements. At present, the coliforms remain the most sensitive and specific ones to detect contamination and assess treatment efficiency. They are usually present in water contaminated with human and animal feces and related to the waterborne diseases. When present in water samples, they indicate the potential for recent fecal contamination, which in-turn suggests the possible presence of pathogens. In treated water, their relative numbers are primarily used to indicate the effectiveness of water treatment processes.

Although a majority of water utilities primarily rely on the coliform examination to assess the microbiological quality of water, this indicator organism also has its limitation. It was evident that specific pathogens respond differently to the various treatment processes (AWWA, 1990). Consequently, it may not be correct to assume that treatment removes all pathogenic organisms to the same degree that it removes the coliform bacteria. For example, viruses may penetrate through rapid sand filters more readily than coliform bacteria. Some viruses and cysts appear to be more persistent in water and more resistant to disinfection. A 1991 to 1992 survey on waterborne diseases showed that coliforms were detected for 88 % of outbreaks associated with bacterial, viral or unknown etiologies, but for only 33% of the protozoan outbreaks (Moore et al., 1994). The AWWA committee on the Status of Waterborne Diseases in the United States and Canada commented on the

limitations of routine coliform surveillance in preventing disease outbreaks as follows (AWWA, 1981):

> "Coliform organism identification is used as an indication of fecal contamination of water supplies and is widely employed for routine surveillance. Negative results are usually interpreted as assurance that water is free of enteric pathogens. This interpretation must be reevaluated, as outbreaks of waterborne disease have occurred in water systems where coliforms have either not been detected or have not been found to exceed standards."

Despite these limitations, the use of coliforms has been approved to help overcome a number of waterborne diseases successfully. They have offered a practical approach for monitoring the water source quality and controlling water treatment processes. The WHO (1993) stressed that the presence of *E. coli* or thermotolerant coliform bacteria can never be ignored, because the presumption remains that the water has been fecally contaminated and that treatment has been incomplete. When resources for microbiological examination are limited, coliform organisms should still be the indicator of choice.

Several different tests have been used for determining microorganisms. These include the total coliform (TC), fecal coliform (FC), heterotrophic plate count (HPC), and others. Detailed analytical procedures can be found in Standard Methods (APHA-AWWA-WPCF, 1989).

3.0 NEW AND PROPOSED DRINKING WATER REGULATIONS

Drinking water regulations which are legally enforced are the primary factors determining the water treatment goals. Thus, the understanding of relevant regulations become crucial for discussing the selection of available treatment technologies. A summary of provincial regulations governing drinking water treatment in the Northern River Basins area is presented in this section. For the purpose of comparison, the US drinking water regulations and WHO guidelines for microbiological water quality are also presented. This provides a perspective for future development of drinking water regulations in Alberta.

3.1 PROVISIONAL DRINKING WATER QUALITY REQUIREMENTS

In Alberta, the drinking water quality requirements for municipal waterworks are regulated by Alberta Environment. It is only the province that has adopted the Guidelines for Canadian Drinking Water Quality as its legal standards. This requires that all drinking water suppliers should routinely analyze for coliform bacteria (TC) and the general bacterial population (HPC). The maximum acceptable concentration for total coliforms in drinking water is zero organisms detectable per 100 mL. However, considering the heterogeneous distribution of organisms in water and the considerable variation in enumeration in analysis, the following conditions have been set for drinking water in compliance with the total coliform maximum acceptable concentration (Guidelines for Canadian Drinking Water Quality, 1993):

"1. No sample should contain more than 10 total coliform organisms per 100 mL, none of which should be fecal coliforms;
2. No consecutive sample from the same site should show the presence of total coliform organisms; and
3. For community drinking water supplies:
   a) not more than one sample from a set of samples taken from the community on a given day show the presence of coliform organisms; and
   b) not more than 10 % of the samples based on a minimum of 10 samples should show the presence of coliform organisms."

To enforce the above standards, a sampling procedure was specified based on the quality of the source water, the number of water sources, the past frequency of unsatisfactory samples, the adequacy of treatment and capacity of the treatment plant, the size and complexity of the distribution system, the practice of disinfection, and the size of the population served. The recommended minimum frequency of sampling was listed in Table 4.

Another criterion related to the microbiological water quality is turbidity. It requires that drinking water entering a distribution system should be less than 1 NTU for 95 % of samples. This is mainly based on the fact that the turbidity can affect the disinfection efficiency and interfere with the detection of microorganisms.

Table 4. Sampling Frequency for Drinking Water Suppliers in Alberta

Population Served	Minimum No. of Samples per Month
up to 5,000	4
5.000 to 90.000	1 per 1,000 of population
more than 90,000	90 + (1 per 10,000 population)

To achieve these goals, disinfection was designed to destroy pathogenic organisms and thereby prevent waterborne diseases. If disinfection alone does not satisfy the requirements, other treatment processes become necessary. However, the best technologies that can be used for different water suppliers were not specified in the guidelines.

3.2 REGULATIONS AND GUIDELINES PROMULGATED BY THE US AND WHO

In the United States, the federal government develops national drinking water regulations to protect the public health and welfare. Under the 1986 Amendments to Safe Drinking Water Act, the US EPA promulgated the Surface Water Treatment Rule, the Enhanced Surface Water Treatment Rule, Groundwater Disinfection Rule and the Coliform Rule to specify the microbiological treatment requirements (see Table 5). It is also required to propose the best available technology for the purpose of complying with these regulations. For the total coliforms, no more than 5 % of the samples per month should be positive if the more than 40 samples are collected. For systems collecting fewer than 40 samples per month, no more than 1 sample per month should be positive. If a repeat total coliform sample is fecal coliform or *E. coli*-positive, or verse vice, it is also considered to be in violation of the regulation for total coliforms. For turbidity, the grab samples at least 4 hours or continuous monitoring are required. The systems should demonstrate the treatment effectiveness of at least 80 % turbidity reduction or producing less than 0.5 NTU effluent, depending on raw water turbidity level. For all the groundwater systems, a detectable disinfectant residual in the distribution system should be maintained continuously or the HPC be less than 500/mL. For surface water or ground water under direct influence of surface water, treatment technologies were stipulated to control microbiological contaminants in drinking water systems. Based on the Surface Water Treatment Rule, water treatment systems should provide at least a 3 log removal/inactivation of *Giardia* and a 4 log removal/inactivation of viruses via filtration and disinfection (US EPA, 1989). However, a failure to pass the Surface Water Treatment Rule in the 103rd US congress forced the US EPA to propose the enhanced Surface Water Rule. It is expected that the enhanced surface water treatment will expand the treatment requirements to provide the protection against *Cryptosporidium*. In addition, it is expected that an additional one log removal of *Giardia* may be required (Pontius, 1995).

Table 5. Drinking Water Regulations Promulgated by US EPA[a]

Contaminants	Regulation[b]	Status	MCLG, mg/L[c]	MCL[d]	BAT[e]
Cryptosporidium	ESWTR	Proposed	Zero	T	C-F, SSF, DEF, DF, D
E. coli	TCR	Final	Zero	†	D
Fecal coliform	TCR	Final	Zero	†	D
Giardia lamblia	SWTR	Final	Zero	T	C-F, SSF, DEF, DF, D
HPC	SWTR	Final[f]	Zero	T	C-F, SSF, DEF, DF, D
Legionella	SWTR	Final[f]	Zero	T	C-F, SSF, DEF, DF, D
Total coliforms	TCR	Final	Zero	‡	D
Viruses	SWTR	Final[f]	Zero	P	C-F, SSF, DEF, DF, D
Turbidity	SWTR	Final	Zero	T	C-F, SSF, DEF, DF, D

[a] Adapted from Pontius, 1995

[b] ESWTR - Enhanced Surface Water Treatment Rule, TCR - Total coliform Rule, SWTR - Surface Water Treatment Rule.

[c] MCLG - maximum concentration level goals.

[d] MCL - maximum concentration level.

[e] BAT - best available techniques, C-F - coagulation and filtration, D - disinfection, DEF - diatomaceous earth filtration, DF - direct filtration, SSF - slow sand filtration.

[f] Final for systems using surface water; also being considering for ground water.

T - treatment technique, P - performance standard.

† - if a repeated total coliform sample is fecal coliform- or *E. coli*-positive, the system is in violation of the MCL for total coliforms. The system is also in violation of the MCL for total coliforms if a routine sample is fecal coliform- or *E. coli*-positive and is followed by a total coliform-positive repeat sample.

‡ - No more than 5 percent of the samples per month may be positive. For systems collecting fewer than 40 samples per month, no more than 1 sample per month may be positive.

The frequency of sampling for total coliforms by the U.S. EPA regulations are summarized in Table 6. It is based on the population served by a particular water system. When the sample is identified as total coliforms-positive, additional samples should be taken. Realizing the difficulty in monitoring the *Giardia* and viruses, the CT_{10} concept was developed to measure the effectiveness of disinfection. It assumed that the efficiency of chemical disinfection is a function of the product CT_{10}, where C is the concentration of disinfectant in water (mg/L) and T_{10} is the contact time the microorganisms are exposed to the disinfectant. The required CT_{10} values for different disinfectants at different temperature and pH can be found in Guideline Manual (US EPA, 1989).

The best available treatment technologies were specified to implement the regulations (Pontius, 1995). These include coagulation, filtration and disinfection. However, whether these processes should be used in combination must be evaluated on a case-by-case basis. The impacts of these new regulations, particularly on small systems, will concern some of fundamental aspects of water treatment. Many systems will be required to improve treatment for the removal of microorganisms (Cromwell et al., 1992).

Table 7 summarizes the microbiological drinking water quality recommended by the World Health Organization. The minimum sampling frequencies in the distribution system based on the population served are also incorporated in Table 6. It requires that no detectable *E. coli*, thermotolerant coliform or total coliforms should be present in drinking water. Otherwise, immediate action, including repeat sampling, should be taken. In the case of sufficient samples being analyzed, the total coliforms should be present in less than 5 % of samples throughout any 12-month period.

Table 6. Sampling Frequency for Community Water Systems Required by WHO and US EPA[a]

Population served	Minimum routine samples to be taken monthly[b]
WHO	
Less than 5.000	1
5,000 to 100,000	1 per 5.000 population
More than 100,000	1 per 10,000 population plus 10 additional samples
US EPA	
25 to 1.000	1
1,001 to 2,500	2
2,501 to 3,300	3

[a] Adopted from US EPA, (1989) and WHO, (1993)

[b] Applicable for community water systems using surface water, or ground water under the direct influence of surface water.

Table 7. WHO Recommended Bacteriological Quality of Drinking Water[a,b]

Organisms	Guideline value
All water intended for drinking	
E. coli or thermotolerant coliform bacteria[c,d]	Must not be detectable in any 100-mL sample
Treated water entering the distribution system	
E. coli or thermotolerant coliform bacteria[c]	Must not be detectable in any 100-mL sample
Total coliform bacteria	Must not be detectable in any 100-mL sample
Treated water in the distribution system	
E. coli or thermotolerant coliform bacteria[c]	Must not be detectable in any 100-mL sample
Total coliform bacteria	Must not be detectable in any 100-mL sample. In the case of large supplies, where sufficient samples are examined, must not be present in 95% of samples taken throughout any 12-month period.

[a] Source: WHO, (1993).

[b] Immediate investigation must be taken if either *E. coli* or total coliform bacteria are detected. The minimum action in the case of total coliform bacteria is repeat sampling; if these bacteria are detected in the repeat sample, the cause must be determined by immediate further investigation.

[c] Although E. coli is the more precise indicator of fecal pollution, the count of thermotolerant coliform bacteria is an acceptable alternative. If necessary, proper confirmatory tests must be carried out. Total coliform bacteria are not acceptable indicators of the sanitary quality of rural water supplies, particularly in tropical areas where many bacteria of no sanitary significance occur in almost all untreated supplies.

[d] It is recognized that, in the great majority of rural water supplies in developing countries, fecal contamination is widespread. Under these conditions, the national surveillance agency should set medium-term targets for the progressive improvement of water supplies, as recommended in Volume 3 of *Guidelines for drinking-water quality*.

4.0 SOLUTIONS TO MICROBIAL CONTAMINATION IN WATER: OVERVIEW

4.1 BASIC APPROACHES FOR MICROBIAL CONTAMINANT CONTROL

The supply of safe drinking water at the most attractive overall costs is a complex task. It can be achieved only after the a careful assessment of water sources and creative implementation of treatment systems. For microbiological contaminants, the multiple barrier concept has been evolved to provide a safeguard against waterborne transmission of diseases. Under the multiple barrier concept, reliance is placed on the multiple steps of treatment and multiple points of control between the sewage discharges and water supply intakes. The philosophy underlying this concept is that any type of treatment and management options are fallible, so natural barriers should be maintained wherever possible and multiple water treatment processes should be considered. The approach is illustrated in Figure 3. Excellent presentations related to this topic can also be found in Geldreich (1986) and Craun (1988).

Figure 3. Illustrative Diagram of Multiple Barrier Concept[a]

Source	Fecal Coliforms (FC)	
Human fecal coliform discharge	1,950,000,000 FC per person/day	
	Fecal Coliforms per 100 mL	
Municipal raw sewage		
Sewage treatment reductions		
	Cumulative Reduction, %	**FC Surviving**
Primary	50	4,130,000
Secondary	80	1,652,000
Tertiary	90	165,000
Disinfection	99.99	800
Self purification and effluent dilution	10 to 50 %	400 to 700
Water supply treatment		
	Cumulative Reduction, %	**FC Surviving**
Raw water storage	50	200 to 350
Coagulation-sedimentation	60	80 to 140
Filtration	99.9	0.8 to 1.4
Disinfection	99.9999	0.00008 to 0.00014

[a] Source: Geldreich, 1986.

As mentioned above, the first step of the multiple barrier concept approach to control pollution is the collection of all waste for treatment at specified sites. Experience demonstrates that this barrier may result in a substantial reduction in the fecal contaminants in numerous water supplies and recreation lakes. The next barrier is natural self purification common to all components of the aquatic environment. The purification mechanisms include sedimentation, nutrient limitations, competitive microorganisms, predators, aeration, sunlight exposure, water temperature, water pH and retention time in the water body. However, The fragile nature of the natural barriers warrants the necessity that appropriate water treatment should be used to remove and inactivate waterborne pathogens, especially protozoa. This is because the natural systems usually have limited capacity to purify these types of pathogens due to their persistence in the environment. Surface runoff, feedlots and a host of other activities may contribute a significant portion of pollution into a water course that may be the source water for a water supply. Even the most "pristine" watershed can be contaminated since numerous wild and domestic animals have been identified as important primary or intermediary sources of infection for giardiasis and other waterborne diseases. This problem has important implications for water treatment because it is impossible to exclude infected animals from the watershed. Therefore, effective water treatment, in most cases, is essential in the prevention of waterborne diseases.

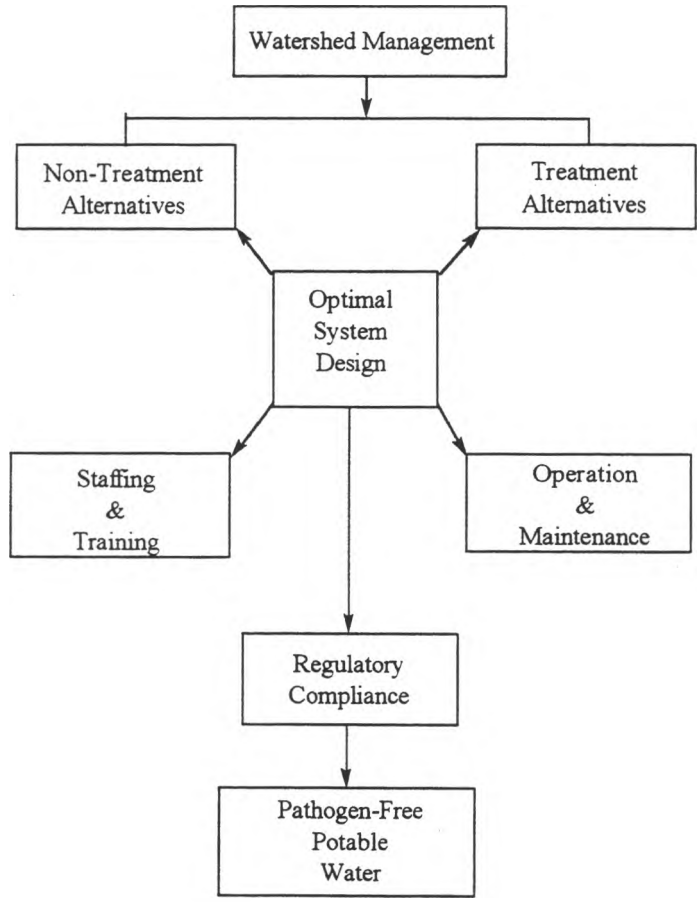
In water treatment, the multiple barrier concept involves the use of multiple water treatment processes to ensure a safe public water supply. At conventional rapid sand filtration plants. coagulation, flocculation and sedimentation provide the first treatment barrier for the removal of microorganisms; the second is provided by filtration. Disinfection is the last line of defense barrier to inactivate the remaining microorganisms. For the disinfection to be an effective barrier, the preceding barriers must reduce the microbiological population and remove possible interfering substances so that disinfection will be most efficient. This is particularly important for removing protozoa contaminants from water because they are resistant to chlorination employed in normal water treatment practices. Such an importance has been stressed by AWWA Committee on the Status of Waterborne Diseases in the US and Canada as follows:

> "Simple disinfection as the only treatment for surface water sources is ineffective in preventing waterborne transmission of giardiasis. All surface water should receive pretreatment and filtration in addition to disinfection. Both pressure and gravity sand filters have proven ineffective in removing *Giardia* cysts under conditions of poor, or simple causal, operation. This has occurred primarily in systems where the raw water turbidity was low. Under these conditions, turbidity removal has been achieved without coagulants but passes *Giardia* cysts. Outbreak data, engineering experience, and filtration theory indicate that *Giardia* cysts can be reduced dramatically by properly functioning conventional sand filters, but the water must be effectively pretreated before filtration. Effective pretreatment includes coagulation, flocculation, and settling prior to filtration, or, if the settling process is not used, the addition of appropriate chemicals for conditioning the water or filter media. ... [S]afe drinking water can be assured only by properly designed and operated ... plants that utilize coagulants or filter aids in addition to disinfection."

Thus, providing the public with a microbiologically safe water involves both the management of water resources and the use of effective water treatment. Accordingly, both non-treatment alternatives and treatment alternatives may be needed (SMC Martin, 1983). This integrated approach

is diagrammed in Figure 4. Based on the Terms of Reference stipulated for this report, further discussion will be limited to the treatment alternatives.

Figure 4. Integrated Approach for Control of Microbial Contamination in Drinking Water[a]



[a] Source: SMC Martin, 1983.

4.2 ISSUES SPECIFIC TO THE NORTHERN RIVER BASINS COMMUNITIES

In the Northern River Basins area, a majority of communities are small in scale and located in remote regions. For these small community water treatment systems, a number of particular problems exist in providing drinking water that meets the requirements of new regulations (Cromwell et al., 1992; Tamburini and Habenicht, 1992). First of all, small systems are often identified as the most frequent violators of drinking water regulations. Microbiological violations account for the vast majority of failures. Second, small systems have a limited financial base for the installation and operation of treatment. Construction of facilities with limited resources is a challenge. Economical scales are often favorable to the large systems. As a result, imaginative and creative solutions are needed. Even if the treatment processes have been constructed successfully, the production of high quality water can be achieved only when the plants are operated effectively. Thus, resources are also required to pay for the operators and plant operation and maintenance. Because of limited revenues, operation expertise, recruitment and retention, and staff time availability represent other difficult challenges for small systems. Finally, most of water treatment technologies have been developed on the large scale basis, and thus penalize small scale applications.

Besides the small scale of the water treatment facilities for most northern Alberta river basins communities, they are located in a cold region with an average winter temperature of around -25 °C. As the performance of most water treatment processes are temperature related, the technologies and experience developed from the warm environment may not be suitable in the cold environment. For example, a slower rate of chemical disinfection occurs as the temperature drops. Consequently, it is necessary to extend the contact time or increase the disinfectant residuals in water to ensure a desired process performance. Unfortunately, less attention has been received for the development of cold water treatment technologies from research and industrial activities.

With the challenges described above, the treatment processes must have low construction and operating costs, simple operation, adaptability to part-time operation, low maintenance, and no serious residual disposal problems. As a result, construction of custom-designed plants made of reinforced concrete is often not possible. Instead, alternatives such as package plants housed in steel buildings may be the affordable installations. Also, treatment processes that require frequent modification, adjustment, and monitoring by an operator may not be the best choice for a small system. Likewise, processes that have high chemical or energy requirements are not suitable to small systems, because high operating costs that continue day after day, year after year, will consume the limited revenues needed for other community projects or programs.

4.3 OVERVIEW OF TREATMENT TECHNOLOGIES

Table 8 lists the treatment options developed to assist in the microbiological contaminants from drinking water treatment processes, along with the stage of the technologies development and the suitability to different treatment plant sizes. Emerging technologies have proven themselves in the laboratory, but are not yet widely used in the water industry. Established technologies are commonly used in the field. Detailed discussions of all technologies are provided in Sections 5.0 to 7.0, as follows:

1. Prefiltration for treatment of primarily turbidity and color - Section 5.0,
2. Filtration for removal of turbidity and parasites - Section 6.0,
3. Disinfection for inactivation of pathogenic microorganisms, including *Giardia* cysts, *Cryptosporidium* oocysts, bacteria and viruses - Section 7.0, and
4. Package plants - Section 8.0.

It should be pointed out that water treatment usually consists of several unit operations and processes. The treatment by the upper stream processes will significantly affect the performance of subsequent processes. Therefore, it is necessary to consider all the water treatment processes employed at the plant as a whole. An evaluation of each individual process for removal of microorganisms from water should be based on both its achievable efficiency and its impacts on subsequent processes.

Table 8. Overview of Treatment Alternatives[a]

Treatment	Stage of acceptability	Size suitability	Comments
Filtration			
Conventional filtration	Established	All	Most common; adaptable for adding other processes
Direct filtration	Established	All	Lower cost alternative to conventional filtration
Slow sand filtration	Established	Especially small, but all sizes	Operationally simple; low cost, but requires large land areas
Package plant filtration	Established	Mostly small	Compact; variety of process combinations available
Diatomaceous earth filtration	Established	Mostly small	Limited applicability; potentially expensive for small systems
Membrane filtration	Emerging	Mostly small	Experimental, expensive
Cartridge filtration	Emerging	Small	Experimental, expensive
Disinfection			
Chlorine	Established	All	Most widely used; concerns about health effects of by-products
Chlorine dioxide	Established	All	Relatively new to the US; concerns about inorganic by-products
Monochloramine	Established	All	Secondary disinfectant only; some by-products concerns
Ozone	Established	All	Very effective but requires a secondary disinfectant
Ultraviolet radiation	Established	All	Simple, no harmful by-products but requires a secondary disinfectant
Advanced oxidation (O_3+H_2O_2; O_3 + UV)	Emerging	All	Not much information concerning disinfection aspects of this process

[a] Adopted from US EPA, (1990a).

5.0 PREFILTRATION

Prefiltration processes in water treatment may include the coagulation, flocculation, sedimentation, or some combinations of the three. The use of these processes is primarily to remove the particulate matter in water, condition the characteristics of remaining particulates to enhance their removal by filtration, and reduce the disinfectant demanding compounds to ensure disinfection efficiency. Along with the removal of particulates, microorganisms can also be removed to a certain degree by sedimentation. Therefore, pretreatment processes are integral components of water treatment with respect to the removal of microorganisms. In this section, the fundamentals of these prefiltration processes will be briefly presented. This is followed by a review of process performances in terms of the removal of the turbidity and the microorganisms including bacteria, viruses and protozoan in water. Finally, the various issues affecting the process applicability in the Northern River Basins area will be evaluated to ensure an appropriate design and operation of the facilities.

5.1 GENERAL

5.1.1 Coagulation

Coagulation is a process for combining small particles into larger aggregates. In doing so, coagulants are injected into water to destabilize the fine particles, allowing them to stick together and form larger, easily removed particles. This is accomplished by an initial flash mixer which ensures intimate contact between the chemicals added and particulates. The process can be considered as three separate and sequential steps: coagulant formation, particle destabilization and interparticle collisions.

Two principal coagulants used in water treatment practices are alum and iron (III) salts, with the alum probably having the most widespread use. The actual chemical species operative in the process, however, are their hydrolysis products. These products are formed during and after their being mixed with the water. For example, alum can be hydrolyzed into insoluble precipitates, involving a series of reactions with the hydroxyl ions (see Table 9). As shown, three polymeric species [$Al_2(OH)_2^{+4}$, $Al_3(OH)_4^{+5}$, $Al_{13}O_4(OH)_{24}^{+7}$] and five monomers [Al^{+3}, $AlOH^{+2}$, $Al(OH)_2^{+}$, $Al(OH)_3$, $Al(OH)_4^{-}$] are in equilibrium with freshly precipitated $Al(OH)_3$ (amorphous). Figure 5 shows the solubility diagram of aluminum at equilibrium with gibbsite and amorphous $Al(OH)_3$ as a function of pH. Aluminum is least soluble at a pH of about 6.2. At higher pH values (pH>8), the principle soluble species at equilibrium is the monomeric anion $Al(OH)^{4-}$. At lower pH values (pH <6), the dominant soluble species are the cationic monomers such as Al^{+3} and $Al(OH)^{+2}$. However, in this pH range, aluminum speciation in water is kinetically controlled and depends on many factors.

Other coagulants have also been used in water treatment. As early as 1937, Baylis introduced activated silica as a coagulant aid to improve the treatability of water from Lake Michigan in the combination with alum during cold winter months. A more recent development was the preparation and use of polymeric inorganic coagulants such as polyaluminum chloride, polyaluminum silicate

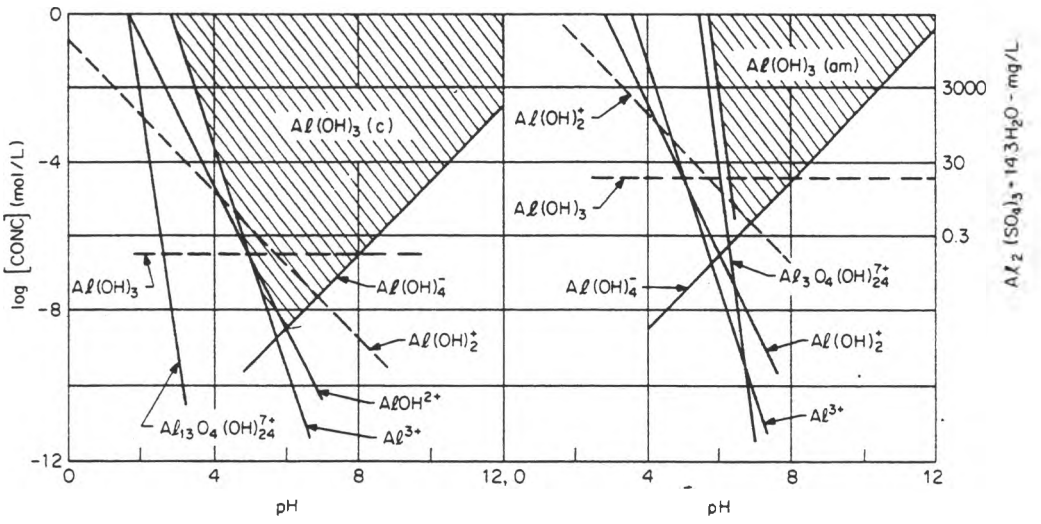
sulfate, and polyferric chloride. Their success in water treatment has been well documented in numerous reports, particularly for cold, soft and turbid water.

Table 9. Reactions of Alum in Water[a]

Reaction	log *K* (25 °C)
$Al^{3+} + H_2O = AlOH^{2+} + H^+$	-4.97
$AlOH^{2+} + H_2O = Al(OH)_2^+ + H^+$	-4.3
$Al(OH)_2^+ + H_2O = Al(OH)_3 + H^+$	-5.7
$Al(OH)_3 + H_2O = Al(OH)_4^- + H^+$	-8.0
$2Al^{3+} + 2H_2O = Al_2(OH)_2^{4+} + 2H^+$	-7.7
$3Al^{3+} + 4H_2O = Al_3(OH)_4^{5+} + 4H^+$	-13.94
$13Al^{3+} + 28H_2O = Al_{13}(OH)_{24}^{7+} + 32H^+$	-98.73
$Al(OH)_3(am) = Al^{3+} + 3OH^-$	-31.5
$Al(OH)_3(c) = Al^{3+} + 3OH^-$	-33.5

[a] Adapted from AWWA, 1990.

Figure 5. Solubility Diagrams of Alum in Water (a. gibbsite; b. amorphous)[a]



[a] Source: AWWA, 1990.

Another category of coagulants are synthetic organic polymers, which are mostly used as coagulant and filtration aids. They are made either by homopolymerization of the monomer or by the copolymerization of two monomers. Therefore, organic polymers can be manipulated to have varying molecular weights, charge groups, charge density and structure. Because of the commercially available polymers with a wide spectrum of characteristics and the complexity of interactions between the polymers and particles, the current methods to select a most appropriate polymer at a given condition is still based on trial and error tests, although efforts have been made to develop rational selection procedures.

The interactions between the coagulants and the particles in water are complex. It was recognized that the destabilization of particles could occur in four mechanisms: (1) double layer compression, (2) charge neutralization, (3) interparticle bridging and (4) enmeshment (AWWA, 1990). A thorough review on this topic can be found in Stumn and O'Melia (1968). Briefly, the double layer compression occurs due to counterions compressing the double diffuse layers surrounding the particles, thus, allowing the short-range attractive forces (primarily London-van der Waals forces) to produce successful collisions between particulates. The effectiveness of the ions can be described by the Schulze-Hardy rule, which states that the amount of a coagulant concentrations required for destabilization of particles is inversely proportional to the sixth power of the charge on the ion. Thus, for the natural particles such as the microorganisms which are negatively charged at a neutral pH, trivalent ions such as Al^{3+} and Fe^{3+} are more effective than di- or mono-valent ions.

Charge neutralization occurs by adsorption of opposite charged coagulants on particle surfaces. This leads to a reduction in the electrostatic repulsive forces between the particles. Different from the double layer compression, only a small amount of coagulants are usually required to achieve the destabilization of particles. If the coagulants are overdosed, the net charge on the particles may be reversed, as a result, the particles will be destabilized in water. In practice, efficient charge neutralization is controlled by measuring the zeta potential of particles. It is usually accepted that the particles are destabilized if the zeta potential is less than 15 mV.

When a metal salt such as alum or ferric chloride is added to water in an amount sufficiently high to cause the precipitation of a metal hydroxide, particles can be enmeshed in these precipitates as they are formed. This type of removal mechanism is called the enmeshment mechanism. The mechanism is dominant in water treatment applications where pH values are generally maintained from pH 6 to 8 and alum or iron salts are used at a concentration exceeding saturation with respect to the formation of amorphous metal hydroxide. For water with low turbidity and cold temperature, solids could be added to the water to be treated to facilitate the precipitation of metal hydroxide.

The interparticle bridging concept was developed to explain the destabilization of biocolloids and other particulate systems with the same surface charge. It occurs when segments of a polymer chain adsorb on more than one particle, thereby, linking the particles together. Schematically, when a polymer molecule comes into contact with colloidal particles, some of the reactive groups on the polymer adsorb at the particle surface, leaving other portions of the molecule extending into the solution. If a second particle with some vacant adsorption sites contacts these extended portions, a bridge is created. Effective bridging requires that adsorbed polymers extend far enough from the particle surface to attach to the particles, and also that some free surface is available for adsorption of the extended segments. If the excess polymer is used, the particles are restabilized by surface

saturation. LaMer and Healy (1963) concluded that an optimum dose of polymers should cover around 50 % of particle surface. It is believed that this mechanism is the major mechanism controlling the aggregation of bacterial and algae suspensions (Tenney and Stumn, 1965).

In fact, these four mechanisms may occur simultaneously in coagulation processes. The dominant mechanism depends on the type and dose of coagulants, the concentration and properties of particles and water quality. In general, the enmeshment mechanism is the most important when the inorganic coagulants are used in water with variable turbidity. The interparticle bridging and neutralization mechanisms are significant when the inorganic or organic polymers are used as coagulation or filtration aids. In some cases, a combination of inorganic coagulants and polymers may provide the most effective solution to remove the particles from water at the lowest cost.

To successfully use the coagulants in water treatment, the coagulants should be adequately dispersed into water to promote more uniform distribution of polymers. Recently, attempts were made to define the mixing requirements on the basis of the dominant mechanisms of coagulation (AWWA, 1990). It was concluded that a rapid dispersion for charge neutralization is imperative so that the hydrolysis products that develop in 0.01 to 1 s will cause the destabilization of the colloid. The optimum mixing intensity is the velocity gradient G values from 700 to 1000 s^{-1} or from 3000 to 5000 s^{-1}. Accordingly, both backmixers and in-line blenders should be used. In contrast, for the enmeshment mechanism where the hydroxide formation is in the range of 1 to 7 s, extremely short dispersion times and high intensities of mixing are not so crucial. In this case, little difference in the turbidity for settled water was noted with rapid mixing intensities from 300 to 16000 s^{-1}. For polymer applications, it was identified that the promotion of interparticle bridging and the control of possible breakup of aggregated floc caused by excessive turbulence are the most important. The optimum mixing intensity may range from 300 to 800 s^{-1}, depending on the molecular weight of polymers.

Temperature also plays an important role in coagulation, particularly for water treatment plants in cold climates. In general, lowering the temperature increases the density and viscosity of water and reduces the chemical kinetics of coagulants, thereby, decreasing the efficiency of coagulation. Few studies have been conducted on coagulation of very cold water (0 to 4 °C). Morris and Knocke (1984) have shown that the temperature had great effects on coagulation with alum. Although the effects were lower with ferric chloride, they were still significant. Some alleviation of these effects can be obtained by: (1) changing coagulants from alum to ferric chloride or polymeric iron chloride; and (2) switching coagulation from sweep coagulation to adsorption-charge neutralization by adding solids such as bentonite clay.

5.1.2 Flocculation

Flocculation is another particle contact process with less intense mixing to facilitate the formation of flocs that can be easily settled out. During the flocculation, three principal modes of particulate transport are identified: (1) Brownian motion, (2) differential movement due to fluid shear, and (3) differential movement from particle sedimentation. Their relative importance is determined by the particle size and the mixing intensity. For small particles, e.g. diameter less than 1 μm, Browning motion is generally predominant, while for large particles the last two become more important. Ideally, the mixing must be thorough enough to encourage interparticle contact, but gentle enough to

prevent disintegration of existing flocculation particles. Detailed rationales for mixing intensity are described by AWWA (1990).

Besides the size of flocs, the floc density is another important parameter which affects floc settling velocity. It is determined by the particle composition, mixing intensity and the dosages of coagulants. As the mixing intensity used in the flocculator is increased, the floc density will increase. On the other hand, the steady-state, characteristic floc size will decrease. Also, the floc density increases as the amount of coagulant relative to the concentration of particulate matter decreases. However, reducing the amount of coagulant also reduces the floc volume concentration, which adversely affects the flocculation performance. These relationships link the floc formation in the flocculator to the floc removal in the sedimentation process. A trade-off between the size and the density of flocs exists, which dictates the selection of the optimum mixing.

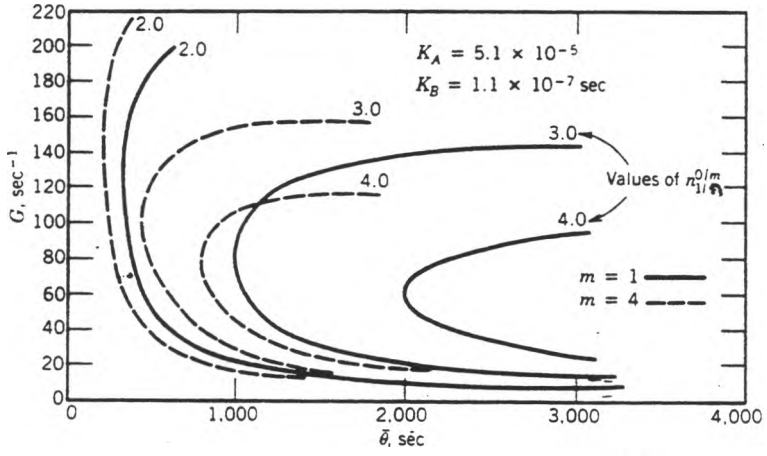
The configuration of the flocculation tank also affects the formation of flocs. Argaman and Kaufman (1970) applied the rate of aggregation and breakup to a flocculator system with the erosion of flocs larger than the Kolmogoroff microscale. A theoretical analysis was plotted in Figure 6, which relates the total residence time and the velocity gradient to the system performance. Two important conclusions can be drawn: (1) a minimum time exists below which no additional flocculation occurs, whatever the mixing intensity, and (2) compartmentalization significantly reduces the overall detention time required for the same degree of treatment. In engineering, the flocculator is operated with higher mixing intensity in the first compartment and progressively smaller mixing intensity in the subsequent compartments. The higher mixing intensity cause a rapid transformation of the primary particles into higher density flocs, and the lower mixing intensity causes the buildup of progressively larger size flocs for better settling. In this way, the process of flocculation can be improved significantly.

Several types of flocculators are used for flocculation. The most common flocculators used in practice are the mechanical mixers. Paddle and flat blade turbine mixers are known as low-energy mechanical mixers. They are used to maximize floc size rather than floc density. Axial flow propellers or turbines are known as the high energy mechanical mixers. They create smaller and denser flocs which settle faster and occupy less volume in the filter bed than the larger floc created by low energy mixers. They also produce uniform turbulence and are simpler to install and maintain.

5.1.3 Sedimentation

Sedimentation is a mechanically simple process in which particles are settled out by gravity. The basic design requirement is that the water must flow through the basin at a velocity slow enough to permit the particles to settle to the bottom before the water exits the basin. The process efficiency is a function of both particle size and density and the water temperature. In general, increasing the size or density increases the settling velocity, thereby, facilitating removal. Lowering the water temperature increases the density and viscosity of water, consequently, adversely affecting the sedimentation. In most cases, the sedimentation is preceded by flocculation and followed by filtration. Detailed fundamentals of sedimentation have been described by AWWA (1990).

Figure 6. Flocculator Performance Curves with Aggregation and Breakup



[a] Source: JMM, 1985.

Sedimentation can be made more efficient with devices known as tube settlers, which are used in newer installations and can be easily retrofitted in existing sedimentation tanks. The devices channel the flow through inclined bundles of plastic tubes, minimizing the detrimental large scale fluid motion found in conventional water treatment. Another feature is to decrease the distance the particles must settle before they are incorporated into a mass of settled particles. The detailed theory and design of tube settlers have been discussed by Yao (1973) and Culp et al. (1969).

The most common types of sedimentation facilities include the horizontal flow basins (either rectangular or circular) and upflow solids contact clarifiers. Their advantages and disadvantages, along with design criteria, are summarized in Table 10. It should be noted that these design criteria should be modified according to the influent quality and the desired effluent quality. For example, the sedimentation facilities should be operated at a lower loading rate for a cold, turbid water experienced in some cold regions.

5.2 EVALUATION OF PROCESS PERFORMANCES

The controlling of microorganism in drinking water by prefiltration processes has been recognized for many years. However, much less quantitative information is available to assess their performance, because the main purpose of these processes in water treatment is to remove turbidity causing materials instead of microorganisms. Also, most of the published results are the overall efficiency of a sequence of treatment, it is difficult to separately evaluate the removal efficiency for each of individual processes. Table 11 summarizes the representative data for bacterial removal by prefiltration processes.

Table 10. Comparison and Design Criteria of Various Sedimentation Facilities[a]

Type of Clarifier[b]	Design criteria	Advantages and Disadvantages
Rectangular basin (Horizontal flow)	Surface loading: 20 to 60 $m^3/m^2 \cdot d$ Water depth: 3 to 5 m Detention time: 1.5 to 3 h Width to length ratio: 1:5	More tolerance to shock loads Predictable performance under most conditions Easy operation and low maintenance costs Easy adaptation to high-rate settler modules Subject to density flow creation in the basin Requires careful design of inlet and outlet structures Usually requires separate flocculation facilities
Upflow (radial)	Surface loading: 30 to 45 $m^3/m^2 \cdot d$ Water depth: 3 to 5 m Settling time: 1 to 3 h Weir loading: 170 $m^3/m \cdot d$	Economical compact geometry Easy sludge removal High clarification efficiency Problems of flow short circuiting Less tolerance to shock loads Need for more careful operation Limitation on particle size unit May require separate flocculation facilities
Reactor-clarifier	Surface loading: 50 to 75 $m^3/m^2 \cdot d$ Flocculation time: ~20 min Settling time: 1 to 2 h Weir loading: 170 to 350 $m^3/m \cdot d$ Upflow velocity: >50 mm/min	Flocculation and clarification incorporated in one unit Good flocculation and clarification efficiency due to a seeding effect Some ability to take shock loads Requires greater operator skill Less reliability than conventional clarifiers due to a dependency on one mixer Subject to upsets from thermal effects
Sludge blanket	Surface loading: 50 to 75 $m^3/m^2 \cdot d$ Flocculation time: ~20 min Settling time: 1 to 2 h Weir loading: 170 to 350 $m^3/m \cdot d$ Upflow velocity: >50 mm/min Slurry circulation rate: up to 3 to 5 times the raw water inflow rate	Good softening and turbidity removal Compact and economical design Adaptable to limited change in flowrate and raw water quality Sensitive to shock loads Sensitive to temperature change 2 to 3 days required to build up the necessary sludge blanket Plant operation dependent on a single mixer Higher maintenance costs and a need for greater operator skill

[a] Source: JMM. (1985).

[b] Reactor-clarifiers and sludge blanket clarifiers are often considered as one category: solid-contact clarifiers

Table 11. Bacterial Removal from Water by Prefiltration Processes[a]

Materials	Turbidity, %	Total coliform, %	Acid-fast organisms, %	Yeast, %	Optimum conditions
Alum, kaolinite clay and 1% raw wastewater	96 to 97	97 to 98	91 to 99.1	80 to 99	10 mg Al_2O_3/L, pH 7, 20 to 50 min, 25 to 50 rpm
Alum, kaolinite clay and 1% raw wastewater	80 to 98	93 to 99	89 to 93	89 to 98	10 mg Al_2O_3/L, pH 7, 20 to 50 min, 25 to 50 rpm
Alum, river water	85 to 95	93 to 98	>93	92 to 98	5 mg Al_2O_3/L, pH 7, 30 to 50 min, 30 to 50 rpm
Ferric chloride, kaolinite clay and 1% raw wastewater	95 to 99	98 to 99.5	>95	97 to 99	30 mg Fe_2O_3/L, pH 9.6, 30 to 50 min, 30 to 50 rpm
Ferric chloride, river water	70 to 98	60 to 97	>90	78 to 94	30 mg Fe_2O_3/L, pH 7.9, 30 to 50 min, 30 to 50 rpm
Lime, kaolinite clay and 1% raw wastewater	85 to 96	99.97 to 99.98	>99.8	98 to 99	300 mg $CaCO_3$/L, pH 10.9, 40 to 50 min, 40 to 50 rpm
Lime, river water	75 to 80	99.7 to 99.97	N/A	97 to 99.8	500 mg $CaCO_3$/L, pH 10.7, 40 to 50 min, 35 to 50 rpm

[a] Adapted from Haas et al., 1985.

As early as the end of last century, pilot plant tests at Pittsburgh, Pennsylvania (Logsdon and Rice, 1985) were used to determine the removal efficiency of plate count bacteria by coagulation, flocculation and sedimentation. With a hydraulic detention time from 35 to 40 minutes, the monthly average bacterial removal ranged from 24 to 55 %, at a variety of alum doses. Considerable variation was observed in daily results, and sometimes plate count bacteria concentrations in settled water were as high as those in the raw water.

Three decades later, Streeter (1927, cited by Logsdon and Rice, 1985) evaluated bacterial removal at full scale plants. It was reported that the prefiltration processes could result in a removal of bacteria ranging from 46 to 83 %. The better removals reported by Streeter might reflect the use of sedimentation tank with longer hydraulic detention time of several hours.

More recently, Cummins and Nash (1978, cited by Logsdon and Rice, 1985] reported that total coliform removal by coagulation and sedimentation at a water treatment plant was 42 % when these processes had been preceded by a 48-hour raw water storage reservoir. Haas et al. (1985) reported that total coliform removals by coagulation and sedimentation ranged from 60 % to 99.5 % when aluminum or iron salts were used under optimum condition in jar test. For other indicator organisms such as acid-fast organisms and yeasts, similar removal efficiencies could be achieved. Logsdon and Rice (1985) studied the capability of conventional water treatment to remove the bacteria at a US EPA pilot plant in Cincinnati. Raw water came from the Ohio River, with the turbidity normally ranging from 5 to 25 NTU. It was found that the removal of heterotrophic plate count organisms by sedimentation ranged from 34 % to 94 %. More significantly, microorganism removal by sedimentation was found to be similar to the degree of turbidity removal accomplished by sedimentation on a percent basis.

A number of important studies have been reported for the removal of viruses by prefiltration processes (Malek, et al., 1981). Table 12 summarizes the bench test results for the virus removal in prefiltration processes. Only recent data are summarized because they are obtained by applying more strict laboratory techniques. In general, with alum and ferric chloride as coagulants at dosages from 18 to 50 mg/L, the virus removal could range from 80 % to over 99 %. In contrast, a lower dosage could substantially reduce the process efficiency. For example, Rao et al. (1988) studied the removal of spiked hepatitis A virus, poliovirus and rotavirus from water by laboratory jar tests. At two dosages of 8 and 16 mg/L for both alum and ferric chloride, consistent removal of over 99% was obtained for rotavirus. For poliovirus and hepatitis A virus, the removal efficiencies were lowered from 40 to 79 %. Under this condition, the effluent turbidities ranged from 0.93 to 1.38 NTU, representing a reduction of 90 to 94 % reduction in the initial turbidity, which is typical of field experiences. However, when the dosage of coagulants increased to 20 mg/L or higher, the removal efficiencies for hepatitis A virus, poliovirus and rotavirus increased to 93 %, 91 % and over 99 %, respectively.

The results conducted at full scale water treatment plants for removal of indigenous viruses are summarized in Table 13. Thus, they should be considered to be particularly valuable for evaluating the process performance. It is indicated that virus removal can be very different according to the viruses measured, the type of plant, and even the seasons. The removal efficacy could range

Table 12. Virus Removal from Water by Prefiltration Processes[a]

Coagulant	Dosage mg/L	Raw water	Removal, %			
			MS2	Poliovirus	Rotavirus	Hepatitis virus
Alum	5	14 NTU	insignificant			
	6		insignificant			
	7		insignificant			
	8		insignificant			
	9		insignificant			
	10		insignificant			
	20		94			
	30		99			
	40		99.5			
	50		99.7			
Alum	8	4 - 8.6		90.7	>99	92.9
				90.7	>99	91.1
	16	20 - 26		87.6	>99	96.7
				92.0	99	98.5
	20	120 - 146		95.7	>99	93.6
				97.2	>99	>96.8
$FeCl_3$	16	4 - 8.6		52.7	>99	91.6
				52.7	>99	>96.5
	16	20 - 26		91.0	>99	96.0
				94.0	>99	>99.2
	32	120 - 146		>99	>99	>94.5
				>99	>99	>94.5
Cat-Floc T	2	14 NTU	75			
	4		71.5			
	6		64			
	8		65.5			
	10		45			
Nalco 8101	2	14 NTU	96			
	4		97			
	6		95.5			
	8		97			
	10		96			
Nalco 8102	2	14 NTU	63			
	4		58			
	6		28			
	8		41			
	10		38			
Nalco 8103	2	14 NTU	57.5			
	4		55.5			
	6		23.5			
	8		41			
	10		43.5			

[a] Adapted from Malek et al., 1981 and Rao et al., 1988.

Table 13. Removal of Indigenous Viruses in Full-Scale Water Treatment Plants[a]

Virus type	Coagulant	Water type	Viral units/L	% Removal[b]
Enterovirus	Alum	River	0 to 0.77 pfu/L	~60
Reovirus	Alum	River	3.3 mpncu/L	100
Enterovirus	Alum	River	3.3 mpncu/L	99.53
Enterovirus (pilot)	Alum 35 to 50 mg/L	River	0.19 to 1.42 pfu/L	31 to 90
Enterovirus (full scale)	Alum 15 to 20 mg/L	River	0.01 to 0.146 pfu/L	48.6 to 50
Rotavirus (dry season)	Alum	River	610 IF pfu/L	75
Rotavirus (rainy season)	Alum	River	1745 IF pfu/L	0
Enterovirus (dry season)	Alum	River	55% positive	37
Enterovirus (rainy season)	Alum	River	7% positive	0
Phage (dry season)	Alum	River	11 pfu/L	63
Phage (rainy season)	Alum	River	47 pfu/L	66
Reovirus, enterovirus	Alum	River, lake	0 to 22 pfu/L	20 to 66

[a] Source: Payment and Armon, 1989

[b] Percent removal reported as cumulative removal, i.e., compared to virus density in raw water.

from zero to near 100 %. As a result, Payment and Armon (1989) concluded that the virus removal by prefiltration processes using alum as a coagulant is a very sensitive process and that it must be controlled properly. Water treatment plants, where the viruses were detected in the finished water, had been improved by a very careful control of their prefiltration processes.

The removal of protozoan pathogens has been studied only for the last two decades. As a result, little information is available on the removal of *Giardia* cysts by the prefiltration processes. Arozarena (1979) reported that cyst removal in jar tests involving alum coagulation and sedimentation ranged from 58 to 99 %. That work was done with a clear gravel pit water (usually <5 NTU) to simulate the water quality in places where *Giardia* cysts are found. The results suggested that the prefiltration could remove a portion of the cysts present in raw water. In a view of lack of reliable information in this aspect, a thorough evaluation of conventional water treatment performance for removal of *Giardia* was initiated by U.S. EPA using a continuously flowing pilot plant (Logsdon et al. (1985). The cysts were spiked into waters with different turbidities. Alum was used as primary coagulant, while a high molecular weight anionic polymer as the coagulant aid. Results are summarized in Table 14. It was shown that a continuously flowing sedimentation basin is capable of removing a significant fraction of *Giardia* cysts, ranging from 65 to 86 %. Cyst removal appears to improve with the increase in turbidity removal and the use of polymer. However, as compared to batch test results of Arozarena (1979), the pilot test results were inferior. This was believed due to the existence of short-circuiting.

Table 14. Removal of *Giardia* Cysts by Prefiltration Processes

Raw water turbidity, NTU	Chemical dose, mg/L		Turbidity removal %	Cyst removal %
	Alum	Polymer		
22 to 25	27.5	none	81	
22 to 25	27.5	none	79	
22 to 25	27.5	none	79	
22 to 25	27.5	none	77	
11 to 15	25.4	0.048	77	79
11 to 15	25.4	0.048	82	93
11 to 15	25.4	0.048	76	80
11 to 15	25.4	0.048	71	70
7.5 to 9.5	24.8	0.095	81	81
7.5 to 9.5	24.8	0.095	80	86
7.5 to 9.5	24.8	0.095	78	87
7.5 to 9.5	24.8	0.095	75	83
27 to 32	13.7	none	72	71
27 to 32	13.7	none	67	68
27 to 32	13.7	none	69	83
27 to 32	13.7	none	66	65

[a] Source: Logsdon et al., 1985.

The fundamentals of removing microorganisms by prefiltration have been a subject of a few studies (Berbhardt and Clasen, 1991). Ives (1956) and Tenny and Stumn (1965) speculated that the flocculation and filtration of microorganisms follows the same law as the elimination of colloidal and finely dispersed substances, irrespective of their inorganic or organic nature. This implies that the mechanisms underlying coagulation can be directly employed to explain the destabilization of microorganism particles. According to Ongerth (1990), similar phenomenon also applies to *Giardia* cysts and *Cryptosporidium* oocysts. Recently, Berhardt and Clasen (1991) studied the flocculation of various microorganisms using inorganic iron and aluminum and compared their effectiveness with the differently charged organic polymers. They suggested that bacteria, cysts, as well as round, small and non-motile algae, can be flocculated and filtered according to the principles of charge neutralization. An exception was observed for filamentous algae, larger algae, or species with bristles on their cell surface. A satisfactory flocculation of these algae is possible only if a large amount of aluminum hydroxide flocs are produced in the water which enmesh the algal cells (sweep coagulation).

6.0 FILTRATION

Filtration is a process to remove suspended solids from water as the water passes through a porous bed of materials. From the perspective of controlling the microorganism in drinking water, filtration is beneficial in two ways: (1) to remove many microorganisms as possible, particularly those resistant to disinfection such as *Giardia* and *Cryptosporidium*, (2) to achieve the desired turbidity standards, thus reducing the interfering materials for subsequent disinfection process. As mentioned before, filtration, combined with disinfection, has been identified as the best available technology for the control of microbiological contaminants in water.

In this section, different filtration technologies, ranging from commonly used conventional systems to new and emerging technologies are reviewed. These include:

1. conventional treatment;
2. direct filtration (gravity and pressure filters);
3. slow sand filtration;
4. diatomaceous earth filtration; and
5. membrane filtration.

Conventional treatment and direct filtration are the most widely used systems. Slow sand and diatomaceous earth filtration are considered technologies not widely used in the North America, but have a broad applicability. Membrane filtration is considered emerging technology because it shows promise but has been not widely used in water treatment practices. Other options such as the package plants will be reviewed separately (Section 8.0) because they are only suitable for small community water treatment plants and have distinguished considerations in system design and operations.

Pressure filters, as the name indicates, are operated under pressure to achieve rapid filtration. The filter media are contained in a steel pressure vessel. While the pressure filter has an outward appearance different from the gravity filter, the filtration process is exactly the same. The use of the same principles of operation and filter media would lead to a comparable filtrate quality under a given situation. Most researchers have considered the pressure filter as one of direct filtration. Thus, its performance and selection will be not reviewed separately.

6.1 SOME FUNDAMENTALS OF FILTRATION

The removal of suspended particles during filtration involves the straining through pores in the filter bed, the deposit of particles on the surface of filter media or the attachment to the particles deposited previously, coagulation while traveling through the pores, and in the case of slow sand filters the biological degradation. The mechanisms are considered at least in three steps: transport, attachment and detachment (Amirtharajah, 1988). The transport step is to bring the particles close to the surface of filter media. It is the combined effects of physical and hydrodynamic processes including diffusion, sedimentation, interception, inertia and hydrodynamic actions. For the granular filtration, it is generally accepted that the dominant mechanisms are diffusion, sedimentation and

interception (Habibian and O'Melia, 1975). For membrane filtration, the principal mechanism of particle removal is straining. The attachment mechanisms involve either electrostatic interactions, van der Waals forces, or surface chemical interactions (O'Melia and Stumm, 1967). Attachment is affected by both physical and chemical factors. It has been shown, both theoretically and experimentally, that particle capture will be favorable when surface charges of the particles and media are of opposite sign. Where the media surface is covered by deposited particles, the collection is effective only if the particles have been adequately destabilized. O'Melia and Stumm (1967) suggested that these conditions are exactly analogous to coagulation. The detachment mechanisms include the scour due to increased interstitial velocity gradients in the bed or as a result of floc shearing. Its magnitude would depend on the influent concentration, the length of filter run, the hydrodynamic forces and deposit morphology. During the filtration, the mechanisms of attachment and detachment may occur simultaneously and the detachment mechanisms often control the effluent particle concentration and particle size distribution as the significant portion of particles in the effluent come from the detached flocs (Ginn et al., 1992). Table 15 summarizes the qualitative effects of increasing each of process parameters on particle removal efficiency.

Table 15. Effects of Different Parameters on Particle Efficiency[a]

Parameter	Change in Parameter	Removal Efficiency
Influent particle concentration	Increase	No change
Particle density	Increase	Increase
Interstitial velocity (filtration rate)	Increase	Decrease
Filter pore diameter (medium grain diameter)	Increase	Decrease
Length of the filter pore (depth of the medium)	Increase	Increase
Particle attachment efficiency (degree of destabilization)	Increase	Increase

[a] Adapted from Letterman, 1987.

Another consideration for filtration processes is the buildup of headloss within the filter bed. It was recognized as early as in the 1900's that this pressure drop could be attributed to the combined effects of drag friction at the surface of media and continuous contraction and expansion of the fluid as it passes through pore openings in the filter.

If straining is the controlling mechanism, the particles may form a layer of deposit on the surface of filter medium. The headloss across this layer depends on the size distribution and mechanical properties of the filtered particulates. The rate of headloss buildup per unit mass of filtered particulates increases as the size of the particulates increases and as the size distribution becomes increasingly narrow (more monodispersed).

The development of headloss in granular filters (where deposition occurs at least in part within the interstitial void spaces) is much more complicated. Its rate of development depends on the rate of particle volume removal, the filtration rate, and the size and total volume of the interstitial spaces. The lowest rates of development of headloss and the longest filter runs are obtained when the region in which deposition takes place is deep (long pore lengths) and the mean grain size is large (large pore diameters). The development of headloss is minimized by effective utilization of all the void space in the bed. Low filtration rates also tend to yield low rates of headloss development. For a given mass concentration of particles, increasing particle density decreases the volume of interstitial void space consumed in the deposition process and therefore decreases the rate of development of headloss (Letterman, 1987). Table 16 summarizes the effects of increasing certain parameters on the rate of development of headloss.

Table 16. The Effects of Increasing Certain Parameters on Headloss[a]

Parameter	Change in Parameter	Change in Headloss Buildup
Rate of particle deposition	Increase	Increase
Filtration rate	Increase	Increase
Filter pore diameter	Increase	Decrease
Length of the filter media	Increase	Decrease
Particle Penetration	Increase	Decrease

[a] Adapted from Letterman, 1987.

Efficient backwashing of filter media is necessary to produce desired filtrate quality, to prevent gradual deterioration of the media, and to maintain filtration water production. The common backwash method is an up-flow water wash with fluidization of the media. Auxiliary surface water wash or air scour is often used to enhance solids removal under these more demanding conditions. The surface wash systems uses the injection jets of water from orifices located about 25 to 50 mm above the fixed-bed surface. Surface wash jets are operated for 1 to 2 minutes before the upflow wash and usually are continued during most of the upflow wash, during which time they are immersed in the fluidized filter media. Air scour-assisted backwash is supplying air to the full filter area from orifices located under the filter media. Air scour can be used in three different ways: (1) air scour is used before the water backwashing, (2) air scour is used as a portion of the water backwash, and (3) air scour and water backwash are used simultaneously.

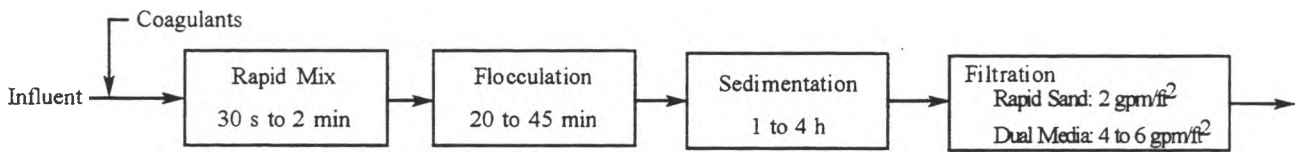
The best criteria for backwash effectiveness are the quality of the filtered water and the long-term absence of dirty filters and mudball formation. A number of investigators (Cleasby et al., 1977; Amirtharajah 1988) have suggested that little or no contact occurs between fluidized media particles. Hence, particulate fluidization with water alone is an intrinsically weak cleaning process. Air scour, which causes abrasions between particles throughout the depth of the bed, and surface wash, which causes collisions at the top of the bed, are effective auxiliaries for cleaning.

Adequate pretreatment prior to filtration is essential to successful filter performance. Pretreatment will affect the mass loading to the filter, the particle size distribution, the attached particle resistance to shear, and the particle surface characteristics. All these factors pose important impacts for the retention of particles in the filtration process.

6.2 PROCESS DESCRIPTION FOR DIFFERENT FILTRATION TECHNOLOGIES

Conventional treatment consists of the pretreatment steps of coagulation, flocculation and sedimentation followed by filtration. Its flow diagram, along with typical operation parameters, is shown in Figure 7. The filter can be either sand, dual-media, or even tri-media. The use of multi-layer media is to encourage the penetration of particles deep into the filter bed. Water flow is by gravity through the media in a downward mode, although other arrangements are possible. Traditionally, the superficial flowrate is around 5 m/h for rapid sand filtration. However, the advances in pretreatment and facility design have led to using flowrates as high as 15 m/h. Their operation actually follows a sequential cycle consisting of filtration and filter backwash. Three criteria may be used to terminate the filtration to the backwash: (1) turbidity breakthrough, (2) headloss breakthrough, and (3) the filtration length exceeding a preset period (James M. Montgomery, 1985).

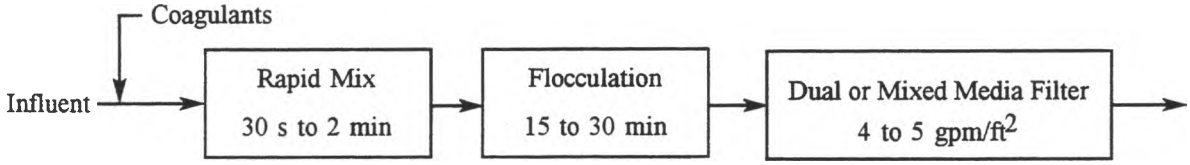
Figure 7. Conventional Water Treatment Scheme



In contrast to the conventional treatment, direct filtration does not use sedimentation in prefiltration treatment. However, it always includes coagulation and filtration, and sometimes includes flocculation or a contact basin after the coagulation process. These pretreatment processes are to form the pin flocs which can be effectively removed by filtration. Typical coagulant dosages range from less than 1 up to 30 mg/L. The commonly used coagulant is cationic polymers, however, nonionic polymers sometimes are added to improve the filtration efficiency. Filter media can be either dual-media or mixed media. Water flow through the filter can be either by gravity or by pressure. A flow diagram for typical direct filtration systems is shown in Figure 8.

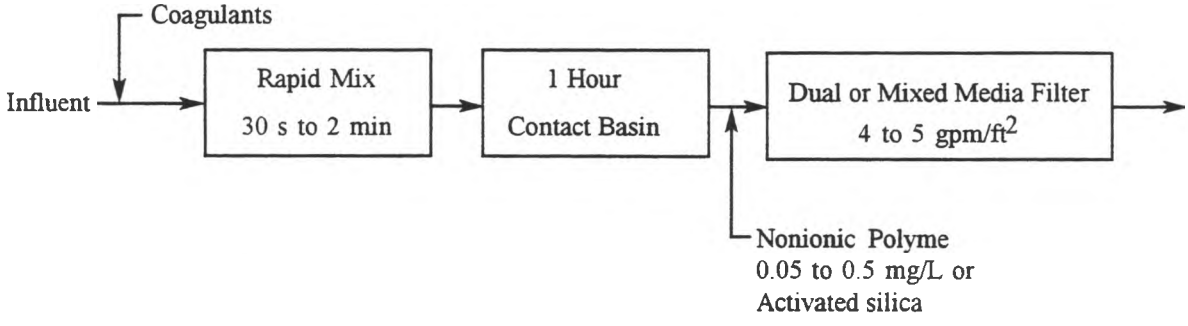
Direct filtration has several modifications: in-line direct filtration and contact filtration. Their flow diagrams are also shown in Figure 8. The in-line direct filtration consists of the coagulation followed by filtration. There is no separate flocculation step. The contact direct filtration includes an one-hour detention time basin, which primarily serves to condition the floc in the filter influent. However, it also provides pretreatment by equalizing the influent quality and removing the silts and sands.

Figure 8. Flow Diagrams of Direct Filtration



(a) Typical Direct Filtration

(b) In-Line Direct Filtration



(c) Contact Direct Filtration

Slow sand filtration consists of a layer of fine sand on the top of a layer of graded gravel. The filters operate at a very low filtration rate (normally, around 0.06 $m^3/m^2/s$), dependent on the gradation of the filter media and the quality of raw water. Coagulation and sedimentation are usually not provided prior to the slow sand filtration. The removal efficiency depends on the cake filtration at the surface of the filter for particle straining. When the fine sand becomes clogged, the filter must be cleaned. Cleaning is accomplished by scraping off the top layer of the filter bed. A ripening period after cleaning ranges from 1 to 2 days to produce the functional surface cake. As a result of this extended cleaning period, a standby system is required.

Diatomaceous earth filtration uses a very thin layer of diatomaceous earth as a filter material which is coated on a porous septum or filter element. The septum is placed in a pressure vessel or operated under a vacuum in an open vessel. Additional diatomaceous earth (or body feed) is normally added to the filter influent during the filtration process to prolong the filter run. Higher body feed doses are needed for higher suspended solids in the raw water. When plugged, the filter is backwashed to remove the deposited particles along with the coated diatomaceous earth. Like the slow sand filtration, pretreatment such as employing coagulation and sedimentation is usually not needed.

Membrane filtration, often reserved for ultrafiltration, uses hollow fiber membranes to intercept the particles from water. The membrane fibers are compacted in a pressure container or cartridge, and operate under a pressure ranging from 10 to 100 psi. Traditional membrane filters induce water to the inside of the hollow fiber membrane, with the permeate exiting from the outside of the membrane. State-of-the art membrane filters are designed to let the influent flow either inside or outside. After the membrane filter is clogged, it is cleaned by backflushing, chemical cleaning or air pressure. Some manufacturers have developed self-cleaning systems to extend the time between the chemical cleaning.

6.3 EVALUATION OF FILTRATION PERFORMANCES

Filtration processes provide various levels of microbial contaminant removal. A number of studies have been conducted to evaluate the filtration performance in order to meet the U.S. EPA Surface Water Treatment Rule. Tables 17 and 18 summarize the microbial removal capacities of various filtration processes. For the removal of viruses the results indicate that filtration without disinfection can remove 99 % of viruses in water supplies (Gerba et al., 1985). For *Giardia* cysts, an even higher removal efficiency (>99.9%) can be achieved by conventional filtration, or by direct filtration (Cornwell et al., 1991). Diatomaceous earth filtration and slow sand filtration is especially effective in removing *Giardia* cysts (Bellamy et al., 1985a; 1985b; Langé, 1986). Membrane filtration is extremely effective and is virtually capable of removing all the *Giardia* cysts from water (Jacangelo et al., 1991). However, the proper use of coagulants is necessary to achieve high levels of virus and *Giardia* removal, particularly for direct filtration.

Further evaluations of process performances from full scale filtration plants have confirmed the laboratory or pilot test results presented above, when they are designed and operated properly. Logsdon et al. (1985) thoroughly compared slow sand filtration, diatomaceous earth filtration, and conventional and direct filtration, using the information from filtration studies at pilot scale and full scale. He demonstrated that all of the filtration processes can reduce the concentration of *Giardia* cysts by 99 % or more with an optimum dosage of chemical coagulant. Many of studies also achieved *Giardia* removals of 99.9 %.

Table 17. Removal Efficiencies of Viruses by Water Filtration[a]

Unit process	% Removal	Operating parameters	Testing
Slow sand filtration	99.9999	0.2 m/h, 11 to 12 °C	Pilot scale
	99.8	0.2 m/h[c]	
	99.8	0.4 m/h, 6 °C	
	91	0.4 m/h[c]	
Diatomaceous earth filtration	>99.95[b]	With cationic polymer coat	Laboratory
		Cationic polymer into raw water	
Direct filtration	90 to 99	2 to 6 gpm/ft, 17 to 19 °C	Pilot scale
Convention filtration	>99	2 to 6 gpm/ft, 17 to 19 °C	Pilot scale

[a] Adapted from Troyan and Hansen, 1989.
[b] No viruses recovered
[c] No temperature data given

Table 18. Removal Efficiencies of *Giardia* Cysts by Water Filtration[a]

Unit Process	Raw water concentration	% Removal	Operating parameters	Studies
Rapid filtration with coagulation, sedimentation	23 to 1100/L	96.6 to 99.9	Min. alum = 10 mg/L Opt. pH = 6.5 Filt. rate = 4.9 to 9.8 m/h	Laboratory and pilot scale
Direct filtration with coagulation	~20 x 10^6/L	95.9 to 99.9	Min. alum = 10 mg/L pH range = 5.6 to 6.8	Laboratory and pilot scale
No coagulation		~48	Filt. rate = 4.9 to 9.8 m/h Eff. NTU = 0.02 to 0.5 Inf. NTU = 0.7 to 1.9 Eff. poor during ripening	Laboratory and pilot scale
With flocculation		95 to 99	Alum = 2 to 5 mg/L Polymer = 1.2 mg/L Temp. = 5 to 18 °C Eff. NTU = 0.05 Inf. NTU = 1.0 Filt. rate = 4.8 to 18.8 m/h	Laboratory and pilot scale
No coagulation		10 to 70		Laboratory and pilot scale
Diatomaceous earth filtration	1.5 x 10^5 to 9.0 x 10^5/L	99 to 99.99	Filter aid = 20 mg/L Body feed	Laboratory
	10^2 to 10^4/L	>99.9	Filt. rate = 2.4 to 9.8 m/h Temp. = 5 to 13 °C Eff. NTU = 0.13 to 0.16 Inf. NTU = 1.0 to 2.0	Laboratory
Slow sand filtration	50 to 5 x 10^3/L	~100	Filt. rate = 0.04 to 0.4 m/h Temp. = 0, 5 and 17 °C Eff. NTU = 3 to 7 Inf. NTU = 4 to 10	Laboratory

[a] Adapted from Troyan and Hansen, 1989.

The excellent performances achievable by filtration for removing viruses and *Giardia* cysts can be best described by the CT_{10} credits in the Surface Water Treatment Rule (see Table 19). The filtration processes can claim a reduction in 2 to 2.5 log units for *Giardia* and 1 to 2 log units for viruses, dependent on the type of filtration systems. Further required reductions are expected by the disinfection processes. Currently, the total reduction required by the Surface Water Treatment Rule is 3 log units for *Giardia* and 4 log units for viruses if the raw water contains 1/100 mL cyst on the average daily basis.

Table 19. CT_{10} Credits for Removal of *Giardia* Cysts and Viruses in Recognized Treatment Systems[a]

Treatment system	Log removal of *Giardia* cysts	Log removal of viruses
Conventional	2.5	2
Direct filtration	2	1
Slow sand filtration	2	2
diatomaceous earth filtration	2	1

[a] Source: Letterman, 1991.

However, it should be noted that the filtration performances presented above are those obtained from the normal operation. The filter ripening and turbidity breakthrough stage significantly deteriorate the microbiological effluent quality. Logsdon and Rice (1985) studied the effects of filter ripening on the removal of microorganisms by spiking *Klebsiella* in filter influent. The filters were operated at approximately at 3 gpm/ft^2. They observed consistently that after backwashing with dechlorinated tap water, the bacteria concentration rose rapidly, and then gradually declined. The rise and decline occurred at about the same time as the rise and decline in turbidity. When chlorinated water was used as backwash water, no *Klebsiella* organisms were detected for the first 10 minutes. Similar deterioration was observed for the removals of *Giardia* cysts during the filter ripening (Logsdon et al., 1985). The cysts concentrations during filter ripening could be three to ten times higher than those after the filter had matured. Since the cysts are resistant to chlorine, they suggested that a filter-to-waste after the backwash should be practiced in order to improve the treated water quality. Based on the study on removing *Giardia* cysts from low turbidity, low temperature water, Horn et al. (1988) recommended that the filter-to-waste period should be 1.5 to 2.0 detention times through the filter system to allow for hydraulic dispersion.

Several studies reported that the turbidity breakthrough will cause the passage of *Giardia* cysts through the filter. Furthermore, it appears that the cyst concentrations are very sensitive to the small change in turbidity. Logsdon et al. (1985) observed that the cysts would increase by factors of 20 to 40 even though the turbidity increased by factors of only 3 to 10. This observation held true even when the raw water turbidity was about 30 NTU and the coagulation-filtration removed the turbidity by 93 to >99 percent. These results lead to the conclusion that in order to keep the cyst

concentration in filtered water as low as possible, the water treatment plant should keep the filtered water turbidity as low as possible.

As well, there are a number of other factors affecting the effectiveness of filtration in removing the microbial contaminants. Among them, the most important one is the proper use of coagulants, particularly for direct filtration. Cleasby et al. (1989) recently concluded that chemical pretreatment prior to filtration is more critical to success than the physical facilities at the plant. They also warned that the plant staff should use a well-defined coagulant chemical control strategy that considers variable raw water quality. Consistently, pilot plant work at Colorado State University investigated the removal of *Giardia* cysts by direct filtration for a range of operating conditions (Hendricks et al., 1988). The water to be treated had a turbidity below 1 NTU and temperatures ranging from 0 °C to 17 °C. They concluded that the proper chemical pretreatment is imperative to ensure that the process is effective. Specific conclusions are listed as follows:

1. With no chemical pretreatment, removal of *Giardia*, bacteria and turbidity can be expected to vary between 0 to 50 percent;
2. Improvement in removal efficiency was not significant when ineffective coagulants or improper dosages were used; and
3. With proper chemical pretreatment, removal of all constituents can be expected to exceed 70 percent for turbidity, 99 percent for bacteria and 95 percent for *Giardia* cysts.

These conclusions are similar to those of others (Al-Ani et al., 1986; Hendricks et al., 1988; Moser et al., 1986) who used direct filtration with dual media, and with Horn et al. (1988) who used dual-stage filtration. More recently, Bellamy et al. (1993) and Jeffery (1991) assessed many water treatment plants with different types of filters and concluded that it is crucial to have optimal coagulation prior to filtration to ensure the effective removal of *Giardia* and *Cryptosporidium* sized particles. They maintained that without optimal coagulation, even the best rapid filtration facilities and the best filter operational procedures cannot ensure good filter performance. If the best filtrate quality is desired, no attempt should be made to scrimp on coagulant dosages to save operating costs.

In addition to alum or ferric coagulants, organic polymers as filter aids may be necessary, especially in high rate filtration and for treating cold water. A recent study at the University of Alberta (Zhu et al., 1994) showed that the proper use of organic polymers can control the penetration of particles in filtration. This control can significantly improve the effluent quality while not affecting the water production. Furthermore, mixing was identified as another important operating parameter for producing excellent filter effluents. This is because proper mixing is essential to uniformly distribute the polymer into the water and form the pin flocs. Other factors such as the type of polymers and their dosages were also examined. Detail information can be found in the report of Zhu et al. (1994).

6.4 CHOOSING FILTRATION TECHNOLOGIES

To choose a most appropriate filtration technology for removing pathogenic microorganisms, a number of factors must be considered, including the treatment efficiency, system reliability, raw

water quality, frequency of the cleaning cycle, operational complexity, site conditions and economic constraints. Table 20 lists the recommended upper limits of influent water quality for achieving satisfactory filtration performance. Table 21 summarizes the main advantages and disadvantages for each of the filtration technologies.

Table 20. Raw Water Quality Limits for Various Filtration Systems[a]

Filtration options	Turbidity, NTU	Color, CU	Coliform count, /100mL	Typical capacity, MGD
Conventional	No restrictions	<75	<20,000	>All sizes
Direct	<14	<40	<500	>All sizes
Slow sand	<5	<10	<800	<15
Package plant		[depends on process utilized		<6
Diatomaceous earth	<5	<5	<50	<100
Membrane	<1	[fouling index of <10]		<0.5
Catridge	<2	NA[b]	NA[b]	<1.0

[a] Source: US EPA, 1990a
[b] NA = not available

The raw water quality is the most important consideration in selecting the filtration technology (US EPA, 1990a). Table 22 contains the recommended upper limits for several influent parameters, including total coliforms, turbidity and color. Conventional treatment is obviously the most versatile filtration technology because it includes coagulation, flocculation and sedimentation, which reduce the turbidity before the water enters the filters. Consequently, it is least paralyzed by the possible variations in water quality from season to season. On the other hand, membrane filtration needs the highest influent quality, most applicable for a water with the turbidity of less than 1 NTU. Consequently, it is usually preceded by high levels of pretreatment in order to reduce the clogging of membrane. However, this limitation will be expected to be relaxed with the advance of new membrane technology. The diatomaceous earth filtration systems, which include little pretreatment, also require the very restrictive influent (<5 NTU) to maintain an appropriate length of a filtration cycle. Like the diatomaceous earth filtration, the direct filtration has no pretreatment separation process, and all particulate matter must be removed by filtration. However, the limits on raw water quality mainly depend on the performance such as the provision of a safety factor, and on economics. Thus, these limits are the most difficult to establish and open to debate. In general, neither the turbidity nor the color of the raw water determines the feasibility of direct filtration, but, rather, the coagulant dose required. More contaminated water requires higher coagulant dosages to accomplish the conditioning of influent. Based on an acceptable minimum filter run length of around 12 h or a water production of about 122 m^3/m^2, Cleasby (1989) recommended the dosages of aluminum and iron salt up to 10 mg/L. Others (Edzwald et al., 1987; Hutchinson, 1976) suggested upper limits of 20 mg/L of iron salt and 12 mg/L of alum, respectively.

Table 21. Advantages and Disadvantages of Filtration Technologies[a]

Technology	Advantages	Disadvantages
Conventional treatment	Most common, Accommodates a wide range of raw water, Reliable *Giardia* removal efficiency, Flexible to add other processes	Requires continuous monitoring and operator attendance, High capital cost, Complex in process control.
Direct filtration	Lower cost alternative to conventional filtration, Low chemical dosages,	Requires high level of operational skills, More stringent raw water requirements, Difficulty in treating clear, cold water,
Slow sand	Operation simplicity and reliability, Low cost, Ability to achieve greater than 99 % *Giardia* cysts removal.	Not suitable for water with high turbidity, Requires large land areas.
Diatomaceous earth	Compact size, Simplicity of operation, Excellent cysts and turbidity removal.	Most suitable for raw water with low bacterial counts and low turbidity, Requires coagulant and filter aids for effective virus removal, Potential difficulty in maintaining complete and uniform thickness of diatomaceous earth on filter septum.
Membrane	Extremely compact, Extremely excellent cysts and turbidity removal, Automated.	Little information available to establish design criteria and operating parameters, Most suitable for raw water with turbidity <1 NTU, Usually must be preceded by high levels of pretreatment, Easily clogged with colloids and algae, Short filter run, Concerns about membrane failure, Complex repairs of automated controls, High percent of water lost in backflushing.

[a] Source: US EPA, 1990b.

In comparison, conventional filtration offers additional advantages over other filtration technologies. The conventional filtration is the most commonly used technology in water treatment has many design and operating experiences available. In addition, it incorporates the coagulation, flocculation and sedimentation together and can be easily adapted to add other processes. However,

because it requires to adjust water chemistry for proper coagulation, the conventional filtration is more difficult to operate as compared to slow sand or diatomaceous earth filtration and is relatively expensive. Therefore, the conventional filtration is most suitable for large community treatment systems.

The direct filtration has become an attractive alternative to the conventional filtration, in particularly for good source water (Logsdon et al., 1990). The capital cost is lower because no sedimentation tank is required. Lower coagulant dosages are usually used in the direct filtration to form pin flocs that are easily filterable, rather than large, settleable flocs. Consequently, the direct filtration results in a lower chemical cost and produces a smaller amount of sludge that must be handled and disposed of. The operating and maintenance costs are also lower. The total capital and operation savings can be as high as 30% from the use of direct filtration. However, the direct filtration has several disadvantages. The main disadvantage includes the inferior performance and restrictive requirements of influent quality. Besides, it is sensitive to seasonal variations and requires higher skills of operation. Between two types of direct filtration, the pressure filter has one advantages over the gravity filter in that the effluent, under pressure, can be delivered to the point of use without repumping. The disadvantages of pressure filters include the need to construct a pressure-sustained vessel and the difficulty in conducting the proper backwash, because the filter media are not usually visible to operators.

The slow sand filtration becomes an attractive technology for small community systems mainly because it has been demonstrated for effective removal of cysts from water (Ellis and Aydin, 1993; Fox et al., 1985; Leland and Damewood, 1990). In addition, it requires no knowledge of coagulation chemistry and little operator's attention. However, for proper application of slow sand filters, the raw water must be of high quality. Another disadvantage is the large land requirement for installation of facilities. In the northern climates where freezing will occur, the filters must be covered, which substantially negates its advantage of low capital cost.

Another filtration technology applicable for small community systems is diatomaceous earth filtration. The most important advantages for using the diatomaceous earth filtration is low capital costs because of smaller land and plant building requirements. In addition, it can achieve high efficiency of cysts removal. The operation skills in coagulation can be avoided, but operators with mechanical skills are required. Like the slow sand filtration, however, the proper use of diatomaceous earth filtration requires very high quality influent.

Membrane filtration is an emerging technology. As a result, less information is available to establish design criteria and operating parameters. However, its extremely excellent performance of removing various microbial contaminants has been well demonstrated in bench and pilot scale studies. It is also extremely compact and can easily incorporate automatic control. Currently, membrane filtration is the most suitable for influent with turbidity less than 1 NTU. The most difficult problem in operating the membrane filtration is the membrane fouling or clogging with colloids and algae. Another major concern is the potential for membrane failure. As a result, a safety apparatus is necessary to trigger an operational shutdown or an alarm to operators when the failure happens.

In summary, an appropriate selection of a filtration technology for a specific site may be a difficult task. Before the evaluation of the existing process or the design of new facilities, the first

step should be to review all raw water quality data to determine the achievable treatment efficiency. When new facilities are to be installed, the alternative technologies should be considered to possibly solve the problems identified for current systems. In some cases, the pilot scale study may be necessary to evaluate alternative treatment options and operating techniques. Otherwise, a thorough literature survey of previous studies in similar situations may be used to derive performance characteristics and design considerations for each alternative. For small systems, the alternatives for controlling microbial contamination may include slow sand filters, diatomaceous earth filtration, membrane filtration and package plants.

7.0 DISINFECTION

Disinfection is a treatment process used to destroy disease causing organisms. It is also the last and perhaps the most important barrier to safeguard the microbiological quality of drinking water In water treatment, primary disinfection provides the desired degree of inactivation of microorganisms such as bacteria, viruses and protozoa. Then, secondary disinfection maintains the disinfectant residual to prevent the regrowth of microorganisms in the distribution systems.

Chlorine is the most widely used disinfectant in drinking water practice. When used properly, it provides a safe, effective and practical technology to control the pathogenic microorganisms in water. It can also maintain a stable residual to prevent regrowth in water distribution systems. Thus, chlorine can be used as the primary disinfectant as well as the secondary disinfectant. However, chlorine can react with organic materials in the water to produce potentially harmful by-products such as trihalomethanes (THMs). In addition, new recognized microorganisms such as *Giardia* and *Cryptosporidium* may be resistant to chlorine, as a result, within a reasonable contact time, the chlorination alone may not meet the requirements of controlling waterborne microorganisms. Because of these concerns, water suppliers are seeking alternatives to chlorination (DeMers and Renner, 1992). Ozone and chlorine dioxide are becoming increasingly popular as the primary disinfectant, while chloramines have been used as the secondary disinfectant.

In this section, various disinfection technologies used today as well as the issues relating to disinfection by-products are reviewed. Section 7.1 briefly presents the fundamentals and process description of disinfection technologies. This is followed by a discussion on their effectiveness of inactivation of the most concerned pathogens. The formation of disinfection by-products and strategies for their control are presented in Section 7.3. Section 7.4 provides a summary of advantages and disadvantages of disinfection technologies.

7.1 FUNDAMENTALS OF DISINFECTION TECHNOLOGIES AND PROCESS DESCRIPTION

7.1.1 Chlorination

Chlorination is a process that uses chlorine as a disinfectant to inactivate the microorganisms in drinking water. Chlorine is available as a gas, solid, or liquid solution. Gaseous chlorine gas is used most widely, especially for larger water treatment systems, while chlorine in solid form ($Ca[OCl]_2$) and in liquid form (NaOCl) are mostly used for smaller systems. When added into water, they are first hydrolyzed as follows:

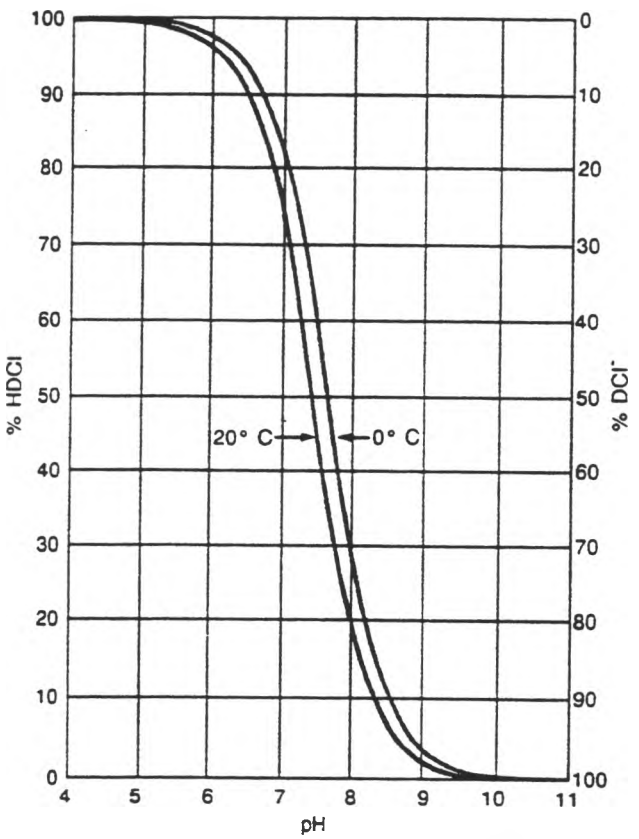
chlorine gas: $Cl_2 + H_2O <----> HCl + HOCl$
calcium hypochlorite: $Ca(OCl)_2 + 2H_2O <----> 2\ HOCl + Ca(OH)_2$
sodium hypochlorite: $NaOCl + H_2O <----> HOCl + NaOH$

The resultant hypochlorous acid (HOCl) dissociates further depending on the water pH:

$HOCl <----> OCl^- + H^+$

The higher the pH, the more it will dissociate. Figure 9 shows a distribution of hypochlorous acid and hypochlorite ions in water at different pH values and temperatures. At neutral pH (pH =7), almost 80 % of the chlorine exists as hypochlorous acid, while increasing pH up to 8, nearly 80 % of the chlorine is in the form of hypochlorite ions. Since the hypochlorous acid is a much more effective disinfecting form, as compared to hypochlorite ions, the ability of chlorine disinfection is strongly affected by the water pH.

Figure 9. Distribution of Hypochlorous Acid and Hypochlorite Ion in Water[a]



[a] Source: US EPA, 1990a.

The hypochlorous acid is also a strong oxidant and can react with a number of substances in water. The chlorine demand is a measure of the amount of chlorine that will react with impurities and therefore will not be available for disinfection. In addition, it can combine with ammonia or other nitrogen compounds to form chloramines that have some disinfecting properties. A series of reactions are as follows:

$NH_4^+ + HOCl <----> NH_2Cl + H_2O + H^-$
$NH_2Cl + HOCl <----> NHCl_2 + H_2O$
$NHCl_2 + HOCl <----> NCl_3 + H_2O$

The combined chlorine refers to the total amount of chloramines in water. The uncombined chlorine that remains in the water after any combined residuals are formed is called free chlorine (i.e., hypochlorous acid + hypochlorite ions). The free chlorine is a more effective disinfectant than combined chlorine. Their relative concentrations depends on the dosage of chlorine as well as the ratio of ammonia to chlorine.

It should be noted that the free chlorine is not available for disinfection until the chlorine demand of the raw water is satisfied. When chlorine dosage exceeds the breakpoint at which chlorine demand is satisfied, additional chlorine will result in an almost linear increase in the free chlorine. The chlorine dosage needed to reach the breakpoint depends on the quality of water to be treated. Figure 10 depicts the typical breakpoint curve of chlorination.

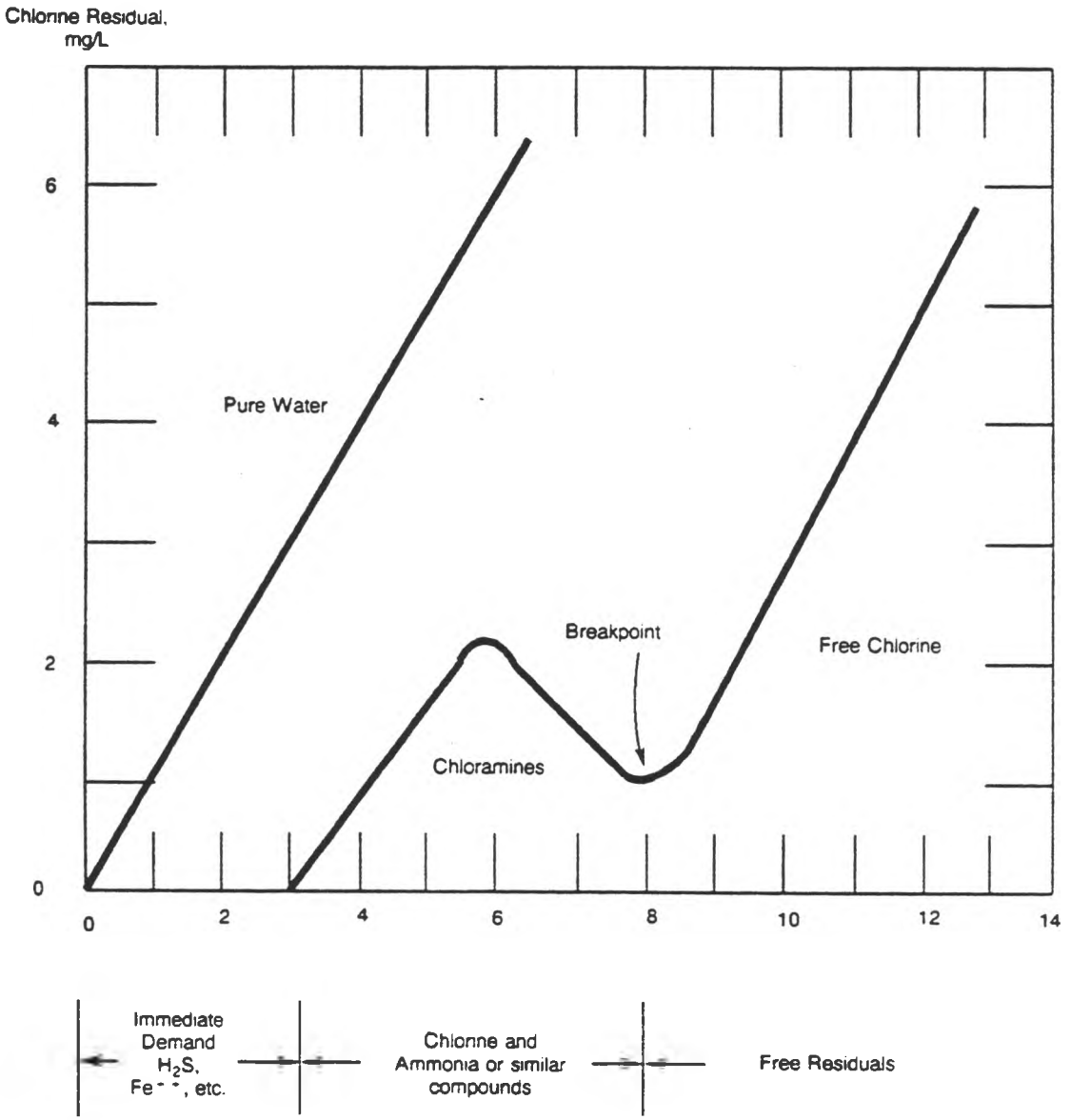
The facilities needed for chlorination include the disinfectant preparation and the feeding equipment. For the chlorine gas, there are two types of feed systems available: pressure-operated direct gas feed units and vacuum operated solution feed units. Direct gas feed units supply pressurized chlorine gas to water and are used only when electrical power is unavailable or the water pressure differentials are insufficient to operate a solution feed system. The solution feed systems mix the gas with a side stream of water to form a solution of hypochlorous acid and hypochlorite ion, which then is mixed with the main stream. These systems operate on a vacuum-controlled basis, automatically shutting off if the side stream flow is interrupted. The solution feed systems are safer to operate and therefore are preferred by most water treatment plants.

Water treatment plants at small communities may use the liquid or solid form of chlorine disinfectant such as sodium hypochlorite and calcium hypochlorite. When the calcium hypochlorite is used, it is first emptied into a mixing tank to be dissolved completely into water. Feeding the calcium hypochlorite solution into water to be disinfected is similar to feeding the sodium hypochlorite. The basic systems include two metering pumps (one serving as a standby), a solution tank, diffuser and appropriate quantities of tubing. The more complex systems may also include the safety accessories, flow meter and signal.

7.1.2 Chloramination

Chloramination is a disinfection technology in which the chlorine combines with ammonia to form chloramines. The above section describes the chemical process involved in the formation of chloramines. The relative contents of monochloramine, dichloramine and nitrogen trichloride depends on the water pH and the ratio of chlorine to ammonia. At a pH of 7 to 8, monochloramine is the principal product when the chlorine-to-ammonia ratio (by weight) is lower than 3 to 1. At higher chlorine-to-ammonia ratio or at lower pH values, some dichloramine will be formed. Care should be taken not to exceed a chlorine-to-ammonia ratio of 5 to 1 or to operate at a pH lower than 5 because nitrogen trichloride may be formed. NCl_3 causes an undesirable taste and odor problem, as well depletes the monochloramine and dichloramine.

Figure 10. Typical Breakpoint Curve of Chlorination



[a] Source: US EPA, 1990a.

The system design for chloramination is similar to that for chlorination. Ammonia gas can be injected into the water just like that for chlorine gas. When ammonium sulfate is used as the source of ammonia, it can be handled similar to sodium hypochlorite.

7.1.3 Chlorine Dioxide

Chlorine dioxide is an unstable gas and is very reactive in water. Because of its unstability, chlorine dioxide is generated on site for drinking water treatment. Several generation technologies have been developed by treating solutions of sodium chlorite with either chlorine gas, sodium hypochlorite or mineral acid. The reaction schemes can be written as follows:

$2NaClO_2 + Cl_2 \text{ ----> } 2ClO_2 + 2NaCl$
$2NaClO_2 + HOCl \text{ ----> } 2ClO_2 + NaCl + NaOH$
$5NaClO_2 + 4HCl \text{ ----> } 4ClO_2 + 5NaCl + 2H_2O$

During the generation, it is possible to release chlorite and form chlorate ions which may cause some health concerns. As a result, the $ClO_2 + ClO_2^- + ClO_3^-$ residual should be no more than 1 mg/L to minimize the adverse effects. Detailed discussion can be found from Aieta and Berg (1986)

For all three preparations, the appropriate aqueous solutions of reactants are metered into and mixed in a chlorine dioxide reactor. The reactor is usually equipped with flow distributing packings, such as Rashig rings, glass beds or hollow glass cylinders. After a few second reaction, the resulting yellow solution containing chlorine dioxide is pumped directly into the water to be treated. In this manner, the dosages of chlorine dioxide are controlled by producing a solution of known strength and feeding it at a controlled rate into a known flow of water.

7.1.4 Ozonation

Ozone is a very strong oxidant. This characteristics makes it one of the best disinfectants known for drinking water treatment. It is also only slightly soluble in water, about 2 to 10 times more soluble than oxygen, depending on the temperature. It is also very reactive and unstable. Consequently, ozone must be generated on site and applied immediately.

Ozone can be generated from the dry gas containing any concentration of oxygen under high-voltage. If the air is used, the most economical operation gives a product stream that contains about 2 % ozone by weight. If pure oxygen is used, the ozone content in the product stream can be increased up to 10 % by weight or even higher. In any case, the inlet gas must be cool, very dry (dew point < -50°C) and free of organic vapors.

When ozone is dissolved in water, two primary oxidation pathways have been proposed (Hoigné, 1982): direct oxidation by the molecular ozone and indirect oxidation by the free radicals which are formed during the ozone decomposition in water. The relative importance of these two pathways is affected by pH, UV light, ozone concentration and the presence of radical scavengers. Over the last two decades, extensive studies have been conducted to investigate the mechanisms of ozone decomposition in pure water (Staehelin and Hoigné, 1982; Tomiyasu et al., 1985). In dealing with natural waters, the ozone chemistry becomes even more complicated. The decomposition process can be influenced by initiators, promotors and inhibitors (Staehelin and Hoigné, 1985). Recent studies have showed that the rate of decomposition cannot be described by simple first- or second-order chemical decay processes because of the existence of initial ozone demand and multiple

oxidations (Zhou, 1995). As a result, the decomposition rate should consider both the raw water quality and the amount of ozone consumed.

The ozonation system is usually complicated as compared to other disinfection systems. It consists of the following four major components:

1. air preparation or oxygen feed;
2. ozone generation;
3. ozone contacting; and
4. ozone contactor exhaust gas destruction.

For many water treatment plants, the use of ambient air as feed gas may be cost effective for ozone systems. Above 1500 kg/d generating capacity, pure oxygen appears to be more economical.

The ozone generation units include the power suppliers and the ozone generators. Several different types of ozone generators are available:

1. horizontal tube, one electrode water cooled;
2. vertical tube, one electrode water cooled;
3. vertical tube, both electrodes cooled; and
4. plate, water or air cooled.

Experiences show that operating an ozone generator at 60 to 70 percent of its maximum capacity is the most cost effective.

The ozone contactor is the key component for successful applications of ozonation. It provides the conditions for mass transfer of ozone from the gas phase into water and the contacting for the inactivation to occur. To achieve a high degree of inactivation, the contactors must have the highest possible mass transfer efficiency. Its importance is based on the fact that ozonation of drinking water, in most cases, is mass transfer controlled absorption (Zhou et al., 1994). Maximizing the mass transfer will lead to the full use of generated ozone and the reduction in the contactor volume. The second consideration is the ozone concentration in water. Like other chemical disinfectants, it is the dissolved ozone that controls the disinfection process. Thus, the control of disinfection should not be based on the dosage of ozone or the utilized ozone because the ozone demand varies widely with raw water quality. The third consideration is that the water flow condition approaches the plug flow. This is because the disinfection efficiency will be adversely affected by the presence of short-circuiting. In engineering, changing the flow condition from complete mixing to plug flow can be achieved by compartmentalizing the contactors in series. The greater the number of ozone contactors, the closer the water will approach the plug flow. Balancing the extra construction from the contactor compartmentilization, most of the ozone contact systems used in practice have two to six stage chambers in series.

The destruction of ozone in exhaust gases from the contacting units is necessary to protect the operators from exposure to excessive ozone in air. In the U.S., the current standard for ozone in ambient air is less than 0.0002 mg/L on the average basis. Typical concentrations in contractor exhaust gases are higher than 1 mg/L. Four primary techniques have been employed in practice.

They include: (1) the thermal destruction (heating gases to over 300 °C for 3 s), (2) thermal/catalytic destruction, (3) catalytic destruction and, (4) moist granular activated carbon.

7.1.5 Ultraviolet (UV) Radiation

Unlike the chemical disinfectants presented above, the UV radiation uses the physical way to inactivate microorganisms. It is an effective bactericide and virucide. but an ineffective cysticide. As a result, its use in drinking water disinfection is not recommended.

7.2 EVALUATION OF DISINFECTION PERFORMANCES

As early as 1908, Chick recognized that the microbial inactivation by chemical disinfectants should be closely similar to chemical reactions. Consequently, the rate of inactivation is controlled by the disinfectant concentration and the contact time. Table 22 lists the concentration-contact time required for 99 percent inactivation of microorganisms from laboratory studies. As shown, there is wide variation both in the resistance of specific organisms to different disinfectants, and in the disinfection requirements for different organisms using a single disinfectant. In general, however, the C•T products in the tables show that *Giardia* cysts are the most resistant to disinfection, followed by viruses, while *E. coli* are the least resistant. Toward a particular microorganism, relative efficiency of disinfectants in descending order are ozone, chlorine dioxide, chlorine and chloramines (DeMers and Renner, 1992; Hibler et al., 1987; Karanis et al., 1992).

For *Cryptosporidium* oocysts, the efficacy of water disinfection is uncertain as the investigations are just beginning. A few studies have reported on the effectiveness of a number of disinfectants used in laboratory studies. Table 23 summarizes the results of *Cryptosporidium* inactivation using different disinfectants. Campbell et al. (1982) reported on the effectiveness of a 3 percent solution of NaOCl. Newborn mice were used to ascertain oocysts viability. Infection was obtained in mice after 18 h exposure. Under similar conditions, bacterial pathogens were readily destroyed. Although no quantification of inactivation was made, it did suggested that *Cryptosporidium* may be extremely resistant to chlorination. This conclusion was later confirmed by Peeters et al. (1989). They seeded demineralized water with controlled numbers of oocysts of *Cryptosporidium parvum* purified from fresh calf feces and subjected them to different treatments with ozone or chlorine dioxide. An ozone dose of 1.11 mg/L with a contact time of 6 min was required to totally eliminate 10^4 per mL of the oocysts. Also, 0.4 mg/L ClO_2 with 15 min contact time was needed to inactivate over 90 % of the oocysts. Korich et al. (1990) studied the effects of ozone, chlorine dioxide, chlorine and monochloramine on *Cryptosporidium parvum* oocysts viability. It was observed that ozone and chlorine dioxide more effectively inactivated oocysts than chlorine and monochloramine. Greater than 90 % reduction in infectivity was achieved by treating oocysts with 1 mg/L of ozone for 5 min. An exposure of 1.3 mg/L of ClO_2 yielded 90 % inactivation after 1 h, while 80 mg/L of chlorine or monochloramine required approximately 90 min for 90 % inactivation. This suggested that *C. parvum* oocysts are 30 times more resistant to ozone and 14 times more resistant to chlorine dioxide than *Giardia* cysts under the same conditions. Comparable results were found by Ransome et al. (1993), who examined the effectiveness of various disinfectants on the oocyst viability by in vitro excystation. However, they observed that the oocysts were much more resistant than

Table 22. Effectiveness of Disinfectants on Inactivation of Microorganisms[a]

Microorganisms	Disinfectant	Conc. C mg/L	Contact T myin	C T	pH	Temp. °C
E. coli	O_3	0.065	0.33	0.022	7.2	1
		0.0023	1.03	0.002	7.0	12
	ClO_2	0.75	0.50	0.38	6.5	5
		0.75	0.30	0.23	6.5	10
	HOCl	0.1	0.40	0.04	6.0	5
	OCl^-	1.0	0.92	0.92	10.0	5
	$NHCl_2$	1.0	5.5	5.5	4.5	15
	NH_2Cl	1.0	175	175	9.0	5
Poliovirus	O_3	0.3	0.13	0.04	7.2	5
		0.245	0.50	0.12	7.0	24
	ClO_2	0.8	6.8	5.4	7.0	5
		0.5	2.0	1.0	7.0	25
	HOCl	0.5	2.1	1.05	6.0	5
	OCl^-	0.5	21	10.5	10.0	5
	$NHCl_2$	100	140	14,000	4.5	5
	NH_2Cl	10	90	900	9.0	15
Giardia lamblia	Free Cl_2	2.5	30	75	6	5
		2.5	47	118	7	5
		2.5	57	142	8	5
Giardia lamblia	O_3	0.15	0.97	0.15	7	25
		0.082	1.9	0.16	7	25
		0.034	5.5	0.19	7	25
		0.48	0.95	0.46	7	5
		0.20	3.2	0.64	7	5
		0.11	5.0	0.55	7	5
Giardia muris	O_3	0.18	1.3	0.24	7	25
		0.10	2.2	0.22	7	25
		0.08	3.4	0.27	7	25
		0.70	2.5	1.8	7	5
		0.40	5.0	2.0	7	5
		0.31	6.4	2.0	7	5
Giardia lamblia	O_3	0.03 to 0.15	5.5 to 1.06	0.17	7	25
		0.11 to 0.48	5.0 to 0.94	0.53	7	5
Giardia muris	Chloramine	1.5 to 2.4	236 to 276	496	7	3
		1.4 to 2.9	122 to 227	354	7	10
		1.0 to 1.9	75 to 241	184	7	18
Giardia muris	Chloramine	5.0 to 16.6	50 to 182	848	7	15
		3.2 to 9.0	58 to 132	466	8	15

[a] Source: Troyan and Hansen, 1989.

Table 23. Effectiveness of Disinfectants on Inactivation of *Cryptosporidium*[a,b]

Disinfectant	Concentration, mg/L	Contact time, min
Ozone	1.8	10
	0.8	15
Chlorine dioxide	5.0	15
Hydrogen peroxide	327	10
Iiodine	120	60
Ultraviolet radiation	80 mW s/cm^{-2}	

[a] Source: Ransome et al., 1993.
[b] Disinfectant concentrations and contact times to achieve 90 % reduction

expected. Even to achieve a modest inactivation, the required chlorine residual and the contact time were considerably beyond those which can be applied in practice.

In UV disinfection, the process effectiveness is evaluated by the UV intensity and contact time. Huff et al. (1965) reported more than four logs of inactivation of polio-, echo- and coxsackie viruses. The intensities varied from 7 to 11 mW s/cm^{-1}. Its effectiveness to kill *Legionella pneumophila* was tested using a follow-through, stainless steel enclosed unit. At the intensities of 30 mW s/cm^{-1}, more than 4 logs reduction can be achieved at both 25 °C and 43 °C. Review by Rice and Hoff (1981) showed that UV radiation is ineffective, at the capacities of most commercially available UV treatment units for the inactivation of *Giardia*. Similar conclusion for inactivating *Cryptosporidium* oocysts was made by Ransome et al. (1993). They concluded that the UV inactivation of 90 % and 99% oocysts needed 80 and 120 mW s/cm^{-1}, respectively. These are much higher than the UV dose of 30 mW s/cm^{-1} in most water treatment practices. As a result, UV is not recommended for drinking water disinfection.

In synthesizing all the information available for chemical disinfection technologies, the US EPA developed the tabulated CT_{10} values in the Surface Water Treatment Rule for controlling microorganisms. Tables 24 and 25 present the CT_{10} values required to attain one-log reductions or three-log reductions of *Giardia* cysts, respectively. The UV radiation was not included because of its ineffectiveness for *Giardia* reduction. As shown, lower temperatures require higher CT_{10} values. For chlorine, an increase in pH also increases necessary CT_{10} values.

Table 26 shows the CT_{10} values for achieving inactivation of viruses at pH 6 through 9. They become the pacing parameter for the amount of additional primary disinfection to be provided by ozone during conventional treatment. In such a case, only 0.5 log inactivation of *Giardia* and 2 log inactivation of viruses should be provided by primary disinfection because 2.5 log reductions of *Giardia* and 2 log reduction of viruses may have been acquired by the conventional treatment. The CT_{10} requirements may be higher for viruses than for *Giardia* cysts.

Table 24. CT_{10} Values Required to Attain One-log Reduction of *Giardia lambia*[a]

Disinfectant	pH	Temperature, °C					
		≤ 1	5	10	15	20	25
Free Chlorine[b]	6	55	39	29	19	15	10
(2 mg/L)	7	79	55	41	28	21	14
	8	115	81	61	41	30	20
	9	167	118	88	59	44	29
Ozone	6 to 9	0.97	0.63	0.48	0.32	0.24	0.16
Chlorine dioxide	6 to 9	21	8.7	7.7	6.3	5	3.7
Chloramines[c]	6 to 9	1,270	735	615	500	370	250

[a] Source: US EPA. 1989.

[b] CT_{10} values will vary depending on concentration of free chlorine. CT_{10} values for different free chlorine concentrations are specified in tables in the Guidance Manual (US EPA, 1989).

[c] To obtain 99.99 % inactivation of enteric viruses with chloramines requires CT_{10} value larger than 5,000 at temperatures of 0.5, 5, 10, and 15 °C.

Table 25. CT_{10} Values Required to Attain Three-log Reduction of *Giardia lambia*[a,b]

Disinfectant	pH	Temperature, °C					
		≤ 1	5	10	15	20	25
Free Chlorine[b]	6	165	116	87	58	44	29
(2 mg/L)	7	236	165	124	83	62	41
	8	346	243	182	122	91	61
	9	500	353	265	177	132	88
Ozone	6 to 9	2.9	1.9	1.4	0.95	0.72	0.4
Chlorine dioxide	6 to 9	63	26	23	19	15	11
Chloramines[d]	6 to 9	3,800	2,200	1,850	1,500	1,100	750

[a] Source: US EPA, 1989.

b These CT_{10} values for free chlorine, chlorine dioxide and ozone will guarantee greater than 99.99 % inactivation of enteric viruses.

[c] CT_{10} values will vary depending on concentration of free chlorine. CT_{10} values for different free chlorine concentrations are specified in tables in the Guidance Manual (US EPA, 1989).

[c] To obtain 99.99 % inactivation of enteric viruses with chloramines requires CT_{10} value larger than 5,000 at temperatures of 0.5, 5, 10, and 15 °C.

Table 26. CT_{10} Values for Virus Inactivation at pH Values between 6 and 9[a]

Disinfectant	Log Inactivation	Temperature, °C					
		0.5	5	10	15	20	25
Free Chlorine[b]	2	6	4	3	2	1	1
(2 mg/L)	3	9	6	4	3	2	1
	4	12	8	6	4	3	2
Ozone[c]	2	0.9	0.6	0.5	0.3	0.25	0.15
	3	1.4	0.9	0.8	0.5	0.4	0.25
	4	1.8	1.2	1.0	0.6	0.5	0.3
Chlorine dioxide[d]	2	8.4	5.6	4.2	2.8	2.1	-
	3	25.6	17.1	12.8	8.6	6.4	-
	4	50.1	33.4	25.1	16.7	12.5	-
Chloramines[e]	2	1,243	857	643	428	321	214
	3	2063	1423	1067	712	534	356
	4	2883	1988	1491	994	746	497

[a] Source: US EPA, 1989.

[b] Data adapted from Sobsey (1989) for inactivation of Hepatitis A Virus at pH = 6, 7, 8, 9, and 10 and at 5 °C. CT_{10} values include a safety factor of 3.

[c] Data adapted from Roy et al. (1982) for inactivation of poliovirus at pH = 7.2 and at 5 °C. CT_{10} values include a safety factor of 3.

[d] Data adapted from Sobsey (1989) are based on the inactivation at pH = 6.0 and at 5 °C. CT_{10} values include a safety factor of 3.

[e] Data adapted from Sobsey (1989) for inactivation of Hepatitis A Virus at pH = 8.0 and at 5 °C, and assumed to apply to pH in the range of 6.0 to 10.0. These CT_{10} values apply only for systems using combined chlorine where chlorine is added prior to ammonia in the treatment sequence. CT_{10} values given here should not be used for estimating the adequacy of disinfection in systems applying performed chloramines, or applying ammonia ahead of chlorine.

In using these CT_{10} values for determining the disinfection effectiveness, one must realize the assumptions underlying the CT_{10} concept (Hoff, 1987). The basic assumptions are that the kinetics of disinfection follows a first-order decay process and the disinfectant concentration, and that contact time are equally important in determining the degree of inactivation. An extensive review of available information shows that the deviation from this first-order process is common in water disinfection (Haas and Karra, 1984). Also, Zhou and Smith (1994) found that the concentration of ozone is much more important than the contact time in ozonation. Second, the U.S. EPA, based on the work of Lev and Regli (1992a; 1992b), developed an approach to determine the characteristic concentration and contact time. Such an approach has been questioned recently by Lawer and Singer (1993) and Zhou et al. (1994). A rational approach, the Back Flow Cell Model, for the design and modelling of ozone disinfection has been introduced, in which the performance of disinfection contactors are predicted by integrating contactor hydrodynamics, mass transfer, ozone decay in water, and susceptibility of microorganisms (Smith and Zhou, 1994; Zhou, 1995).

7.3 FORMATION OF DISINFECTION BYPRODUCTS AND STRATEGIES FOR THEIR CONTROL

Adding the chemical disinfectants into water might result in the production of harmful by-products. This is because the disinfectants are usually very reactive in water. Two basic mechanisms have been identified to lead to the formation of disinfection by-products: (1) reduction, oxidation or disproportionation of the disinfectant itself, and (2) oxidation by the disinfectant with materials already present in water. An example of the first mechanism is the formation of chlorite and chlorate ions associated with chlorine dioxide, while an example of the second mechanism is the formation of trihalomethanes from the chlorination. The major disinfection by-products in finished water are listed in Table 27. Some of them have been identified as possible carcinogenic compounds. Consequently, a current challenge in water treatment is to provide appropriate disinfection of more resistant organisms (cysts and viruses), while minimizing the formation of by-products of public health concern. Nevertheless, the WHO (1993) stressed that the risks to health from these by-products are extremely small in comparison with the risks associated with inadequate disinfection. Therefore, it is important that disinfection should not be compromised in attempting to control such by-products.

Strategies for controlling disinfection by-product formation include (Singer, 1994):

1. source control
2. precursor removal
   a) enhanced coagulation
   b) granular activated carbon adsorption
   c) membrane filtration
3. alternative oxidation and disinfectants
   a) combined chlorine (monochloramine)
   b) ozone
   c) chlorine dioxide
   d) permanganate
   e) advanced oxidation processes
   f) UV light
4. air stripping

Source control strategies involve management of the water source to lower the concentrations of natural organic matter and bromide. Similarly, precursor removal refers to strategies aimed at lowering the concentration of natural organic matter. The alternative oxidants and disinfectants approach involves supplementing or replacing the use of chlorine. Some of the alternative disinfectants, however, can serve only as either a primary disinfectant or a secondary disinfectant, and must be used in combination with chlorine or another of the alternatives listed to ensure adequate disinfection. Another shortcoming is that some of the alternative disinfectant may produce other disinfection by-products that are also of concern. The last approach, air stripping, can provide the removal of the volatile disinfection by-products after they are formed. But it cannot be used to control the other disinfection by-products that are nonvolatile. A detailed review of the strategies for controlling disinfection by-products is beyond the scope of this report and interested readers are referred to Singer (1994) and NAS (1987). Currently, there is a lack of a best available technology

that will effectively solve this problem uniformly. Instead, it must be addressed on a site-specific basis.

Table 27. Major Halogenated Disinfection By-Products[a]

Chemicals	Example	Toxicological effects[b]
Trihalomethanes	Chloroform	C, H, RT
	Dichlorobromomethane	H, RT
	Dibromochloromethane	H, RT
	Bromoform	H, RT
Haloacetonitriles	Chloroacetonitrile	G, D
	Dichloroacetonitrile	M, G, D
	Trichloroacetonitrile	G, D
	Bromochloroacetonitrile	M, G, D
	Dibromoacetonitrile	G, D
Haloacid derivatives	Dichloroacetic acid	MD, C, N, OL, A
	Trichloroacetic acid	HPP
Chlorophenols	2-Chlorophenol	F, TP
	2,4-Chlorophenol	F, TP
	2,4,6-Chlorophenol	C
Chlorinated ketones	1,1-Dichloropropanone	M
	1,1,1-Trichloropropanone	M
	1,1,3,3-Tetrachloropropanone	M
Chlorinated furanones	MX	M, Cl
Chlorinated aldehydes	2-Chloroacetaldehyde	G

[a] Source: US EPA, 1990a.

[b] C = carcinogenic; Cl = clastogenic; D = developmental; H = hepatotoxic; HPP = hepatic peroxisome profilferation; G = genotoxic; M = mutagenic; MD = metabolic disturbance; N = neurotoxic; OL = ocular lesions; RT = renal toxic; TP = tumor promoter.

7.4 CHOOSING A DISINFECTION PROCESS

Table 28 summarizes the important aspects and advantages and disadvantages of various disinfection technologies. Their desired points of application are summarized in Table 29. Table 30 compares basic operational considerations, pH, the presence of by-products, relative operational simplicity, and maintenance requirements.

As shown, chlorine is an excellent bactericidal and virucidal agent, but not an effective disinfectant for protozoan. It provides a stable residual for the distribution system if the water is free of chlorine-demanding ammonia and organic materials. Since chlorine can produce THMs and other Halogenated (TOX) and nonhalogenated organic compounds, the use of chlorine should be minimized, particularly when THM and TOX precursors are present at concentrations high enough

Table 28. Advantages and Disadvantages of Disinfectants[a]

Consideration	Cl_2[b]	Cl_2/deCl_2	O_3	ClO_2	UV
Size of plants	All sizes	All sizes	Medium to large	Small to medium	Small to medium
Equipment reliability	Good	Fair to good	Fair to good	Good	Fair to good
Relative complexity of technology	Simple to moderate	Moderate	Complex	Moderate	Simple to moderate
Safety concerns	Yes	Yes	Moderate	Yes	Minimal
Bactericidal	Good	Good	Good	Good	Good
Virucidal	1[c]	1[c]	Good	Good	Good
By-products of possible health concern	2[c]	2[c]	3[c]	Yes	No
Residual persistence	Long	None	None	Moderate	None
Contact time	Moderate	Moderate	Short	Moderate	Short
Reaction with NH_3	Yes	Yes	No	No	No
pH dependent	Yes	Yes	Slight	Slight	No
Process control	Well developed	Well developed	Developing	Developing	Developing

[a] Source: AWWA, 1990.

[b] Includes chloramination

[c] 1 = moderate for free residual chlorination: poor for combined residual chlorination; 2 = fewer by-products with combined residual chlorination; 3 = health significance of by-products is unresolveed at present.

Table 29. Desired Points of Disinfectant Applications[a,b]

Disinfectant	Comments
Chlorine	Toward the end of the water treatment process to minimize THM formation and provide secondary disinfection
Ozone	Prior to the rapid mixing step in all treatment process, except GAC and conventional treatment processes; prior to filtration for GAC; post-sedimentation for conventional treatment. In addition, sufficient time for biodegradation of the oxidation products of the ozonation of organic compounds is recommended prior to secondary disinfection
Ultraviolet radiation	Toward the end of the water treatment process to minimize presence of other contaminants that interfere with this disinfectant
Chlorine dioxide	Prior to filtration; to assure low levels of ClO2, ClO_2^- and ClO_3^-, treat with GAC after disinfection
Monochloramines	Best applied towards the end of the process as a secondary disinfectant

[a] Source: US EPA, 1990a.

[b] In general, disinfectant dosages will be lessened by placing the point of application towards the end of the water treatment process because of the lower levels of contaminants that would interfere with efficient disinfection. However, water plants with short detention times in clear wells and with nearby first customers may be required to move the point of disinfection upstream to extend the contact time.

Table 30. Comparison of Disinfectants Used in Water Treatment[a]

Disinfectant	Cl_2	ClO_2	Mono-chloramine	O_3	UV
Optimum water pH	7	6 to 9	7 to 8	6	N/A[c]
Bu-products present	Yes	Yes	Yes	Yes	No
Operational simplicity	Yes	No	No	No[b]	Yes
Maintenance required	Low	Low	Low	High	High

[a] Source: US EPA, 1990a.
[b] Using an automated system can simplify the operation
[c] NA = not applicable

to produce amounts of concern. However, the chlorination has long been developed and its successes has been well documented. It is inexpensive and needs low to moderate operation skill, although the safety of handling chlorine gas and related solution must be considered. As a result, chlorine is well suited to all sizes of water treatment systems if the control of disinfection by-products and the removal of protozoan are not compromised.

Chloramines are a weak cysticide and a poor virucide. The contact times and concentrations required for a certain degree of disinfection are much longer and higher than with chlorine, chlorine dioxide and ozone. As a result, chloramines are not recommended as a primary disinfectant. However, it is a weak oxidant and its slow dissociation in water to free chlorine produces only a trace amount of halogenated disinfection by-products. Its stability renders the chloramines as a common secondary disinfectant. Similar to chlorination, the process is inexpensive, well developed and needs low to moderate operation skills. Care should be taken to add ammonia prior to adding chlorine. Otherwise, THMs and other disinfection by-products will be formed during the chlorination. Adding ammonia later will curb further generation of THMs, but the THM level will remain as produced from the initial chlorination.

Chlorine dioxide is a better disinfectant, and is a stronger oxidant than free chlorine. Very little, if any, halogenated organic by-products may be formed. It also does not oxidize bromide ion to bromate as ozone and chlorine do. However, chlorite and chlorate ions are produced, which have undesirable public health consequences. In water, chlorine dioxide is unstable, thus, a secondary disinfectant is definitely needed to maintain the disinfectant residual in the water distribution system. The technology is developing and needs relatively higher operating skills as compared to chlorine because chlorine dioxide must be generated on site and must be properly dosed. The safety of generating and handling chlorine dioxide may be an issue because it has a strong, disagreeable odor and is toxic to humans. The technology has a moderate cost, as a result, may be the most suitable for small to medium sized systems (Lykins et al., 1990).

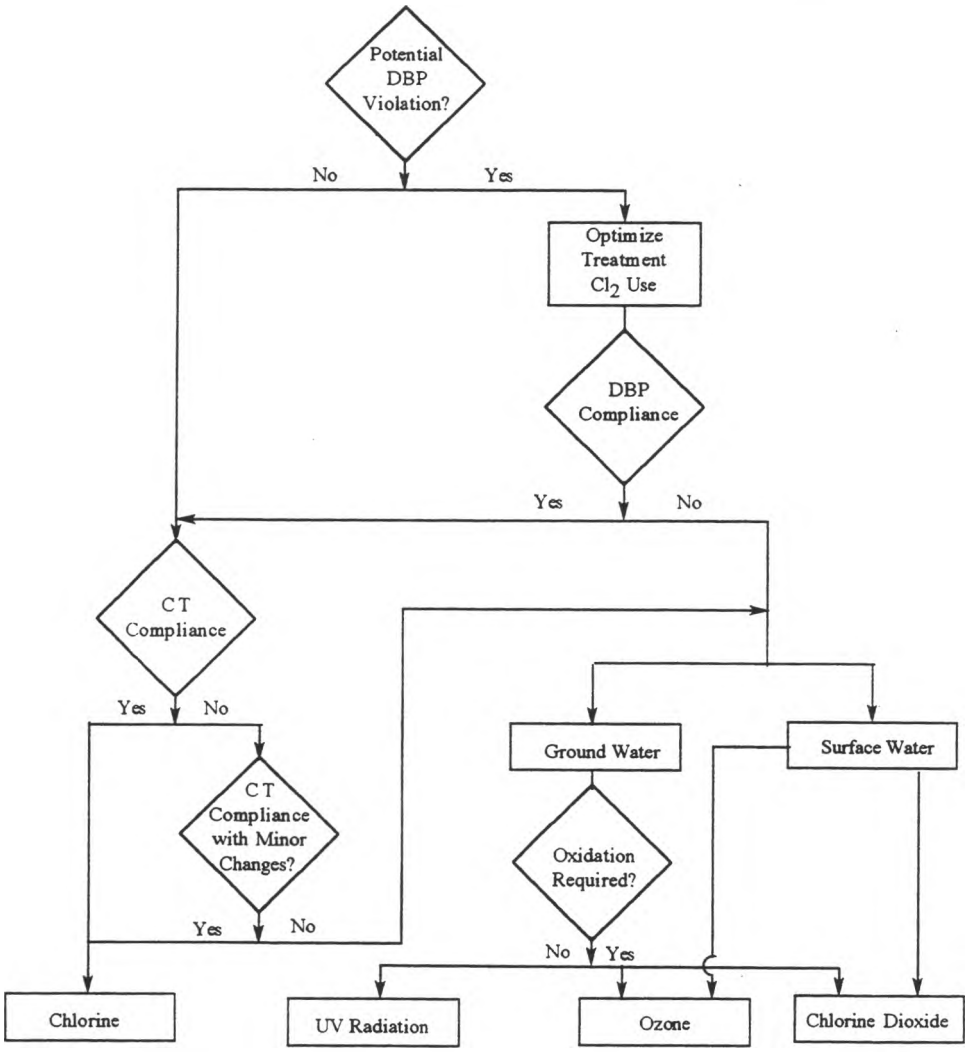
Ozone is a very strong oxidant, as a result, is a very powerful disinfectant. However, it is unstable, and must be generated on site. As a result, it is used as the primary disinfectant, but not

used as the secondary disinfectant because it can not maintain an adequate residual in water distribution systems. In addition, ozone has low solubility, efficient dissolution of ozone from the gas phase into water is therefore essential. Furthermore, excessive ozone in exhaust gas from the contactor must be handled properly. Perhaps the most important advantage of using ozone is that ozone can effectively inactivate not only traditional pathogens, but also protozoans such as *Giardia* and *Cryptosporidium* with reasonable contact times and concentrations. In addition, it does not directly produce halogenated disinfection by-products. However, it can react with bromide ion to form bromate which has potential health effects. Also, it can oxidize natural organic materials to biodegradable oxidation products. Without an adequate post-treatment, these biodegradable oxidation products may cause microbial regrowth in water distribution systems. The technology is complicated and is still being developed, although several thousand units are in operation around the world. The capital costs of ozonation systems are high, but the operating costs are moderate.

In all, each of the disinfectants used in water treatment has some advantages and disadvantages. There appears to be no disinfectant that can be applicable for all situations. Currently, free residual chlorine remains as the predominant primary disinfectant. With increasingly strict regulations toward the disinfection by-products and the better control of newly recognized pathogenic microorganisms, interests have been raised in using alternative disinfection technologies such as ozone and chlorine dioxide. However, none of these resolve all of the disinfection problems the water suppliers are facing. In most cases, minor plant modifications and process optimization can be implemented to allow continued use of chlorine. For example, water treatment plants with large clearwells or finished water reservoirs should investigate the possibility of the installation of baffles to provide sufficient disinfection detention times. If the problem lies in meeting future disinfection by-product regulations, extensive modifications may be necessary to meet CT_{10} compliance and may result in the selection of an alternative disinfectant. In this case, the water treatment plants should optimize treatment first. If the disinfection by-products continue to be a problem, their choice of alternatives depends on weather their source water is groundwater or surface water. In both situations, the possible application of either ozone or chloride dioxide should be evaluated. UV radiation is not recommended because it is ineffective against cysts such as *Giardia*. Figure 11 shows a flow sheet to provide guidance on selecting a primary disinfection alternatives.

With respect to selecting a secondary disinfectant, chlorine is typically favored because of the familiarity of operating staff with the process. However, the use of chloramines are gaining popularity to reduce disinfection by-products. A current trend is to optimize the coagulation, flocculation and filtration to remove the precursors as much as possible, thereby, to reduce the dose of chlorine for controlling the formation of disinfection by-products. Furthermore, advanced oxidation processes such as ozonation and chlorine dioxide coupled with the use of chloramines should be evaluated for the optimization of the disinfection process.

Figure 11. Flow Sheet for Selecting a Primary Disinfectant[a,b]



[a] Source: DeMers and Renner, 1992.
[b] This chart assumes chlorine currently in use at facility

8.0 PACKAGE PLANTS

As discussed above, the water treatment plants in the Northern River Basins Study area are primarily small in scale. These small water suppliers are most likely to exceed drinking water quality standards and face a number of difficulties in complying with the increasingly strict regulations. Besides the technologies reviewed from Section 4.0 to 7.0, additional technologies have been developed to meet the economic and technical requirements specific to small community systems. In this section, different package plant technologies are reviewed.

8.1 PROCESS DESCRIPTION

Package plants are treatment systems that are assembled in a factory, skid mounted, and transported to the treatment site or that are transported as component units to the site and then assembled. The treatment processes used in package plants are virtually variations of coagulation, flocculation, settling and filtration treatment trains. New products, however, may incorporate some innovative technologies. For example, tube settlers, adsorptive clarifiers and high flow rate mixed- or dual- media filters have been used to improve the treatment performance.

Package plants can vary widely in the design specifications and operation requirements. Three basic types of package plant systems are:

1. conventional package plants
2. tube-type clarification package plants, and
3. adsorption clarifier package plants

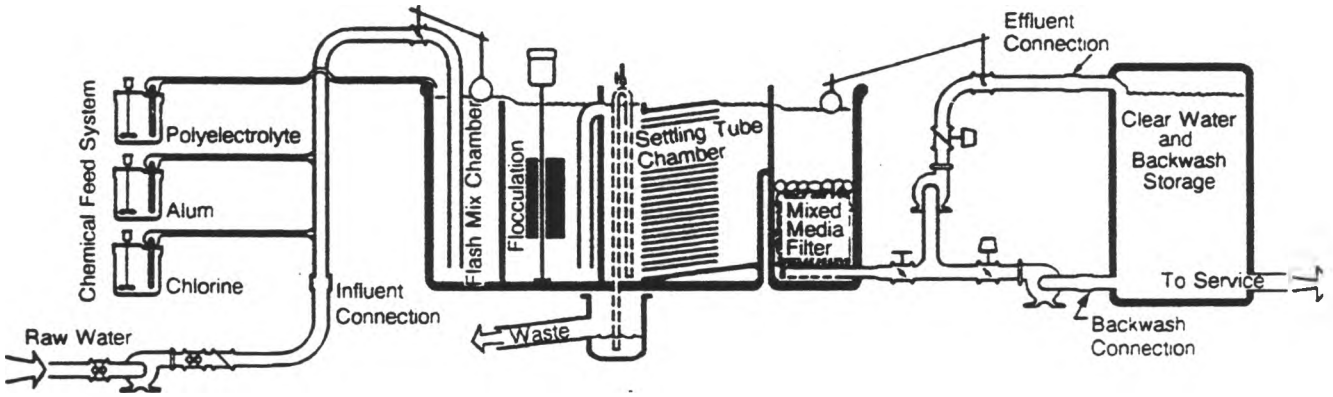
Conventional package plants consists of the processes of coagulation, flocculation, sedimentation and filtration. Typical design standards for these systems are a 20 to 30 min flocculation detention time, a 2 hour sedimentation detention time and rapid sand filtration rated at 4.8 m/h.

Tube-type clarification package plants use the tube settlers to reduce the settling detention time. Its flow diagram is illustrated by Figure 12. The disinfectant and coagulants are added before the influent enters the flash mixer. After the flash mixer, the water enters the mechanical flocculator with a hydraulic detention time from 10 to 20 min. Then, the flocculated water enters the tube settlers. Because the tube settlers have large settling surface and a short settling distance, adequate clarification is attained with less than 15 minutes of detention time. Finally, the clarified water enters a gravity flow mixed media filter. Settled sludge from the tube settlers is flushed during the backwash cycle. Combining backwashing and tube settler flushing simplifies operations.

Adsorption clarifier package plants use a contact bed with plastic bead media (an adsorbent) to replace the flocculation and sedimentation basin, thereby combining these two steps into one. A mixed media filter follows to complete the water treatment. While the water passes through the media, coagulant and water are mixed by expansion and contraction, contact flocculated, and clarified by the adsorption on the media and the previously adsorbed materials. The adsorbed sludge is

cleaned by a combination of air scouring followed by water flushing. A vigorous scrubbing action is necessary to dislodge solids.

Figure 12. Flow Diagram of a Tube-Type Clarification Package Plant (Source: Clark et al., 1994)



It should be noted that other types of package plants are available on the market, with the advance in water treatment technologies. This is particularly true for membrane filtration. Its compact size, automated operation, competitive costs and robust performance make the membrane filtration well suited for small systems. It is believed that membrane filtration will become increasingly important as a practical means to meet the strict requirements.

8.2 EVALUATION OF PROCESS PERFORMANCE

The information on process performances of package plants is still lacking, perhaps due to the less attention paid to small community systems and the less resources available for a thorough evaluation. Clark (1980) surveyed 36 package plants in Kentucky, West Virginia and Tennessee (see Tables 31 and 32). It was revealed that package plants, if properly designed and operated, can meet traditional treatment goals with regard to bacteriological removal and turbidity reduction. Plants that were not meeting the regulations had problems caused by lack of operator attention, e.g., not varying chemical dosage to meet changing raw water quality, or they were not running for lengths of time sufficient to achieve stable operation. Many automatic features, such as backwashing, were either not installed or not used in many cases because operators were reluctant to rely upon them or felt them to be untrustworthy.

Table 31. Bacteriological Results of Package Plants in Finished Water[a]

Raw water	No. of plants	Finished water[b]	
		< 1 NTU	> 1 NTU
< 5 NTU	15	11	4*
6 - 15 NTU	8	8	0
16 - 50 NTU	6	2	4
51 - 100 NTU	0	0	0
> 100 NTU	2	2	0

[a] Source: Clark *et al.*, 1994
[b] One plant did not add coagulants

Table 32. Turbidity Results of Package Plants in Finished Water[a]

Plant	Samples	
	Positive	Negative
A	0	18
B	2	12
C	0	18
D	1	9
E	1[b]	5
F	0	10
G	0	48
Total	4	120

[a] Source: Clark *et al.*, 1994
[b] positive sample probably due to poor sampling or handling at lab

Six of the plants evaluated in the previous analysis were monitored in detail. The results of this second survey were reported by Clark and Morand (1981). Four of the plants had uniform, high-quality source water, but only three plants consistently met the 1-NTU effluent standard. They attributed the problems due to:

1. inadequate design detention time;
2. inadequately trained operators;
3. limited time allocated for the operation; and
4. variability in source water quality.

Another survey of 27 systems was conducted in 1986 (Letterman, 1991). The results showed that all 27 produced the filtered water with an average turbidity less than 1.0 NTU. Among them, 18 plants produced the filtered water with an average turbidity of 0.5 NTU or less. This may be due to better equipment, more highly skilled operators and greater surveillance by regulators.

8.3 CHOOSING AN APPROPRIATE PACKAGE PLANT (SIZE AND INFLUENT)

Package plant systems are most appropriate for plant sizes ranging from 95 to 22,700 m^3/day, although package plants have been used for a larger capacity. In choosing an appropriate package plant, the required water production should be in line with the design capacity. Oversized plants may not only waste a considerable amount of capital costs, but also increase the possibility of failure to run for periods of time long enough to establish stable operation.

The most important consideration in determining the suitability of a package plant is source water quality. Complete source water quality records should be examined to establish seasonal fluctuation in turbidity and temperature. Where turbidity exceeds 100 to 200 NTU, presedimentation may be required as a pretreatment. In some cases, pilot tests may be necessary to select a package plant for more innovative designs.

From the operating perspective, the key consideration is to add optimum amounts of coagulants and filter aids in order to maximize treatment efficiency. The coagulant and filter dosages should reflect the seasonal variations in source water quality. For part-time operators with inadequate training, this will present difficulties that deserve an attention.

The operation of package plants is simplified by automated features. Continuous effluent turbidity and chlorine residual monitoring systems with alarm and emergency shutdown provisions are features that will better control water quality and should be provided. Even with these instruments on the effluent side, Clark et al. (1994) suggested that these instruments may also be necessary on the influent side for the purposes of process control. Otherwise, any changes in chemical feed required to meet changes in turbidity may be too late to improve the turbidity of the finished water.

The costs of package plants may be 10 to 50 percent less than a comparable custom-built system. However, the construction costs vary widely, depending on the size of the plant, nature of the building used to house the equipment, and manufacturers. Logsdon et al. (1990) estimated that the capital costs for plants with a design capacity from 0.1 to 0.25 mgd range from $1 to $2.5 for each gallon per day. The total operating costs are approximately $10,000 per year.

9.0 CONCLUSIONS AND RECOMMENDATIONS

This report reviewed the various water treatment technologies available to remove microorganisms from raw water supplies. Discussion of each technology included a process overview, performance, design considerations, operating and maintenance aspects, costs and status of technology development. Specific considerations were presented for technologies applicable to small community systems such as those located in the Northern River Basins Study area. Also, the impacts of important microorganisms and relevant regulations were examined to highlight the significance and requirements for removing microorganisms in water treatment processes. The following conclusions were drawn from this study:

1. Control of microbial contaminants continues to be the most important consideration for safe drinking water in order to protect public health. Among various pathogens, particular attention should be directed to control newly recognized waterborne microorganisms such as *Giardia*, *Cryptosporidium* and viruses. These microorganisms are often widespread in nature, have a low infectious dose, cause high incidences of waterborne diseases, and are resistant to chlorination.

2. The use of coliforms as an indicator organism presently remains the most sensitive and specific way to detect microbial contamination and assess treatment efficiency. However, one must realize their limitations in predicting the protozoan and viral contamination. It would be desirable to include the particle size distribution determination for performance monitoring.

3. To safeguard against the contamination of waterborne pathogens, a multiple barrier approach should be exercised whenever possible. With this approach, controlling of microbial contamination starts from the collection of all wastes for treatment at specified sites, followed by the use of natural self-purification capacity. In water treatment, the multiple barrier approach involves the use of multiple water treatment processes in ensure a safe public water supply.

4. The best available technologies for the removal of microorganisms in water treatment include both filtration and disinfection. Disinfection alone using chlorine and its derivatives as the only treatment for surface water is ineffective to prevent waterborne giardiasis and cryptosporidiosis. An adequate pretreatment and filtration in addition to disinfection should be implemented for all surface waters.

5. Pretreatment by coagulation and flocculation is necessary to obtain high microorganism removals in filtration. It can also remove a significant portion of the organic materials that interfere with disinfection.

6. The filtration processes, combined with pretreatment, can remove *Giardia* cysts and *Cryptosporidium* oocysts 99 percent or more providing that an optimum dosage of chemical coagulant is used. The efficiency of removing viruses is over 90 percent, dependent on the type of filtration. However, the filter ripening and turbidity breakthrough can substantially

deteriorate the effluent microbiological quality. The water treatment plants should keep the effluent turbidity as low as possible, preferably less than 0.2 NTU.

7. Provided that the raw water quality is adequate, slow sand filters, diatomaceous earth filtration, membrane filtration and package plants are the most applicable filtration technologies to small community systems.

8. The addition of filtration aids is essential for successful removal of microorganisms by rapid rate filtration and direct filtration. The proper dosages should reflect the seasonal variations in filter influent quality. The mechanisms underlying the flocculation and filtration of microorganisms closely follows the same principles as the elimination of colloidal and finely dispersed substances.

9. Different disinfectants exhibit wide variations in the inactivation of microorganisms. In general, their relative efficiency in descending order are ozone, chlorine dioxide, chlorine, and chloramines. Due to their weak disinfection potential, chloramines are most frequently used as secondary disinfectants.

10. Different types of microorganisms have different resistance to the disinfectants. It appears that among the concerned pathogens, the *cryptosporidium* oocysts and *Giardia* cysts are the most resistant to disinfection, followed by viruses. Bacteria are usually the most sensitive to disinfection.

11. Disinfection efficiency is strongly affected by the turbidity, pH, temperature, disinfectant demand causing materials and initial mixing. To ensure adequate disinfection, it is critical to maintain the disinfectant residual and achieve sufficient contact between microorganisms and disinfectant molecules.

12. Most disinfectants will react with various substances in water to form the disinfection by-products. The strategies for controlling the disinfection by-products include the source control, precursor removal, alternative disinfectant and air striping.

13. At present, none of disinfectants employed in practice could solve all the problems the water utilities are facing. The chlorination, in combination with the optimization of coagulation and filtration, remains the most technically effective and economically feasible approach for controlling the microorganisms from water treatment processes. When the disinfection by-products become concerned, the alternative disinfectants such as ozone should be considered.

To ensure the water suppliers in the Northern River Basins Study area meet the microbiological requirements of provincial regulations, the following recommendations are made:

1. The removal of microorganisms is dictated by the technologies applied by a water treatment plant. It would be interesting to investigate the microbiological violations related to treatment process deficiencies so that the appropriate water treatment can be provided. In doing so, a large database should be used to minimize the uncertainties in assessing the effectiveness of water treatment processes.

2. Small community systems are facing the biggest challenges in compliance with increasingly strict regulations. Considering that most of them are lacking the design and operating expertise, correction protocol should be developed to assist the plant operators to optimize the existing facilities. This is particularly necessary for the water treatment plants in the Northern River Basins study area because much less attention has been paid to treat the cold water, although it is known that temperature will affect the effectiveness of water treatment processes.

3. The performance of filtration and disinfection will change from time to time. This is particularly true for plants with inconsistent raw water and occasional operation, thereby resulting in a wide variation in effluent microbiological quality. It is recommended that on-line monitoring facilities should be installed to provide the operators a means to control the process, and to implement emergency measures if necessary.

4. The importance of using proper coagulants and filtration aids in water treatment has been well documented in the literature. Their applications in the Northern River Basins Study Area water utilities should be studied further. Special consideration should be given to the raw water with cold temperature and wide seasonal variation that most of the plants are experiencing.

5. Membrane filtration, as an emerging technology, is a very promising technology, particularly for small systems, because of its compact size, low operating and maintenance requirements, extremely excellent performance for removing microbiological contaminants and comparable costs. Its application for the water treatment plants in the Northern River Basins area should be explored.

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APPENDIX A TERMS OF REFERENCES

Three Literature Reviews on Treatment Efficiencies

I. Introduction

The quality of drinking water is based both on the quality of the source water and also the treatment processes that are used. The methods used and proposed for the treatment of drinking water are many and varied. A great deal of information available in the literature on the performance, advantages and disadvantages of the various processes. A detailed critical review of this information will be performed in this proposed project. The reviews will concentrate on processes which are appropriate for use in the study area and contaminants that are of special concern in the study area. Information will be used for a general assessment on drinking water quality in the basins. This will be completed by assessing the raw water quality and treatment systems that various communities use. In addition the reviews will be valuable information for communities in the study area for selection and assessment of treatment processes the are in use or are proposed.

II. Requirements

The completion of three literature reviews on the efficiency of drinking water treatment processes are proposed for 1994/95. The reviews will include: assessment of inorganic chemical removal efficiencies; assessment of organic chemical removal efficiencies; and assessment of microbial contaminants removal efficiencies. Each review will involve:

1. Assessment of existing water quality data for the study area (inorganic, organic and microbial). Most of this information will be obtained from NRBS studies.

2. Thorough review of pertinent literature. Extensive use will be made of the University of Alberta Library which is the second largest library in Canada. Information obtained from various suppliers, past unpublished research projects, and personal contacts will also be incorporated in the review. The following will be completed as part of the review:

    1. A literature search carried out using facilities at the U of A Library.
    2. Review of literature found.
    3. Review of information from suppliers, personal contacts and other unpublished research reports.
    4. Summarizing available information in a concise form.

3. Evaluation of process alternatives. Treatment methods found in (II) will be evaluated for use in the study area. Evaluation will include factors such as:

    1. Effectiveness of the treatment process
    2. The degree of control, skill and supervision needed to achieve good performance.

3. Technical support required for operation - special skills needed for maintenance and repair.
4. Safety and handling precautions required.
5. Process reliability
6. Climatic effects (water temperatures)
7. Effect of different water quantities and qualities.
8. Level of development of current technology.
9. Public acceptance.
10. Economic considerations.

4. Report