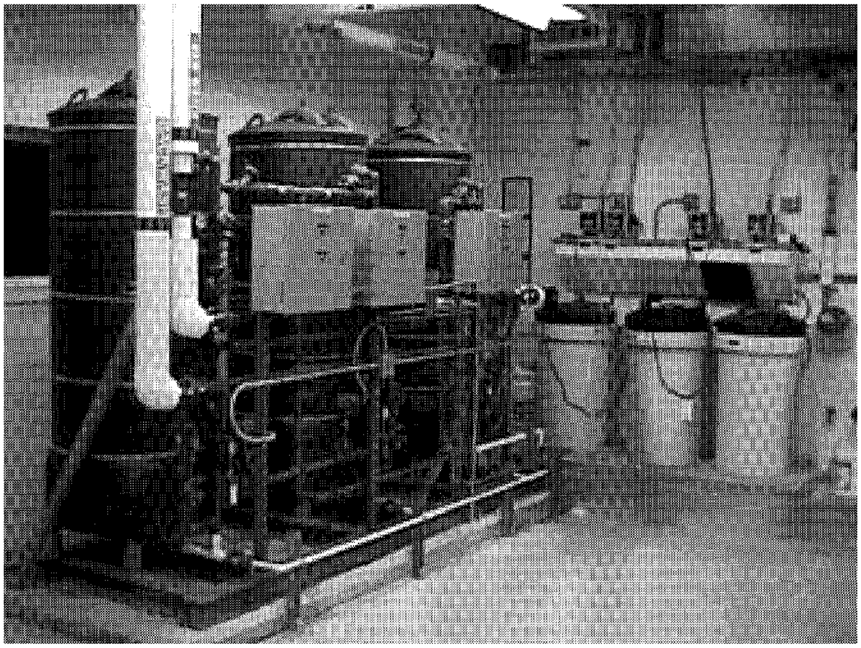
ALASKAN WATER TREATMENT SYSTEMS

AN INTERMEDIATE OPERATOR TRAINING MANUAL



Cover - Upper left: The entrance to the Ship Creek Water Treatment Facility, Anchorage Water and Wastewater Utility. Lower right: the water treatment facility at the Federal Aviation Administration installation in Bethel, Alaska. This photo shows, from left, two manganese greensand filters, a granular activated carbon contactor, chlorine feed tank, potassium permanganate feed tank, and fluoride saturator.

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ALASKAN WATER TREATMENT SYSTEMS

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Northern Testing Laboratories, Inc.
Michael R. Pollen

FOREWORD

Developing affordable, reliable water and sanitation systems in rural Alaska is a major initiative on the part of State and Federal agencies, in partnership with local communities and regional public health organizations. For community-owned utilities to qualify for low-cost loans or grants under various State and Federal programs, they must first demonstrate that they have the capability for utility management and that they will be able to successfully operate the new equipment. The challenge of preparing operators for those new systems is one of the reasons for the development of this manual and associated training course.

In the early 1990's the Alaska Department of Environmental Conservation (ADEC) commissioned a project to develop a basic water systems manual and course, and later, one for basic wastewater systems operations. These texts and courses, developed under ADEC contract by Arasmith Consulting Resources of Albany, Oregon, have been used in the training of hundreds of Alaskan water and wastewater operators. By the end of the 20th Century, nearly 1,000 operator in training (OIT) licenses had been issued to Alaskans who had completed the basic water systems program. As the development of Alaska's sanitation infrastructure progressed and operational requirements expanded, the need for a higher level course became evident.

In 1998, Northern Testing Laboratories, Inc. (NTL), of Fairbanks, Alaska, was contracted by the ADEC to develop a manual and course focused on a more advanced level of understanding by water system operators. The targeted levels for this manual are intermediate water treatment operations, at Levels 2 and 3. This manual and the accompanying course cover the topic of water treatment with the following goals:

- Provide a reference that addresses the state of the art in water treatment systems operation as it is commonly practiced in Alaska today.
- Create a training tool that will help Alaskan water treatment operators obtain Level 2 or 3 certification.

An objective of this manual is to present this information in a user-friendly format and to use examples of water systems typical of Alaska. The author has drawn these examples from his experience in providing monitoring and operations consultation services to hundreds of water systems in all regions of Alaska. Throughout the text, examples from Alaskan systems that have kindly allowed the use of their experiences are used to illustrate the topics being presented.

The Operator's Responsibilities

The water treatment operator serves a most important role as a guardian of public health. A safe water supply is absolutely vital to a community's well being. The water system operator must also operate and maintain the system's equipment as efficiently and economically as possible. This helps to keep the cost to the consumers low. A good preventive maintenance program will increase the useful life of the equipment, which affects long-term capital and replacement costs. Long-term costs may have a direct impact on property taxes and the overall bond indebtedness of the community.

The responsibilities and the amount of knowledge required for Level 2 or 3 certification differ significantly from those required for Level 1. In addition to a more advanced and detailed understanding of the technical aspects of water treatment, the Level 2 and particularly Level 3 operator is expected to assume more of a management role in the operation of their treatment facility. Maintenance, communications, financial management, safety, record keeping, and keeping up with changes in regulations and new water treatment technologies are some of the issues that higher-level operators need to know more about.

With the continuing advancement of water treatment technology and corresponding regulatory controls, the complexity of water utility operations has increased. Moreover, water utilities are now beginning to focus more on customer-oriented business practices, quality of service, and improved economics to remain competitive in a world of increased privatization of public services. As operational requirements increase, so must the skills and qualifications of the personnel who are charged with maintaining vital water utility infrastructures. The path to improvement in these areas includes training, such as that provided by this manual and course.This manual has been developed to provide advanced training to operations personnel.

Student Prerequisites for the Intermediate Course

Only operators who have completed a basic water treatment course and passed the Water Treatment OIT exam, or who have a Level 1 Water Treatment license should attend the course for which this manual has been written. The material in this course begins where the "Alaska Small Water Systems" manual leaves off. For sake of brevity, most of this basic material is not repeated in this manual. The student will find that reviewing the "Alaska Small Water Systems" manual or similar text in advance will be useful in recalling some of the fundamental information that provides a foundation for this course. The student should already have a basic working knowledge of math and will have and be able to use an electronic calculator with logarithm functions (LOG or LOG_{10}).

Using This Manual

The material in this manual is presented in chapters, each dedicated to a particular water treatment process or related topic. Each chapter includes review questions to help the student learn the material presented. Key words set off in bold type can be found in the glossary in Appendix A at the end of the text. A list of references and sources of information is given in Appendix B to foster the operator's continuing education and to help in keeping up with new developments in the field.

Printing This Manual

This manual was developed by the ADEC and Northern Testing Laboratories, Inc., to be used as a publicly available document for the training of operators in Alaska. Northern Testing Laboratories, Inc., retains the right to reproduce and distribute the contents of this manual. Any organization wishing to obtain a camera-ready copy of the manual may obtain one from the ADEC, Facility Construction and Operation Division in Juneau, Alaska.

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Chapter 1

Water Systems in Alaska

Chapter 1 – Water Systems in Alaska

INTRODUCTION

Water is perhaps the single most critical resource to human life on Earth. Billions of tons of water are consumed each day in the United States for agricultural, industrial, and domestic uses. Most importantly, each of us drinks one to two quarts of water every day. Drinking water supplies must be carefully safeguarded to protect the public health. The demand for safe drinking water is growing in the U.S. and worldwide.

Our Water World

We have the good fortune to live in a world with an abundance of water. Although many texts and training manuals have previously been written that describe our planet's water supply as constant or unique, it is certainly neither. Water permeates the universe and is present in abundance on many planets, moons, and in comets. Space probes have discovered ice-rich permafrost buried in craters on the poles of the Moon and ice on the moons and in the atmospheres of Jupiter, Saturn, Uranus, Neptune, and possibly Pluto. Europa, one of Jupiter's moons, may have more water than Earth, maintained in a liquid state under a thin ice layer by heat generated from Europa's contraction and expansion in Jupiter's powerful gravitational field. The surface of Mars bears evidence of ancient river valleys and seas and still may have some ice at the poles. Earth-orbiting satellites have documented a steady rain of small ice-rich comets bombarding the Earth's poles, adding water to our planet every day.

Indeed, we live in a watery, and frequently icy, universe. Earth has abundant, relatively warm oceans, lakes, and rivers of water. Fresh water is found in **aquifers** throughout the Earth's crust, and frozen in the ice fields of the poles and in glaciers. Water is essential for all life on Earth and for the survival of civilization. History shows us that the fortunes of empires have depended on their proximity to water for agriculture, transportation, commerce, and sanitation. Even as we've entered a new millennium, much of the world struggles to find and maintain adequate potable water supplies.

SURFACE WATER SYSTEMS

The U.S. Environmental Protection Agency defines **surface water** as "all water which is open to the atmosphere and subject to surface runoff." Although Alaska has fewer surface water treatment systems than **groundwater** systems, surface water is an important and often the only supply available in a particular area. Surface water supplies tend to vary more in quantity and quality than groundwater supplies, so treatment and storage criteria are often more complex. Operators need to be aware of seasonal changes in surface water supplies, some of which are quite severe in Alaska.

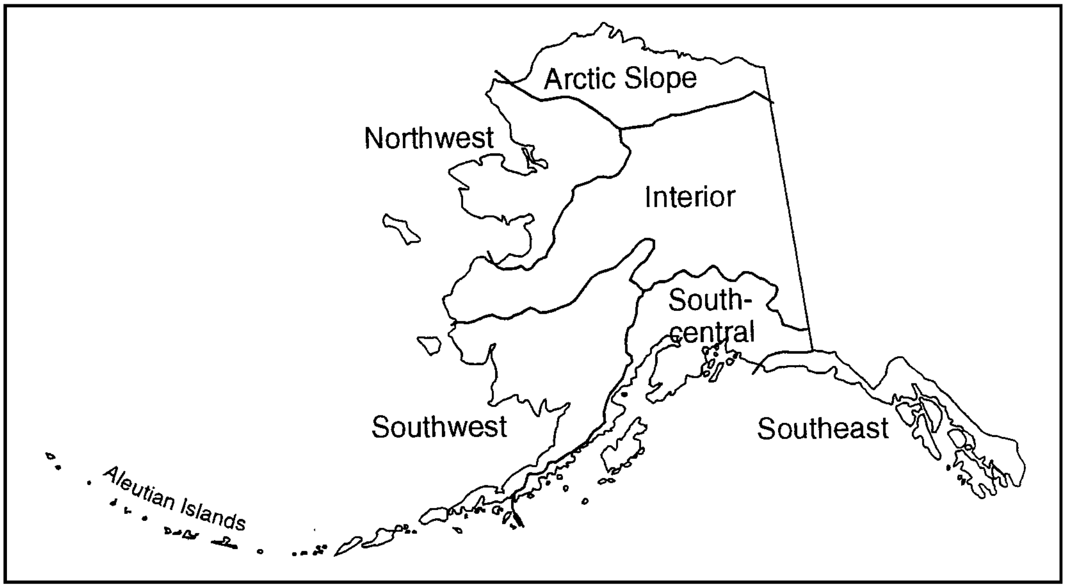
The Surface Water Treatment Rule

The **Safe Drinking Water Act** Amendments of 1986 incorporated a special rule for the treatment of surface water supplies. Known as the **Surface Water Treatment Rule** (SWTR), it established minimum treatment requirements using **filtration** and **disinfection** for surface water and for groundwater supplies found to be directly influenced by surface water infiltration. The primary intent of the SWTR was to control microbiological contaminants such as **pathogenic** bacteria and the protozoan ***Giardia lamblia*** through this "double barrier" approach. To accomplish this, specific requirements for filter design and for disinfection procedures were incorporated into the SWTR.

The SWTR was strengthened further when the Safe Drinking Water Act was amended again in 1996. An "enhanced" SWTR is being developed that is intended to address other microbiological contaminants such as ***Cryptosporidium parvum*** and **naturally occurring**

organic matter[1] that may react with chlorine to form unwanted contaminants in the finished water supply.

For well-protected surface water supplies of exceptional quality, a special provision was included in the SWTR that allowed for a waiver of the filtration requirement. This provision is referred to as "**filtration avoidance**" and requires a comprehensive evaluation of the watershed and a watershed protection program to be in place to ensure the long-term quality of the water supply. Several Alaskan communities are operating under the provisions of this waiver. These regulatory programs are discussed in greater detail in Chapter 2 of this manual.



Map of Alaska, showing the geographic regions discussed in the text. Courtesy of the U.S. Geological Survey.

Southeast Alaska and the Aleutian Islands

Surface water systems are common throughout the Sitka Spruce, Hemlock, and Yellow Cedar rain forests of Southeast Alaska. The forests grow on a thin mantle of soil over bedrock, and groundwater aquifers are primarily in the gravel deposits in the valleys. Many communities utilize dams or **catchments** to collect the usually abundant rainwater and snowmelt. Lakes, rivers, and creeks are used as sources throughout this region. Similar systems exist throughout the Aleutian Islands to collect rainwater and snowmelt from the treeless slopes of those volcanic

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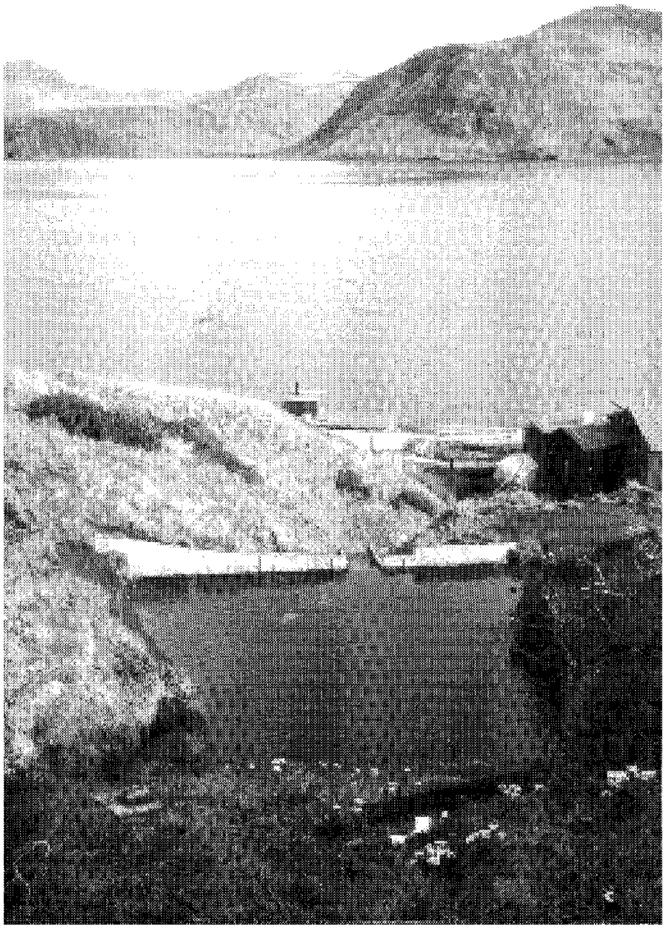
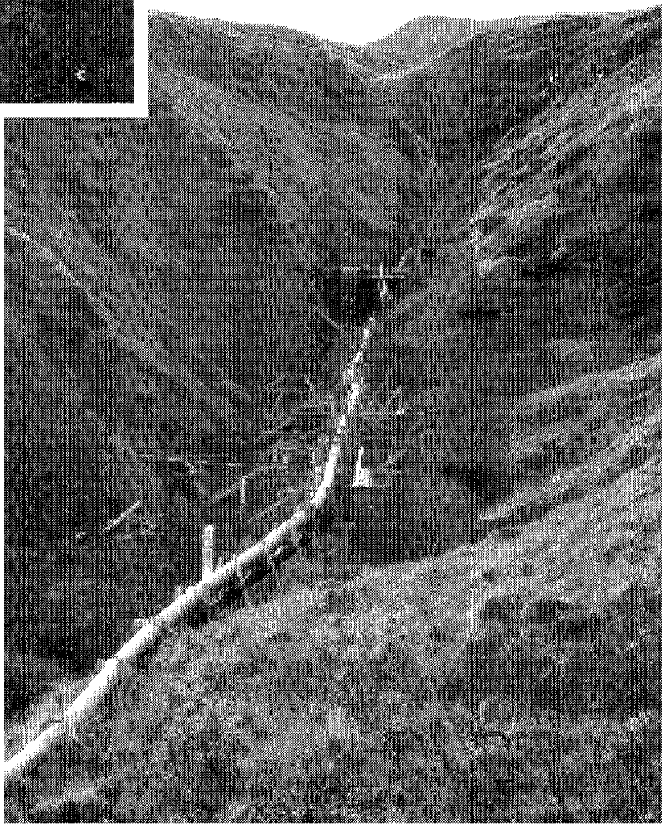
[1] NOM, natural organic matter, is a commonly used term in the engineering and research literature.



Surface water catchment for the Village of Akutan in the Aleutian Islands. The catchment's wooden dam is equipped with a high water overflow (center).

Insulated raw water transmission line from the Akutan catchment. The line delivers water to a filtration building in the village.



islands. Water quality conditions are quite similar for surface waters throughout the vast range of Alaska's southern coastal islands.

Typical water quality characteristics include low **turbidity**, high organic **color**, relatively low **alkalinity**, and low **hardness**. As with all surface water supplies, microbiological concerns are ever present. Several water systems in Southeast Alaska presently operate under filtration avoidance status. This means that under the SWTR, if the source water can be adequately protected and the water is of consistently good quality, only disinfection is required for treatment. Sitka and several other communities obtain water from surface lakes of such good and consistent quality that this has been possible.

Several smaller systems, particularly those with high organic color caused by water percolating through a mat of vegetation, have difficulty with disinfection by-products caused from the reaction of chlorine and naturally occurring organic matter. In such cases, **granular activated carbon** filtration or coagulant addition followed by sand filtration may be required to reduce the organic material before disinfection. The relatively low turbidity levels create some interesting challenges in the selection of effective chemical coagulants for these systems.

The hardness, low alkalinity, and accompanying low pH levels characteristic of snowmelt and rainwater also have consequences with respect to **corrosion** in water distribution systems. Chemical adjustment of the alkalinity, calcium, and pH levels or the addition of **corrosion control** chemicals may be required to correct corrosive conditions.

North Slope and Arctic Coastal Plain

The Arctic Coastal Plain is a vast region of treeless tundra underlain by as much as 2,000 feet of permafrost with virtually no usable groundwater. The surface of the tundra is a patchwork of more than one million lakes, typically rectangular in shape, aligned perpendicular to the prevailing wind. These lakes are mostly shallow, undergo dramatic water quality changes throughout the seasons, and may contain brine from seawater intrusion or salt lenses in the frozen ground. Average precipitation is very low, less than 10 inches per year, so recharge of water in the tundra lakes is minimal in most cases. Many communities supplement their water supplies with snow fences designed to capture snow that would otherwise blow away in the steady prevailing winds.

Water quality problems include organic color, microbiological contaminants, wind-influenced variations in turbidity levels, and occasionally **salinity**. Because much of the water in the shallow lakes is snowmelt, low levels of pH, alkalinity, and hardness are common, with associated corrosion control problems. There are exceptions, however, with some lakes having extraordinarily high hardness and dissolved solids, which increases significantly as the ice thickens in the winter. In many cases, water quality in the shallow North Slope lakes becomes so poor during the winter that treatment becomes very difficult. In Barrow, for example, the surface reservoir was originally a tidal salt lagoon that has been slowly freshened over time by allowing the brine to be displaced by fresh water in an overflow dam system.

Barrow, Alaska, showing the Isatkoak Reservoir (water body in the foreground), separated by the Isatkoak Lagoon by the Isatkoak Dam (running horizontally through the center of the photograph). The Arctic Ocean is on the horizon, and the small Tasigarook Lagoon lies between the ocean and Isatkoak Lagoon. The Barrow Utilities and Electric Cooperative, Inc., water treatment plant lies on the upper, left-hand shore of Isatkoak Lagoon.

Some of the lakes become so tightly sealed with ice that the slowly decaying organic detritus on the bottom produces anaerobic conditions. When holes are drilled through the ice during the winter months, a pungent hydrogen sulfide odor may be encountered.

Water in the larger rivers such as the Colville tends to be of particularly good quality in the winter, but becomes laden with silt and organic debris during the brief spring thaw. The source of the winter flow in the north-flowing rivers is from limestone formations in the northern foothills of the Brooks Range, which adds calcium and alkalinity to the river water.

Glacial Silt Rivers

Throughout Southcentral and Interior Alaska, rivers and creeks often provide water supplies of better quality than the iron-rich, hard groundwater typical of these regions. Glacial silt and organic matter are often present in these streams and the water quality conditions can vary significantly from summer to winter. Some of the large rivers, such as the Yukon, provide a virtually inexhaustible source of water, but also present a considerable set of challenges to tapping that supply. During spring thaw, in addition to significant water quality changes, operators have to contend with ice damage to intake structures, flooding, and changing channels as silt and gravel bars migrate in the dynamic flows.

As with the North Slope rivers, winter water quality is typically excellent with low turbidity and color and moderate levels of alkalinity and hardness. With the onset of spring thaw, however, water quality conditions change dramatically with high turbidity, suspended sediment, organic color and larger debris. Some iron and manganese may also be present. Microbiological concerns are a constant issue with river systems so filtration, frequently with coagulant addition, and disinfection are required. Operators find the transition from winter to summer and the reverse in the fall to be particularly difficult as coagulant addition and filter backwashing schedules have to be adjusted.

The Tanana River, an Interior Alaska glacial silt river.

GROUNDWATER SYSTEMS

Groundwater systems are important water sources throughout much of Southcentral, Southwestern and Interior Alaska. Parts of Southeast Alaska also have some groundwater wells with good yields and good water quality. Usually the groundwater aquifers provide a natural barrier to microbial pathogens such as bacteria and protozoan forms like *Giardia lamblia* and *Cryptosporidium parvum*. In the larger river valleys such as the Yukon, Tanana, and Matanuska-Susitna where yields are high, problems with groundwater are usually related to chemical quality and treatment.

Deep Well Groundwater Systems

Deep wells (more than100 feet below ground surface) are common throughout much of Alaska. Many areas have several aquifers with variable yields and quality of water. For example, the Tanana, Yukon, Kuskokwim, and Matanuska-Susitna Valleys have relatively high-yield water table aquifers. The volume of water is so abundant that it is common practice to use high output wells with dedicated pump stations for fire reserves. This is practiced in the Cities of Fairbanks and North Pole.

Water quality varies from moderate hardness and low iron levels to very hard water, typically with high iron, manganese, and arsenic levels. The source of iron, manganese, and arsenic is the mineral composition of the aquifer. For example, arsenic may result from arsenopyrite ore, often associated with gold deposits. Indeed, many areas of Alaska with a history of gold exploration have a high incidence of arsenic in the groundwater wells. It is not uncommon to find hydrogen sulfide or methane and high levels of organic matter from ancient deposits of vegetation buried deep in old river channels.

Groundwater is cold, often only a few degrees above freezing. This affects treatment efficiencies and keeps carbon dioxide levels relatively high, resulting in low pH. Problems with copper pipe corrosion may result from the high CO_2 levels. Operators often observe that the pH changes from slightly acidic to slightly alkaline when deep well water is brought to the surface and allowed to stand. This is due to the release of CO_2 as the water warms and is exposed to atmospheric pressure that is lower than the pressure in the water-bearing aquifer.

Treatment technologies include an array of iron filtration systems with manganese greensand filters being one of the most common. High concentrations of hydrogen sulfide significantly increase the demand for potassium permanganate, chlorine, or other oxidants in some of these treatment systems.

Lime or ferric sulfate **coagulation** has been used in several of the larger systems, and is still in use in Fairbanks for iron and manganese reduction and to reduce hardness. In such cases, with proper pH control, the calcium and alkalinity levels can be adjusted to maintain a positive **Langelier Index** as an alternative corrosion control treatment.

In some wells, the iron and manganese levels are sufficiently low that **sequestration** with phosphates is used rather than removal. Problems with deposition of rust in distribution lines have limited this application somewhat.

Springs

Alaska has an abundance of natural springs, including thermal springs. True spring water results when an aquifer flows out on the surface because of the structure of the underlying geological formations. If the spring can be properly developed and protected from surface contamination and the water quality is determined to be relatively consistent, that source may be classified as a spring and regulated accordingly.

Many of the thermal springs are highly mineralized. Sulfur odors are common and high hardness, iron, arsenic, and a variety of other inorganic chemicals may be present. Aside from some purported medicinal quality of such water, treatment to achieve conventional potable water quality standards can be difficult and expensive. Conversely, some cold water springs have water of extraordinarily good quality. An example of that is the famous Fox Spring outside of Fairbanks where high-quality water is produced year-round.

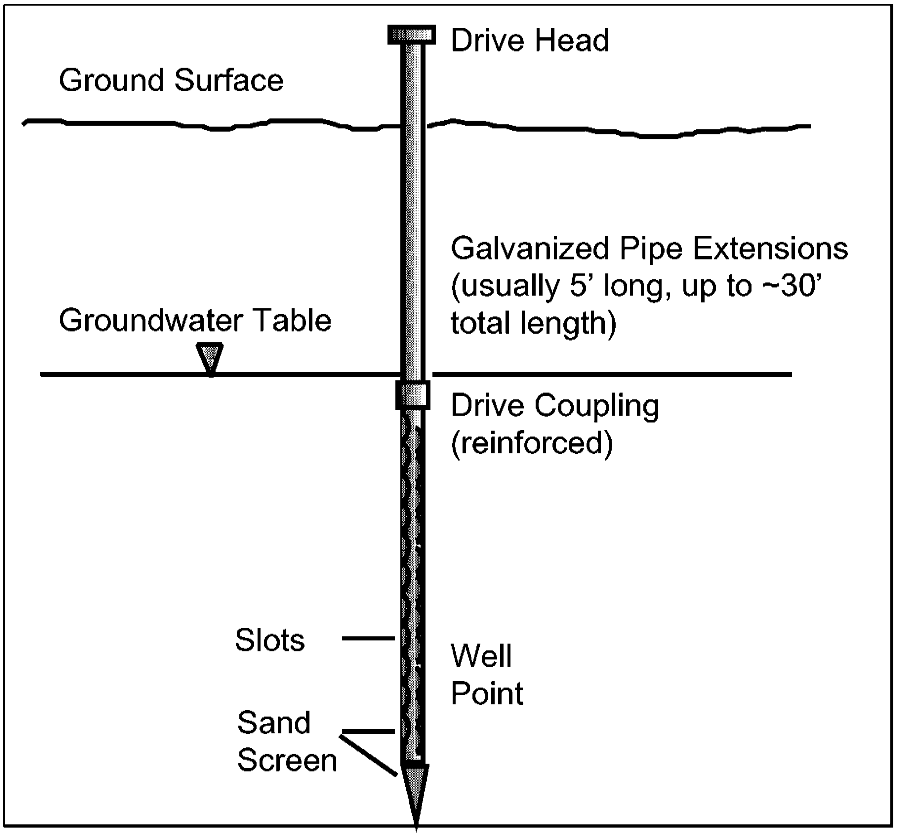
Shallow Well Groundwater Systems

In many areas of the river valleys the upper groundwater table is only a few meters below the surface. This type of aquifer is referred to as an **unconfined aquifer** or **water table aquifer**. In such cases shallow wells may be developed by driving **well points** into the water table. In some cases the water quality may be better, with less iron or arsenic than water from deeper wells. The problem with shallow wells is that the groundwater table can be affected by surface water contamination, septic tank leach fields, or leaking underground fuel tanks. The next section discusses this condition.

GROUNDWATER UNDER THE DIRECT INFLUENCE OF SURFACE WATER

Where shallow wells are used for public water systems and the water quality changes significantly with seasonal or precipitation events, the wells are usually classified as **groundwater under the direct influence of surface water** (**GWUDISW**). More elaborate treatment systems may be required for sources that are determined to be GWUDISW.

As noted above, some shallow wells and other types of systems such as **infiltration galleries** dug or drilled under river bottoms may be under the direct influence of surface water. In such circumstances, these systems may be classified and regulated as surface water systems. Under the SWTR, filtration and disinfection may be required to control microbiological contaminants.



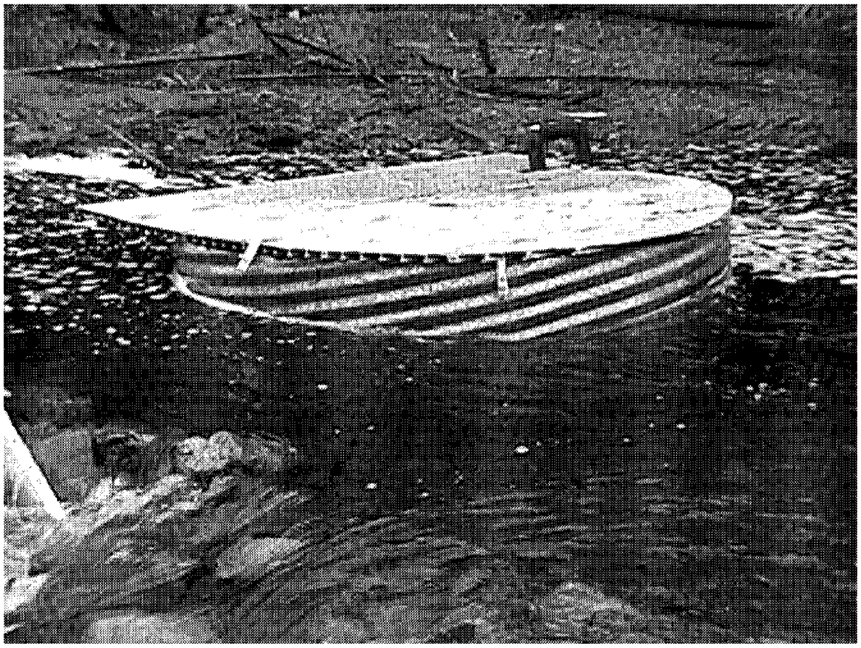
Shallow water table well point installation.

Shallow Well Systems

In several residential areas of high population density near Fairbanks and Anchorage, shallow well systems are at risk from contamination by septic tank leach fields and leaking underground fuel tanks. Microbiological contaminants, nitrite and nitrate, surfactants, and other chemicals may infiltrate into the groundwater and not be adequately removed before the water is drawn into adjacent shallow wells. Special restrictions on waste disposal fields and shallow wells have been applied in some communities to address this situation.

River Infiltration Galleries

For public water systems located adjacent to rivers, the relatively porous sand and gravel underlying the river provide an opportunity for natural straining and filtration, making an infiltration gallery an attractive option. Infiltration galleries may be as simple as a horizontal or vertical perforated corrugated metal pipe placed under or next to a river. Submersible pumps are used to transfer water through insulated transmission lines to the water treatment building. In some cases, the water quality is quite good even during the summer when the river may contain high concentrations of silt and organic debris. The natural gravel and sand in the riverbed can accomplish a high level of straining or prefiltration, improving the quality of the source water.



River infiltration gallery, Coffman Cove, Alaska.

In some river communities, horizontal wells have been used to tap the abundant aquifers underneath a river. With advancements in horizontal directional drilling technology, this practice may be expanded in the future.

Even with innovative well and infiltration gallery construction techniques, water appropriated by this method is often classified as GWUDISW. As with all surface water sources, filtration and disinfection are required for these systems. Advantages of a well designed infiltration gallery include better reliability of the water supply, better and more consistent water quality, and some freeze protection if designed and built properly.

REVIEW QUESTIONS

1. True or False: Earth is the only planet that contains water in our solar system.
   True _______
   False _______
2. One of the most basic responsibilities of a water system operator is that of a guardian of ____.
3. General treatment requirements for surface water systems under the Surface Water Treatment Rule are ________________ and ________________.
4. Systems with protected watersheds and exceptional water quality can apply for a ________________________________ waiver.
5. List four typical water quality characteristics of surface water systems in Southeast Alaska and the Aleutian Islands:
   a. ______________________________ b. ______________________________
   c. ______________________________ d. ______________________________
6. Naturally occurring organic matter can react with chlorine to form
   ____.
7. True or False: The most common water source on Alaska's Arctic Coastal Plain is shallow lakes. These may be soft (low hardness) or quite saline from sea salt or brine lenses.
   True _______
   False _______
8. During spring thaw, glacial silt-laden river water presents several problems for water plant operators. List two of these.
   a. ____
   b. ____
9. Groundwater quality is usually more consistent than surface water quality, and aquifers provide a natural barrier to ____________________________________.
10. True or False: Arsenic occurs in deep wells in Alaska primarily as a consequence of industrial pollution.
    True _______
    False _______
11. Cold water increases the solubility of carbon dioxide, which results in high levels of carbonic acid and low pH. This produces water with a tendency to corrode what type of pipe? ________________
12. List four common groundwater quality problems in deep wells in Alaska:
    a. ______________________________ b. ______________________________
    c. ______________________________ d. ______________________________

13. Shallow groundwater wells can be developed by driving ____________________ ____________________ directly into the aquifer.

14. List four potential contaminants in shallow groundwater wells in densely populated areas:
    a. ___________________________________ b. ___________________________________
    c. ___________________________________ d. ___________________________________

15. Infiltration galleries near or under rivers may be classified as __________________ ____________________ of surface water.

Chapter 2

Drinking Water Regulations

Introduction

History

Federal Drinking Water Regulations

Current Legislative and Regulatory Framework
1986 Amendments to the Safe Drinking Water Act
1996 Amendments to the Safe Drinking Water Act

1999 Alaska Drinking Water Regulations

Article 1, General Drinking Water Requirements
Article 2, Public Water System Review and Approval Requirements
Article 3, Standards, Monitoring, Variances and Exemptions
Article 4, Coliform Bacteria Requirements
Article 5, Lead and Copper Requirements
Article 6, Surface Water Treatment
Article 7, Enhanced Surface Water Treatment (Reserved)
Article 8, Groundwater Disinfection (Reserved)
Article 9, Disinfection and Disinfection By-Products (Reserved)
Article 10, Public Notice Requirements
Article 11, Laboratory Certification Requirements
Article 12, Administrative Penalties (Reserved)
Article 13, General Provisions

Review Questions

CHAPTER 2 – DRINKING WATER REGULATIONS

INTRODUCTION

This chapter describes how drinking water systems in Alaska are regulated and describes changes that are taking place that will impact Alaskan water treatment systems and operators in the future. First, however, it is useful to review some of the history of water quality standards and regulations. The development of the standards parallels the development of water treatment technology and the advancement of our understanding of chemistry and microbiology.

History

Throughout much of history, aesthetic qualities such as appearance, odor, and taste were used to determine the perceived quality of drinking water. Because little was known about the methods of disease transmission until the 1800's, treatment by filtering, boiling, or other simple means was used to improve the aesthetic qualities. For example, in about 400 BC, Hippocrates, the father of medicine, wrote that water should be boiled and strained to control odors and prevent hoarseness. The first edition of the *Encyclopedia Britannica* in 1771 included the definition of a filter made of fibrous or paper material in a funnel shape to clean water. Even today the clarity, color, odor, and taste are what guide public perception of the acceptability of water. Unfortunately, these qualities do not always provide the best indication of the **potability** of water.

In 1854, a **cholera** epidemic in London caused over 700 deaths in 17 weeks. The source was a well on Broad Street contaminated with sewage from a house determined to be the origin of the first cholera case. The epidemic was traced to users of that well in the immediate area and to households who transported water from the contaminated well because it tasted better than water from their own wells.

Although Louis Pasteur developed the germ theory of disease transmission in the 1840's, it was not until the end of the 19th century that bacteriological tests were available. In 1884, Theodore Escherich isolated bacteria from the stool of a cholera patient, which he thought was the causative agent of that disease. Later it was determined that he had discovered the coliform bacteria that today bears his name, ***Escherichia coli,*** or ***E. coli.*** In 1892, the New York State Board of Health adopted a bacteriological test to study pollution in the Mohawk and Hudson Rivers.

By the early 1900's, slow sand water filters were common in New England and in 1907, chlorine was introduced as a disinfectant. These developments, along with proven microbiological testing techniques, led to the first water quality standards in the United States.

FEDERAL DRINKING WATER REGULATIONS

In 1914, the U.S. Public Health Service (USPHS), part of the Department of Treasury, introduced the first microbiological standards for drinking water supplied to the public. These standards were for bacterial plate count and a member of the coliform group of bacteria, *Bacillus coli* and applied only to interstate public transportation such as railroad passenger cars. The objective was control of interstate disease transmission.

The USPHS standards were revised in 1925, 1942, 1946 and 1962. Each revision added new standards for chemical and aesthetic quality and updated the bacteriological standards. The 1962 standards included radioactive contaminants for the first time. The USPHS interstate commerce standards became the de facto standards for potable water in the U.S. and were adopted by many state and local governments.

Finally, in 1974, Congress passed the **Safe Drinking Water Act** (SDWA), which gave the new Environmental Protection Agency (EPA) the authority to set national standards for drinking water quality delivered to the public by community water suppliers. EPA developed a set of National Interim Primary Drinking Water Regulations (NIPDWR) in 1975 that essentially embodied the 1962 USPHS standards. The NIPDWR standards listed ten inorganic chemicals, six pesticides and herbicides, four radioactive parameters, turbidity and total coliform bacteria.

In 1979, the first standard for **trihalomethanes** (**THM**s) and a set of secondary parameters were added. The secondary standards covered aesthetic qualities of water such as color and odor plus a set of additional parameters that affect the appearance, taste, and odor such as foaming agents, iron, manganese, copper, and corrosivity.

1986 Amendments to the Safe Drinking Water Act

In 1986, Congress again amended the SDWA with a significantly expanded list of contaminants to be regulated and new programs to be implemented. The 1986 changes included the following:

1. The list of inorganic parameters was revised to include asbestos, cyanide, and four new metals.
2. The list of herbicides and pesticides was expanded to 26 compounds.
3. A new list of 21 **volatile organic chemicals** (**VOC**s) was added, which included contaminants associated with fuel spills, along with an additional list of seven "other organic contaminants" including PCBs and Dioxins.
4. The amendments included several additional lists (totaling approximately 45 compounds) of "unregulated contaminants" that were to be monitored and reported but not yet regulated.
5. The list of radioactive contaminants was expanded to five.
6. The list of secondary parameters was revised.
7. A new turbidity standard was added.
8. A new total coliform bacteria standard of zero was included.
9. A treatment technique standard was included, to limit dosages of two classes of water treatment polymers: epichlorohydrin and acrylamide.
10. A requirement was added that the EPA was to identify and regulate at least 25 new contaminants every three years.
11. Monitoring frequencies and reporting and public notification requirements were revised.
12. The 1986 amendments included a new corrosion control monitoring program requiring sampling for lead and copper at consumers' taps, known as the **Lead and Copper Rule.**
13. A new rule for the treatment of surface water was introduced, requiring filtration and disinfection of all surface water supplies including groundwater determined to be under the direct influence of surface water.

The last rule, referred to as the **Surface Water Treatment Rule** (SWTR), focused on removal or inactivation of ***Giardia lamblia***, the protozoan associated with "beaver fever." The SWTR also addressed treatment techniques for removing enteric viruses and *Legionella* bacteria. The State of Alaska completed the adoption of virtually all of the provisions of the 1986 SDWA Amendments by late 1994.

Current Legislative and Regulatory Framework

Beginning with the original SDWA in 1975, the legislative and regulatory framework has evolved to its present modern status. Essentially, the system works on a tiered approach. The U.S. Congress establishes the law (SDWA), then periodically amends it as science, technology, and public opinion advances. Any Federal law must be signed by the President or otherwise empowered by an override of a presidential veto. The latter occurred in 1986 when a two-thirds majority of Congress overrode a veto of the SDWA Amendments by then President Ronald Reagan.

The law is implemented at the Federal level by the EPA, which is part of the Administrative Branch of the U.S. government. EPA writes the regulations, which are the specific guidelines for implementing the intentions of the Congress as described in the law. The regulations are the enforceable standards that EPA uses to administer the national drinking water program.

Any state government that chooses to do so may implement a state law and equivalent set of regulations which meets or exceeds those of the EPA. The state can then request "primacy" from the EPA Regional Administrator (the U.S. is divided into ten Regions by EPA) and essentially takes over control of the drinking water program inside its borders. State regulations must be revised periodically to maintain consistency with changes in the EPA regulations and new Congressional Amendments or risk losing primacy. Primacy states accept responsibility for management and enforcement of the drinking water program but also are allowed certain privileges and some leniency. Alaska has primacy, as do nearly all of the other states, and receives part of its funding for management of the drinking water program from EPA. The Alaska Department of Environmental Conservation (ADEC) uses those funds to help operate the drinking water program in Alaska.

1996 Amendments to the Safe Drinking Water Act

On August 6, 1996, President Clinton signed into law new amendments to the SDWA. Originating as Senate Bill 1316 (S.1316), the amendment was widely supported in Congress and greatly modified both the scope and focus of the drinking water programs in the United States.

Significant modifications to the SDWA in S.1316 include the following:

1. Selection of new contaminants was reduced from selecting 25 new ones every three years to a more scientific approach of listing contaminants, reviewing them, and selecting five for a decision process on whether or not to regulate them.
2. An outline of a **Disinfectants and Disinfection By-Products (D/DBP) Rule** was developed in a "regulation-negotiation" or "Reg-Neg" process prior to the 1996 amendments. The D/DBP Rule in the 1996 Amendments establishes maximum contaminant limits for disinfectants for the first time and expands the list of regulated chemical compounds that may form from the reaction of disinfectants and naturally occurring organic matter in water. THMs are in this class of compounds, as are a new group, **haloacetic acids** (**HAA**). The D/DBP Rule lowers the THM limit to 0.080 milligrams per liter (mg/L) and sets a limit for HAA at 0.060 mg/L. Other by-products of chlorine dioxide disinfection (chlorite) and ozone disinfection in the presence of bromide (bromate) are also regulated.
3. An Enhanced Surface Water Treatment Rule (ESWTR) is included in the 1996 Amendments that is based on the protozoan ***Cryptosporidium parvum***, which was the causative agent in a massive outbreak of infectious illness in Milwaukee, Wisconsin in 1993. In that outbreak, some 400,000 people became ill, over 5,000 were hospitalized and over 100 people with suppressed immune systems died. The Milwaukee incident is credited with being one of the main drivers behind the nearly unanimous congressional approval of the 1996 Amendments.
4. A new **Groundwater Treatment Rule** was included that requires some groundwater supplies to be disinfected to prevent the transmission of enteric viruses.
5. New standards for arsenic, radon and sulfate will be established.
6. A Source Water Protection Program will be developed to help water systems and municipalities protect their source water supply.
7. New rules for state primacy allow additional time for implementing the new amendments and subsequent regulations.
8. Modifications to rules for small system variances and exemptions were included.
9. A list of small system technologies which may be used to address the new regulations will be developed.
10. A Capacity Development Program that requires states to determine the technical, managerial and financial viability of water systems before they are allowed to be constructed will be implemented for the first time. Existing systems are also to be reviewed under this provision.
11. **Consumer Confidence Reports** (**CCR**) must be prepared by community water systems each year for their customers. The CCRs list any contaminants that exceeded standards during the previous year and any other violations that may have occurred. In addition, the CCRs are to explain what the utility did to correct any deficiencies. As of June 2000 the ADEC is in the process of adopting the CCR requirement.

12. Operator Certification will be required for all community and non-transient, non-community public water systems by Federal law for the first time in history. In Alaska, these systems are defined as Class A systems.
13. A new State Revolving Loan Fund was established to provide a low interest loan program in each state for potable water infrastructure development.

In addition, S.1316 contained several other special funding programs and targeted regulations. Among these was a special provision to provide $15 million per year for four years to the State of Alaska as matching grants to improve sanitation in rural Alaskan villages.

In summary, the 1996 Amendments shifted the focus of drinking water regulations away from an ever-lengthening list of chemical contaminants that may be expensive to remove but may pose little if any risk to the consumer. The new regulations focus instead on microbiological protection, disinfection by-products, infrastructure development, and source water protection. Of particular interest is the renewed focus on controlling microbiological contaminants, the impetus behind the first regulations nearly 100 years ago.

1999 ALASKA DRINKING WATER REGULATIONS

In October 1999 the ADEC updated the Alaska regulations to begin addressing the 1996 Amendments. The Alaska drinking water regulations were amended on October 1, 1999, and are codified in Title 18 of the Alaska Administrative Code, Chapter 80 (18 AAC 80). A complete text of the drinking water regulations can be obtained from ADEC or accessed on the Internet. The Alaska Drinking Water Regulations contain 13 Articles, each of which is discussed briefly in the following sections.

Article 1, General Drinking Water Requirements

This section states, "the purpose of this chapter (18 AAC 80) is to protect public health and safety by establishing…standards for the design, construction, maintenance, and operation of a public water system; and…contaminant monitoring requirements for drinking water provided by a public water system." Article 1 also includes rules for well protection, source water protection, and well decommissioning to protect the quality of water supplies. An important component is the establishment of minimum separation distances between drinking water sources and potential sources of contamination.

MINIMUM SEPARATION DISTANCES[a] BETWEEN DRINKING WATER SOURCES AND POTENTIAL SOURCES OF CONTAMINATION (measured horizontally in feet)		
Potential Sources of Contamination	Type of Drinking Water System	
	Class A & Class B Public Water Systems	Class C Public Water Systems
Wastewater treatment works,[b] wastewater disposal system,[b] pit privy,[b] sewer manhole, lift station, cleanout	200	150
Community sewer line, holding tank,[b] other potential sources of contamination[c]	200	100
Private sewer line, petroleum lines and storage tanks,[d] drinking water treatment waste[e]	100	75

Notes:

[a] These minimum distances will be expanded, or additional monitoring will be required.

[b] Distance to a drinking water source is measured from the nearest edge of the drinking water source to the nearest edge of the potential source of contamination.

[c] Other potential sources of contamination include sanitary landfills, domestic animal and agricultural waste, and industrial discharge lines.

[d] The minimum separation distances for petroleum storage tanks do not apply to tanks that contain propane, or to above-ground storage tanks or drums that, in the aggregate, have a storage capacity of less than 500 gallons of petroleum products, and that store only petroleum products necessary for the operation and maintenance of pumps, power generation systems, or heating systems associated with a potable water source.

[e] Drinking water treatment wastes include the backwash water from filters and water softeners, and the reject water from reverse osmosis units.

Article 1 describes provisions to prohibit **cross-connections** and to facilitate backflow prevention. A cross-connection is any point where a potable and a nonpotable water supply are joined, creating a public health risk. This article also sets standards for chemical additives and materials used in public water systems and outlines requirements for disinfection of nonsurface water supplies such as water haulers, rain catchments, sea water and groundwater sources.

Article 2, Public Water System Review and Approval Requirements

Article 2 covers the ADEC classification of water supplies and requirements for plan approval of system design or modifications. Requirements for engineering plans are listed, such as the requirement that a minimum pressure of 20 pounds per square inch be maintained under all flow conditions in the water system. Minimum raw water testing requirements for new sources are listed. Class A systems must be tested for total coliform bacteria, inorganic chemicals including nitrate, VOCs, and secondary contaminants. For Class B supplies, only total coliform bacteria and nitrate tests are required for new water sources. A "capacity" determination is included in Article 2 that prevents the ADEC from issuing approvals for any Class A water system that does not have "the managerial, financial, and technical capacity to operate in compliance" with the State and Federal regulations.

Article 2 also describes procedures for ADEC review of plans, for revocation of approval, for submittal of plans and specifications for water delivery vehicles and for the testing of innovative technology or devices. The requirements for a "Qualified Operator" to operate any public water system that fluoridates is also listed in Article 2.

Article 3, Standards, Monitoring, Variances, and Exceptions

Article 3 lists the primary **maximum contaminant levels** (MCL) for all classes of potable water contaminants that have public health consequences, and the **secondary maximum contaminant levels** (SMCL) for those contaminants that affect the aesthetic quality of the water. The primary MCLs for inorganic chemicals, VOCs, turbidity, and **total coliform bacteria**, and the SMCLs are presented in the tables and text below.

INORGANIC CHEMICAL CONTAMINANTS GENERAL	
Contaminant	Maximum Contaminant Level (mg/L)
Antimony	0.006
Arsenic	0.05
Asbestos	7 million fibers/liter, for fibers longer than 10µm
Barium	2
Beryllium	0.004
Cadmium	0.005
Chromium	0.1
Cyanide	0.2, as free cyanide
Fluoride	4.0
Mercury	0.002
Nickel	0.1
Nitrate	10, as nitrogen
Nitrite	1, as nitrogen
Total nitrate and nitrite	10, as nitrogen
Selenium	0.05
Thallium	0.002

ORGANIC CHEMICAL CONTAMINANTS PESTICIDES	
Contaminant	Maximum Contaminant Level (mg/L)
Alachlor	0.002
Atrazine	0.003
Carbofuran	0.04
Chlordane	0.002
Dalapon	0.2
Dibromochloropropane	0.0002
Dinoseb	0.007
Diquat	0.02
Endothall	0.1
Endrin	0.002
Ethylene dibromide	0.00005
Glyphosate	0.7
Heptachlor	0.0004
Heptachlor epoxide	0.0002
Lindane	0.0002
Methoxychlor	0.04
Oxamyl (Vydate)	0.2
Pentachlorophenol	0.001
Picloram	0.5
Simazine	0.004
Toxaphene	0.003
2,4-Dichlorophenoxy acetic acid (2,4-D)	0.07
2-(2,4,5-Trichlorophenoxy)-propionic acid (2,4,5-TP)	0.05

VOLATILE ORGANIC COMPOUNDS (VOCs)	
Contaminant	Maximum Contaminant Level (mg/L)
1,1-Dichloroethylene	0.007
1,1,1-Trichloroethane	0.2
1,1,2-Trichloroethane	0.005
1,2-Dichloroethane	0.005
1,2-Dichloropropane	0.005
1,2,4-Trichlorobenzene	0.07
Benzene	0.005
Carbon tetrachloride	0.005
cis-1,2-Dichloroethylene	0.07
Dichloromethane	0.005
Ethylbenzene	0.7
Monochlorobenzene	0.1
o-Dichlorobenzene	0.6
para-Dichlorobenzene	0.075
Styrene	0.1
Tetrachloroethylene	0.005
Toluene	1
trans-1,2-Dichloroethylene	0.1
Trichloroethylene	0.005
Vinyl chloride	0.002
Total xylenes	10

Total trihalomethanes: The MCL for total trihalomethanes (TTHMs) is 0.10 mg/L; this MCL applies only to a Class A public water system that serves a resident population of 10,000 or more individuals and that adds a disinfectant to the water during any part of the drinking water treatment process.

OTHER ORGANIC CONTAMINANTS	
Contaminant	Maximum Contaminant Level (mg/L)
Benzo[a]pyrene	0.0002
Di(2-ethylhexyl)adipate	0.4
Di(2-ethylhexyl)phthalate	0.006
Hexachlorobenzene	0.001
Hexachlorocyclopentadiene	0.05
Polychlorinated biphenyls (PCBs)	0.0005
2,3,7,8-TCDD (Dioxin)	3×10^{-8}

Turbidity: the MCL for turbidity for any system is 5 nephelometric turbidity units (NTU) in any single sample. However, systems using **conventional filtration** (coagulation, flocculation, sedimentation and filtration) or **direct filtration** (coagulation, flocculation and filtration without sedimentation) must not exceed 0.5 NTU in 95 percent of the samples collected each month. Other filtration systems and systems that do not filter must not exceed 1 NTU in 95 percent of the samples collected each month.

RADIOACTIVE CONTAMINANTS	
Contaminant	Maximum Contaminant Level
Gross alpha radioactivity, including radium-226 but excluding activity from radon and uranium	15 pCi/L
Combined radium-226 and 228	5 pCi/L
Strontium-90	8 pCi/L
Tritium	20,000 pCi/L
Gross beta radioactivity	4 mrem

pCi/L, picocurie per liter; mrem, millirem

Total coliform bacteria: the MCL for total coliform bacteria is based upon the presence or absence of total coliforms in a sample, as follows: for a system that collects 40 or more routine and repeat samples in a month, if no more than 5 percent of the samples collected during a month are total coliform positive, the system is in compliance with the MCL for total coliforms; for a system that collects fewer than 40 routine and repeat samples in a month, if no more than one sample collected during a month is total coliform positive, the system is in compliance with the MCL for total coliforms. A fecal coliform-positive or *Escherichia coli*-positive repeat sample, or an *Escherichia coli*-positive routine sample constitutes a violation of the MCL for total coliforms, and is an acute risk violation of the MCL for total coliforms for the purposes of public notice requirements.

SECONDARY MAXIMUM CONTAMINANT LEVELS

Contaminant	Secondary MCL
Chloride	250 mg/L
Color	15 color units
Copper	1.0 mg/L
Corrosivity	Noncorrosive
Fluoride	2.0 mg/L
Foaming agents	2.0 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 threshold odor number
pH	6.5 minimum – 8.5 maximum
Sodium	250 mg/L
Sulfate	250 mg/L
Total dissolved solids	500 mg/L
Zinc	5 mg/L

The mechanisms, based on sample points and averaging of data, to determine compliance with MCLs are given. For example, inorganic and organic chemical MCL compliance is determined by averaging all of the data for a sample point in one year. THM compliance is determined as an annual average of four quarterly samples. Each type of water system, Class A or B, surface or groundwater, has different routine sampling and analysis requirements for each class of contaminants. Article 3 describes the requirements for this and for follow-up sampling if an MCL is exceeded during routine monitoring. Article 3 also lists the acceptable analytical procedures and reporting requirements for each contaminant. One section also explains a special variance procedure for total coliform sample holding time, normally 30 hours in Alaska, but that may be extended to 48 hours for extraordinary transportation circumstances.

Rules regarding the use of bottled water and **point of entry** or **point of use** treatment devices in public water systems are included in this section. Finally, provisions for variances and exemptions to the MCL regulations are described.

Article 4, Coliform Bacteria Requirements

Article 4 outlines the coliform bacteria sampling frequency based on system size (see the table below). Requirements for review and approval of a total coliform sample-siting plan are described. The sample-siting plan shows where the routine total coliform samples are to be collected throughout the water distribution system. Article 4 outlines the repeat coliform sampling requirements if a positive result is obtained on any sample. Generally, a system has to begin collecting repeat samples within 24 hours of being notified of a positive result. The number of repeat samples required and the locations to be sampled vary with system size and complexity.

TOTAL COLIFORM MONITORING FREQUENCY FOR CLASS A PUBLIC WATER SYSTEMS	
Population expected to be served	Minimum number of daily samples per month*
25 to 1,000[a]	1[b]
1,001 to 2,500	2[b]
2,501 to 3,300	3[b]
3,301 to 4,100	4[b]
4,101 to 4,900	5
4,901 to 5,800	6
5,801 to 6,700	7
6,701 to 7,600	8
7,601 to 8,500	9
8,501 to 12,900	10
12,901 to 17,200	15
17,201 to 21,500	20
21,501 to 25,000	25
25,001 to 33,000	30
33,001 to 41,000	40
41,001 to 50,000	50
50,001 to 59,000	60
59,001 to 70,000	70
70,001 to 83,000	80
83,001 to 96,000	90
96,001 to 130,000	100
130,001 to 220,000	120
220,001 to 320,000	150
320,001 to 450,000	180
450,001 to 600,000	210
600,001 to 780,000	240
780,001 to 970,000	270
970,001 to 1,230,000	300
1,230,001 to 1,520,000	330
1,520,001 to 1,850,000	360
1,850,001 to 2,270,000	390
2,270,001 to 3,020,000	420
3,020,001 to 3,960,000	450
3,960,001 or more	480

Notes:

* For seasonal operations that include partial months, the owner or operator shall consider the first partial month of operation as an entire month of operation; the owner or operator need not sample during the last partial month of operation.

[a] If a Class A public water system has at least 15 service connections, but serves fewer than 25 individuals, the minimum number of samples per month is the number for a system expected to serve 25-1,000 individuals daily.

[b] This number is subject to the requirement for additional routine samples.

This article also outlines the rules for **sanitary surveys** of public water systems and how sanitary survey inspectors are approved. Sanitary surveys are required for public water systems every five years unless the water system is a protected groundwater supply that disinfects, in which case a sanitary survey is required once every ten years.

Article 5, Lead and Copper Requirements

With the exception of an allowance for leaded joints in cast iron pipes, Article 5 requires the use of "lead-free" pipes or solder in public water systems. This Article, also known as the **Lead and Copper Rule**, defines how a water supplier is to determine whether or not lead or copper is being released to the water in a distribution system. Sampling is done at consumer taps under this rule using a **first draw** cold water sampling procedure. The first draw sample is the first 1 liter of cold tap water from a tap that has been flushed and then isolated for six hours before sample collection. The number of samples required and the frequency of sampling depends on the system size and the results of previous sampling. Compliance with the rule is determined by calculating the 90th percentile value for lead and copper as shown in the following example:

Example: 90th Percentile Lead and Copper Determination

A potable water system collects 10 cold water first draw lead and copper samples from residences in their system and has to report the 90th percentile values to the ADEC. The results of the tests are arranged in order from the lowest to the highest concentration obtained for each analysis and calculated as follows:

No.	Lead, mg/L	Copper, mg/L	
10	0.0210	1.85	
9	0.0142	1.65	90th Percentile = 9th value of 10
8	0.0095	1.40	
7	0.0082	1.25	
6	0.0055	1.02	
5	0.0032	0.90	
4	0.0017	0.73	
3	0.0006	0.58	
2	<0.0005	0.33	
1	<0.0005	0.19	

If the 90th percentile lead value exceeds the 0.015 mg/L action level or the 1.3 mg/L copper action level, the system then exceeds the "action levels" and must begin a process of determining optimal corrosion control treatment for their water supply. In the above example the 90th percentile lead level was 0.0142 mg/L, which does not exceed the lead action level, but the 90th percentile copper level of 1.65 mg/L does exceed the copper action level. This utility would now have to begin the process of corrosion control assessment.

To determine the 90th percentile value for a number of samples not equal to ten, multiply the total number of samples by 0.90. If the result falls between two numbers, but is closer to the higher than the lower number, use the higher number. If the result is closer to the lower number, or falls midway between the two, use the average of the two numbers.

Initially, the source water is tested to see if lead or copper is present at high concentrations and the distribution system is tested for a series of corrosion-related water quality parameters. For smaller systems, the corrosion control treatment determination may use a process called a "desk-top study" for smaller water systems, in which several possible treatment alternatives are compared. The possible treatments include:

- alkalinity and pH adjustment
- calcium hardness adjustment
- addition of a phosphate or silicate-based corrosion inhibitor
- treatment system modifications

Once the optimal corrosion control treatment is selected and submitted to the ADEC, approval and implementation of the selected treatment follows a timetable outlined in Article 5. If the source water is determined to be the problem, treatment of the water supply is required. Other provisions of this article describe the replacement of lead service lines (of which there are very few in Alaska) and notification of the public if the action levels are exceeded.

Article 6, Surface Water Treatment

The Surface Water Treatment Rule (SWTR) applies to all surface water systems and to systems classified as groundwater under the direct influence of surface water (GWUDISW). Article 6 explains how GWUDISW determinations are made using testing records, a site inspection, or more advanced testing techniques such as microscopic particulate analysis or tracer studies. In general the SWTR requires that water systems either filter and disinfect to achieve a **3-log reduction** (99.9 percent) of *Giardia lamblia* cysts and **4-log reduction** (99.99 percent) of viruses or meet the requirements for avoiding filtration. This requires a water system to obtain a filtration avoidance waiver from the ADEC.

Under either option a disinfectant residual is required. Primary disinfectants that do not produce a residual in the distribution system, such as UV radiation or ozone, will need to be supplemented with a secondary disinfectant such as chlorine that produces a disinfectant residual. Adequate disinfection includes the requirement to maintain minimum amounts of disinfectant residual concentration (C) and contact time (T) under varying conditions of pH and water temperature. Sets of “CT” tables are provided in Article 6 for this purpose.

The turbidity standard for systems using conventional or direct filtration is 0.5 NTU in 95 percent of the samples collected each month. The filtration requirement for slow sand filters and diatomaceous earth filters is 1 NTU in 95 percent of the monthly samples. For all filtration systems a maximum limit of 5 NTU is established for any single sample. Special requirements are also described for alternative filtration systems that can remove or inactivate the required levels of *Giardia* and viruses.

The rule also establishes the minimum sampling frequency for disinfectant residual and turbidity for systems practicing filtration. Disinfectant residual monitoring at the point of entry to the distribution system is required at the following frequency:

Size by Population	Samples/day
500 or fewer	1
501 - 1,000	2
1,001 - 2,500	3
2,501 - 3,300	4
Greater than 3,300	Continuous monitoring

For systems sampling more than once per day, the time of sampling must be varied and for systems using continuous monitoring, if the automatic analyzer fails, sampling at 4-hour intervals may be substituted for up to three days while the analyzer is being repaired. The minimum disinfectant residual required is 0.2 mg/L at the entry point to the distribution system. Similarly, the operator also must sample at locations in the distribution system where total coliform samples are collected.

Different monitoring rules apply for systems avoiding filtration. Article 6 also establishes reporting and record-keeping requirements for filtered systems and systems meeting filtration avoidance criteria.

Article 7, Enhanced Surface Water Treatment (Reserved)

This Article has been reserved for the new ESWTR being developed by the EPA. This rule will focus on treatment for the pathogenic protozoan *Cryptosporidium parvum*; the original SWTR focused on *Giardia lamblia.*

Article 8, Groundwater Disinfection (Reserved)

Article 8 has been reserved for future inclusion of the new Groundwater Treatment Rule being developed by EPA. A primary goal of this rule will be treatment to inactivate tiny viruses that may be transported through aquifers and contaminate groundwater wells.

Article 9, Disinfection and Disinfection By-Products (Reserved)

Article 9 has been reserved by the ADEC for the new EPA Disinfectants and Disinfection By-Products (D/DBP) Rule that will incorporate new standards for THMs and HAAs as discussed previously. This rule will also establish new maximum disinfectant residual levels (MDRLs), which will set maximum limits for chlorine residual in public water systems. An MDRL of 4 mg/L has been proposed for both chlorine and chloramines and 0.8 mg/L for chlorine dioxide. These disinfectants are discussed in more detail in Chapter 14.

Article 10, Public Notice Requirements

In the event that a public water system violates an MCL or treatment technique or fails to comply with a compliance schedule imposed by the ADEC, notification must be given to the consumers served by that utility. Notice must be given within 72 hours for acute risks to public health. This can include high nitrate or nitrite levels, occurrence of a waterborne disease outbreak in an unfiltered system or violation of the MCL for total coliform bacteria if fecal coliform or *E. coli* bacteria is detected in samples from the distribution system. For other violations notification can be made by newspaper within 14 days and by direct mail delivery within 45 days.

Specific language for public notices including mandatory health effects language for each of the primary contaminants is provided in Article 10. The article also includes special public notice requirements for operating under a variance or exemption, and for violations of sanitary survey, monitoring or testing procedures.

Article 11, Laboratory Certification Requirements

Article 11 covers the requirements for laboratory certification for the analysis of drinking water samples from Alaskan public water systems. On-site inspection requirements and certification fees are listed.

Article 12, Administrative Penalties (Reserved)

This Article is reserved for a future section on administrative penalties.

Article 13, General Provisions

General provisions include requirements for certification of reports forwarded to the ADEC by the owner and operator of the public water system. Records retention requirements are given for laboratory results (five years for bacteriological analyses and 10 years for chemical analyses), for records of actions taken to resolve violations (three years) and for variances and exemptions (five years after expiration of the variance or exemption). Article 13 also includes a fee schedule for ADEC services to public water systems and a section on filing of appeals following a plan approval decision. The final section of Article 13 is a listing of definitions, abbreviations, and symbols used in the regulations.

REVIEW QUESTIONS

1. Early water treatment practices were mainly used to improve the ______________ qualities of water since it wasn't until the 1800's that waterborne disease transmission was understood.

2. The first drinking water standards were established in the United States in 1914 by the U.S. ____. In 1974, the U.S. ______________________________________ began setting the national drinking water standards.

3. The pathogenic protozoan targeted for removal or inactivation by the SWTR is ____.

4. The most recent amendments to the Federal Safe Drinking Water Act, Senate Bill 1316, were signed into law on August 6, _____________________.

5. Under the new SDWA amendments, the ____________________________ SWTR will target the pathogenic protozoan ________________ for removal or inactivation.

6. Also under the new SDWA amendments, a new Groundwater Treatment Rule may require some wells to be ___________ to remove or inactivate ______________.

7. Article 1 of the Drinking Water Regulations prohibits cross-connections, which are any points in a water system where a ______________________________ and a ____________________________ water source are connected.

8. MCL stands for ____, and SMCL for _______________ MCL.

9. In Alaska, the standard holding time for total coliform bacteria samples is _______ hours. For extraordinary transportation problems, the holding time can be extended up to _______ hours with ADEC's permission.

10. The lead and copper level action limits are determined as the _________________ value of a series of samples ordered from lowest to highest value. The action level for lead is __________________ mg/L and for copper is _________________ mg/L.

11. CT tables are used to help determine proper inactivation of *Giardia* and viruses under the SWTR. CT stands for ________________ x ________________ .

12. Under the SWTR, 3-Log removal of *Giardia* = ____________% removal, and 4-Log removal of viruses = ____________% removal.

13. The conventional and direct filtration SWTR turbidity standard is ___________ NTU in ____________ % of the tests taken each month. For slow sand filters or diatomaceous earth filters, the turbidity standard is ____________ NTU in ____________ % of the tests taken each month.

14. The minimum disinfectant residual level required at the point of entry to the distribution system is ___________ mg/L. Minimum frequency for disinfectant residual monitoring for the smallest water systems is ____________.

15. For a violation that represents an acute risk to public health, public water systems must notify their consumers within ____________ hours.

Chapter 3

Source Development and Treatment

Chapter 3 – Source Development and Treatment

SOURCE DEVELOPMENT

Any water source that is proposed for development as a public water supply must be approved by the Alaska Department of Environmental Conservation (ADEC) before use. The approval process includes testing the raw water supply and developing a set of engineering plans for the intake system, transmission lines, treatment facility, and distribution system.

Raw Water Testing

The minimum testing requirements of raw water quality for new sources are listed in Article 2 of the Alaska Drinking Water Regulations. For Class A systems, total coliform bacteria, inorganic chemicals such as **nitrate**, **volatile organic compounds**, and **secondary contaminants** must be tested. For Class B supplies, only **total coliform bacteria** and nitrate tests are required for new water sources.

In addition to these minimum requirements, utilities or engineering firms studying the development of the supply will test for the secondary contaminants listed in the drinking water regulations. These include iron, manganese, and many other parameters that help identify the treatment requirements for that source. Other tests that are useful in determining the treatment requirements, but not listed in the ADEC criteria for raw water sources, include **hardness** and **total organic carbon** (**TOC**). Although both magnesium and calcium are components of hardness, only calcium is included in the list of secondary contaminants, as part of the **Langelier Index** test for **corrosivity**. TOC is an indicator of the concentration of organic matter that may be present in the raw water. TOC reacts with chlorine or other disinfectant chemicals to form **disinfection by-products** (**DBP**s).

If the proposed source is surface water, a spring, infiltration gallery under a river or lake, or a shallow well, it also is useful to have a **microscopic particulate analysis** (**MPA**) run to help determine the treatment requirements. In addition, the MPA test will help determine if a shallow well, infiltration gallery, or spring is **groundwater under the direct influence of surface water**

(GWUDISW). If the MPA test result indicates probable GWUDISW, the source will have to be treated to surface water treatment standards rather than groundwater standards. The **Surface Water Treatment Rule** requires **filtration** and **disinfection** as treatment processes.

Pilot Testing and ADEC Plan Approval

Once the raw water tests have been completed, an engineering plan must be prepared for submittal to ADEC for approval. The requirements for plan submittal listed in Article 2 of the Alaska Drinking Water Regulations specify that a professional engineer (PE) registered in the State of Alaska must seal the drawings. The PE's seal represents their "stamp of approval," and that they certify the design is technically feasible and addresses the applicable regulatory criteria.

As part of the design process, engineers will run a **pilot test** of the new water source. A pilot test is a demonstration of the proposed treatment process. The test apparatus is essentially a miniature treatment plant with chemical addition, filters, and monitoring equipment that can be modified for different treatment procedures. Various treatment methods may be compared in a pilot test and the treated water tested for compliance with the ADEC drinking water standards. In addition to water quality, test criteria may include comparison of the capital and operations costs of the processes and a description of potential operational problems such as short filter runs or formation of DBPs.

The pilot test may be performed directly by the PE, by the utility operators, or by a subcontractor such as a certified laboratory. In most cases, successful pilot testing requires the collaboration of all three entities. Pilot test results can be used to optimize the design of the new treatment facility. The results also may provide the operators with valuable information about chemical doses and other operational parameters during the start-up process.

SOURCE TREATMENT

The operator may use source or "in-situ" treatment to improve the water quality before transmission to the treatment plant. Several important water quality problems can be amended in some surface water supplies, particularly in **reservoirs**, whereas rivers and groundwater wells are not as amenable to in-situ treatment. Source treatment includes aquatic plant control and reservoir management techniques. In general, it usually is more economical to correct some water quality problems at the source rather than further along in the treatment process.

Problems with Aquatic Vegetation

Aquatic vegetation includes **algae** and **aquatic plants**. Algae are simple plant forms that may be a single living cell or a colony of cells floating in the water and gathering energy from sunlight. Some species of aquatic plants exist as floating mats on the surface of the water and others may be rooted in the bottom or side slopes of a reservoir. Some rooted plants remain submerged while others grow up and emerge above the water line. Often, aquatic plants form a complex community or ecosystem consisting of both rooted and floating forms along with a variety of algae species. The structure and composition of the aquatic plant community changes seasonally.

Aquatic plants have beneficial effects such as removal of nutrients and trace contaminants from the water. The control of algae populations that results from this reduction in nutrients may outweigh the nuisance posed by the aquatic plants themselves. These plants also may provide fish habitat if the water source serves the dual purpose of water supply and fish propagation. However, the excessive growth of aquatic plants can cause a variety of operational problems that are most economically treated at the source.

Problems with growths of aquatic vegetation include the following:

- **Color, taste, and odor** (both algae and aquatic plants) result from organic molecules produced at different stages of the life cycle. Colors range from yellow to green to red or brown. Taste sensations vary among individuals, but typically are described as unpleasant, particularly for certain types of algae. Odors may include “grassy,” “musty,” or “fishy,” among others.
- **Filter clogging** (primarily algae and **diatoms**) is a common problem during periods of accelerated growth or “bloom” of these tiny plants. Filter clogging can cause short filter runs and frequent backwashing.
- **Clogging of pump intakes and screens** (primarily aquatic plants) reduces pumping capacity and may cause cavitation of pump impellers.
- **Corrosion and slimes** (mainly algae) result when algae attach to the surfaces of pipes, fittings, tanks, and other treatment structures. Under the slime coating, algae may release strong acids that corrode metal.
- **Toxicity** may result from the release of poisonous chemicals by a few species of algae, particularly blue-green algae. Effects on humans are usually manifested as skin irritation, gastrointestinal illness, or allergies. Effects on animals or fish may be even more severe.

- **DBPs** such as **trihalomethanes** are formed from the reaction of chlorine and organic matter, such as algae.

Aquatic Plant Control

Control of algae in reservoirs can be accomplished by chemical addition or by blocking sunlight essential for the growth of algal cells. Generally, the most effective chemical for algae control is copper sulfate, although potassium permanganate also is effective. Chemical addition for aquatic plant control is not widely practiced in Alaska and is limited by Federal law. The addition of chemicals for control of nuisance species in a reservoir is controlled under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). FIFRA regulations require proper labeling of chemicals and chemical addition limited to the labeled dosage and frequency allowed for that chemical.

Copper sulfate is not effective for all species of algae, and the dosage is limited by the alkalinity and pH of the water. If the total alkalinity is greater than 50 milligrams per liter (mg/L) as calcium carbonate ($CaCO_3$), the standard dosage is 1 mg/L applied to the upper 2 feet of water in the reservoir. The following example shows the calculation for the pounds of copper sulfate to add per acre of water-surface area:

1) Calculate the amount of water to be dosed, in millions of gallons (MG):
$43{,}560\ \text{ft}^2/\text{acre} \times 2\ \text{ft} \times 7.48\ \text{gallons}/\ \text{ft}^3 = 651{,}657.6\ \text{gallons/acre}$
$651{,}657.6\ \text{gallons} \div 1{,}000{,}000\ \text{gallons/MG} = 0.6516576\ \text{MG/acre}$

2) Calculate the dosage of copper sulfate to be added, in pounds per acre:
Dosage (lbs/acre) = PPM copper sulfate added x MG/acre x 8.34 lbs/gallon
1 PPM x 0.6516576 MG/acre x 8.34 lbs/gallon = 5.4348 lbs/acre
≈ **5.4 lbs./acre**

For higher-alkalinity water, this dosage will effectively treat the top two feet of water. Below this depth, copper sulfate is not effective since it tends to precipitate or settle out. Copper sulfate also tends to be more effective at pH levels between 8.0 and 9.0.

If the alkalinity is less than 50 mg/L as $CaCO_3$, the dosage should be only 0.3 mg/L calculated for the total depth of water. The dosage in pounds per acre-foot can be calculated as follows:

1) Calculate the amount of water to be dosed, in millions of gallons (MG) per acre-foot:
$43{,}560\ ft^2/acre \times 7.48\ gallons/ft^3 = 325{,}828.8$ gallons/acre-foot
325,828.8 gallons/acre-ft ÷ 1,000,000 gallons/MG = 0.3258288 MG/acre-ft

2) Calculate the dosage of copper sulfate to be added, in pounds per acre-foot:
Dosage (lbs/acre-ft) = PPM copper sulfate added x MG/acre-ft x 8.34 lbs/gallon
0.3 PPM x 0.3258288 MG/acre-ft x 8.34 lbs/gallon = 0.815 lbs/acre-ft
≈ **0.8 lbs/acre-ft**

If the reservoir is also used to raise fish, even this dosage may be too high, because many species of fish are susceptible to copper toxicity. Wildlife authorities should be consulted about acceptable dosages.

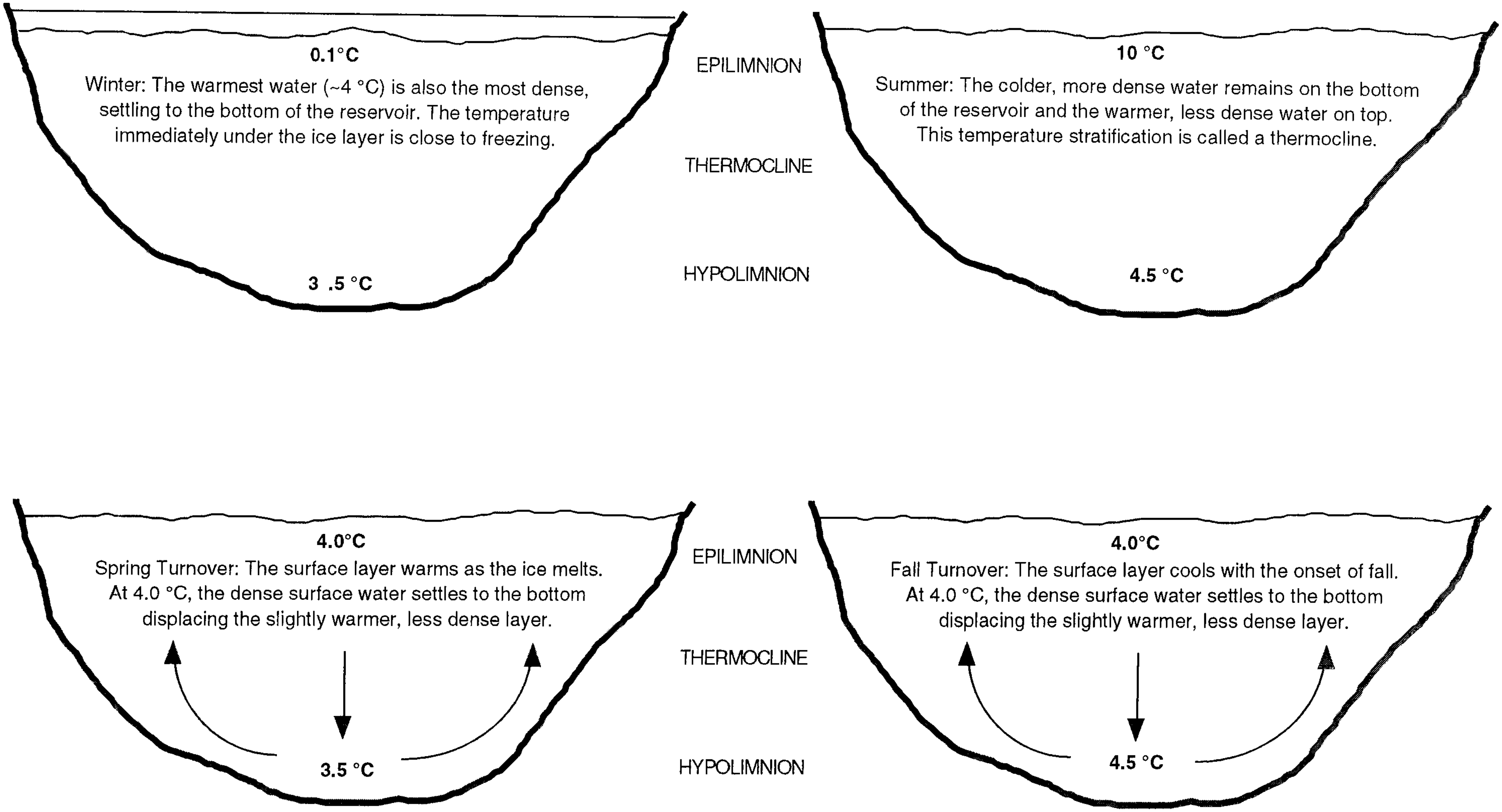
Control of rooted plants can be accomplished by mechanical harvesting or dredging, or by using a liner to cover the bottom of the reservoir to inhibit root growth. The growth of both rooted plants and algae can be inhibited by shading the water with a dark floating cover or by the addition of clay or powdered activated carbon to limit light penetration into the water. Shading is not commonly used in Alaska as a control technique.

Reservoir Management

Deep reservoirs undergo a semiannual destratification, or turnover, in the spring and fall in which the upper layer (**epilimnion**) mixes with the lower layer (**hypolimnion**). This mixing of layers results from density differences caused by seasonal temperature changes. When this turnover occurs, the water quality may be poor for several days. When a deep reservoir is stratified, the hypolimnion can lose its dissolved oxygen and become anaerobic, or stagnant. This condition can be amended by aerating the reservoir to mix the layers together, but it is not a common problem in Alaska.

Under ice cover in the winter, reservoirs in Alaska may become stagnant. This situation creates an interesting opportunity to amend poor water quality conditions in the reservoir. Barrow Utilities and Electric Cooperative, Inc., uses water from the Isatkoak Reservoir, which was created by a permafrost core dam constructed across a brackish (moderately salty) water lagoon near the coast of the Arctic Ocean. The salinity during the peak of winter had been as high as 5,000 mg/L of total dissolved solids (TDS), forcing the utility to desalinate the water to make it

SEASONAL RESERVOIR STRATIFICATION AND TURNOVER IN ALASKA



Winter: The warmest water (~4 °C) is also the most dense, settling to the bottom of the reservoir. The temperature immediately under the ice layer is close to freezing.

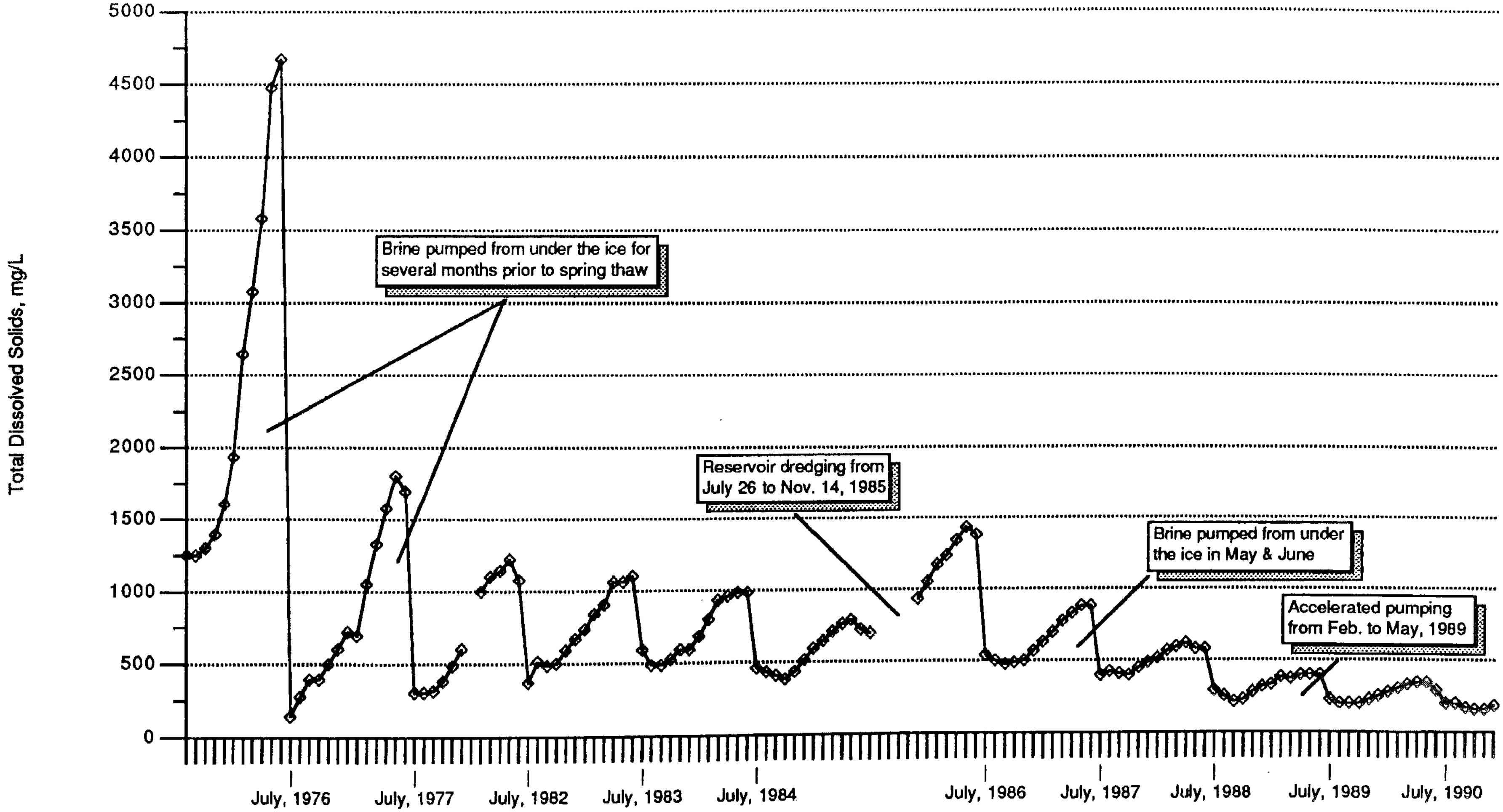
Summer: The colder, more dense water remains on the bottom of the reservoir and the warmer, less dense water on top. This temperature stratification is called a thermocline.

Spring Turnover: The surface layer warms as the ice melts. At 4.0 °C, the dense surface water settles to the bottom displacing the slightly warmer, less dense layer.

Fall Turnover: The surface layer cools with the onset of fall. At 4.0 °C, the dense surface water settles to the bottom displacing the slightly warmer, less dense layer.

potable. Using a plan developed originally by Public Health Service engineers, the reservoir was effectively desalinated.

Each winter, an ice layer up to 8 feet thick forms on the surface of the reservoir, effectively trapping much of the fresh water while concentrating the salty water on the bottom. For several years, in the spring just before breakup, the utility operators pumped the salty water off the bottom of the reservoir into a downstream lagoon that overflows to the ocean. During breakup, fresh snowmelt refilled the reservoir with low-salinity water. This process was repeated until the salinity of the reservoir declined to potable water levels (less than 500 mg/L of TDS). The graph on the next page shows the decline in TDS levels in the Isatkoak Reservoir during the period from 1976 to 1990.



Changes in total dissolved solids in the Isatkoak Reservoir in Barrow, Alaska, from 1976 to 1990. This salty basin was converted to fresh water by pumping brine from under the ice layer in late winter of each year.

REVIEW QUESTIONS

1. Any water source planned for use as a public water supply must first be approved by the ______________________________.
2. List the tests required for the raw water from a source being proposed for a Class A water supply:
   a. ______________________________ b. ______________________________
   c. ______________________________ c. ______________________________
3. The ____________________________ test will help to determine if a proposed water supply is groundwater under the direct influence of surface water.
4. Plan approval for a proposed water treatment system must be stamped by an Alaskan _____________________________.
5. Two types of aquatic vegetation that can cause water quality problems in reservoirs are _____________________ and ____________________.
6. List six general problems that can be caused by aquatic plants:
   a. ____
   b. ____
   c. ____
   d. ____
   e. ____
   f. ____
7. One method of controlling algae in reservoirs is chemical addition. Application of any chemical to eradicate nuisance species in a public water source is regulated under the ____.
8. Calculate the pounds of copper sulfate that should be added to a reservoir with a surface area of 6.5 acres if the alkalinity of the water is 75 mg/L as $CaCO_3$.
9. Turnover is an event that occurs when the ______________ (upper layer) and ______________ (lower layer) of a reservoir mix together. The primary water quality problem that occurs when a reservoir stratifies is ______________ .

10. True or False: In the winter, coastal arctic reservoir water becomes saltier as fresh water is lost to the formation of ice.
    True ________
    False ________

Chapter 4

Preliminary Treatment

Chapter 4 – Preliminary Treatment

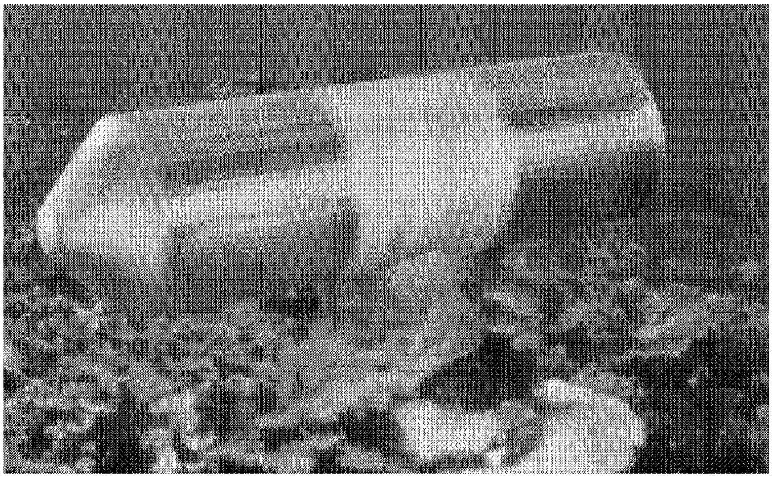
INTRODUCTION

Preliminary treatment, or **pretreatment**, often is used in water systems that contain large amounts of debris, such as sticks, leaves, or other suspended solids, or that contain heavy loads of sediment. This material can cause serious problems for water treatment systems by jamming and damaging water intake equipment, pumps, and piping, and by increasing the load on the conventional water treatment processes. The principal preliminary treatment processes discussed in this chapter are **screening**, **presedimentation**, and **microstraining**.

WATER INTAKE SYSTEMS

Generally, river water intakes are located in protected areas along the shore, and lake water is withdrawn below the surface to minimize the collection of floating debris. However, screening sometimes is used to remove floating materials that may block treatment equipment, plug pipelines, or damage pumps and other appurtenances. Most often, coarse screens are attached directly to the raw water intake structure and are referred to as trash or debris racks. Several types of trash racks or screens are available, some of which are cleaned mechanically.

An example of a popular water intake system is the high-efficiency Johnson Screens passive water-intake screen system. This system has no moving parts and a slow, uniform intake flow that does not trap debris or aquatic life against the screen. The cylindrical screen can be oriented parallel to flow, allowing debris to pass by with ambient currents. Some newer models include an air backwashing system. The City of Kotzebue uses an early model of this type of screen on their lake water supply.



One style of a passive high-efficiency water-intake screen system. Courtesy of USFilter/Johnson Screens.

Bar Screens

Bar screens are usually made of metal bars attached to a frame. They are manufactured with several opening widths between the bars:

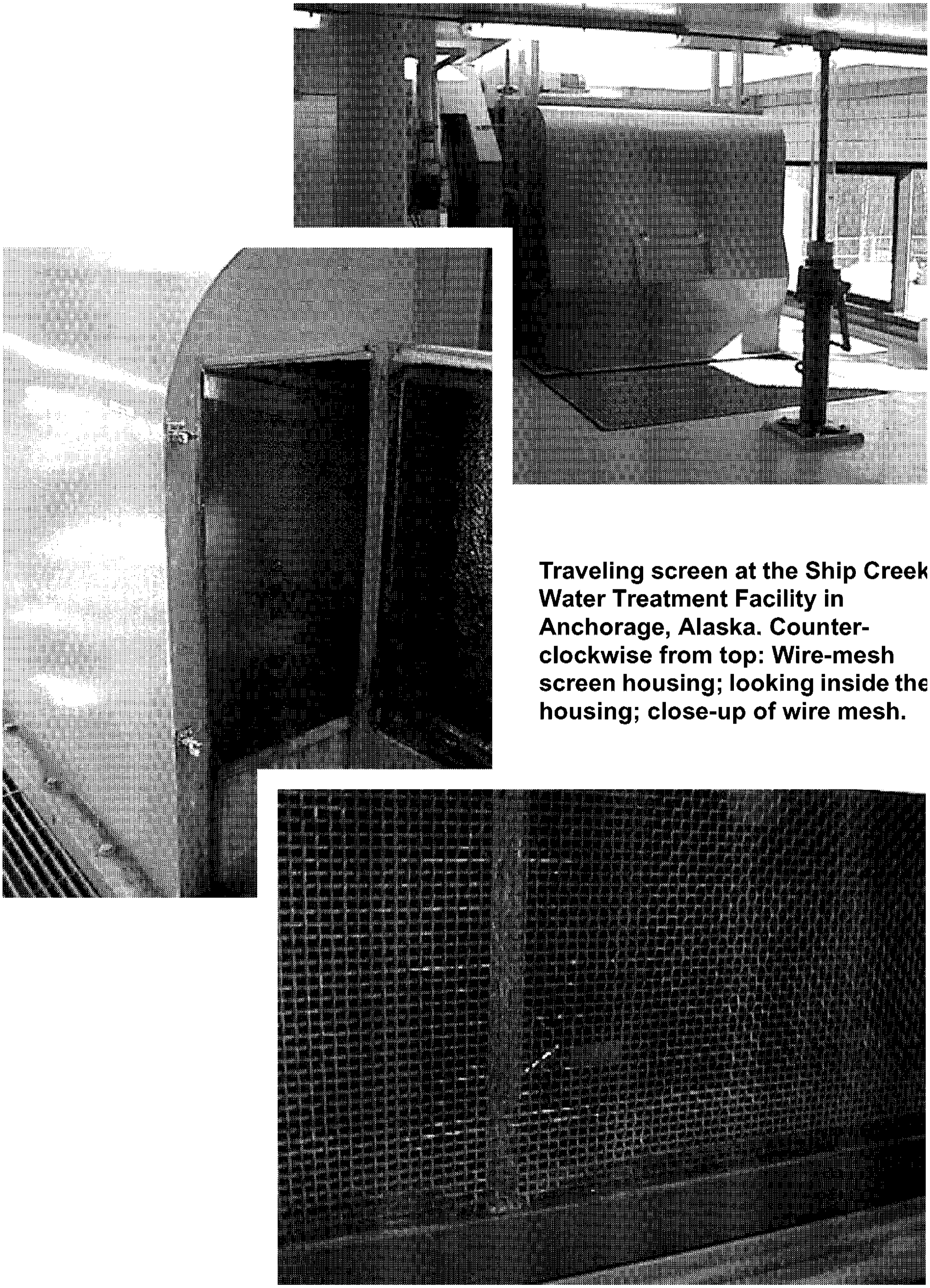
- Fine screens have openings between $^1/_{16}$ and $^1/_2$ inch
- Medium screens have openings between $^1/_2$ and 1 inch
- Coarse screens have openings between $1^1/_4$ and 4 inches

Bar screens are normally positioned in the flow channel tilted back at a slight angle from vertical to accommodate mechanical cleaning of the screens with a traveling rake. Debris is raked upward along the slope of the bars and removed from the water flow channel above the water level.

Wire-Mesh Screens

Wire-mesh screens, also known as traveling water screens, are constructed of durable material with openings ranging from $^1/_{60}$ to $^3/_8$ inch (0.4 to 10 millimeters) wide. They usually are configured in a mechanical apparatus that allows continuous cleaning of the screen with a water spray.

Both bar screens and wire-mesh screens require routine inspection and cleaning to ensure proper operation. Screens can become fouled with debris, particularly during heavy rainfall or spring runoff events and should be checked more often at those times. Occasionally, large objects



Traveling screen at the Ship Creek Water Treatment Facility in Anchorage, Alaska. Counter-clockwise from top: Wire-mesh screen housing; looking inside the housing; close-up of wire mesh.

will jam a screen and initiate a mechanical shutdown. Alarms or warning lights are useful to indicate such a problem. Operators should maintain records of inspections, maintenance activities, and quantity of debris removed.

PRESEDIMENTATION

Sand, gravel, and silt can be removed by presedimentation. These materials may settle and clog transmission lines, valves, pumps, and other appurtenances. In addition, they usually are abrasive, potentially damaging pump seals, impellers, and other critical equipment. Accumulations of this material, sometimes referred to as "grit," can reduce capacity in flocculators, clarifiers, and other treatment tankage. Presedimentation systems include:

- **Presedimentation Basins** that may be constructed as an earthen impoundment on a riverbank or as a concrete, steel, or wood reservoir. Large impoundments may allow the growth of algae that can produce taste and odor problems. If located outside, they also are susceptible to freezing and potential damage from ice buildup. Cleaning usually involves seasonal dewatering and mechanical removal of the dried grit.
- **Sand Traps** that are usually located at the inlet to a treatment plant and are designed to provide a brief slowing of the flow velocity to allow heavier grit to settle out. Sand traps are usually cleaned by draining and flushing the accumulated grit down a drain line to a disposal area. Additional water can be used to hose down the inside of the sand trap while it is being cleaned.
- **Mechanical Grit or Sand Removal Equipment**, including plate or cyclone (centrifugal) separators that modify the velocity of the water sufficiently to selectively remove the heavier material in a relatively small space. These systems are usually equipped with a mechanical grit removal system, but should be inspected regularly to ensure optimal performance.

Results of settling tests on samples collected from the inlet and outlet of presedimentation systems will help to quantify the amount of settleable solids removed and the removal efficiency. To ensure a representative sample, the inlet and outlet tests can be collected as composite samples comprising several grabs taken over a 24-hour period and combined together into a single sample. The settleable solids procedure is run using a 1-liter settling cone, called an Imhoff Cone, graduated in milliliters on the bottom to quantify the volume of grit accumulated after the requisite 60-minute settling time. The percent removal efficiency is calculated as shown in the following example:

Calculate the percent removal efficiency of a presedimentation basin using the following test results:

Imhoff Cone 60-Minute Settleable Solids test results: Inlet = 20 ml/L, Outlet = 0.5 ml/L

% Removal = [(Inlet result – Outlet result) ÷ Inlet result] X 100%

% Removal = [(20 ml/L – 0.5 ml/L) ÷ 20 ml/L] x 100% = [19.5 ml/L ÷ 20 ml/L] x 100%

% Removal Efficiency = 97.5%

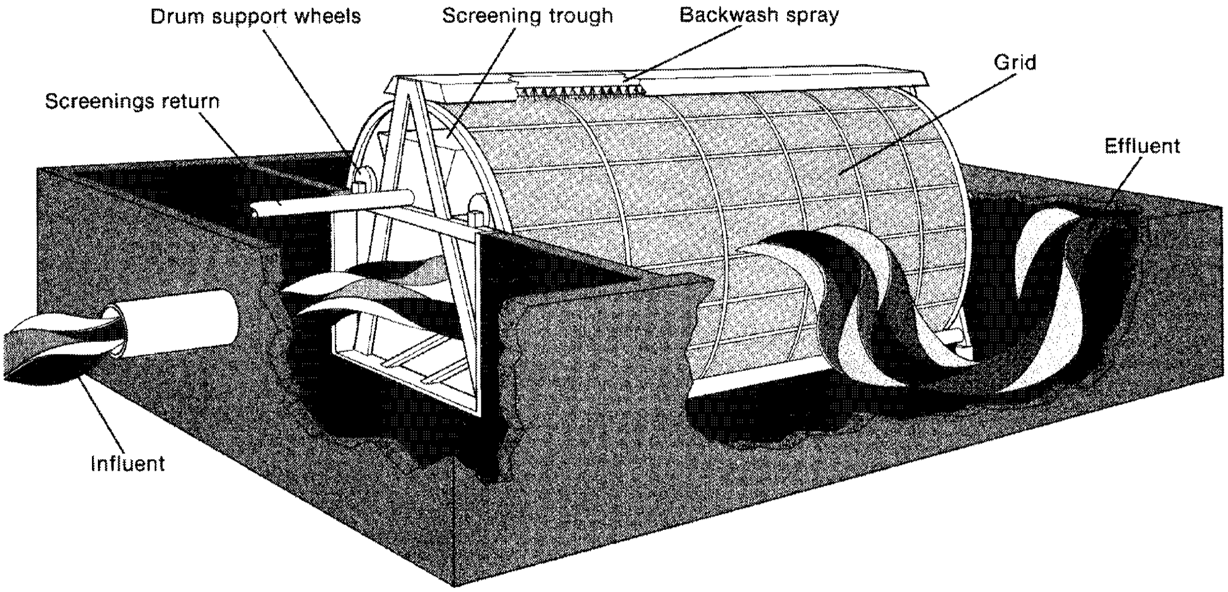
Operational records that log inspections, maintenance, and quantity of material removed should be kept for all presedimentation systems.

MICROSTRAINING

Microstrainers or microscreens are mechanical filtration devices made up of a fine mesh fabric mounted on the outside of a horizontal, continuously rotating drum. Designed to remove algae and other fine debris that may clog filters, microstrainers employ a much finer mesh than used in wire-mesh screening. Microstrainer screens may have openings as small as 1 micron, and typically in the 15- to 60-micron (millionths of a meter) range, with as many as 160,000 openings per square inch (250 per square millimeter). The rotating drum is equipped with high-pressure spray jets that clean the screen. Raw water flows into the center of the drum and out through the mesh screen. Approximately three-fourths of the drum is submerged during normal operation. The cleaning sprays deposit the debris in a trough located inside the drum near the top that discharges the material out of the screen.

Water treatment plants using a surface supply may use microscreens as an initial treatment step to remove a significant amount of the suspended solids, reducing chemical costs and increasing the performance of downstream treatment processes.

A recent addition to microstraining technology is the use of microfiltration, a type of membrane separation. Microfilters are manufactured with pore sizes as small as a few tenths of a micron. Please refer to Chapter 13 of this manual for a discussion of microfilters.



An example of a microscreen, showing the influent and effluent streams, rotating drum, automatic self-cleaning spray nozzles, screening trough and screenings return, and drum support wheels. This type of microscreen is used in industrial and wastewater applications as well as in potable water treatment. Courtesy of USFilter/Envirex.

REVIEW QUESTIONS

1. True or False: Coarse screens are also called trash racks or debris racks.
   True ________
   False ________
2. Two types of screens are ____________ and ____________.
3. Standard bar screen openings for medium screens is from ________ to ________ inch.
4. Presedimentation is a unit process that can remove materials such as ________________, _________________, and ________________ that may be abrasive to valves and pumps. This material is also referred to as ________.
5. List three types of presedimentation systems
   a. ____
   b. ____
   c. ____
6. Operational records for presedimentation systems should include:
   a. ____
   b. ____
   c. ____
7. Cyclone separators operate on the principal of ____________________ force.
8. Calculate the percent removal efficiency of a presedimentation basin that has 50 ml/L of settleable solids in the inlet and 2.5 ml/L of settleable solids in the outlet.
9. Microstrainers are used to remove ___________________________ and fine ___________________________ that may clog filters.
10. An alternative to microstrainers is ___________________________.

Chapter 5

Water Treatment Process Overview

Chapter 5 - Water Treatment Process Overview

INTRODUCTION

Water treatment involves numerous different unit processes. The treatment used in a particular system depends on the characteristics of the water source and finished water quality goals. After the pretreatment processes described in the previous chapter, most water treatment systems incorporate several different unit processes in their plants. In general, the progression of unit processes follows a similar order among systems. This chapter presents an overview of the different processes commonly used in today's water treatment plants. In addition, the basic elements of a typical water treatment plant are illustrated, and three examples of complete water treatment plants currently operating in Alaska are described.

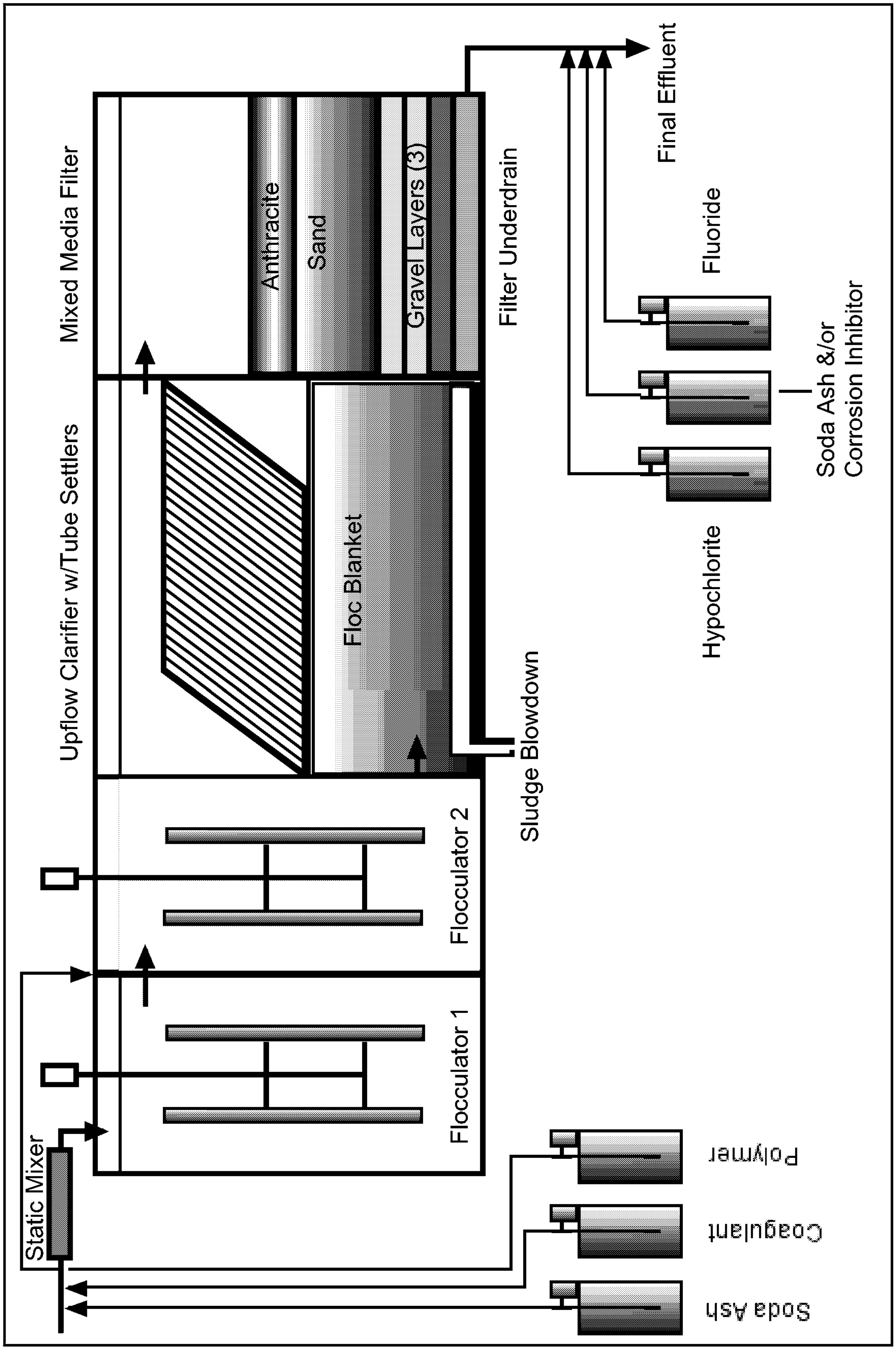
WATER TREATMENT PROCESSES

Each of the unit treatment processes introduced in this chapter is covered in detail in a subsequent chapter of this manual. The topics introduced in this chapter are the following:

- aeration
- coagulation and flocculation
- clarification
- filtration
- softening
- iron and manganese treatment
- adsorption
- membrane separation
- disinfection
- fluoridation
- corrosion control treatment

A Typical Water Treatment System

The water treatment process, from intake of raw water and pretreatment to finished water ready for the distribution system, can be generally illustrated by the following figure:



An example of a package conventional water treatment plant.

Raw water enters the treatment plant through intake screens and a pumping system. The water may then undergo a **prechlorination** step to oxidize iron and manganese, begin killing pathogenic organisms, or to minimize taste and odor problems that could result from biological growths on pipes and filters. However, use of prechlorination may be limited by the potential reactions with **natural organic matter** (NOM) and subsequent disinfection by-product formation. **Aeration** tanks may be used to remove dissolved gases and other volatile constituents, or to oxidize iron and manganese. Then the water undergoes **coagulation** and is transferred to **flocculation** tanks, where fine suspended particles aggregate to form **floc**. The water may then be transferred to a **sedimentation basin** or **clarifier** where the floc is separated out of solution. The water is then filtered through granular media filters to remove any remaining suspended particles or floc. In most treatment plants the water is then disinfected, usually by **chlorination**, to inactivate any remaining **pathogens**. If the water is **corrosive**, chemicals to help control corrosion of distribution system components may be added. The finished water is stored in a basin known as a **clearwell**, or transferred to a storage tank for distribution to system customers.

Additional treatment steps may be included in a particular system, depending on the characteristics of the source water and the water-quality requirements of the end users. These additional processes may include **softening**, specialized **iron and manganese treatments**, **membrane separation**, and **fluoridation**.

Aeration

Aeration is the process of bringing air into contact with the water, to facilitate the removal of a substance from the water (stripping) or to transfer oxygen from the air to the water. In water treatment plants, aeration often is used to remove **dissolved gases**, such as carbon dioxide or hydrogen sulfide; oxidize **dissolved metals**, such as iron or manganese; release **volatile organic compounds**, such as benzene; and occasionally may be used to mix coagulants. Aeration also can be used to increase the concentration of dissolved oxygen in the water, improving its taste. At many treatment plants, aeration is one of the primary methods of water treatment because it can remove or modify some constituents that could interfere with subsequent treatment processes.

Aeration works by both physical mixing and chemical oxidation. The main controlling factors on the effectiveness of aeration as a water treatment method are the surface area of the air-to-water interface, partial pressure of the gases in the aerator atmosphere, temperature, and time of exposure. The aeration process is sometimes referred to as desorption or air stripping.

Several different methods of aeration are available and fall into two general categories: water-into-air types and air-into-water types. Combination methods may also be used. Water-into-air types of aerators produce small droplets of water that fall through the air. Air-into-water types produce small bubbles of air that rise through the water being aerated. Aeration and types of aerators are discussed in greater detail in Chapter 6.

Coagulation and Flocculation

Many organic and inorganic particles suspended in raw water are too small to be filtered by the initial screening steps or to settle out in a sedimentation basin in a reasonable period. These particles are called **nonsettleable solids**. These nonsettleable particles are generally of a size known as **colloids**. Colloids are particles less than 1 micron (μm) in size and may take days to years to settle out of the water naturally. **Turbidity** in water is caused primarily by the presence of colloids. Colloids must be aggregated, or coagulated, to form larger particles that will settle out of solution in a reasonable period of time.

Colloidal particles usually have negative ionic charges on their surfaces, which is one of the reasons they can remain suspended for so long; the individual particles repel one another. The addition and rapid mixing of a positively charged chemical called a **coagulant** is used to react with the colloids. The coagulant is usually an iron or aluminum salt or one of several types of synthetic polymers, which reacts with the negatively charged colloids to create positively charged ions on the particle surfaces. The particles will then become less repellent to each other and group together to form larger particles. The type of coagulant used and any **coagulant aids** selected will depend on characteristics of the water source, such as pH, temperature, and **alkalinity**. Coagulant aids (usually polymers) generally are added just before the water enters the **flocculator**.

After coagulation, the water is transferred to a **flocculation** chamber where the water is slowly agitated with paddles to further aggregate the particles. This physical process must be done gently because the particles are delicate and easily broken up. The resulting large gelatinous aggregates are called **floc** and have a snowflake-like appearance. Floc particles are relatively large and heavy and can be settled or filtered out. Coagulation and flocculation are discussed in detail in Chapter 7.

Clarification

If large quantities of floc are produced, **clarification** or **sedimentation** will follow coagulation and flocculation. The water may be transferred to a **sedimentation basin** where the large floc particles settle out under the influence of gravity. Alternatively, **solids-contact basins**, also known as **upflow clarifiers,** may collect the floc on a floating media, most commonly plastic, that is held in place by a screen. A sedimentation basin may be equipped with **tube settlers** placed at an angle of 5° to 60° inside the basin. As water rises through the tube settlers, floc settles on the surfaces of the tube settlers and on the tank bottom. As the floc particles accumulate and grow larger, they begin to slide down the surfaces of the tube settlers, picking up more floc in their wake and growing larger still. The floc forms **sludge** on the tube settlers and the tank bottom; it is drawn off the bottom of the tank either by gravity or by mechanical means. The operator must take care to ensure that the sludge does not build up on the bottom of the tank or the settling tubes. If only small quantities of floc are produced, the clarification step can be eliminated and the coagulated water is passed directly through the filters. This process is known as **direct filtration**. Clarification is discussed in detail in Chapter 8.

Filtration

The main goal of **filtration** is to remove **turbidity** from water. In **conventional filtration**, the water that has completed the steps of coagulation, flocculation, and sedimentation must then be filtered to remove any remaining particles, such as floc, microorganisms, and chemical precipitates, that cause turbidity. **Direct filtration** is another filtration method that is widely used in Alaska. In direct filtration, unlike conventional filtration, the clarification or sedimentation step is eliminated and water flows directly into the filter from the flocculation basin or in-line mixing unit. Direct filtration can incorporate either gravity or pressure filters, with pressure filters most commonly used in Alaska.

The different types of filters fall into three basic categories: **slow sand** filters, **gravity filters**, and **pressure filters**. Slow sand filters incorporate a fine sand filter medium, gravity filters include rapid sand and mixed-media filters, and pressure filters include sand or mixed media,

cartridge and bag filters, and **diatomaceous earth** filters. Filtration employs both mechanical straining, in which particles are trapped in the interstices of the filter medium, and by adsorption, in which particles adhere to the surfaces of the grains of filter media by the same ionic forces that are at work in coagulation and flocculation.

Slow sand filtration is generally not used for water with high turbidity. The material filtered out of the water forms a **schmutzdecke**, a mat of suspended matter and microorganisms on the surface of the sand that becomes part of the filtration medium. Slow sand filters are cleaned by scraping about 1 inch of sand off the top layer of filter medium, rather than by backwashing.

A rapid gravity sand filter is made up of layers of filter media, such as sand or a combination of anthracite coal, sand, garnet, and gravel, placed in various arrangements of ascending or descending grain size and density. The water passes through the filter media under the force of gravity and collects in an underdrain system. For maintenance, the filter media must be backwashed between filter runs to flush and clean the surfaces of the grains of filter media and the voids within the material.

Pressure filtration is similar to gravity filtration but the water is forced through the filter under pressure. A pressure filtration system may use sand or mixed-media, such as a combination of anthracite coal, sand, or garnet sand, or may use diatomaceous earth as the filter medium. Diatomaceous earth filters were first used by the U.S. Military during World War II to control outbreaks of amoebic dysentery. The material used is mined and processed from deposits of ancient diatoms. Diatomaceous earth filters can be operated as either pressure or vacuum filters and are often used in Alaska to filter swimming pool water. The village of Quinhagak, Alaska, has a diatomaceous earth filter for municipal water treatment. Filtration is discussed in detail in Chapter 9.

Softening

Softening may be necessary if the water source has a high concentration of dissolved minerals, commonly known as **hardness**. Several salts of calcium and magnesium contribute to the hardness of water. The dissolved bicarbonate salts of calcium and magnesium ($Ca[HCO_3]_2$ and $Mg[HCO_3]_2$), and to a lesser extent, calcium and magnesium carbonates ($CaCO_3$ and $MgCO_3$) and magnesium sulfate ($MgSO_4$) can form thick deposits on the interior walls of pipes and other system components. Hardness in water is also objectionable to customers because soap reacts with the calcium or magnesium salts in the water, leaving a sticky film and making it necessary to use more soap in showering, dishwashing, and washing clothes. Two common processes are used for softening: **precipitation** and **ion exchange**. Membrane separation technology, discussed in Chapter 13, also can be used as a softening method.

One of the classical softening methods using precipitation is **lime softening**. Lime softening is used if the water contains very little or no magnesium hardness. The addition of lime ($Ca[OH]_2$) to the water causes $CaCO_3$ to precipitate out of the water according to the following chemical reaction:

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2CaCO_3\downarrow + 2H_2O$$

If a component of magnesium hardness is present in the water, the use of both lime and soda ash is necessary. If the water contains a high concentration of CO_2, the pH may need to be raised in order to remove the excess CO_2 and stabilize the $CaCO_3$.

Because dissolved minerals, such as those causing hardness, dissociate into charged ionic particles in water, they can be removed or neutralized by other ions. Ion exchange processes incorporate a material called resin to exchange hardness-causing ions for ions that do not cause hardness. The most common ion exchange softening resin is a sodium zeolite, which exchanges sodium for **divalent** cations. In this type of ion exchange softening, two Na^+ ions are substituted for each Ca^{++} or Mg^{++} ion. The sodium is replaced when the resin bed is regenerated with a salt (NaCl) solution. Softening is discussed in detail in Chapter 10.

Iron and Manganese Treatment

If the source water contains a high concentration of dissolved metals, such as iron and manganese, specialized treatments may be necessary to remove them to acceptable levels. Excessive iron and manganese in water causes operational and aesthetic problems. Oxidized iron and manganese will precipitate out of the water and deposit on pipes and other system components. They also can contribute to objectionable tastes and odors in drinking water. Clothes washed in water containing iron and manganese can be permanently stained, as can plumbing fixtures, resulting in a high level of customer dissatisfaction.

The principal methods of iron and manganese treatment are precipitation followed by filtration, ion exchange, and sequestration. Excess iron and magnesium can be oxidized and precipitated out of water by aeration or chemical oxidation. Chlorine and potassium permanganate are the most frequently used chemical oxidants. After the iron precipitate forms, it is removed either by conventional or direct filtration using either standard granular media filters or specialized manganese "**greensand**" filters that use glauconite as the filter medium. Greensand filters incorporate adsorption in addition to physical filtration.

Ion exchange, discussed in detail in the chapter on softening (Chapter 10), can remove iron and manganese along with calcium and magnesium. Ion exchange as a method of iron removal is only cost-effective if the iron concentration in the water is low, less than 5 milligrams per liter (mg/L), and the iron is in soluble form. If the water contains oxidized iron precipitate it may clog the resin bed and decrease system efficiency.

Sequestration, another iron and manganese treatment method, is appropriate only if the iron and manganese concentration in the water is less than 1.0 mg/L. Sequestration does not remove iron and manganese from water, but rather keeps it in solution so it does not precipitate out to clog pipes and discolor the water. However, because the iron remains in solution, it can still cause bacterial slimes to form on system components. Chemicals such as polyphosphates or sodium silicates are added to the water to sequester the iron and manganese in solution before the water is exposed to the air or other oxidants.

Other processes that may be used to remove excess iron and manganese from water are lime softening, coagulation, and membrane separation. Iron and manganese treatment is discussed in detail in Chapter 11.

Adsorption

Adsorption is the process by which organic particles adhere to the surface of some granular medium, called an **adsorbent**. The adsorbent most commonly used in water treatment is **activated carbon**. If the conventional processes of aeration, coagulation, sedimentation, and filtration do not decrease the organic constituents to an acceptable level, adsorption may be a suitable alternative treatment method. In adsorption, organic particles are trapped by the adsorbent by complex physical and chemical processes. The organic molecules are attracted to the surface of the adsorbent material. Thus, the surface area of the adsorbent is a critical factor in the adsorption process. The greater the surface area, the more sites available to which the organic particles may adhere. The adsorbent chosen must provide an adequate surface area to volume ratio so that a tank of reasonable size may be used for the process. Activated carbon is used as an adsorbent because of its porosity, which is created through the activation process. The vast network of pores of different sizes in activated carbon gives it a large surface area and the capacity to adsorb molecules of different sizes. The two kinds of activated carbon used are **granular activated carbon**, used like filter media, and **powdered activated carbon**, which is added with coagulants. Adsorption is discussed in detail in Chapter 12.

Membrane Separation

Membrane separation technology provides the water system designer with a process that can be used to engineer water treatment plants that are capable of removing specific sizes of molecules, including dissolved molecules. Conventional filtration with sand, anthracite, or other relatively coarse media only effectively remove particles down to 0.1 micron (μm) in size. Conventional ion exchange treatment such as in salt-regenerated softeners simply trades ions, exchanging two sodium atoms for each calcium or magnesium ion. Membrane softening, by comparison, removes calcium and magnesium by selective rejection of those ions while forcing the water through a membrane at high pressure. The membrane allows water molecules to pass, but rejects dissolved ions. One common application of membrane treatment is reverse osmosis desalination of seawater, in which enough dissolved salt is removed to make the water potable.

Membrane processes include many different alternatives, including **microfiltration**, **ultrafiltration**, **nanofiltration**, and **reverse osmosis**. The common component is a semipermeable membrane with different separation or rejection capabilities for various particles or dissolved ions in water.

Microfilters are true particle filters that may be used as prefilters for more sensitive membrane processes such as nanofiltration or reverse osmosis. Microfilter membranes are manufactured to a selective pore size ranging from 0.1 to 2.0 μm. These can be used to replace conventional gravity or pressure filters.

Ultrafiltration and nanofiltration are emerging as cost-effective technologies to remove hardness and large organic molecules that produce color, thereby minimizing the formation of disinfection by-products in treated water. Ultrafilters, which are more porous than nanofilters, are designed to remove only higher molecular weight materials such as large organic molecules that cause color in water. Ultrafilter pore sizes range from 0.002 to 0.1 µm. The porosity of ultrafilter membranes is selectively designed to remove substances up to a particular **molecular weight cutoff.** Nanofilters have pore sizes ranging from 0.001 - 0.02 µm, and can selectively remove larger dissolved molecules while allowing smaller ones to pass through.

Reverse osmosis membranes provide the highest salt removal efficiency of the major types of membranes available. In reverse osmosis, membranes with pore sizes of < 0.001 µm (< 1 nanometer) are operated at sufficient pressure to overcome the osmotic pressure of the salt water and literally push the fresh water through the membrane, leaving the salt behind.

Membranes can be easily fouled, however, because of the extremely fine porosity and physical structure of the membranes. If the water is not pretreated property to reduce the potential for precipitate deposits or biological growths, the performance of the membrane will decline rapidly. Membrane separation, which is rapidly advancing as a cost-effective treatment technique, is discussed in detail in Chapter 13.

Disinfection

Disinfection may be incorporated at different stages in the water treatment process, but is generally the final treatment process to remove any remaining pathogens from the finished water and to provide a chlorine residual in the distribution system. The most common agent used for disinfection is chlorine. Possible alternate forms of **chlorination** are **chloramination** and **mixed-oxidant processes**, such as the MIOX® plant in operation at the University of Alaska Fairbanks. Other disinfection methods include ozonation and ultraviolet irradiation. It is important that excess NOM and turbidity be removed from the water before chlorine disinfection, because of the danger of forming **trihalomethanes** and other **disinfection by-products** that may be harmful to human health. Disinfection is discussed in detail in Chapter 14.

Fluoridation

Fluoride may be added to the water to improve dental health. Water **fluoridation** can decrease the incidence of cavities in children's teeth. When it was discovered that people using drinking water sources containing naturally occurring fluoride had fewer cavities, many public drinking water supplies began to add fluoride chemicals to the water. The use of fluoride in water is a "public health" decision and may be quite controversial in some communities. The maximum contaminant level for fluoride is 4.0 mg/L, and the secondary maximum contaminant level is 2.0 mg/L. In Alaska, the recommended range for beneficial fluoridation is between 1.1 to 1.5 mg/L. Fluoridation is discussed in Chapter 15.

Corrosion Control Treatment

Corrosion of materials is a costly problem for the potable water industry and related industries. **Corrosive** water also can dissolve toxic metals from distribution and plumbing fixtures. Other metals in system components can also be leached into the water, causing taste and odor problems. Some leached metals can form scale deposits in pipes, which can clog the distribution system and protect microorganisms from chlorine disinfection. Moreover, Federal and State lead and copper regulations require water-system operators to treat their water if lead and copper corrosion products are present in the water at elevated concentrations. Several standard treatment methods are in use to control corrosion of water-system components: pH and alkalinity adjustment, application of a protective $CaCO_3$ coating, and the addition of corrosion inhibitors and sequestering agents, such as phosphates or silicates. Corrosion control treatment is discussed in Chapter 16.

EXAMPLES OF ALASKAN WATER TREATMENT SYSTEMS

The following are examples of actual water treatment plants currently operating in Alaska. This section outlines the basic treatment components of each plant. Specific unit processes in operation at the plants will be emphasized in subsequent chapters.

The University of Alaska Fairbanks--Aeration and Conventional Filtration

The University of Alaska Fairbanks (UAF) water treatment plant is a Class III system that incorporates aeration and conventional treatment, followed by mixed-oxidant disinfection. The plant capacity is 1 million gallons per day (MGD) and serves a resident and nonresident population of 4,600 people. The actual plant production is 0.25 to 0.3 MGD (about 174 to 208 gallons per minute). The water source is two groundwater wells located at the base of the University hill. One of the wells is 70 feet deep and the other is 90 feet deep. The groundwater wells had been contaminated by benzene from fuel product spills, but air spargers on the wells have lowered the raw-water benzene concentration from about 400 to 26 parts per billion. The raw water also has high concentrations of iron (15-17 mg/L), manganese (0.6 mg/L), and hydrogen sulfide.

The UAF groundwater is very cold, coming out of the ground at 35 °F. Before it enters the water treatment plant, this water is used to cool the turbines of the adjacent power plant. When the water reaches the intake at the treatment plant, it has been warmed to about 50 to 56 °F, vastly improving the treatment efficiency of the water plant.

The pre-heated water first passes through two aeration basins containing 49 Ramco® air diffusers supplied by two 40-horsepower Roots® rotary lobe blowers. Each of these blowers has a capacity of 1,000 cubic feet per minute. Potassium permanganate is added to the water at the entrance to the aerators to enhance oxidation of iron and manganese. In the aeration system, the water has a distinct orange tint from the high concentration of dissolved iron. An iron bacteria, *Crenothrix*, accompanies the iron and forms slick deposits on the system's components. The water also contains sufficient hydrogen sulfide to give the air inside the plant a rotten-egg smell. Both hydrogen sulfide and benzene are stripped out of the water in the aerator tanks, released to the air, and then ventilated out of the building.

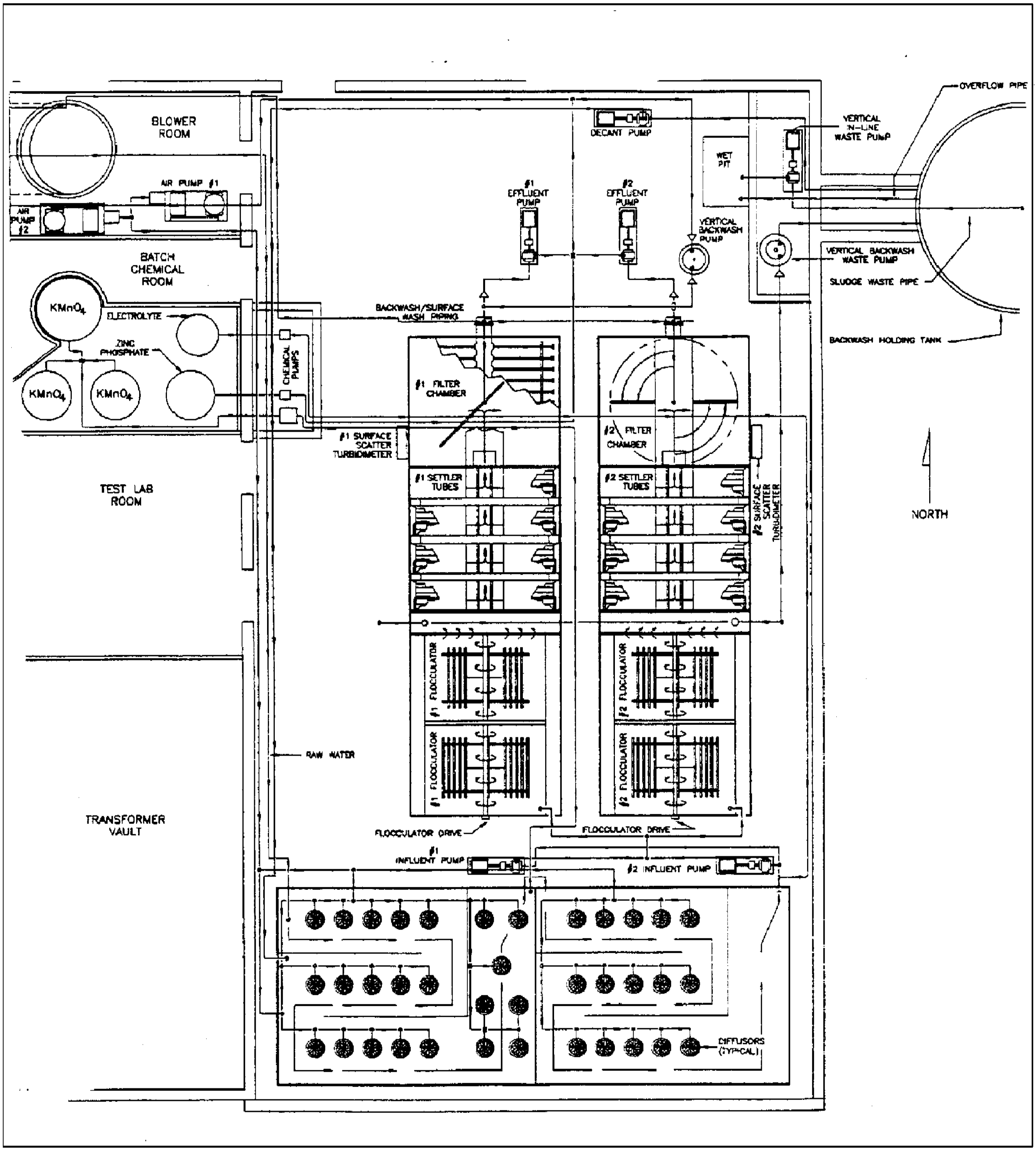
After the aeration tanks, the water flows into two 0.5-MGD Neptune Microfloc Aquarius® conventional filtration plants. A synthetic-polymer coagulant aid, 7768N, is fed in line as the water enters the first stage of the Aquarius® plants, the flocculators. The flocculation system consists of dual tanks in a parallel arrangement.

The UAF water treatment plant. In the foreground, froth forms on the water being agitated in the aerator. Behind the aerator are the two sets of two flocculation tanks, the sedimentation tanks with their submerged tube settlers, and the filter tanks at the end of the treatment line.

In the first flocculation tanks, five paddles provide for rapid mixing of the coagulant chemicals with the water. The second flocculation tanks have four paddles each, mixing the water a little more gently to allow the floc to form, grow, and aggregate.

After the flocculation tanks, the water flows into the bottom of a sedimentation basin filled with a honeycomb of hexagonal tube settlers. The floc that formed in the flocculation tanks continues to grow larger and eventually slides down the tube settlers into a sludge layer at the bottom of the tank. The sludge is collected in an underdrain system, and the settled water flows over the top of the basin into a distribution trough or weir.

The water flows from the sedimentation basins into the top of multi-media gravity filters. The filters contain an upper 18-inch layer of granular anthracite coal, underlain by an 18-inch layer of silica sand. The next three layers of media consist of different sizes of filter support gravel. The total height of the filter column is 6 feet. The filtered water is pumped into a 1.5-million-gallon reservoir. As the water is pumped from the reservoir into the water mains feeding the campus, it is disinfected with a mixed-oxidant solution called MIOX®. The MIOX® Corporation claims this system produces a solution containing a mix of chlor-oxygen species, including hypochlorite, by on-site electrolysis of a sodium chloride brine.

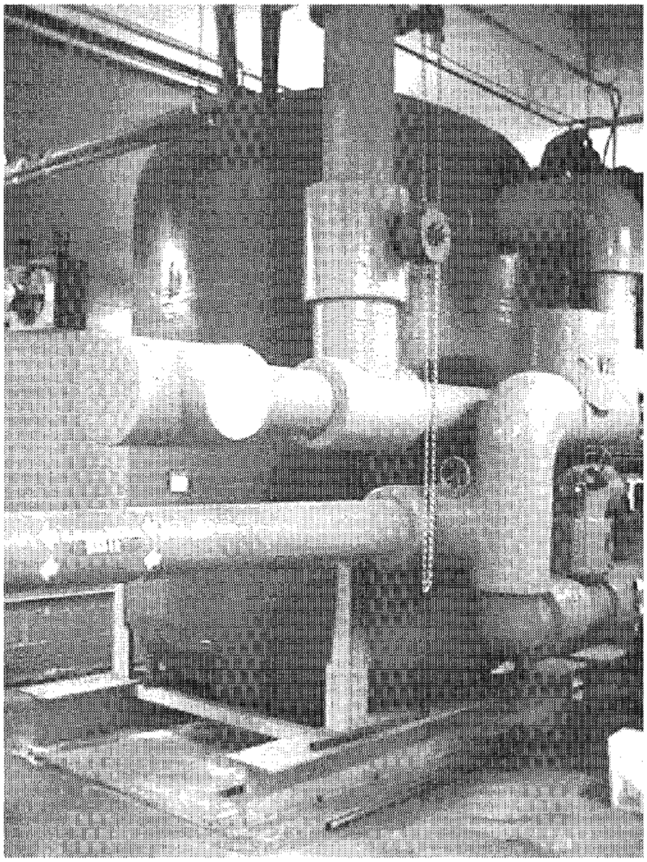


Process flow schematic of the water treatment plant at the University of Alaska Fairbanks.

City of North Pole – Direct Filtration and Iron and Manganese Removal

The City of North Pole, Alaska, draws its water supply from two groundwater wells drilled in the alluvium of the Tanana River. The main well is 180 feet deep and the auxiliary well is 165 feet deep. The capacity of North Pole's water treatment plant is approximately 330,000 gallons per day. The iron and manganese concentrations in the raw water are 0.3 and 0.8 mg/L, respectively, and the pH is 7.2. The well water is dosed with 2.5 mg/L potassium permanganate before the water enters the treatment plant to enhance oxidation and filter-media adsorption of iron and manganese.

The dominant plant process is direct greensand filtration, designed to remove iron and manganese. Two 8-foot-diameter pressure greensand filters, each of which has a **hydraulic loading rate** of approximately 2.7 gallons per minute per square foot, provide the filtration capacity for the plant. The media in the filters consist of 20 inches of anthracite over 20 inches of greensand. The filters are taken out of service for two hours each day for backwashing, which uses about 30,000 gallons of filtered water. After filtration, the water is treated with 35 mg/L soda ash to adjust the pH as a corrosion control measure.



One of the two manganese greensand filters at the City of North Pole's water treatment plant. The influent raw water pipe is shown in the upper center, darker colored pipe, below center, is the filtered water effluent pipe.

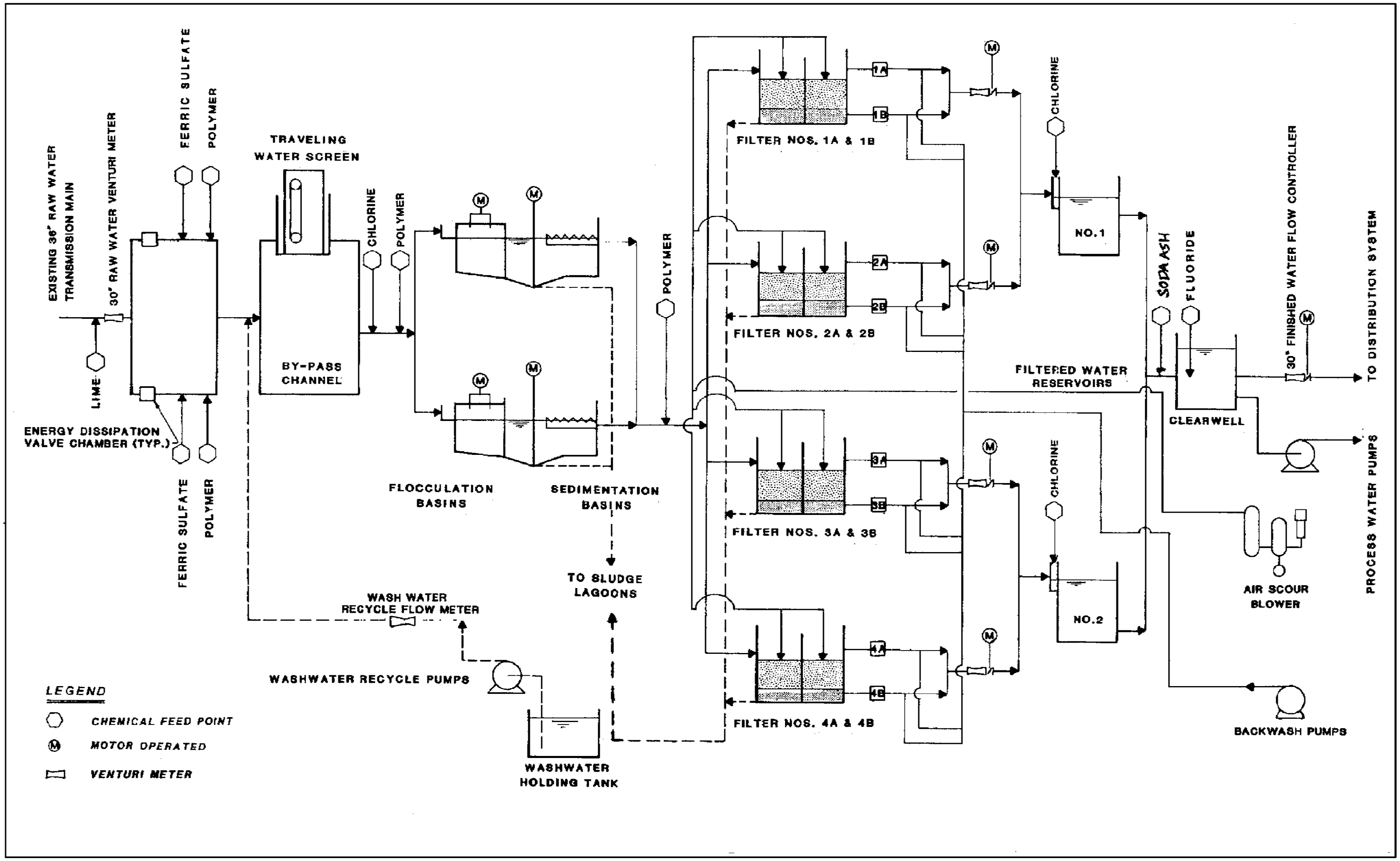
Anchorage Water and Wastewater Utility, Ship Creek Water Treatment Facility – Conventional Surface Water Treatment

The Ship Creek Water Treatment Facility (Ship Creek WTF) in Anchorage, Alaska, is operated by the Anchorage Water and Wastewater Utility (AWWU). The water source for the plant is an impound dam on upper Ship Creek, which is recharged from a protected 100-square-mile watershed in the Chugach Mountains. The plant's production capacity is 24 MGD, supplying 28 percent of the system's water demand. The Anchorage area is also supplied with water from the Eklutna Water Treatment Facility, sourced from Eklutna Lake, and by 16 deep wells located throughout the Municipality of Anchorage.

The raw water supplied to Ship Creek WTF is moderately soft, with an average hardness in 1999 of 67 mg/L as $CaCO_3$, and has a pH of 7.5. Seasonal changes cause a wide variation in the surface-water quality. The turbidity can range from less than 1 nephelometric turbidity unit (NTU) to more than 600 NTUs. During the annual spring run-off from snowmelt high in the mountains, the levels of NOM, color, and dissolved metals increase considerably.

The Ship Creek WTF uses conventional water treatment, beginning with coagulation and flocculation. Before beginning treatment, soda ash is added to the raw water to raise the alkalinity before coagulant addition. Ferric sulfate is used as the primary coagulant. After chemical addition, the water flows through a traveling screen to remove large debris. Before entering the two flocculation basins, the water may be chlorinated and polymer added if the process warrants.

From the flocculators the water is transferred to two parallel sedimentation basins where the floc settles out. The clear water is then channelled from the top of the sedimentation basins over saw-toothed weirs to four filters, and the sludge is drawn off the bottom of the basins and transferred to sludge lagoons for dewatering before disposal. The multi-media filters contain layers of anthracite coal, sand, and gravel that remove any remaining turbidity. A small amount of chlorine for disinfection, soda ash for pH stabilization and corrosion control, and fluoride are added to the finished water before it enters the distribution system.



Process flow schematic of the Ship Creek Water Treatment Facility, Anchorage, Alaska.

REVIEW QUESTIONS

1. Aeration is a process that mixes ________________ with ________________.
2. What is a colloid? ____
3. What are the four components of conventional water treatment?
   a. ____
   b. ____
   c. ____
   d. ____
4. The unit process in conventional filtration that is not included in direct filtration is ____.
5. The active layer of suspended matter and microorganisms (algae, bacteria, protozoans) that forms on the surface of a slow sand filter and facilitates treatment is called ________________________________.
6. Two common categories of softening methods are ______________________ and ______________________________.
7. In ion exchange softening two _______________ ions are substituted for each ________________ or ________________ ion.
8. A common direct filtration media used for iron and manganese removal in Alaska is ____________________________. If the iron and manganese levels are below 1.0 mg/L _________________________ can be used instead of removal.
9. Two treatment methods for removing organic molecules that can form disinfection by-products are:
   a. ____
   b. ____
10. Three common methods of corrosion treatment in small water systems are:
    a. ____
    b. ____
    c. ____

Chapter 6

Aeration

Chapter 6 - Aeration

INTRODUCTION

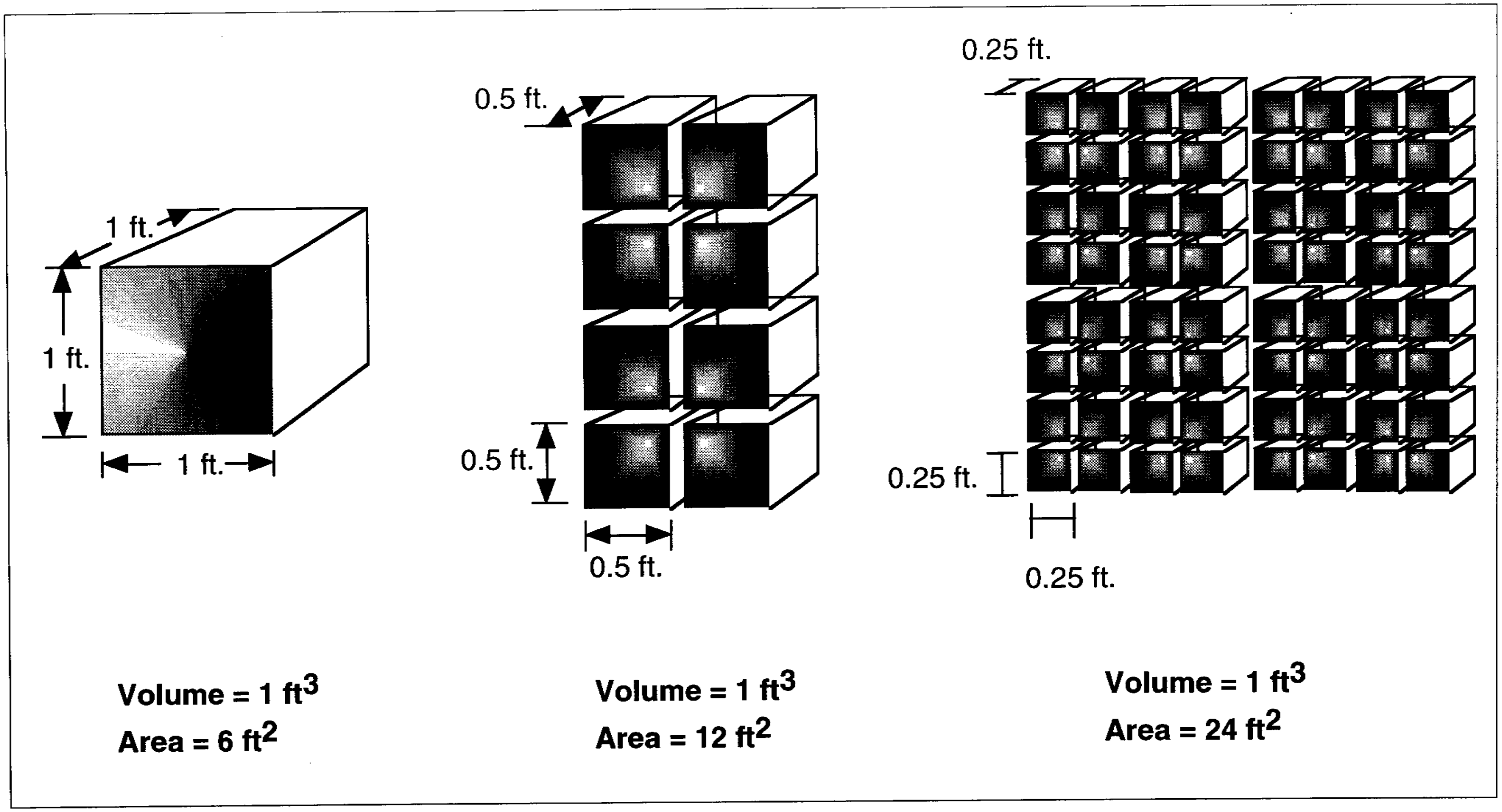
Aeration, the process of mixing air with water, occurs in many natural settings, such as waterfalls and turbulent streams. As the water falls through the air or splashes over rocks, air dissolves into the water, while gases dissolved in the water escape into the air. The water treatment professional uses aeration to remove **dissolved gases** (degasification), oxidize **dissolved metals**, release **volatile organic compounds**, and occasionally to help mix **coagulants** or **flocculants**. At many treatment plants, aeration is one of the primary methods of water treatment because it can remove or modify some constituents that could interfere with subsequent treatment processes.

Both physical and chemical mechanisms are at work during the aeration process. The physical mixing and agitation created by the turbulent addition of air into water exposes dissolved gases to the atmosphere, allowing them to escape from the water. When aeration is used for this purpose, it is called desorption or stripping, a common treatment method for removing volatile organic compounds. Chemically, aeration exposes dissolved metals in the water to molecular oxygen, which transforms these metals by oxidation from a dissolved state (reduced form) to an insoluble state (oxidized form). The metal oxides will then precipitate and drop out of solution. Oxidation of soluble iron and manganese can be accomplished by aeration.

The main factor controlling the effectiveness of aeration as a water treatment method is the quantity of surface area of water exposed to air in the aeration process, also referred to as the area-to-volume ratio, A/V. If A can be increased relative to V, the more efficient the process will be.

$$A/V = \text{area-to-volume ratio}$$

The smaller the water droplets or air bubbles in the system, the greater the surface area of exposure. Because the volume of a spherical water droplet or air bubble increases as the cube of the diameter, even a small percentage of large drops or bubbles can considerably reduce the surface area of exposure and, thus, aeration efficiency. Moreover, a reciprocal relation exists between A/V and time, t. As long as the product of A/V and t is constant, the **aerator** performance will remain constant. In other words, t may be increased at the expense of A/V and conversely



Relation between volume and surface area. As the dimensions of each cube are cut in half, the surface area doubles.

without losing aerator efficiency. This relation is applied in the design of the various types of aerators discussed later in this chapter.

Temperature is also a factor in aeration; the solubility in water of gases such as oxygen and carbon dioxide decreases as temperature increases. Other factors that influence the effectiveness of aeration in water treatment include the characteristics of the **volatile** substances to be removed, the partial pressure (or saturation levels) of the gases in the aerator atmosphere, and time of exposure. Adequate ventilation of the aerator atmosphere ensures that the gases to be removed do not reach high saturation levels in the air, which would hinder gas release from the water and could result in a hazardous atmosphere in the plant.

SUBSTANCES AFFECTED BY AERATION

The following dissolved gases and other constituents can be removed or altered using aeration:

- carbon dioxide
- hydrogen sulfide
- methane
- radon
- volatile organic compounds
- iron and manganese (oxidation to a precipitate)
- tastes and odors

Dissolved Gases

Dissolved gases in water can cause numerous problems, including objectionable tastes and odors, corrosion of pipes and system components, and health and safety hazards. Aeration can help to remove dissolved gases by exposing them to the atmosphere until the concentration of the gas in the water is in equilibrium with the concentration of the gas in the atmosphere. The following dissolved gases are susceptible to removal by aeration.

Carbon Dioxide

Carbon dioxide (CO_2) is highly soluble in water. As much as 1,700 milligrams per liter (mg/L) can be dissolved in water at 20 °C, and even higher concentrations can be attained in colder water. CO_2 is more likely to be found in groundwater wells than in surface water. Although CO_2 does not pose a health risk when dissolved in drinking water (in fact, carbonated soft drinks get their "fizz" from dissolved carbon dioxide), it can pose operating problems for the water system. Dissolved CO_2 increases the acidity of the water, which can cause corrosion of system components. Excess CO_2 in water may keep iron in solution, making iron removal more difficult, and can react with calcium carbonate during lime-softening treatment, making it necessary to use more lime in the process. Excess CO_2 is a common problem in Alaska because of the cold groundwater here. Aeration can decrease dissolved CO_2 concentrations in water to the point of equilibrium with the surrounding air.

Hydrogen Sulfide

Hydrogen sulfide (H_2S) is associated with groundwater sources more often than with surface waters, although H_2S can occur in lakes and reservoirs under ice cover in winter. It produces the rotten-egg odor found in some groundwater wells and can affect the taste of coffee, ice cubes, and many foods prepared with it; silverware washed in water containing H_2S can turn black. H_2S is a corrosive gas that forms sulfuric acid in water and can damage water system components. Moreover, H_2S is a poisonous gas that can be hazardous if concentrated in a treatment plant. Breathing air containing H_2S at concentrations as low as 0.1 percent by volume for less than 30 minutes can be fatal.

The formation of H_2S is pH-dependent, with H_2S predominating below a pH of 7.5. Consequently, the pH must be below 7.5 to ensure a high percentage of the sulfur is in the H_2S form to encourage stripping by air. It is unlikely that H_2S will be completely removed by aeration; oxidation with chlorine may be necessary if complete removal is required. Adequate ventilation in the treatment plant is essential to optimize the aeration process and to minimize the inhalation hazard to plant personnel.

Methane

Methane (CH_4) is often found in groundwater supplies located near natural gas deposits. Also called "swamp gas," CH_4 is produced by the decay of organic material such as vegetation buried in old river channels under permafrost. The gas is colorless, odorless, and tasteless, but when dissolved in water it can make the water taste like garlic. CH_4 poses an explosion hazard if it is allowed to accumulate in an enclosed space. Aeration can easily remove methane from water because methane is only slightly water-soluble. However, care must be taken to provide adequate ventilation in the treatment plant so that the methane is adequately dissipated to avoid explosion hazards.

Radon

Radon is a radioactive gas that is a suspected carcinogen. It is a natural decay product of uranium and is present at unacceptable levels in many groundwater supplies in Alaska. Many of these supplies are located near **granitic plutons**, which may be rich in uranium, and may also be associated with natural hot springs that are fueled by the heat produced by the radioactive decay process. Radon must be removed from drinking water supplies because of the extreme health risk associated with it. Radon is released from showers, washing machines, and other plumbing fixtures, and can concentrate in enclosed spaces, creating an inhalation hazard. Because it is easily released from water, almost any aeration method is effective in removing radon, but care must be taken to ensure that the removed gas does not accumulate in the treatment plant.

Volatile Organic Compounds

Volatile organic compounds (VOCs) are ubiquitous in industrial and commercial settings, and are integral components of gasoline and other fuels, paints, and many solvents (including dry-cleaning chemicals). Because VOCs are considerably less volatile than CO_2 and H_2S, their removal by aeration requires more sophisticated aeration devices. Air-sparging units are used on groundwater wells in industrial areas where spills of VOCs have occurred. For example, air-sparging units are operating on wells at military installations in Alaska to treat accidental releases of petroleum-hydrocarbon compounds. Air spargers are also in use on the groundwater wells that supply water to the University of Alaska Fairbanks.

The relative volatility of a substance can be expressed by Henry's Law, which states that "the weight of any gas that will dissolve in a given volume of a liquid, at constant temperature, is directly proportional to the pressure that the gas exerts above the liquid."[1] Henry's Law is expressed by the following equation:

$$C_{\text{equil}} = \alpha p_{\text{gas}}$$

Where

C_{equil} = the concentration of gas dissolved in the liquid at equilibrium,

p_{gas} = the partial pressure of the gas above the liquid, and

α = Henry's Law constant, which is a function of the vapor pressure, molecular weight, and solubility of the substance at a given temperature.

Removal of a gas from a liquid is determined on the basis of the difference between C_{equil} and the actual concentration of the gas in solution. Removal of VOCs, H_2S, CO_2, and other volatile substances during aeration is thus driven by a relatively low concentration of the undesirable substance in air. Henry's Law predicts that the low concentration in air (low p_{gas}) will result in a lower C_{equil} than the actual concentration in the water. Thus the undesirable substance will be released during aeration, essentially moving from an area of higher concentration to an area of lower concentration.

Dissolved Metals

Dissolved metals, most commonly iron and manganese, can be treated by aeration because circulating air through the water can promote chemical oxidation of the reduced metals, causing them to precipitate out of solution. Oxidation of soluble iron by aeration forms insoluble ferric hydroxide by the following chemical reaction:

$$2Fe^{2+} + {}^{1}/_{2}O_2\,(aq) + 5H_2O \rightarrow 2Fe(OH)_3\,(s) + 4H^+$$

The ferric hydroxide will then drop out of solution as a precipitate. Iron and manganese oxidation reactions are enhanced by an increase in pH. This makes it desirable to remove CO_2 from the water, which will occur if aeration is efficient. Organic substances in the water and low water temperature will slow the rate of the oxidation reaction. Oxidation of manganese by aeration is

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[1] *Chemistry for Environmental Engineering*, C.N. Sawyer and P.L. McCarty, 1978.

such a slow process that aeration is not a preferred treatment method if the water contains a high concentration of dissolved manganese. However, raising the pH can enhance manganese removal by aeration.

Tastes and Odors

Many volatile substances that cause objectionable **tastes and odors** may be removed by aeration. The removal of volatile compounds from water is referred to as **degasification**. Because the air contains a lower concentration of the volatile compound than the water, circulation of air through the water will cause the volatile material to leave the water and move into the air. This process alone is often adequate to reduce the offending volatile substance to an acceptable concentration. Some volatile odor- and taste-producing compounds also may be easily oxidized by aeration. However, the oxidation capability of conventional aeration methods is usually not adequate to oxidize organic compounds, and more sophisticated systems must be used. Aeration is not effective for removing less volatile compounds or taste-causing inorganic compounds that do not oxidize readily like iron does, and is rarely used alone for taste and odor control. H_2S is one of the few taste and odor compounds that can effectively be removed by aeration. Phenol, on the other hand, which is often associated with an “off taste” in water, has a relatively low vapor pressure and is not effectively removed by aeration.

Dissolved Oxygen

Aeration can be used to increase the concentration of **dissolved oxygen** (DO) in water to improve its taste. Given sufficient time, aeration will adjust the DO concentration in water until it achieves equilibrium with the concentration in the ambient air. However, high DO concentrations in water will increase corrosion. Many plants in the United States have abandoned aeration because the higher DO levels do increase the corrosivity of the water, but others have continued to use aeration without reporting any problems.

TYPES OF AERATORS

Several different methods of aeration are available and fall into two general categories: water-into-air types and air-into-water types. Combination methods incorporating both types also may be used. Water-into-air aerators produce small droplets of water that fall through the air. Air-into-water types produce small bubbles of air that rise up through the water being aerated.

Water-into-Air

The more common water-into-air types of aerators are discussed below and include the following:

- cascade
- cone
- tray
- draft
- spray
- packed towers

Cascade Aerators

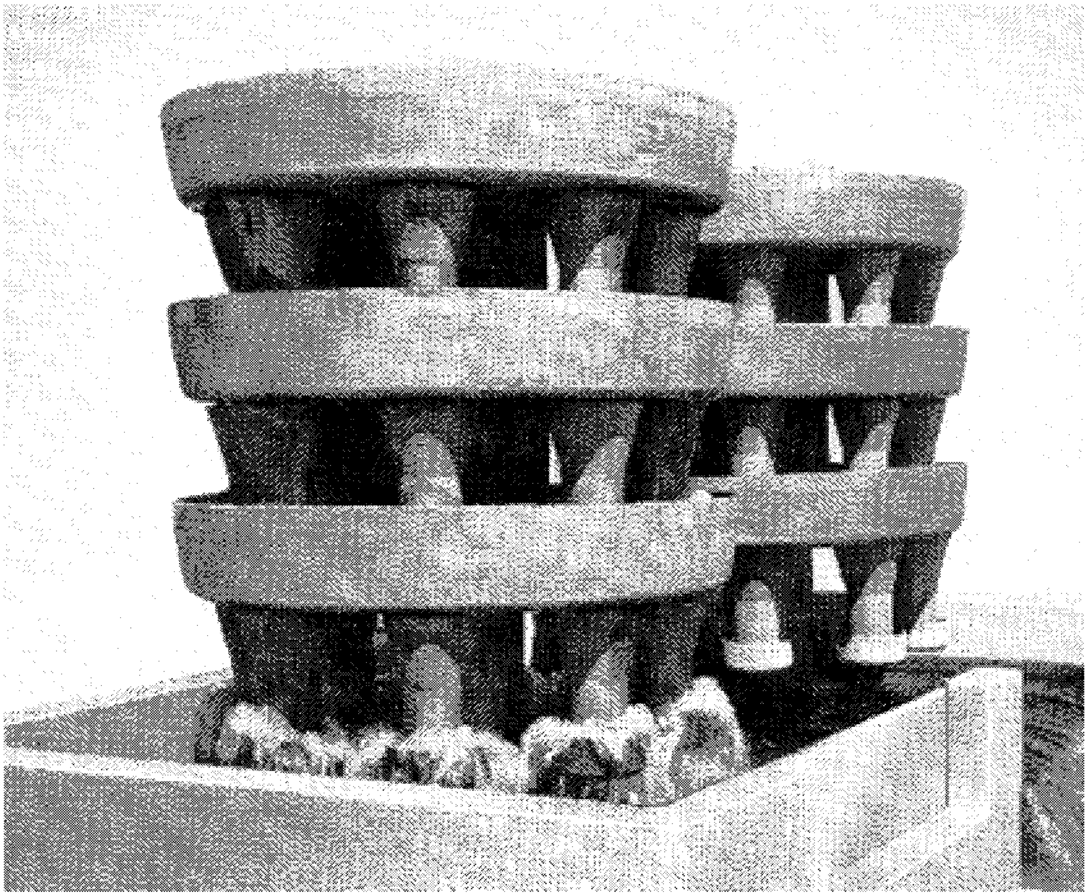
Cascade aerators force the water to flow over a series of obstructions, creating turbulence. A cascade aerator is designed with a series of steps, like a stairway, or with stacked metal rings. The water enters through an inlet conduit or a central feed pipe at the top of the aerator, spreads out in a thin sheet, and then falls down to the next level and so on. The aeration occurs in the splash areas on the steps or rings. Blocks or riffle plates form the splash areas on the inclined cascade. These aerators can be used to oxidize iron and to partially remove dissolved gases.

Cone Aerators

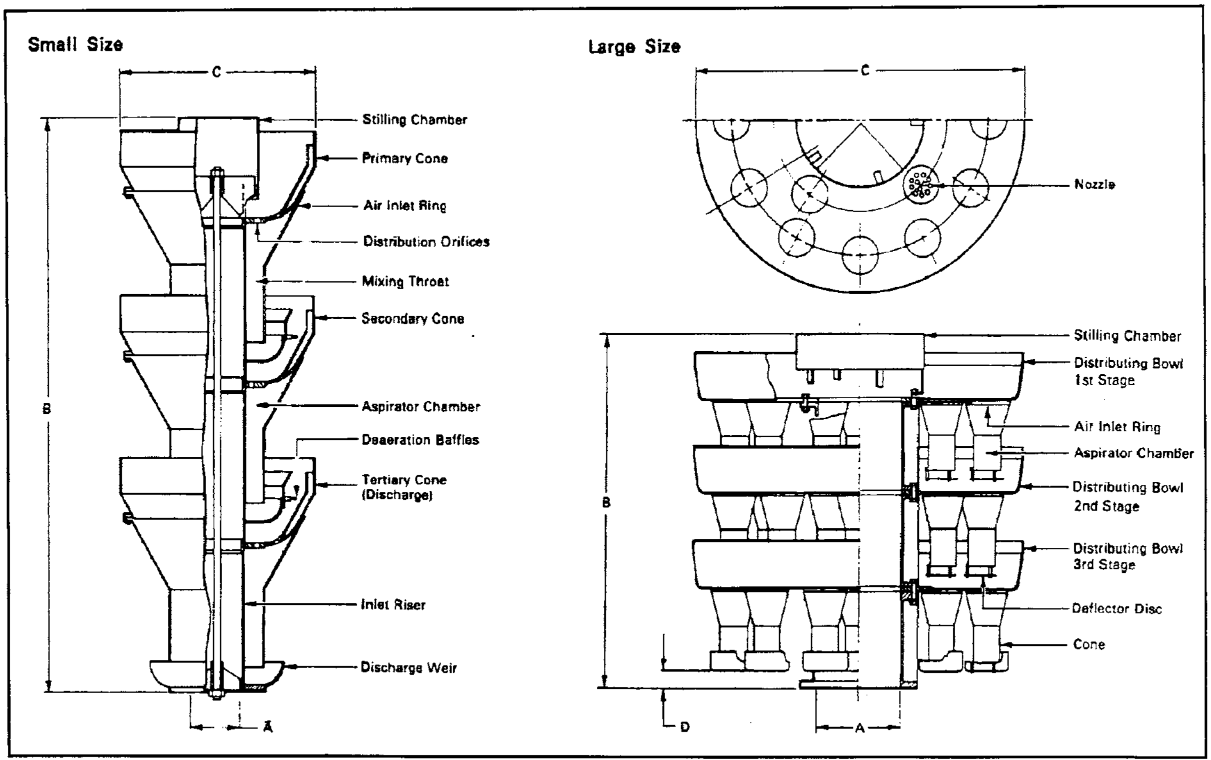
Cone aerators are similar to ring-type cascade aerators, but the water cascades down a series of stacked pans from the top layer through specially designed cone-shaped nozzles in the bottom of each lower-level pan. Air portals draw air into the stacked pans to mix with the falling water. These aerators are also used primarily to oxidize iron but may also partially remove dissolved gases.

Tray Aerators

Tray aerators are constructed from stacked trays with spaced wooden slats, typically made of redwood or cypress. Early forms of this type of aerator were usually filled with about 6 inches of 3- to 4-inch-diameter pieces of coke. Today, rather than coke, the media is more likely to be rock, ceramic balls, limestone or other materials. As the water travels down from one level to the next, it splashes on the media, breaking up the water and mixing it with air. Again, this type of aerator is used to oxidize iron, and to a limited extent, to remove dissolved gases.



Above: Multicone Aerator, by Infilco Degremont, Inc.
Below: Multicone Aerator components. Courtesy of Infilco Degremont, Inc.



Draft

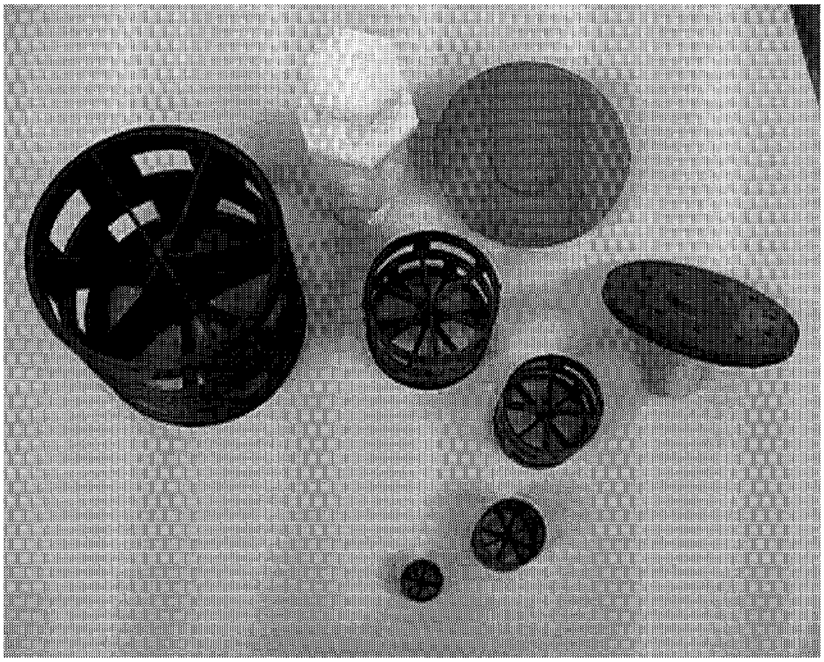
Draft aerators are similar to those previously discussed, with the addition of an external blower or other device that produces an active draft through the apparatus. As the water splashes down through a tower of slats, air is blown through the chamber, removing the released gases.

Spray

A spray aerator is constructed of spray nozzles attached to a central pipe manifold. The water is released at high pressure in a fine spray that falls through the surrounding air like a fountain. A spray aerator tower has the advantage of protecting the water from windblown losses and freezing. This type of aerator is often used in combination with cascade and draft aerators to optimize the best features of each. Spray aeration is effective at oxidizing iron and manganese, and is very efficient at increasing the DO concentrations in the water.

Packed Tower

Packed tower or packed column aerators, or air-strippers, are relatively new systems for drinking water treatment. This type of aerator combines a cascade-type system with an air blower. A packed tower has a cylindrical tank containing a packing medium made of shaped pieces of ceramic, stainless steel, or plastic that may be randomly dumped into the tank. This type of packing is called dumped packing, whereas fixed packing material made up of prefabricated sheets may also be placed into the tower. Another packing option is called loose packing. An air blower connected to the lower part of the tank sends air up through the system while the water falls down through the packing medium. The size of the tank, or depth of the packing, and the power of the air blower required depend on the volatility of the substances to be removed from the water. The temperature of the water also affects the design of the packed tower. For example, at 75 °F, assuming a 20:1 air-to-water ratio, a packing depth of 8 feet is required. The same design treating water at 40 °F would require a 16-foot bed. Consequently, in Alaska it may be more cost effective to heat the water before packed tower treatment, especially if a source of waste heat is readily available. The packed tower aerator is most effective at removing volatile substances.



An assortment of aerator packing material and diffusers, including two snap caps (upper right) used in some Alaskan aerators.

Air-into-Water

Air-into-water aerators are designed to bubble compressed air through the water, usually slowly but with considerable turbulence. In this way, some of the oxygen in the air is released to the water, increasing the DO content of the water.

Diffuser Aerators

A **diffuser** aerator system consists of a steel or concrete aeration basin equipped with compressed air piping, manifolds, and diffusers. The individual diffusers involved may be simply holes drilled in the manifold piping, or may be one of a variety of non-clog type diffusers such as “snap-caps,” shown in the figure above. Compressed air is injected to produce bubbles. as the bubbles rise, turbulence is created and the opportunity for the exchange of volatile substances is enhanced.

Draft-Tube Aerators

A draft-tube aerator is a submersible pump with an air-intake pipe called a draft tube. A partial vacuum is created in the pump’s spinning turbine impeller, causing air to enter through the draft tube and water to enter through the water intake. The air and water are mixed by the turbine impeller and then discharged into the aeration basin. The draft-tube aerator is a convenient, low-cost way to add aeration to an existing basin or tank.

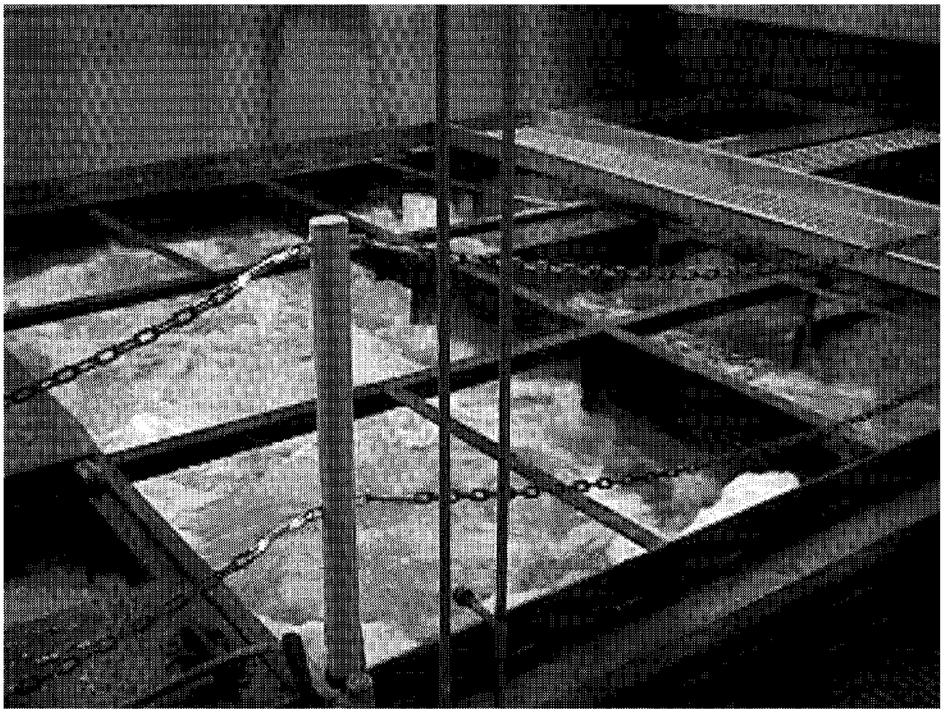
Combination

Several types of combination aerators are available that incorporate two or more of the methods described above. Mechanical aerators provide mixing by a motor-driven propeller-like mixing blade that violently mixes the air and water together. Examples of mechanical combination aerators include surface aerators, submerged aerators, combination surface and submerged aerators, and combination surface and draft-tube aerators. As an alternative to mechanical mixing, pressure aerators supply air under pressure to a system, either spraying water into high-pressure air or diffusing air directly into a pressurized pipeline channeling flowing water.

UNIVERSITY OF ALASKA FAIRBANKS

The University of Alaska Fairbanks (UAF) uses forty-nine 8-inch Ramco® turbine air diffusers submerged in two basins. This combination-type diffuser consists of a plastic cylinder equipped with rotating blades powered by a new 40-horsepower Roots® rotary-lobe air blower with a capacity of 1,000 cubic feet per minute. Air is supplied through a small-diameter pipe with a slit in it inside the diffuser housing. The diffusers release tiny bubbles of compressed air into the water near the bottom of the aeration basin. The bubbles rise turbulently through the water, creating a rolling-type mixing pattern.

New Ramco® air diffuser and used diffuser encrusted with iron precipitates. The new slitted blow-tube replaces encrusted tube with holes drilled in it.

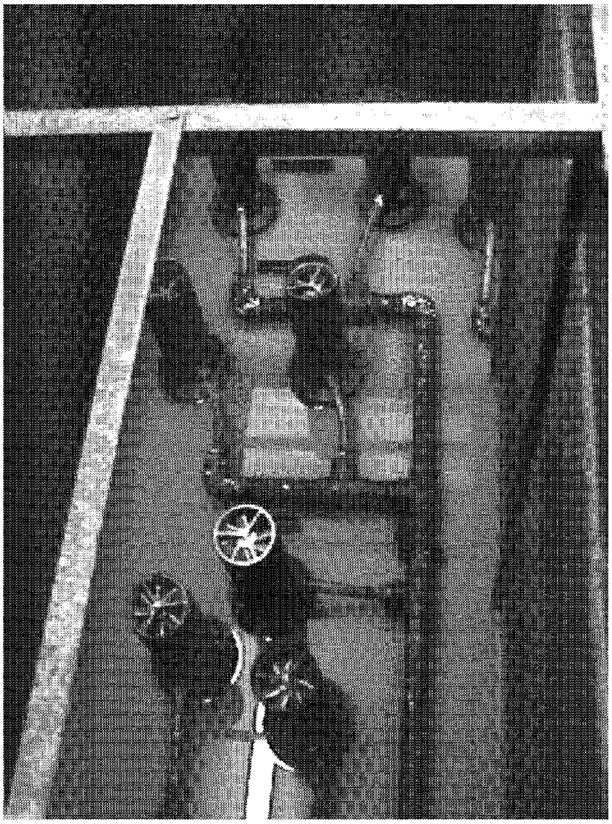


The aerator at the University of Alaska Fairbanks water treatment plant. The 49 Ramco® air diffusers are submerged in the tank, creating a frothy turbulence in the water. Aeration is the first treatment process the raw water undergoes as it enters the plant.

Along with the physical mixing, each air bubble releases some oxygen, increasing the DO concentration in the water. In addition, potassium permanganate is added to the raw water at the influent, to aid in the oxidation process. This system provides for oxidation of the heavy metals in the water such as iron and manganese. The oxidized metals are removed later in the sedimentation basins and by the filters. The aeration process also removes H_2S and benzene, which volatilize into the air in the treatment plant.

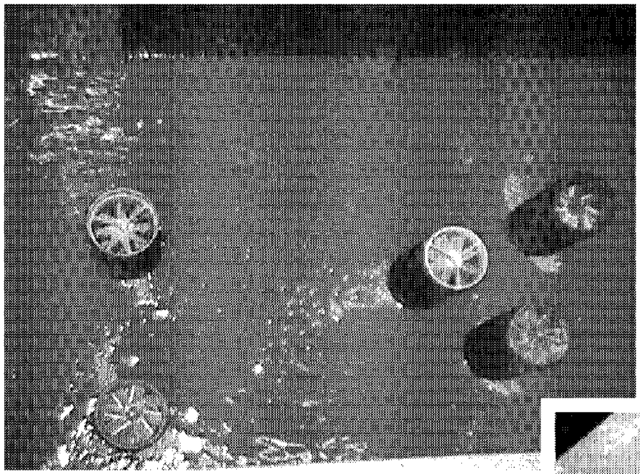
Because of the high iron content, an iron bacteria called ***Crenothrix*** is also present in the UAF raw water. This bacteria and the oxidized iron that precipitates out during aeration form a reddish-orange slime that encrusts the air supply headers, diffusers, and walls of the basin. This necessitates a regular program of preventive maintenance, which involves shutting down the water plant, draining the aeration basin, and hand scrubbing and hosing down every diffuser and wall in the aeration chamber. The frequency of this cleaning and maintenance is determined by the pressure of the supply air. The pressure increases as the air-supply nozzles become clogged with iron bacterial and oxide precipitates. When the pressure at the air blowers reaches 5.8 pounds per square inch (psi), the system is shut down for maintenance. After cleaning, the system air pressure is about 3.5 to 3.7 psi.

The new 40-horsepower Roots® rotary-lobe air blower at the University of Alaska Fairbanks that powers the 49-diffuser aerator array.



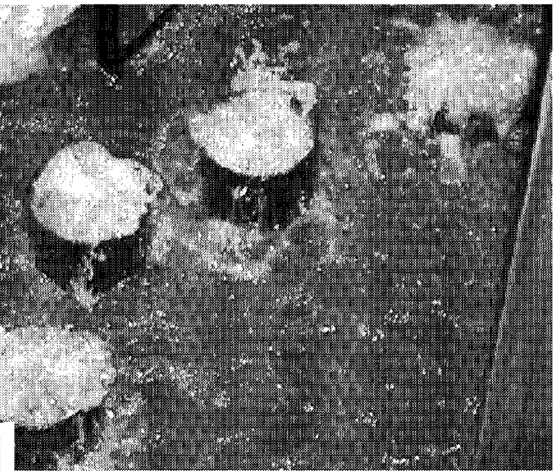
UAF aerator basin drained for cleaning. Note blades inside diffuser housings and piping between diffusers.

Aerator basin at UAF, beginning to refill with water after cleaning the basin and diffusers.

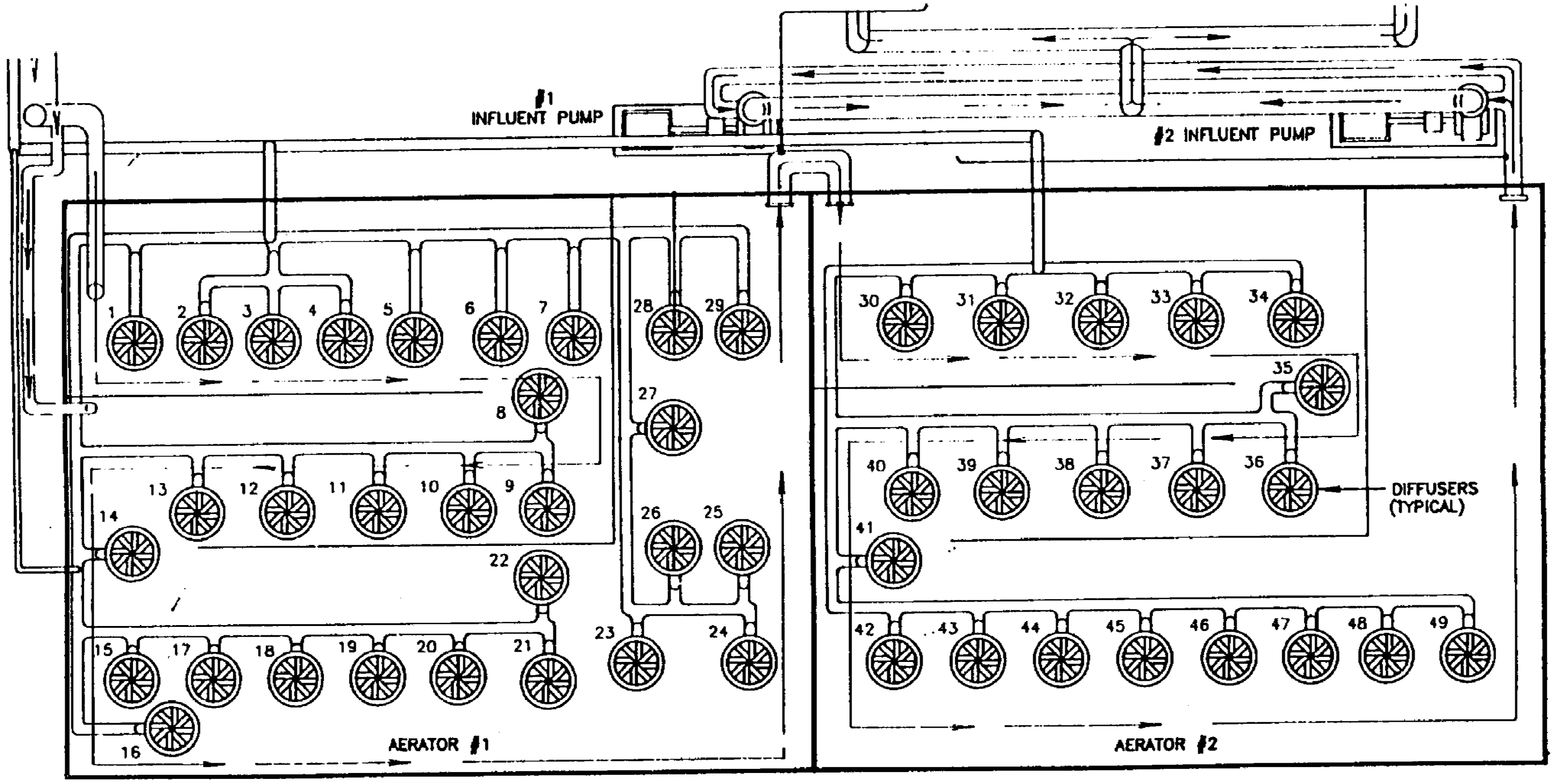


Water continuing to fill the aerator basin.

Start-up of diffuser action with aerator basin partially filled.



Diffusers back in action, with aerator basin nearly completely filled with water.



The diffuser array at UAF, showing the arrangement of the 49 Ramco® air diffusers.

BARROW UTILITIES AND ELECTRIC COOPERATIVE, INC.

From 1983 to 1999, Barrow Utilities and Electric Cooperative, Inc., used diffused aeration for CO_2 stripping and coagulant mixing for treatment of an impounded surface water supply in Barrow. Air was provided by rotary-lobe air blowers and then diffused through "snap-cap" type diffusers arranged at the bottom of a 10,000-gallon tank. Alum was added to the raw water before it entered the aeration tank. Aeration thus served to mix the coagulant and remove CO_2 from the raw water. Additional CO_2 was released from the reaction of alum with the alkalinity in the water. The aerated and coagulated mixture was then pumped to a conventional filtration plant for further treatment. A similar process was used at the surface water treatment plant in Kotzebue.

OPERATIONS MONITORING

To ensure the aerator is functioning properly, the water treatment plant operator may incorporate process control tests into the routine operations of the plant. The results of process control tests and notes on daily activities may be used to ensure optimal plant performance, regulatory compliance, and to help with troubleshooting operational problems.

Process Control Tests

Aeration process monitoring may include DO, pH, and temperature tests. Testing for DO can be used to monitor the quantity of oxygen being dissolved in the water. Knowing the DO requirements of the system and monitoring the amount of DO present can help minimize over- or under-aeration. An increase in the pH of the water undergoing aeration can be used as an indicator of CO_2 removal. In addition, maintaining a specific pH range is important for effective removal of H_2S and iron and manganese. H_2S removal is optimized at a pH of 6 and iron and manganese oxidation is most efficient at a pH range of 8 to 9. The amount of oxygen or CO_2 that can dissolve in the water is affected by temperature. Higher dissolved gas concentrations are possible at lower water temperatures.

Other process control tests may be necessary depending on the water source and the particular constituents being removed by aeration. Surface water is more susceptible to frequent quality changes than well water, so the frequency of raw water testing must be appropriate to the variability of the water source. If toxic components, such as VOCs or radon, are being removed by the aeration process it is critical to test the finished water periodically to ensure the system is achieving the required degree of removal. The analytical tests for these substances are complicated and must be performed by a qualified laboratory. State regulations specify the required sampling frequency and the maximum contaminant levels allowed for these constituents.

Operating Problems

One of the common operating problems associated with aerators is contamination of the air source. Particulate and other contaminants may react with chemicals used in later water treatment processes. In addition, biological growths such as algae or iron bacteria can accumulate and clog system components. Because excessive levels of DO in water can increase its corrosivity, the aeration process should be controlled to ensure that the water does not become over-aerated and that the positive aspects of aeration are not achieved at the expense of creating a larger problem. Preventive maintenance must be regularly scheduled to clean equipment and system components before operating problems arise.

SAFETY AND MANAGEMENT

The water treatment plant operator is responsible for maintaining safety standards and plant operating records, and for the plant's regulatory compliance. Some of the principal aspects of treatment plant management relating to aeration are described below.

Safety Considerations

As mentioned previously, some of the dissolved gases such as H_2S, CH_4, radon, and benzene that are removed by aeration may be hazardous if allowed to concentrate in the facility. Adequate ventilation is critical to maintaining safe air quality in the treatment plant.

Record Keeping

Some important aeration process records that should be maintained by the water treatment plant operator include the following:

- results of periodic raw water analyses, to monitor for changes in constituents the aeration process is designed to alter or remove
- daily volume of water treated by the aeration process

- results of periodic analyses of finished water, to determine whether the aeration process is successfully mitigating or removing constituents from the raw water as intended
- inspections and monitoring for safety hazards such as the release of toxic or explosive gases
- details of aeration equipment maintenance
- changes made in the equipment or process operation
- observed changes in other treatment processes that might be caused by failure or improvement in the aeration process

Regulations Pertinent to Aeration

Most of the regulations that pertain to aeration deal with the removal of radon and VOCs. Because new Federal regulations restrict the concentration of radon in drinking water, many drinking water systems will be affected. Because aeration is effective at removing radon aerators intended for this use may be required to meet minimum standards provided by the regulations. Moreover, some issues related to Clean Air Act requirements for discharged air may affect some aeration installations at high-volume water treatment plants.

REVIEW QUESTIONS

1. True or False: Aeration involves both physical and chemical processes.
   True __________
   False __________

2. Aeration occurs in natural settings, such as ________________________
   and ___________________________.

3. List three constituents that may be removed from water using aeration.
   a. ________________________
   b. ________________________
   c. ________________________

4. List two of the problems associated with dissolved CO_2 in water:
   a.________________________
   b.________________________

5. H_2S gas is hazardous if it is not adequately dissipated in a treatment plant because _____________________________________.

6. The hazard posed by inadequate ventilation of methane gas is ________________________.

7. What are the two main categories of aerators?
   a. ________________________ and b. ________________________

8. Which of the following is an air-into-water diffuser?
   a. cascade
   b. packed tower
   c. draft-tube
   d. spray

9. True or False: The saturation level of dissolved CO_2 (or any gas) in water is higher at colder temperatures.
   True __________
   False __________

10. At which pH level will iron and manganese be most efficiently oxidized?
    a. 6.5
    b. 7.0
    c. 7.5
    d. 8.0

Chapter 7

Coagulation and Flocculation

Safe Chemical Handling
Record Keeping
Regulations

Review Questions

Chapter 7 – Coagulation and Flocculation

INTRODUCTION

Throughout the hydrologic cycle, water comes in contact with a variety of substances, including vegetation, soil, and rock formations. Many of these substances become dissolved in the water, because of its excellent solvent properties, while others are simply transported by the flowing water. These impurities cause water to be turbid or colored or to taste or smell unpleasant. Because many of these particles have a density only slightly greater than that of water, and because the electrical charges on the particle surfaces tend to make the particles repel one another, they must be brought together and aggregated into larger particles so that they can be removed from the water.

Coagulation and **flocculation** are integral processes in conventional water treatment systems. These two processes, working together, bring the small suspended particles together so they can be removed in subsequent treatment steps. Coagulation, which requires the addition of a chemical agent called a **coagulant**, is necessary to overcome the natural repellent forces on the suspended particles. Flocculation, which usually follows the coagulation or rapid-mix stage, is a time-dependent process that enhances particle contact so they can aggregate together to form larger particles.

Impurities that may be removed by coagulation and flocculation include **color** and **turbidity**, which may be made up of microorganisms, algae, organic compounds, oxidized iron and manganese, calcium carbonate, and clay particles. Clay, fine silt, and glacial flour are a large part of the natural turbidity in Alaska's raw waters. The overall purpose of coagulation and flocculation is to improve the efficiency of the subsequent treatment processes, usually clarification or filtration, or both. This chapter describes the theory behind coagulation and flocculation treatments and presents some of the principal technical aspects of this water treatment process.

TURBIDITY AND CONVENTIONAL WATER TREATMENT

Many impurities suspended in raw water are too small to be filtered or to settle out in a sedimentation basin in a reasonable period of time. These particles are called **nonsettleable solids**. Nonsettleable solids may include biological constituents, bacteria, viruses, protozoans, organic matter, and fine inorganic matter such as silt. Particles are categorized on the basis of their relative sizes. **Colloids** are particles less than 1 micron in size and are primarily responsible for turbidity in water, which is undesirable for both aesthetic and health reasons. Colloidal particles in water can harbor **pathogenic** microorganisms, making it more difficult to inactivate the **pathogens** by **disinfection**. Organic particles, visible as color, may react with disinfectants to form harmful **disinfection by-products**. Different particle sizes and their settling times are presented in the table below.

SETTLING TIMES FOR PARTICLES IN WATER		
Particle Diameter (mm)	Example Particle	Settling Time in 1-foot (0.3-m) Depth
10	gravel	0.3 seconds
1	coarse sand	3 seconds
0.1	fine sand	38 seconds
0.01	silt	33 minutes
0.001	bacteria	55 hours
0.0001	color	230 days
0.00001	colloidal particles	6.3 years
0.000001	colloidal particles	63-year minimum

mm, millimeter; m, meter
Source: *Water Treatment*, American Water Works Association, 1995

For most water treatment plants that treat surface water, a major objective is to lower turbidity to a predetermined standard. Normally the plant objective is to consistently reach a finished water turbidity goal. Turbidity is regulated by the State of Alaska, Department of Environmental Conservation, on the basis of treatment method. The **maximum contaminant**

level (**MCL**) for turbidity is 5 **nephelometric turbidity units** (**NTU**) for any one sample. Moreover, depending on the treatment method used, water systems may have to meet more stringent "filter performance standards," of less than 0.5 NTU[1] or 1.0 NTU[2] in at least 95 percent of the measurements reported each month. Individual plants may impose their own more stringent turbidity goals in an effort to produce water of the highest quality. Turbidity is measured by a nephelometric turbidimeter, which measures the amount of light scattered by the suspended material in the water. The water treatment plant operator must ensure that the turbidity in the finished water supply does not exceed the MCL. The treatment most often used for removing turbidity and color from water is known as **conventional treatment**. This method consists of the following steps:

- **Coagulation:** addition and rapid mixing of chemical coagulants into the raw water.
- **Flocculation:** slow, gentle mixing of the chemicals in the water to help form larger particles, called **floc**.
- **Clarification:** allowing the floc to settle out of or separate from the water in a large sedimentation basin or clarifier.
- **Filtration:** removing nearly all of the remaining suspended matter by passing the water through filters.

The last two steps, clarification and filtration, are discussed in Chapters 8 and 9, respectively.

COAGULATION

Colloidal particles are not easily susceptible to settling under the force of gravity for two main reasons: 1) they are so small that their surface area is disproportionately large compared to their density, allowing them to stay afloat in the water; and 2) they have repellent ionic charges on their surfaces that are stronger than the **van der Waals forces** that would normally attract them to each other. The term used to describe the repellent force between particles is **zeta potential**. Most frequently, the charges on colloidal surfaces are negative or **anionic**. The addition and rapid mixing of a positively charged coagulant reduces the zeta potential of the particles by a process called **charge destabilization**.

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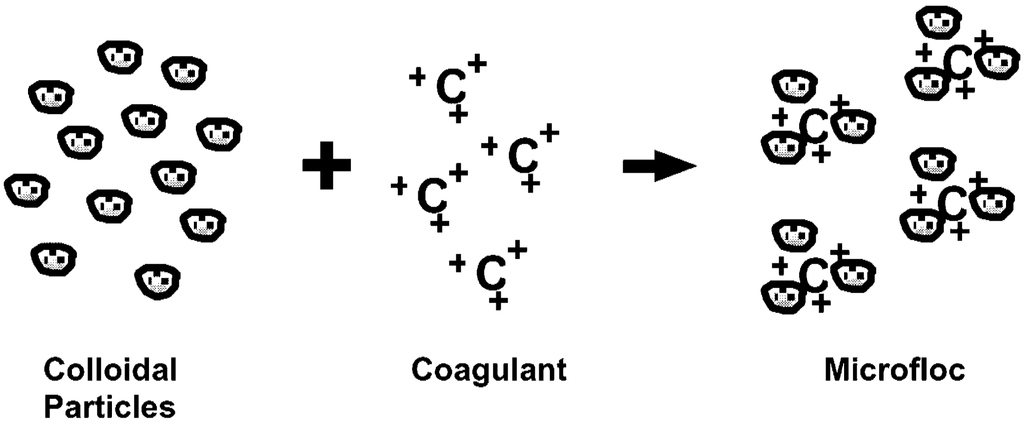
1. filter performance standard for conventional or direct filtration systems
2. filter performance standard for slow sand or diatomaceous earth filtration systems

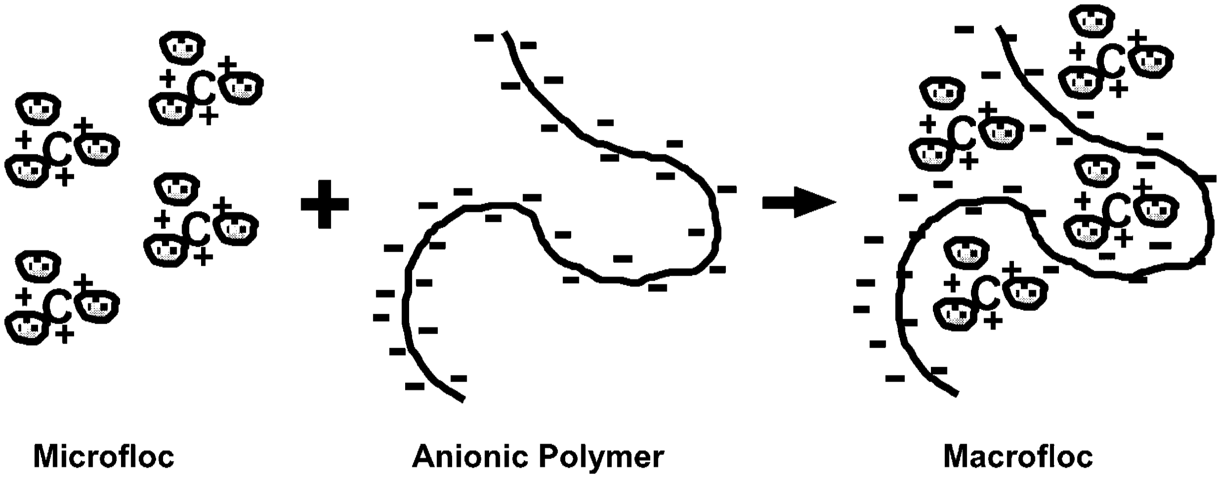
COAGULATION:

Colloidal particles (turbidity, color, bacteria, algae) with a negative surface charge are repelled by like charges until a positively charged coagulant is added, resulting in charge destabilization and the formation of microfloc.



FLOCCULATION:

The microfloc particles are gently stirred during flocculation, usually after the addition of a flocculant, typically a polymer with a negative (anionic) or a balanced negative and positive (nonionic) charge, forming large macrofloc.



Basic theory of coagulation and flocculation.

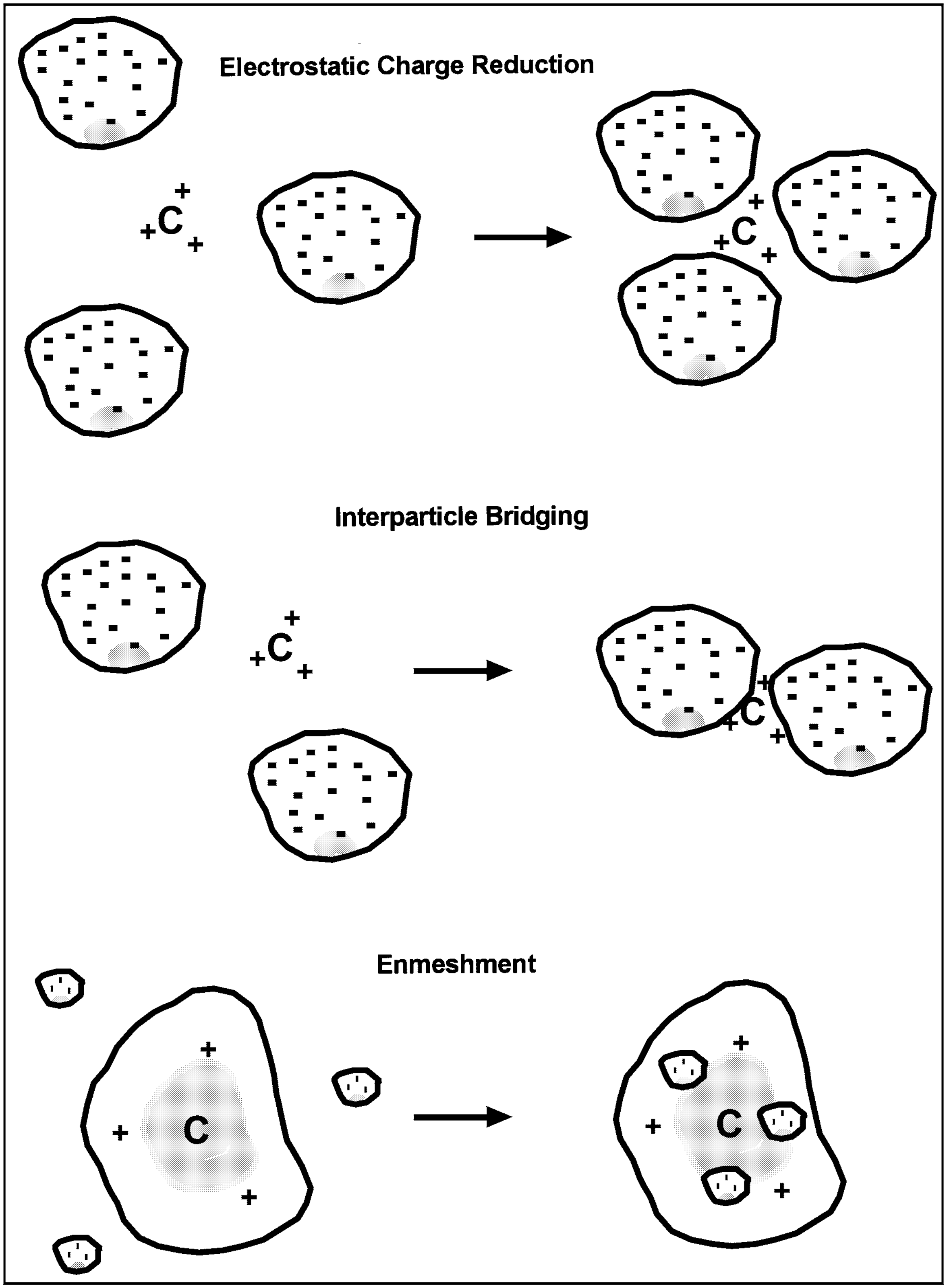
Other mechanisms of coagulation are **interparticle bridging** and **enmeshment**, also known as **sweep floc** coagulation. In interparticle bridging, the coagulant molecules serve as bridges between colloids that have charges opposite to those on the surfaces of the coagulant molecules. In enmeshment, the formation of sweep floc is achieved by converting soluble metal ions to insoluble forms by reaction with hydroxide ions in high-alkalinity water. The insoluble metal hydroxide precipitates formed from this reaction result in the formation of sweep floc, which then enmeshes, or envelops, the smaller colloidal particles.

The coagulant is usually a salt of aluminum or iron, or one of several types of synthetic polymers that will react with the negatively charged colloids to create positively charged ions on the particle surfaces. The particles will become less repellent to each other and group together to form larger particles. The first small aggregates of these particles are called **microfloc** or **pin floc**. The type of coagulant used and any **coagulant aids** selected will depend on characteristics of the water source, such as pH, temperature, and alkalinity.

Primary Coagulants

Primary coagulants are used to destabilize the suspended particles. Common coagulant chemicals are metallic salts and polymers. The most commonly used metallic salts include **alum**, or aluminum sulfate ($Al_2[SO_4]_3$), ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2[SO_4]_3$), ferrous sulfate ($FeSO_4$), and sodium aluminate ($Na_2Al_2O_4$). Although uncommon, the oxidant potassium permanganate ($KMnO_4$) may be used to form insoluble particles; this is practiced at the University of Alaska Fairbanks to enhance iron removal.

Alum is the most commonly used coagulant, but iron salts may be more appropriate for some applications because they are effective over a broader pH range than alum. For example, in the treatment of soft, colored water, color removal is best obtained at a low pH and iron salts may be the preferred coagulants. The Ship Creek Water Treatment Facility uses ferric sulfate as a primary coagulant. Sodium aluminate may be used as a primary coagulant with ferric chloride as the coagulant aid, or may be used with alum to improve coagulation. The long string-like molecules of synthetic polymers can help form very large floc particles when thoroughly mixed into the water. The many positive charges on cationic polymers provide excellent charge destabilization of negatively charged colloidal particles. Aluminum polymers, such as



Coagulation mechanisms.

polyaluminum chloride (PACl) and blends of PACl and cationic polymers, are also gaining acceptance as coagulants.

Alum

Because alum contains aluminum as a **trivalent** ion (Al^{3+}), it has more positive charges than a coagulant containing **divalent** or **monovalent** ions. Alum is therefore quite effective at destabilizing the negative charges on colloidal particles. When alum is added to turbid water, it reacts with the natural alkalinity in the water to form aluminum hydroxide by the following chemical reaction:

$$Al_2(SO_4)_3 + 3Ca(HCO_3)_2 = 2Al(OH)_3 + 3CaSO_4 + 6CO_2$$

Aluminum hydroxide is the sticky floc material to which the particulate matter in the water will adhere. The equation above predicts that each milligram per liter (mg/L) of alum will consume approximately 0.5 mg/L of alkalinity (as $CaCO_3$). If the water does not contain sufficient **alkalinity** to react with the alum and buffer the pH, floc formation will be inhibited. In such cases, it is necessary to raise the pH and the alkalinity of the water by adding lime, soda ash, caustic soda, or sodium bicarbonate. Sodium aluminate ($Na_2Al_2O_4$) also can be used with alum to improve coagulation. If floc does not form completely because of insufficient alkalinity or less than an optimal pH value (between 5.5 and 8.5), it could form later in the system. This could cause customer dissatisfaction and a build-up of sediment in the distribution system.

It is important to note that one by-product of the above reaction is CO_2, carbon dioxide, which may result in the formation of gas bubbles in the floc, giving the floc unwanted buoyancy. Aeration can be used to release the CO_2 gas after coagulation to overcome this problem. This situation is particularly prevalent when cold water is being treated and warms up during treatment.

A similar process results from the use of ferric sulfate as the coagulant. Ferric sulfate has the advantage of being effective at a broader range of pH, but has the disadvantage of being more corrosive and more difficult to store and handle than alum.

Coagulant Aids

The purpose of coagulant aids, or secondary coagulants, is to add density and strength to the floc. The different types of coagulant aids are **polyelectrolytes**, alkalinity enhancers, weighting agents, and activated silica.

Polyelectrolytes

The polyelectrolytes, or **polymers**, are also referred to as **flocculants** because they assist in forming larger and heavier pieces of floc. Whereas cationic polymers are generally used as primary coagulants because of their charge-destabilization abilities, the polymers used as coagulant aids are generally anionic or nonionic. This is because these polymers are effective at bridging between particles to build bigger floc.

Chemicals That Increase Alkalinity

As noted above, some coagulant aids increase the alkalinity of the water to augment the reactions that form sticky metal hydroxides. These coagulant aids include the following:

COAGULANT AIDS THAT INCREASE ALKALINITY		
Common Name	Chemical Name	Chemical Formula
lime	calcium hydroxide	$Ca[OH]_2$
soda ash	sodium carbonate	Na_2CO_3
caustic soda	sodium hydroxide	$NaOH$
sodium bicarbonate	same	$NaHCO_3$

Weighting Agents

Weighting agents are added to the water to form additional particles to encourage floc formation. These additives are generally used in water that is high in color but low in turbidity and dissolved metals. This combination would otherwise form weak, slow-settling floc. Increasing the suspended particle content of the water increases the number of collisions between particles, which speeds the formation of floc. Both calcium carbonate ($CaCO_3$) and bentonite clay may be used as weighting agents.

Activated Silica

Activated silica has long been used as a coagulant aid with alum. The product actually supplied to the treatment plant is sodium silicate ($Na_2O \bullet [SiO_2]_x$). Plant personnel activate it by adding an acid such as hypochlorous acid. Activated silica may increase the rate of coagulation, reduce the necessary dosage of primary coagulant, and increase the pH range for effective coagulation. Its primary advantage is that it strengthens the floc, making it less likely to break apart during subsequent treatment processes. On the other hand, activated silica must be carefully controlled. It must be added either before or after the alum because they will react with each other and too much silica may form a gel that will clog filters.

Treatment Options for Different Combinations of Turbidity and Alkalinity

Different combinations of turbidity and alkalinity in water call for different approaches to coagulation treatment. In Alaska, seasonal surface-water changes may cause high-turbidity, low-alkalinity water in the spring and summer, and low-turbidity, high-alkalinity water in winter. Possible treatment options for different combinations of turbidity and alkalinity are shown in the table below.

POSSIBLE TREATMENT OPTIONS FOR DIFFERENT COMBINATIONS OF TURBIDITY AND ALKALINITY IN WATER

Turbidity	Alkalinity	Treatment Options
High	Low	Easiest system to treat; only optimal coagulant dosage must be determined.
High	High	Higher coagulant dosage necessary, or alkalinity may be reduced by washing and lower dose of coagulant used at a lower pH.
Low	High	High coagulant dosage or use of coagulant aid to increase colloid concentration and rate of interparticle contacts
Low	Low	Most difficult system to treat; metal hydroxide formation is inhibited, as is rate of interparticle contacts. Use high coagulant dosage, coagulant aids, and increase alkalinity.

Rapid Mixing

When the coagulant is first added to the water, it must be **rapid** or **flash mixed** to ensure that the chemicals are thoroughly distributed into the water. Violent agitation is critical for maximizing the number of collisions between particles and for complete coagulant reaction, which is a chemical process. Treatment plants may be equipped with mechanical mixers that can be set at the desired speed to optimize mixing, or in-line mixers may be installed just after the point of coagulant addition. Several types of rapid-mix equipment are available, including mechanical mixers, static mixers, pumps and conduits, and baffled chambers.

Mechanical Mixers

Mechanical mixers are popular because of their control features. A mechanical mixer is usually placed inside a small chamber or tank that generally has a short **detention time**. These mixers may be equipped with propellers, impellers, or turbines, and may have either single or multiple blades. The mixing energy may be automatically controlled or manually adjusted. Alternatively, mechanical mixers may be installed inside a pipeline, with the coagulant added just before entry into the flocculator. In-line mixers allow for increased control by the operator. The point at which coagulant is added is important, to prevent floc formation and settling within the piping system. The University of Alaska Fairbanks water treatment plant uses in-line mixing for the addition of its coagulant polymer.

Static Mixers

Static mixers have no moving parts; fixed sloping vanes within the housing, which is installed directly in the piping, provide turbulence as the water flows through. Although static mixers are economical to install and operate, head loss through the device is considerable. Moreover, because mixing efficiency is dependent on the flow rate, the mixing energy cannot be adjusted by the operator.

Pumps and Conduits

Pumps and conduits may be installed in the pipeline between the coagulant injection point and the flocculator. The turbulence in such a system is provided by the speed of the pump. If this is adequate for proper rapid mixing, this alternative may be economical and advantageous in that it does not cause system head loss. However, it may be difficult to adjust the operation to suit changing treatment needs, and coagulants may corrode the pump.

Baffled Chambers

Baffled chambers are equipped with barriers that extend alternately from the top and bottom of the chamber. These baffles provide turbulence to the water as it flows over and under them. As with static mixers, the disadvantage to baffled chambers is that the turbulence is determined by the rate of flow, which generally is difficult to control.

FLOCCULATION

Solids that are coagulated and precipitated in the coagulation and rapid-mix treatment step often are still too small for effective removal. Consequently, after coagulation, the water is transferred to a **flocculator** in which the water is slowly stirred with paddles to maximize contact of the floc particles. Sometimes flocculants are added just before the water enters the flocculator. Unlike coagulation, flocculation is a physical process that slowly builds a more settleable and filterable floc. This physical process must be done slowly and gently, because the particles are delicate and easily broken up. For direct filtration, a small dense floc is required; this type of floc is formed with higher energy mixing. If settling is practical before filtration, a larger floc is required, so a lower mixing energy is applied in the flocculator. The resulting larger and heavier gelatinous aggregates are called **macrofloc**, and have a snowflake-like appearance. The flocculation process takes longer than the fast flash mixing of coagulation. Rather than a matter of seconds, flocculation tanks have detention times of 5 to 30 minutes. Several factors affect floc development, including basin detention time, mixing speed, proper dosing and mixing speed during coagulation, and water characteristics such as pH, alkalinity, temperature, and turbidity. From the flocculators the water moves into the sedimentation basins or **clarifiers**.

Conventional Flocculation Basins

Conventional **flocculation basins** are available with different features, such as horizontal or vertical paddle wheels, turbines, or propellers. Commonly two or more flocculation basins are set up in series, with each one providing less agitation than the previous one. This process is called tapered energy mixing. It is recommended to always have two sets of basins so that if one is taken out of service for cleaning or maintenance the other can be used to maintain production. The University of Alaska Fairbanks water treatment plant uses two parallel sets, each of which consists of two horizontal paddle-wheel basins. The first two basins have five paddles each, followed by a second set of tanks with four paddles each for more gentle mixing.

Calculate the detention time for water flowing through a flocculation basin that is 8 feet wide, 10 feet long, and 6 feet deep, with a pumping rate of 180 gallons per minute (gpm).

The basic equation is:
detention time (t) = volume of basin ÷ flow rate

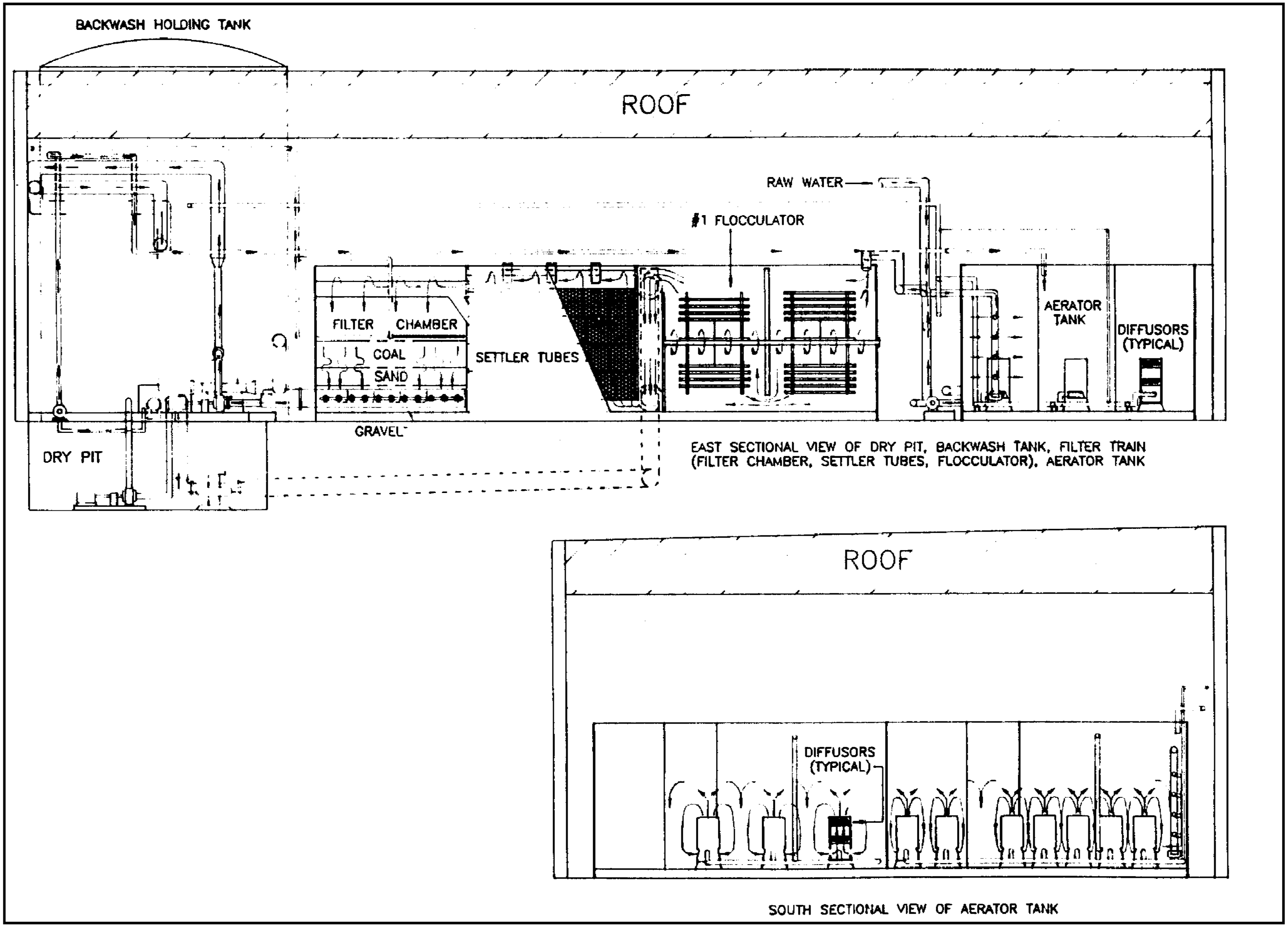
So, detention time, $t = (8 \times 10 \times 6)\ ft^3 \times 7.48\ gal/ft^3 \div 180\ gpm$

$t = 20$ minutes

Solids-Contact Basins

Solids-contact basins, also known as **upflow clarifiers**, combine the processes of coagulation, flocculation, and upflow clarification in one basin. The solids-contact process works by suspending a sludge blanket, or slurry, in the clarifier. The water enters through an influent line in the bottom of the clarifier, and the particles in the water coagulate and flocculate as the water flows upward through the slurry. In this way, the sludge blanket acts as a coagulant aid, helping to trap particles, and provide a substance to which particles may adhere. Water passes through the sludge blanket and the clear effluent flows over the raised baffled edges of the clarifier, known as **weirs**, into effluent **launders**, or troughs, which channel the water to the filters.

It is critical to monitor the size and the position of the sludge blanket. If it is too light it will float too high in the clarifier, possibly mixing with the effluent as it flows over the weirs. If the sludge blanket becomes too heavy it could collapse into the bottom of the tank, making it necessary to shut down the system for maintenance. Another solids-contact type of clarifier is the Microfloc® Trident® Adsorption Clarifier™, which incorporates a layer of plastic media held in place by a screen in place of a sludge blanket. Solids-contact basins are also discussed with clarifiers in Chapter 8.



Sectional view of the University of Alaska Fairbanks water treatment plant, showing one train of flocculators. The first flocculator has five paddles; the second has four to provide more gentle mixing for optimal floc growth.

APPROVAL OF ADDITIVES TO POTABLE WATER

Many water treatment processes involve the addition of chemicals to the water. All chemicals used during water treatment must be approved by a Federal or State regulatory agency as safe for addition to potable water. Article 1 of the Alaska Drinking Water Regulations (Title 18 of the Alaska Administrative Code, Chapter 80) specifies that "direct additives for water treatment and materials in contact with potable water may be used on a public water system only if they are approved for that use by the National Sanitation Foundation (NSF), Underwriter Laboratories, or an equivalent organization that evaluates products using NSF Standards 60 and 61." NSF Standard 60 applies to chemical additives, whereas Standard 61 applies to materials that come in contact with water, such as coatings, construction materials, and system components used in processing and distributing potable water.

NSF Standard 60 establishes testing procedures for each type of chemical, sets limits on the percentage of each chemical that can safely be added to drinking water, and places limitations on harmful chemical impurities. Manufacturers of chemicals intended for addition to public drinking water supplies must submit samples to NSF for testing and approval. Water treatment plant personnel must ensure that labels on chemical containers indicate that the chemical is approved and that supplier instructions are followed.

CHEMICAL STORAGE AND FEED EQUIPMENT

Coagulant chemicals may be in the form of dry granules or powders or may be in liquid form. Chemicals should always be stored in a dry place, at moderate temperatures. Dry chemicals usually are supplied in bags or drums. Storing chemicals in bags on pallets allows air to circulate around the bags and eliminates the exposure of chemicals to moisture, which can cause them to harden and cake. Chemicals in liquid form are preferred by many treatment plant operators because they are easier to store and handle, produce less dirt and dust in the plant, and generally pose fewer safety hazards than dry chemicals. It is most efficient to store chemicals above the chemical feed equipment feeding the coagulation and flocculation basins.

It is important to note that polymers in dilute solution have a limited shelf life and should be used as soon as possible after mixing. Many polymer stock solutions begin to lose strength within a few days of mixing. Polymer breakdown may involve reactions with dust or other airborne or waterborne contaminants, breaking of polymer chains caused by heat, mixing, light, and oxidants, and biodegradation.

Depending on the chemical and system requirements, different types of facilities are available on the market for the addition of chemicals. The two basic categories are dry feeders and solution feeders; decant tanks also may be used to provide consistent solution concentrations without introducing undissolved precipitates from the bottom of storage containers.

Dry Feeders

Dry chemical feeders may be either volumetric or gravimetric. Volumetric feeders measure the chemical by volume per unit time. Gravimetric feeders measure the chemical by weight. Volumetric feeders are generally less expensive but also less accurate than gravimetric feeders. The feeder mechanism may be a rotating or oscillating disk, a rotary gate, a belt, or a screw. The volume or weight of chemical to be added can be adjusted manually or automatically according to the water flow rate, turbidity, zeta potential, or signal from a streaming current meter.

Before dry chemicals can be added to the water treatment system, they must be dissolved completely into solution in a mixing tank. Many coagulant chemicals are not easily dissolved, so it is important to provide good agitation and sufficient time in the mixer for the solution to form as the dry chemical is added. In some cases, it may be necessary to soften the feed water to minimize the formation of unwanted precipitates. The solution can then be metered into the coagulation treatment process.

Calculate the chemical feed rate in pounds per day if the desired dosage of coagulant chemical is 80 mg/L and the flow rate is 1.25 MGD.

(Try varying the percentages of active ingredient in the chemical and the chemical purity to see the effect of these parameters on the result.)

The basic chemical feed rate formula is:
Chemical Feed Rate (lbs/day) = Dosage (mg/L) x Flow Rate (MGD) x 8.34 lbs/gal

Chemical Feed Rate = 80 mg/L x 1.25 MGD x 8.34 lbs/gal = **834 lbs/day**

Solution Feeders

Solution feeders are used to add liquid coagulant chemicals. The feeder may draw the liquid chemical directly from the storage container or from a tank, sometimes referred to as a day tank, in which the chemical is initially diluted. The most common type of solution feeder is a metering pump that delivers a precise volume of solution with each stroke or rotation of the pumping mechanism. This pumping rate can be adjusted manually or automatically controlled by a pre-programmed control signal.

Chemical feed stations at the Barrow Utilities and Electric Cooperative, Inc., water treatment plant.

OPERATIONAL CONSIDERATIONS

Many different factors affect the processes of coagulation and flocculation. Plant operating factors that may decrease the efficiency of floc formation include inadequate flash mixing, improper flocculation mixing, and inadequate flocculator detention time. Characteristics of the water being treated are also important to consider, such as water temperature, pH and alkalinity, and variations in color and turbidity.

Temperature

Low water temperatures can cause problems in all water treatment processes. A low water temperature may inhibit the coagulation reaction, making it necessary to use more chemicals to maintain consistent results. Because cold water may slow the growth of healthy floc in the flocculator, the flocculator detention time should be adjusted according to the temperature of the water.

TEMPERATURE AND FLOCCULATOR DETENTION TIME GUIDELINES

Temperature, °C	Detention time factor (20 °C = 1)
0	1.35
5	1.25
10	1.15
15	1.07
20	1.00
25	0.95
30	0.90

pH and Alkalinity

As discussed in the section on coagulation, pH and alkalinity are important controlling factors in chemical coagulant reactions. Of these two, pH is the most important variable. The coagulation process must be operated within the correct pH range for the coagulant being used, to optimize the process and minimize the dosage. The alkalinity is important in buffering the pH to make it more stable. If the pH and alkalinity of the water are too low, an alkaline coagulant aid may be necessary, such as lime or soda ash.

Variable Color and Turbidity

Variations in the color and turbidity of the water being treated may be caused by seasonal changes in precipitation and runoff. These can be especially extreme in surface water sources during the spring snowmelt period and intense rainfall events. Color in water is caused by organic compounds that may react with the coagulant chemicals, making coagulation more difficult. Oxidation and adsorption may be used to pretreat the water to remove some of the organics before coagulation. In general, increased color and turbidity in the water will necessitate the use of more coagulant chemicals.

Although turbidity removal is the goal of coagulation, insufficient turbidity may prevent adequate particle collisions for optimal floc formation. If the water is deficient in turbidity, a weighting agent such as bentonite clay may be added.

PROCESS CONTROL MONITORING

Physical and chemical process control is a critical component of water treatment. Different types of tests may be used to assess coagulation and flocculation performance. One of the most valuable process control tools is the **jar test**. Jar testing is used to simulate the treatment process on a small scale in the laboratory. In addition, turbidimeters may be installed in line for continuous monitoring, or turbidity may be checked by grab samples every four hours or so. Particle counters can be used to check the number and size of suspended particles in the effluent, and streaming current monitors can measure the ionic charge of the water.

Jar Testing

The jar test can be used as the basic tool to identify the best treatment chemistry and to model the treatment plant operation on a small scale. Jar testing allows the plant operator to determine the best chemical dosage, which is important because either over- or under-dosing will result in less than optimal results. In a single jar, the coagulation, flocculation, and sedimentation steps can readily be simulated. Jar testing can be done rapidly and with a wide range of variables with respect to chemicals used, reaction times, mixing speeds, and sequence of chemical addition. It allows the operator to try many variations on the treatment process quickly, without actually disrupting the plant. The major elements of the jar test are explained below in simple steps.

Stock Solutions

Stock solutions of the chemicals to be used in the test should be made up according to the manufacturer's recommended strengths. If information is not readily available, the general mixtures listed in the table below can be used. The mixtures are expressed in 1-percent concentrations throughout the discussion.

RECOMMENDED STOCK SOLUTION MIXTURES

Type of Chemical	Form	Stock Solution Mixture	mg/L per ml added to a 1,000-ml sample*
Inorganic Coagulants (including $KMnO_4$)	Dry powders	1.0% (1.0 g in 100 ml)	10.0
		0.1% (0.1 g in 100 ml)	1.0
Polymers	Liquids	1.0% (1.0 ml in 99 ml)	10.0
	Emulsions	0.1% (0.1 ml in 99.9 ml)	1.0
	Dry Powder	0.05% (0.05 g in 100 ml)	0.5

mg/L, milligrams per liter; ml, milliliter; g, gram
*The standard jar test sample is 1,000 ml (one liter). Each ml of a 1.0% solution will add 10 mg/L to the 1,000-ml sample.

Powdered forms of chemicals should be weighed carefully on an analytical balance and mixed with the appropriate amount of water. Dry powder inorganic coagulants such as alum or ferric sulfate can be added to a beaker containing the correct amount of water and stirred until dissolved. No special mixing time is required.

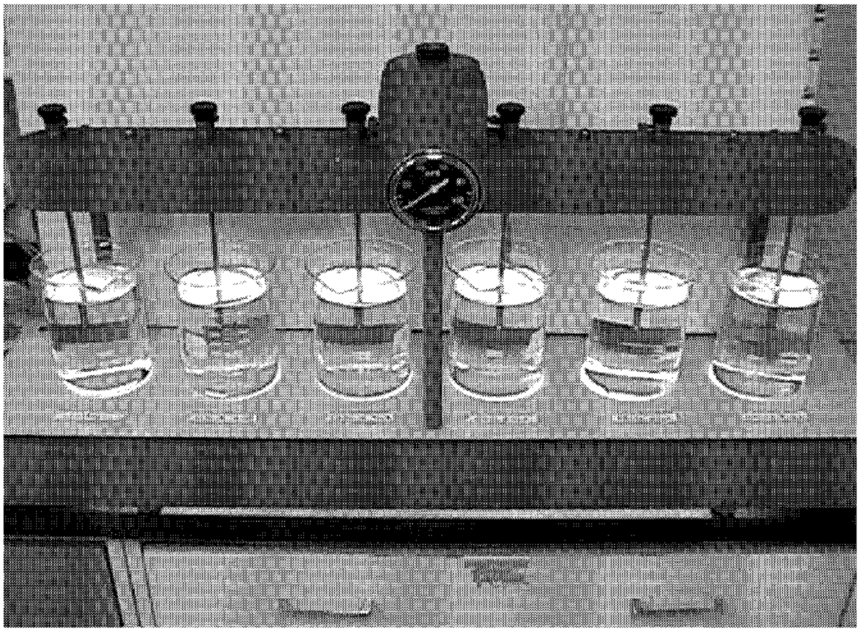
Liquids and emulsions can be measured with a pipet or a syringe directly into a volumetric flask, and the appropriate amount of water added to bring the solution to the correct dilution. The mixture should then be stirred gently for 10 to 30 minutes to allow proper activation and full extension of the polymer molecules.

Dry polymers should be added slowly to water mixing on a magnetic stirrer or with a laboratory stirrer with a propeller blade. Add the powder directly to the stirring vortex of the water very slowly, with a salt-shaker type of motion, to prevent the formation of "fish eyes," or globules of unwetted polymer. A constant gentle stirring for 10 to 30 minutes is required to fully activate and extend the polymer molecules.

Stock solutions should be kept in tightly sealed bottles (plastic works well) and labeled with the following information: chemical, percent strength, date prepared, and analyst's initials. Prepare fresh stock solutions of polymers every few days for best results. Some polymers will still work well up to a week after the stock solution is prepared, but will usually work better if prepared fresh.

Jar-Testing Apparatus

Several different types of jar test mixers are available on the market. Most use either a series of paddles mounted on a stand, allowing for 4 to 6 one-liter samples to be stirred at once, or a spinning magnetic bar on a base that will hold one or more beakers. The mixing dynamics in a small glass beaker are probably better than those in the plant under full-scale treatment. In general, if chemical addition is being tested for an existing plant, match the treatment plant flocculator detention times and mixing speeds as closely as possible in the jar test. Some stirrers have a light under the platform. Although this can improve the visibility of the floc formation, heat from the light will sometimes cause gas bubbles to form in the floc, causing the floc to float during the test. Ideally, the temperature of the water should be maintained as close as possible to the actual plant water temperature; for this reason jar tests should be done on site and as quickly as possible.



An example of a variable-speed, multiple-sample jar stirrer, with a light table to illuminate the samples.

Test Procedure

Coagulants should be flash mixed for 10 to 60 seconds at high speed, then gently stirred for several minutes to match the flocculator **detention time**. Many coagulants will work better and at lower doses if good initial flash mixing and longer slow mix cycles are used. Flocculants should be added after the coagulants are fully reacted, and a second flash mix (more gentle than the coagulant flash mix) applied to disperse the polymer throughout the microfloc formed from the coagulant addition. A slower final mix for several minutes or up to the full detention time of the flocculator should follow the second flash mix. An example sequence of mix speeds and times on a paddle stirrer apparatus for the two-step coagulant and flocculant additions is:

- Add coagulant, stir for 1 minute at 100 revolutions per minute (rpm), then slow to 50 to 60 rpm.
- Add the flocculant, stir for 1 minute at 60 rpm, then slow mix at 30 rpm for 10 minutes or up to the full detention time of the flocculator.

Chemicals can be added with pipets using pipet bulbs for filling or with syringes. If the dosages are in tenths of milliliters, use a 1.0-milliliter (ml) pipet. If the dosage is in milliliters, a 5- or 10-ml pipet or syringe is preferable.

After the reaction is complete, turn off the stirrer and observe the quality of the floc (size, completeness of formation), and the settling rate. A somewhat subjective rating scale can be used to rank a series of jar tests and to record the results of the test. An example of a rating scale is shown below:

Floc Quality (size)		Floc Settleability	
None	No visible floc formation	None	No discernible settling
Fine	Floc barely visible to the naked eye	Slow	More than one minute to settle (< 1 cm/minute)
Small	Floc less than 1 mm in diameter	Medium	90% settles in < one minute (> 1 cm/minute)
Medium	Floc approximately 1 to 2 mm in diameter	Fast	90% settles in < 30 seconds (> 20 cm/minute)
Large	Floc greater than 2 mm in diameter	Very Fast	90% settles in < 10 - 15 seconds (> 40 cm/minute)
Very Large	Floc greater than 5 mm in diameter		

To determine the **supernatant** quality, a turbidity test is usually run on the settled supernatant from each beaker. The most accurate measure of turbidity is from a filtered sample. Filter funnels or syringe filters equipped with a filter of appropriate porosity will work for this. Standard suspended solids filters (Whatman® GF-C, 934AH, or equivalent) with a porosity of 1-2 microns work well. Turbidity and pH are then measured and recorded. If color removal or another parameter such as iron or manganese is of concern, that can be tested as well.

For direct filtration tests, the samples can be drawn out at the end of the flocculation detention time directly from the beakers while stirring. A syringe filter works particularly well for this. The filtrate is then tested as discussed above.

Successful comparisons between jar tests, regardless of the rating system used, require consistency. It is best to use an actual test method such as turbidity to verify and compare the final product quality because the eye has a limited capacity to see subtle but important differences at low levels.

The example "Jar Test Log Form" is for recording the results of a jar test on a single magnetic stirrer where increasing amounts of coagulant (alum) is added to a 1-liter sample. In the first test, alum was dosed in increasing amounts until the reaction was nearly complete. The

JAR TEST LOG FORM

Sample: Raw Lake Water, 0830					Analyst: MRP							
Jar Test Number	Coagulant (% Stock)	Total Dose		Flocculant (% Stock)	Total Dose		Floc Quality	Settling Rate	Supernatant Quality			
		mls	mg/L		mls	mg/L			Turbidity (NTU)	pH	Temp (°C)	Notes
(Alum requirement test)												
	Raw water						None		22	7.7	4.0	
1	Alum (1%)	1	10				None			7.5	4.5	
		2	20				Fine			7.3	4.6	
		3	30				Small			7.1	4.7	
		4	40				Small			7.0	4.8	
		5	50				Small			6.9	4.9	
		6	60				Medium			6.7	5.0	
		7	70	727 (.05%)	0.5	0.25	Large	Fast	5.0	6.5	5.2	good reaction; supernatant only fair
2	Alum (1%)	8	80	727 (.05%)	1	0.5	Very Large	Very Fast	0.30	6.3	4.7	secondary polymer really builds floc
(Secondary flocculant selection test)												
3	Alum (1%)	8	80	LT27 (.05%)	1	0.5	Very Large	Very Fast	0.20	6.3	4.6	Similar to above test #2
	Alum (1%)	8	80	LT25 (.05%)	1	0.5	Large	Fast	0.45	6.3	4.6	
	Alum (1%)	8	80	LT26 (.05%)	1	0.5	Medium	Fast	0.05	6.3	4.7	smaller floc; better clarity
	Alum (1%)	8	80	7766 (.1%)	0.5	0.5	Large	Fast	0.15	6.3	4.7	emulsion polymer
	Alum (1%)	8	80	LT20 (.05%)	1	0.5	Large	Fast	0.10	6.3	4.8	
	Alum (1%)	8	80	8181 (.05%)	1	0.5	Very Large	Very Fast	0.20	6.3	4.9	largest floc of all

secondary flocculant, a high molecular weight anionic polymer, was then added and the test completed. After the turbidity check indicated that further improvement was possible, a second test was run at a slightly higher dose of both the coagulant and flocculant with excellent results.

This example form can be used to record the results of a series of tests run simultaneously on a multiple-sample jar stirrer. In tests 3-8, several flocculants at a constant dosage are compared to determine the most effective one, using the alum dosage of 80 mg/L determined in the first two tests. The multiple stirrer can also be used to compare varying polymer doses of a single product using a constant amount of coagulant (alum in this case). Possible variations on the types of chemicals used and their sequence of addition, stirring speeds, and mixing times are limited only by the imagination of the operator. The jar tests can be used to optimize an existing plant performance by testing new chemicals on a small scale before trying them in the plant, or they can be used to design or redesign a process.

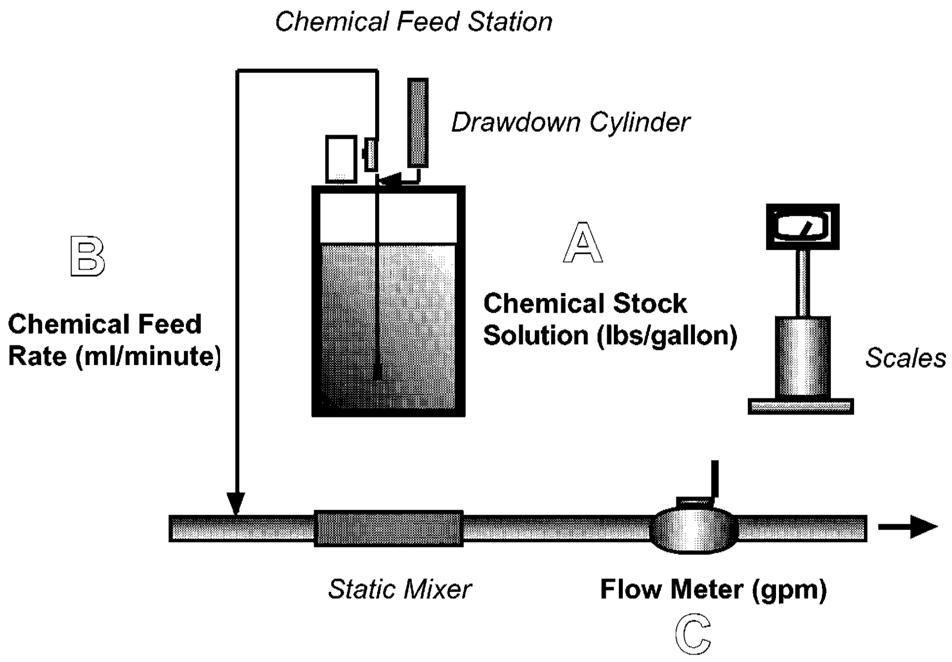
It is important to record observations from the jar tests. Problems such as gas bubble formation and floating floc, incomplete polymer reaction, and other anomalies noted in the tests may be valuable information later if full-scale testing in the treatment plant does not work as well as desired.

The test parameters selected to monitor the performance of the jar test should be those that will be used in the full-scale monitoring of the treatment plant. Turbidity and pH are used in the example and are rapid, easy to use field parameters that will help to verify that the jar test and plant operation are working similarly and that the quality of the treatment process is as it should be. It is possible to construct a pH-to-alum dosage curve from a jar test, and to verify the correctness of the plant dosage by simply monitoring the pH of the flocculator immediately after the chemical addition.

Translation to Full-Scale Treatment

Once the jar test series has been completed and an optimal dosage of coagulant and secondary flocculant has been determined, the results need to be translated from the 1-liter sample to the full-scale treatment plant. A simplified method of computing all of the variables of scale-up is presented in the dosage formula. The formula uses real-world methods of measurement in the treatment plant and incorporates them into a single mathematical equation that can be used to calculate stock solution strengths, chemical feed pump settings, and determine milligram-per-liter doses in an operating system. The jar test results, in milligrams per liter, that produced the desired effect can be plugged directly into the dosage formula.

The optimal dosage of 80 mg/L determined by the example above can be translated into a chemical feed pump setting using the dosage formula as follows:



$$\frac{A \times B \times 31.7}{C} = \text{Applied Dosage (mg/L)}$$

Where:

A = Stock Solution Strength (lbs/gallon)
B = Chemical Feed Rate (ml/minute)
C = Flow Rate of Water (gpm)

Using the Dosage Formula:

To determine dosage in milligrams per liter: $$\frac{\text{lb/gal} \times \text{ml/min} \times 31.7}{\text{gpm}} = \text{mg/L}$$

To find stock solution mixture: $$\frac{\text{mg/L} \times \text{gpm}}{\text{ml/min} \times 31.7} = \text{lb/gal}$$

To find chemical feed pump rate: $$\frac{\text{mg/L} \times \text{gpm}}{\text{lb/gal} \times 31.7} = \text{ml/min}$$

Calculate the chemical feed pump rate required for the following conditions:

Given: Plant flow rate = 100 gpm (read from flow meter)

Alum stock solution mix = 1.0 lb/gal (from operations log)

Desired alum dose = 80 mg/L (from jar test)

Formula: $$\frac{\text{Dosage (mg/L)} \times \text{Plant Flow Rate (gpm)}}{\text{Stock Solution (lb/gal)} \times 31.7} = \text{Feed Pump Rate (ml/min)}$$

$$= \frac{80 \text{ mg/L} \times 100 \text{ gpm}}{1.0 \text{ lb/gal} \times 31.7} = 252 \text{ ml/min}$$

The operator can then adjust the chemical feed pump rate to 252 ml/min, check the pump output by drawdown in a graduated cylinder, and verify the flocculator pH as a final quality assurance check. The complete process from jar test to full-scale operation is thus accomplished.

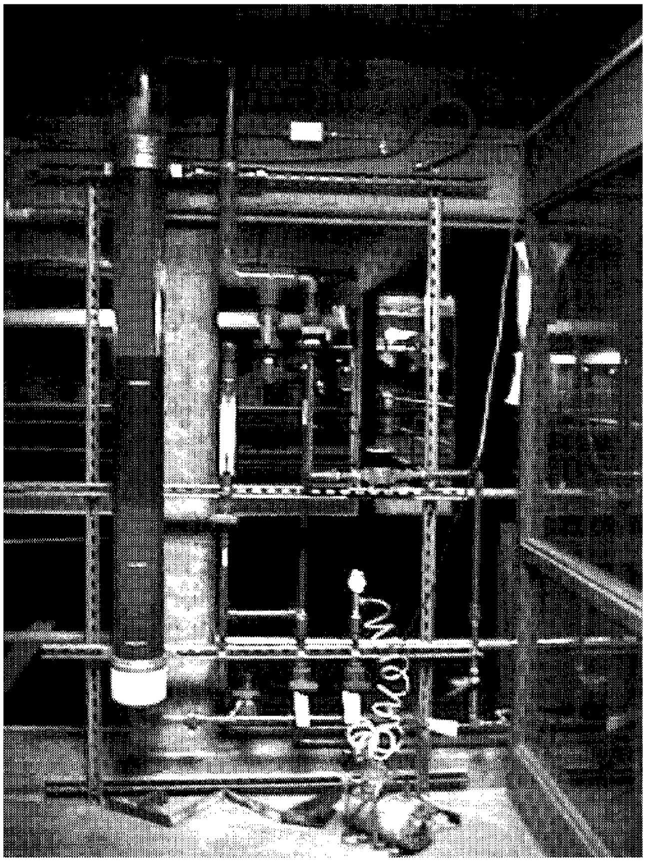
Turbidity Tests

To ensure that sufficient turbidity is removed by coagulation and flocculation to avoid excess loading of filters with suspended solids, the turbidity of the treated water from each filter should be carefully monitored. Turbidity may be measured in jar-test samples, or may be measured by an in-line turbidimeter, which measures the turbidity in nephelometric turbidity units. The turbidity of the raw water and the effluent from the sedimentation basins or clarifier should also be measured to compare with the results predicted by the jar tests. Turbidity should measure 10 NTU or less if coagulation and flocculation are effective. Visible floc carryover from the sedimentation basins to the filters is clear evidence that turbidity is excessive and that filter sealing may become a problem.

Chemical Tests

The raw water and the effluent from the sedimentation basins or clarifier should be monitored for the substances targeted for removal by coagulation and flocculation. Monitoring parameters may include color, iron and manganese, total organic carbon, total dissolved solids, or other substances that are being treated in the raw water.

Filterability Tests

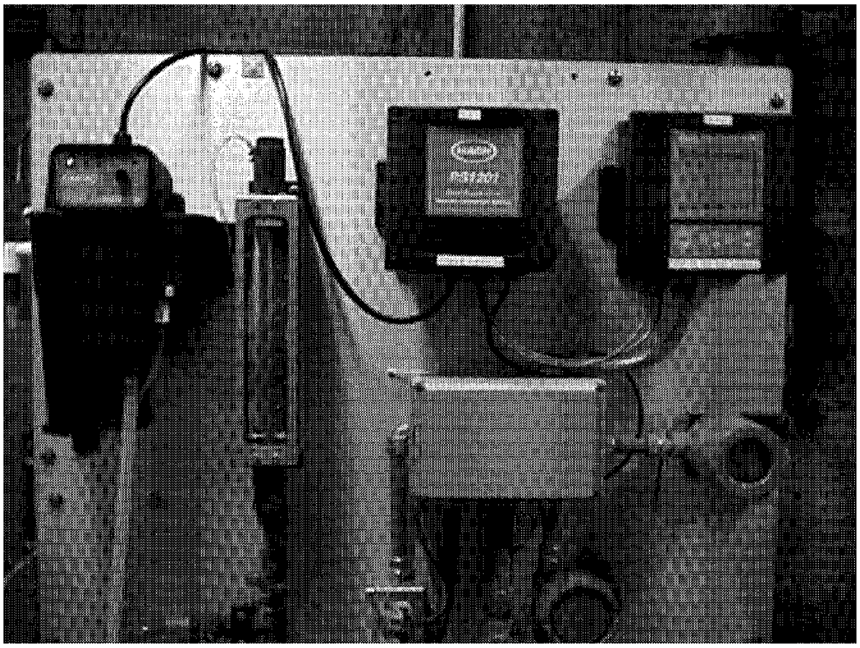


Pilot filter column, Ship Creek Water Treatment Facility, Anchorage, Alaska.

Another tool for determining whether coagulated water will allow optimal filter functioning is the filterability test. A filterability test is a qualitative assessment of the amount of flocculated water that can be filtered in a particular amount of time. The test is done by passing the water, before the sedimentation process, through a small tube called a **pilot filter**. The pilot filter contains the same filter media as the plant filters and is equipped with an in-line continuously recording turbidimeter. A correlation factor can be applied to the length of time it takes before turbidity breaks through to determine how well the plant filters will operate at the same coagulant dosage. The test is done in the actual treatment system, rather than as a simulation, and can occur in a few minutes as opposed to the two or more hours of detention time it would take to pass the water through the full-scale sedimentation and filtration processes. Thus, the test can be directly correlated to the actual type and dosage of coagulant being used, and process adjustments can be made immediately to accommodate changes in raw water quality.

Particle Counters

Particle counters are increasingly being used in surface-water treatment plants because they are effective at measuring the concentrations of particles in the size range of *Cryptosporidium* and *Giardia lamblia* cysts. The concentrations of these cysts that are considered unacceptable in drinking water are below the limits of detection for turbidity tests. In addition, turbidity tests cannot measure particle size. In general, particle counters operate by passing a fine stream of water past a laser or light source, and measuring the light that is blocked or diffused with a photo diode. The signal must then be interpreted by a computer. The use of particle counters requires qualified operators to calibrate and maintain the equipment and to interpret the computer-generated results of the tests.



Filter monitoring system at the Ship Creek Water Treatment Facility, Anchorage, Alaska. From left: one filter's on-line turbidimeter, flow monitor, and particle counter, and a Hach® Aquatrend® Interface datalogger that records information from the turbidimeters and particle counters for all four of the treatment plant's filters.

Streaming Current Monitors

A streaming current monitor measures the net ionic and colloidal surface charge of a continuous stream of coagulated water. This measurement is similar to and can serve as a proxy for measurement of zeta potential (which can be measured with a zetameter). The readings produced by streaming current monitors will vary with pH, so this must be considered in interpreting the results. An important advantage is that if the pH of the plant source water remains constant, a streaming current monitor can automatically control the coagulant dosage.

Troubleshooting and Special Problems

Jar test performance may not precisely emulate the plant performance for several reasons. It is critical that the jar test and the plant be similar in terms of chemical addition, mixing, settling time, and such variables as temperature and pH. In many cases, the actual performance of the plant exceeds that predicted by the jar test. Sometimes this is due to the dynamic nature of filtration following flocculation and coagulation. Floc build-up in the filter media may remove more turbidity or color than can be simulated with a paper or fiberglass filter. Where plant performance is not as good as the jar test, the problem with scale-up may be caused by some hidden mechanical problem in the plant that can be determined by a bit of sleuthing. Many operators are proficient at the art form of troubleshooting. The following troubleshooting tips deal with problems encountered in both scale-up of jar test results and with the routine operation of the plant.

Chemical Pump Problems

Nearly all chemical pumps have a linear dial control that supposedly increases the output proportionally to the numbers on the dial. Unfortunately, as chemical pumps age, become fouled with chemicals, or are moved to an application where they must operate at a different pressure or must pump a more or less viscous chemical, their performance will vary. An operator should not rely on the dial or stroke setting alone to determine output.

Plotting a pump performance curve can help the operator visualize the pump's output under different circumstances. The performance curve is run by pumping the chemical out of or into a cylinder for one minute and recording the milliliters pumped, first at a setting of zero percent, and at each additional 10-percent increment through 100 percent. The results are plotted on a graph. The pump performance curve will vary with the viscosity of the solution and the cleanliness of the pump's feed lines, intake, discharge fittings, pump diaphragm, and liquid connections. Pump curves should be run often enough to determine whether or not the pump is performing properly. Direct measurement of the delivered chemical product in milliliters per minute is recommended when using the dosage formula. This eliminates any uncertainty with the relative output of the chemical feed system.

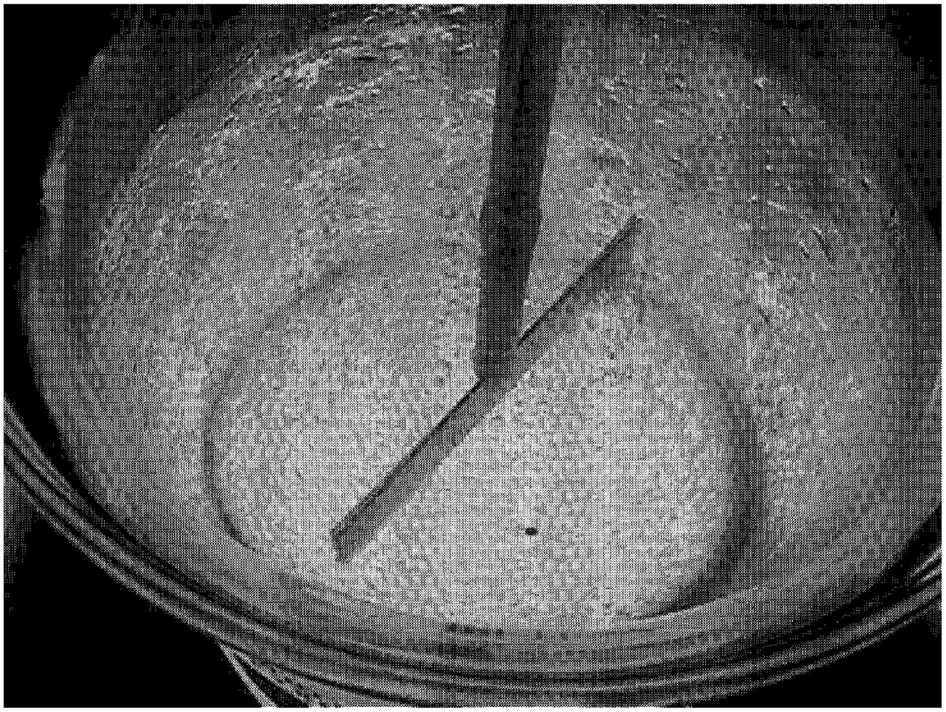
Problems with chemical feed pumps can be minimized with regular cleaning using hot water as a flush fluid. This should be done at least weekly and with sufficient volume to flush the entire run of tubing and liquid ends at least several times.

Stock Solutions

In the jar test, stock solutions are freshly prepared under very controlled conditions in small quantities. In the plant, the stock solutions often are made in batches added to an existing barrel of solution, mixing old chemicals with fresh ones. The method of addition may be by a certain number of scoops, bags, or cups of a chemical to a quantity of water added to a barrel with a scale accurate to only plus or minus 5 percent. The operator should be aware of this problem because it will affect the quality and strength of the chemical solution.

To mitigate these effects, the stock solution drum should periodically be completely run out, cleaned, and returned to service. Each drum should be calibrated for volume by either adding incremental amounts of water from a container of known volume or by calculating from the vessel dimensions. The volume addition method is the most accurate for plastic drums, which tend to bulge in the middle when full. The scoop or measuring cup used to add chemicals should also be calibrated once to ensure that it is accurate.

Water treatment plant personnel at Coffman Cove, Alaska, participating in a class on jar testing. During this course, the plant operators learned to use results of jar tests to optimize their water treatment plant process.



Floc forming during jar testing, Coffman Cove, Alaska.

SAFETY AND MANAGEMENT

Because of the chemicals used in the coagulation process and because of provisions of the Surface Water Treatment Rule that apply to conventional water treatment, safety considerations and record keeping are important aspects of the water treatment operator's job.

Safe Chemical Handling

Most dry chemicals are eye, skin, and mucous-membrane irritants. Personal protective equipment should be worn by operators when handling dry chemicals, and dry chemical feeders should be equipped with dust control devices. Spills of liquid chemicals can be slippery and should be cleaned up promptly. If dry alum and lime mix together, the chemical reaction produced can create an explosion hazard. For this reason, these chemicals should be stored so that they will not come into contact with each other. Material Safety Data Sheets should be posted in the workplace to satisfy the worker's right to know the hazards associated with any chemicals involved in the water treatment process.

Record Keeping

Continuous water-quality and operating records should be maintained, as well as records of variations in raw-water characteristics. Seasonal changes and climate fluctuations such as spring snowmelt, heavy rains, or droughts can cause extreme changes in the color and turbidity of raw water. These variations will affect the efficiency of coagulation and flocculation in the treatment plant. Past experience is the key to future success, and a complete record of plant performance is the key to optimizing and passing on that experience.

Regulations

Federal and State law regulates the types and amounts of chemicals that may be added to potable water. In addition, provisions of the Surface Water Treatment Rule and requirements for reducing disinfection by-products will require more water treatment systems to include filtration, and consequently, coagulation and flocculation, in their treatment processes. Because harmful disinfection by-products may be formed when organic matter in water reacts with disinfectant chemicals, it is important to remove those organic substances before the water passes through the disinfection process. The systems most affected are those supplied by surface water or ground water that has the potential to be contaminated by surface water.

REVIEW QUESTIONS

1. List four types of matter that may be categorized as colloidal particles:
   a. ______________________________ b. ______________________________
   c. ______________________________ d. ______________________________

2. What is zeta potential?
   ____

3. What is van der Waals force?
   ____

4. Two reasons to reduce turbidity in drinking water are:
   a. ____
   b. ____

5. What is one of the problems that organic matter in water may cause in the disinfection process?
   ____

6. What are two important categories of coagulants?
   a. ______________________________ b. ______________________________

7. Name four commonly used coagulant chemicals
   a. ______________________________ b. ______________________________
   c. ______________________________ d. ______________________________

8. Multiple choice: Coagulation is most effective at
   a. high turbidity and low alkalinity
   b. low turbidity and high alkalinity
   c. high turbidity and high alkalinity

9. What two raw water characteristics in surface water sources are especially affected by seasonal changes?
   a. ______________________________ b. ______________________________

10. What type (size) of floc forms during
    a. coagulation? ____
    b. flocculation? ____

11. What are two main types of chemical feeders?
    a. ______________________________ b. ______________________________

12. What is the most common type of solution feeder?
    ____

13. List four types of rapid-mix facilities.
    a. ______________________________ b. ______________________________
    c. ______________________________ d. ______________________________

14. What should the chemical feed rate be in pounds per day if the system required a chemical dosage of 80 mg/L at a flow rate of 1 MGD?

15. Flocculation is a ____________________ process.
    a. chemical
    b. physical
    c. biological

16. List three process control adjustments that may be made to compensate for low water temperature in coagulation and flocculation:
    a. ____
    b. ____
    c. ____

17. What four raw water characteristics can affect the performance of the coagulation and flocculation treatment process?
    a. ___________________________ b. ___________________________
    c. ___________________________ d. ___________________________

18. What are four types of process-control tests that may be used to monitor the coagulation and flocculation process?
    a. ___________________________ b. ___________________________
    c. ___________________________ d. ___________________________

19. What is a pilot filter?
    ____
    ____

20. What are the three main mechanisms by which coagulants initiate particle aggregation?
    a. ____
    b. ____
    c. ____

Chapter 8

Clarification

Chapter 8 – Clarification

INTRODUCTION

Clarification, or **sedimentation**, is the third step in conventional water treatment, after c**oagulation** and **flocculation** and before **filtration**. Clarification is also used after **lime softening** to remove the accumulated lime sludges. In sedimentation, the velocity and turbulence of the system is reduced to allow slow passage of water through a **sedimentation basin** so that suspended material will settle to the bottom of the basin.

CLARIFICATION IN CONVENTIONAL WATER TREATMENT

If large quantities of floc are produced by coagulation and flocculation, clarification will be the next treatment process. The water is transferred from the flocculator to a sedimentation basin where the large floc particles settle out under the influence of gravity. Alternatively, solids separation may proceed in a clarifier of alternative design, such as a solids-contact basin or upflow clarifier. Removal of suspended solids by clarification or sedimentation reduces the solids load on filters, allowing longer filter runs and minimizing such problems as cracking and mudball formation, and improves the efficiency of other treatment processes. However, if only small quantities of floc are produced by coagulation and flocculation, the sedimentation step may be eliminated and direct filtration used for all floc removal.

SEDIMENTATION BASINS

Sedimentation basins may be rectangular, square, or round, and are usually constructed of concrete or steel. Basins can generally be classified as either conventional rectangular or center-feed types, both of which incorporate the horizontal flow of water. Alternatively, the upward flow of water from the bottom of an upflow-type clarifier may allow the floc to collect on a floating media, which may be a blanket of floc, or a layer of plastic held in place by a screen.

Sedimentation basins should be designed to create conditions in which the water flows very slowly through the basin, with minimized turbulence at the entry and exit points and with as little interruption of the flow as possible. To create these quiescent conditions in a conventional horizontal-flow basin, the **detention time** must be long (hours) and the designer must pay particular attention to inlet and outlet structures. Adequate baffling of the influent is important to prevent **short circuiting** of the flow. Short circuiting occurs when some of the water entering the basin travels faster than the rest of the water flowing through the basin. This causes some of the water to remain in the basin for a shorter period than the calculated or theoretical detention time. Improperly designed outlet **weirs** are often responsible for basin short circuiting. Flocculation actually continues inside the sedimentation basin, with slow, even flow allowing many particle collisions and floc growth.

A residue of solids mixed with water, **sludge**, accumulates on the bottom of the basin and must be pumped out for disposal, further treatment, or reuse. Most basins now have automated sludge-removal features, such as a squeegee plow or scraper arm, that operate continuously.

Horizontal Flow Sedimentation

Conventional rectangular and center-feed sedimentation basins incorporate the horizontal flow of water. As the water flows across the basin from the influent to the effluent, the suspended particles of floc gradually drop out along a diagonal pathway.

Simplified Settling Theory

The efficiency of a sedimentation basin in the removal of suspended particles can be determined theoretically. The basis for this settling theory is that the speed at which a particle settles (settling velocity) must be fast enough for that particle to fall to the bottom of the basin by the time it reaches the effluent end. If the particle does not settle to the bottom of the basin by the time it reaches the end, it could be carried over in the effluent.

This critical settling velocity (Sc) can be determined mathematically and serves as the basis for sedimentation basin design. The factors used to calculate the critical settling velocity are detention time, flow rate, and the depth, width, and length of the tank.

$$Sc = D/T;\ T = DWL/Q;\ \text{so } Sc = Q/WL, \text{ in feet per hour}$$

Where

Sc = critical settling velocity,

T = detention time,

Q = flow rate, in cubic feet per hour, and

D, W, and L = the depth, width, and length of the basin, respectively, in feet.

If an even distribution of all suspended particles in the water over the full depth of the basin is assumed, particles having a settling velocity greater than Sc will be completely removed, whereas only some of those with a settling velocity less than Sc will be removed.

Surface Loading Rate

The simplified explanation of settling theory presented above shows that the settling efficiency only depends on the ratio between the influent flow rate and the surface area of the tank. This is called the **surface loading rate**, or the **overflow rate**. If ideal conditions could be achieved in a sedimentation basin, the overflow rate would match the settling velocity of the particles to be removed. This is seldom possible, so it is necessary to reduce overflow rates to less than theoretical values. The surface loading rate is expressed in gallons per day (gpd) per square foot (ft^2):

$$\text{Surface Loading Rate} = \text{Flow (gpd)} \div \text{Surface Area } (ft^2)$$

SEDIMENTATION TANK SURFACE LOADING RATES

Application	Rectangular and circular*	Upflow contact*
Lime softening	1,400-1,700	2,600-3,200
Alum or iron coagulation		
Turbidity removal	1,000	1,200
Organic color removal	700	850
High algae content	500	

* Loading rates are expressed in gallons per day per square foot; the rates shown are guides, and should be adjusted down for cold temperatures.

Source: *Water Treatment Plant Design*, American Society of Civil Engineers and the American Water Works Association, 1990.

Weir Loading Rate

Regardless of the type of design, another important factor is the **weir loading rate**, used to determine the length of weir needed on basins or clarifiers. The weir loading rate is expressed in gallons per day (gpd) per foot (ft):

$$\text{Weir Loading Rate} = \text{Flow (gpd)} \div \text{Length of Weir (ft)}$$

Typically, the weir loading rate should not exceed 20,000 gpd/ft. In the following example the surface and weir loading rates are calculated to determine if they are within the acceptable range for the system.

A rectangular sedimentation basin 20 feet long by 10 feet wide is treating 90 gpm of water from an alum coagulation process removing organic color. A double weir (two weirs on a single launder channel) spans the 10 foot width. Calculate the surface loading rate and the weir loading rate, and indicate whether or not the results are within an acceptable range for this type of clarifier.

$$\text{Surface loading rate} = \frac{90 \text{ gal/min} \times 1{,}440 \text{ min/day}}{10 \text{ ft} \times 20 \text{ ft}}$$

$$= \frac{129{,}600 \text{ gpd}}{200 \text{ ft}^2}$$

$$= 648 \text{ gpd/ft}^2$$

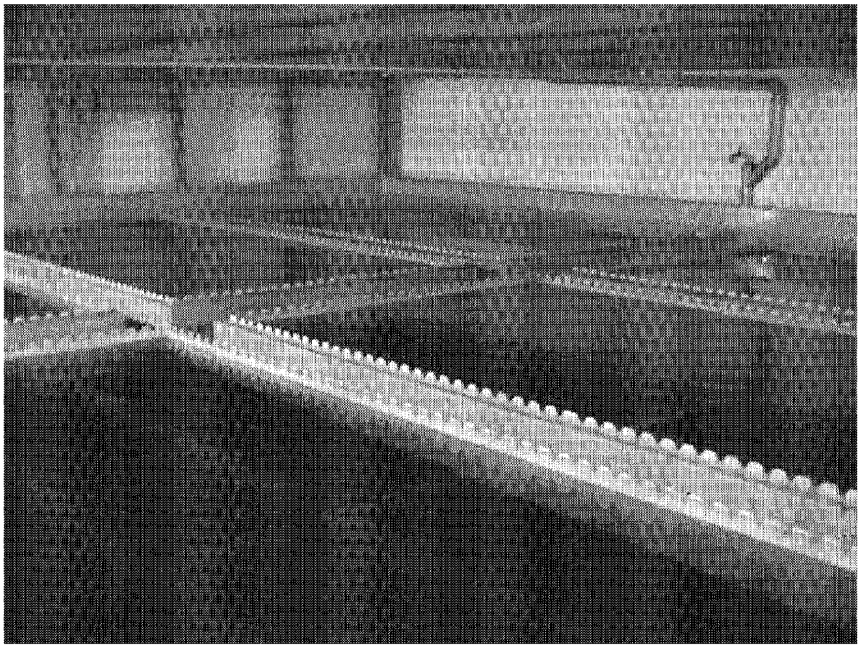
The guideline for this type of clarifier is 700 gpd/ft^2, so this rate is acceptable.

$$\text{Weir loading rate} = \frac{129{,}600 \text{ gpd}}{10 \text{ ft} \times 2}$$

$$= \frac{129{,}600 \text{ gpd}}{20 \text{ ft}}$$

$$= 6{,}480 \text{ gpd/ft}$$

The maximum acceptable weir loading rate is 20,000 gpd/ft, so this rate is acceptable.



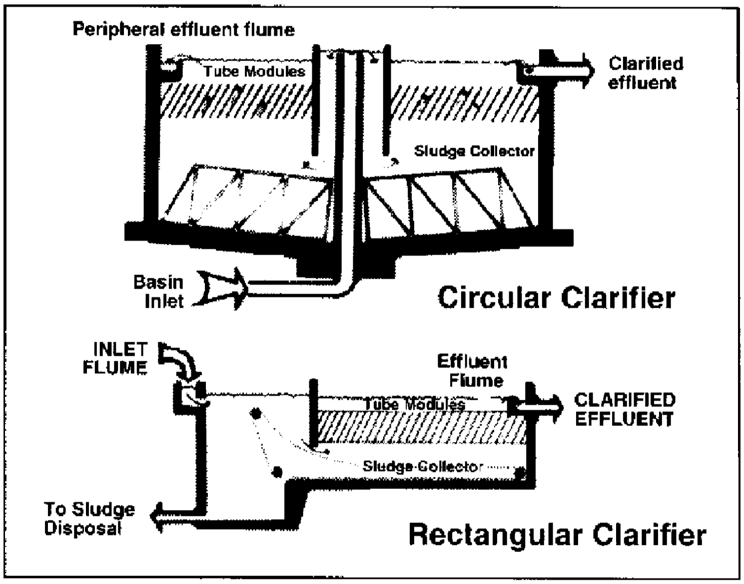
Sawtooth weirs in the clarifier at the Ship Creek Water Treatment Facility, Anchorage, Alaska. The water flows over the weirs and into the launders, which channel the water to the filters.

Conventional Rectangular Basins

In an ideal conventional rectangular (or square) basin, the flow of water is distributed evenly over the full cross section of the basin. If an inlet channel is not part of the basin design, inlet baffles can be retrofitted to provide even flow distribution across the full width of the tank. Because it is denser than the surrounding water, the floc-laden water first entering the basin has a tendency to descend and flow along the bottom of the basin as a **density current**. This tendency is more pronounced in cold water because the colder, denser water sinks as it enters the sedimentation basin. Thus, much of the particle mass falls out near the influent end of the basin, which is why the sludge-collection hoppers are usually located near the influent end, and the basin floor is tilted toward that end as well. In some rectangular basins, the inflow of water is distributed across the influent area, as opposed to a point-source influent pipe, to generate a more uniform flow. Rectangular basins may be the best design for even distribution of flow and less tendency to develop currents and eddies that could disrupt the sedimentation process.

Center-Feed Basins

Center-feed basins are usually circular, but may also be square. The influent pipe is at the center of the basin or, less commonly, the water may be fed from a peripheral pipe. The type of horizontal flow is usually radial and outward, but some peripheral-feed circular basins may be designed for a spiral flow pattern.



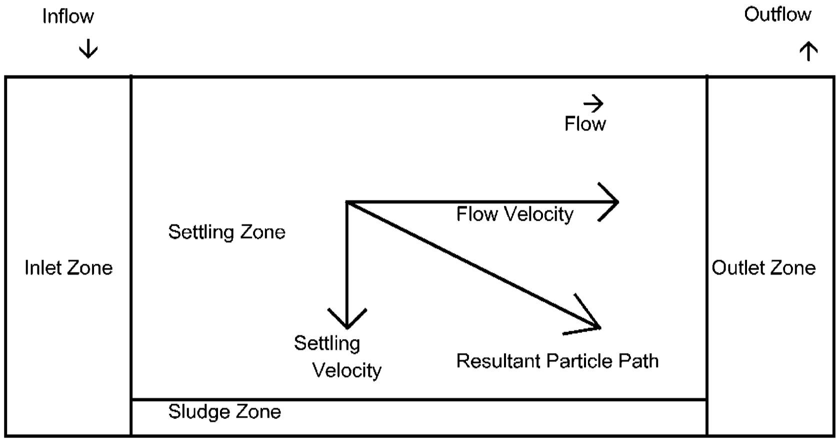
General view of conventional clarifiers, both rectangular and circular designs. Note that either design can incorporate the installation of tube settlers, which are discussed later in the section on shallow-depth sedimentation. Courtesy of USFilter/Microfloc® Products.

Sedimentation Basin Zones

Every type of sedimentation basin has four zones of sedimentation, which comprise the following:

- **The inlet zone** slows the flow rate of the inflowing water and distributes the flow uniformly across the basin.
- **The settling zone** is the quiescent area necessary for the floc to settle.
- **The outlet zone** is like a buffer zone, providing a smooth transition from the settling zone to the effluent flow area. In this area it is important that density currents or eddies do not stir up settled solids and carry them into the effluent.

- **The sludge zone** is the accumulation area for the settled solids, keeping them separated from other particles in the settling zone.



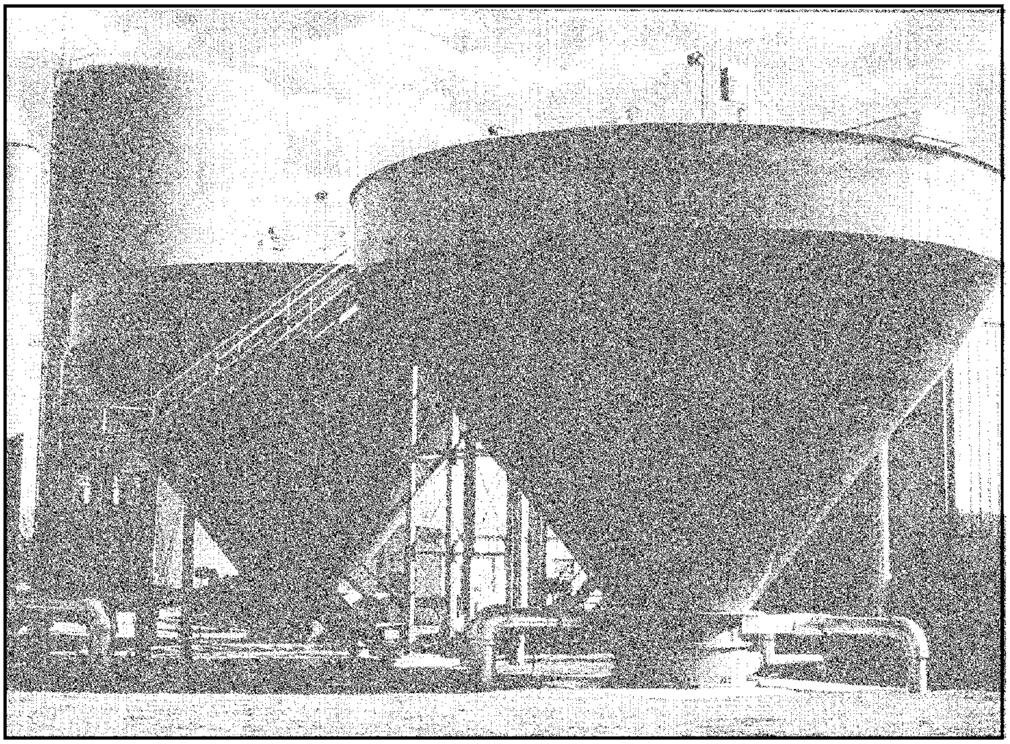
A vertical cross section of a conventional rectangular sedimentation basin, showing the four basin zones and a typical suspended particle pathway.

ALTERNATIVE BASIN DESIGNS

Several types of alternative sedimentation basin designs are in use in water treatment plants. The most common of these are solids-contact basins and shallow-depth sedimentation basins.

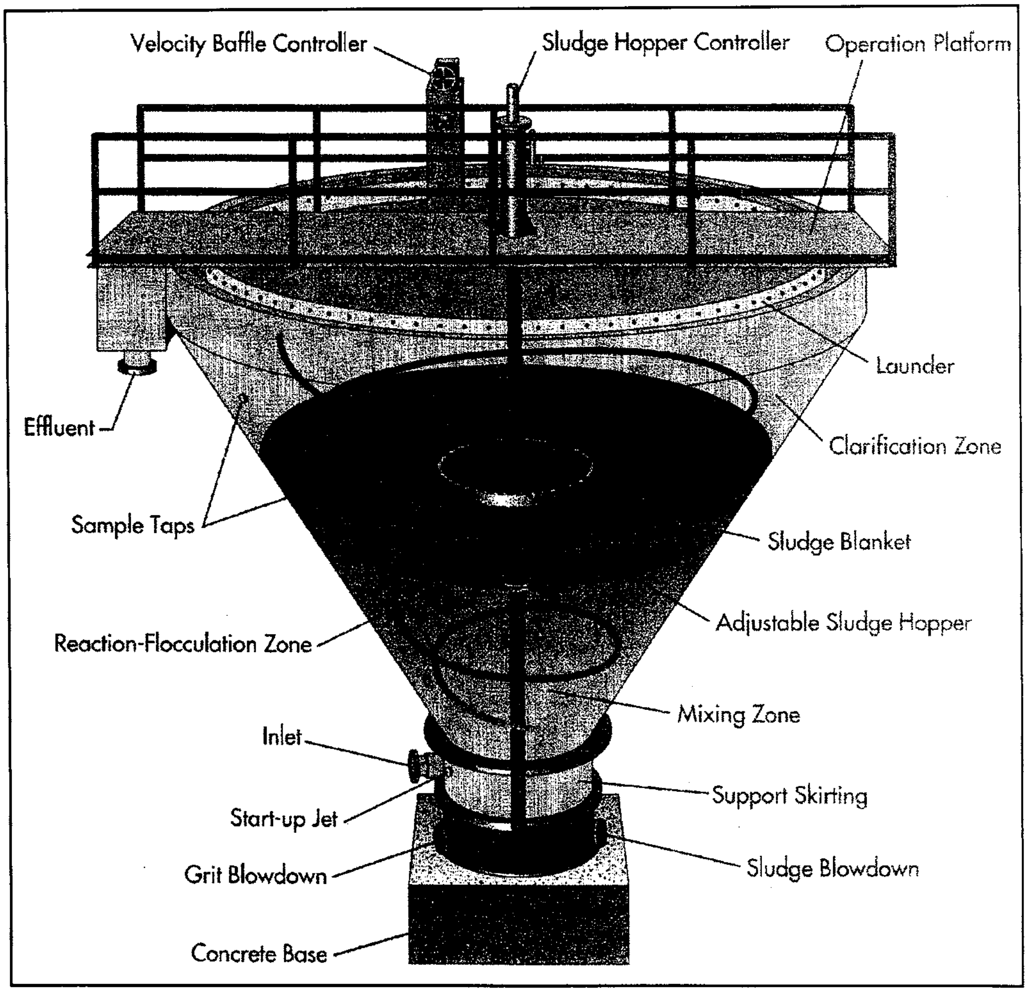
Solids-Contact Basins

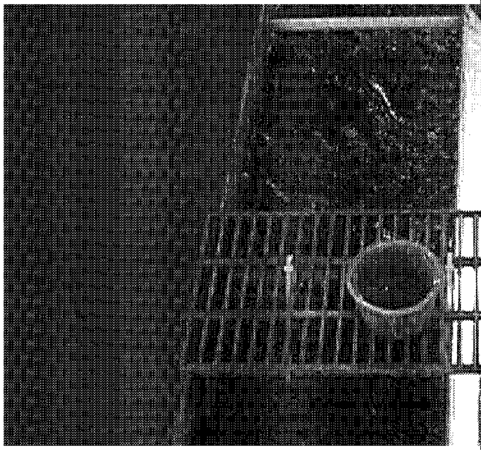
Solids-contact basins, also known as **upflow clarifiers**, solids-contact clarifiers, or sludge-blanket clarifiers, are available in a wide variety of designs. This style of clarifier incorporates the floc-forming effects of a mass of previously formed floc or sludge, called a **sludge blanket**. The water flows upward through the blanket, which traps suspended particles. The thickness and position of the sludge blanket must be carefully monitored. If it rises too high in the basin it could become mixed with the effluent and flow over the weirs into the effluent launders. If the sludge blanket becomes too heavy it could collapse into the bottom of the basin and shut down the system. Typically, mixing, flocculation, and sedimentation processes are combined in a single tank. In general, solids-contact basins are circular and are equipped with components for mixing, flow circulation, and sludge scraping and removal.

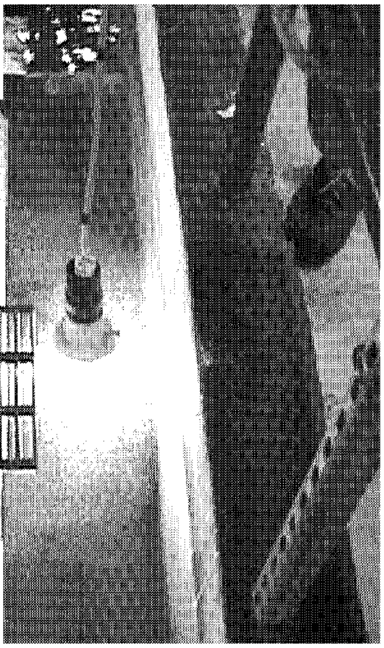


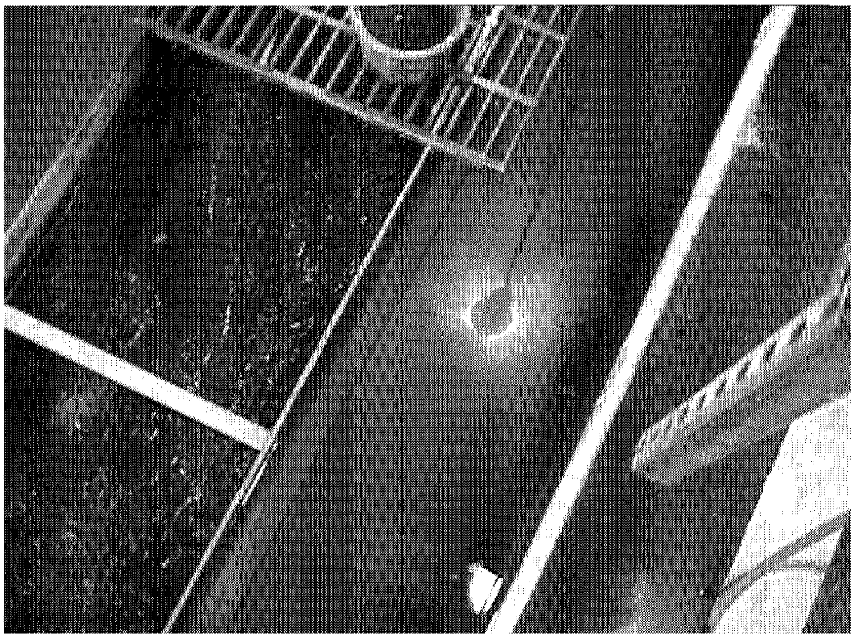
The Spiracone® upflow sludge blanket clarifier is one example of an upflow-style clarifier that combines mixing, flocculation, and sedimentation in a single basin.

The main components of the Spiracone® upflow sludge blanket clarifier. Graphics courtesy of USFilter/ General Filter Company.









Measuring the depth of the floc blanket at the Golden Heart Utilities water treatment plant in Fairbanks, Alaska. The operator lowers a lamp into the clarifier until the light is obscured by the layer of floc.

The water treatment plant at Coffman Cove, Alaska, uses a Microfloc® Trident® Adsorption Clarifier™, which incorporates a floating layer of plastic media held in place by a screen in place of a sludge blanket. Solids-contact basins are also discussed with flocculation in Chapter 7.

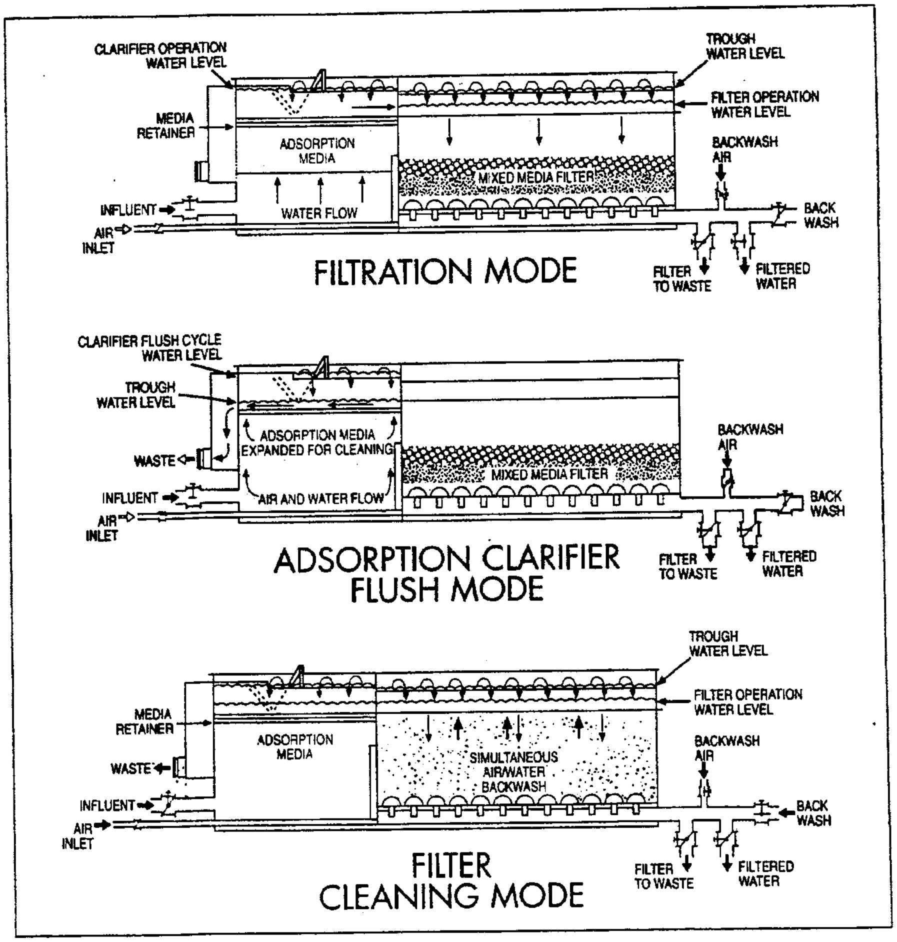
Shallow-Depth Sedimentation

The concept behind shallow sedimentation basins is that less time is required for floc to settle. Most shallow sedimentation basins are equipped with plate or **tube settlers**, which provide extra baffling and additional surface area for particle settling. Tube settlers are installed at an angle of 5° to 60° within the basin to channel the upward flow of water sideways or diagonally, allowing more opportunities for particles to drop out of solution. Sometimes parallel shallow basins are stacked on top of each other, equipped with stacks of plate or tube settlers to optimize surface area, particle contacts, and settling.

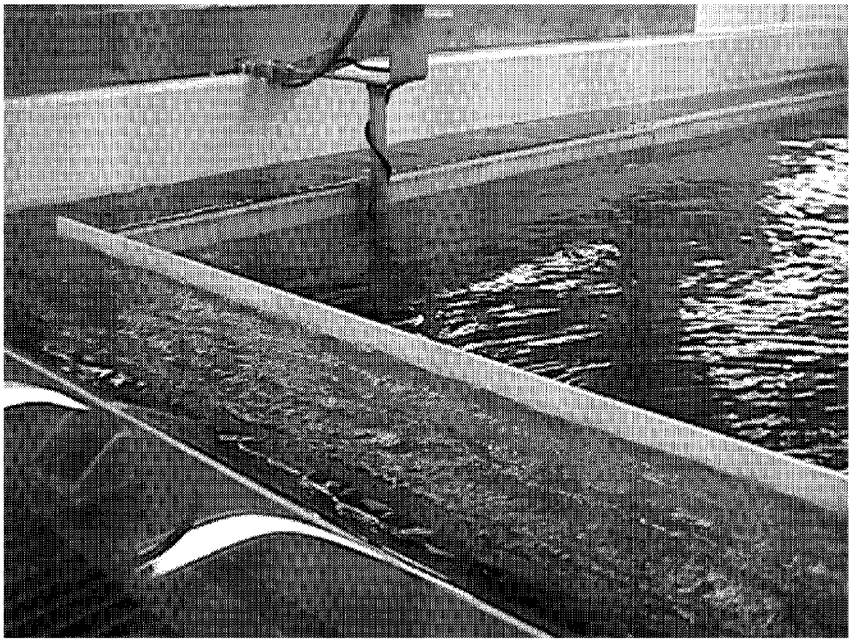
Tube Settlers

As water rises through the tube settlers, floc settles on the surfaces of the tube settlers and on the tank bottom. As the floc particles accumulate and grow larger, they begin to slide down the surfaces of the tube settlers, picking up more floc in their wake and growing larger still. The floc forms sludge on the tube settlers and the tank bottom; the sludge is drawn off the bottom of the tank either by gravity or by mechanical means. High-angle tube settlers are designed to be self cleaning, but shallow-angle tube settlers may need to be hosed off with a hard spray of water during basin cleaning.

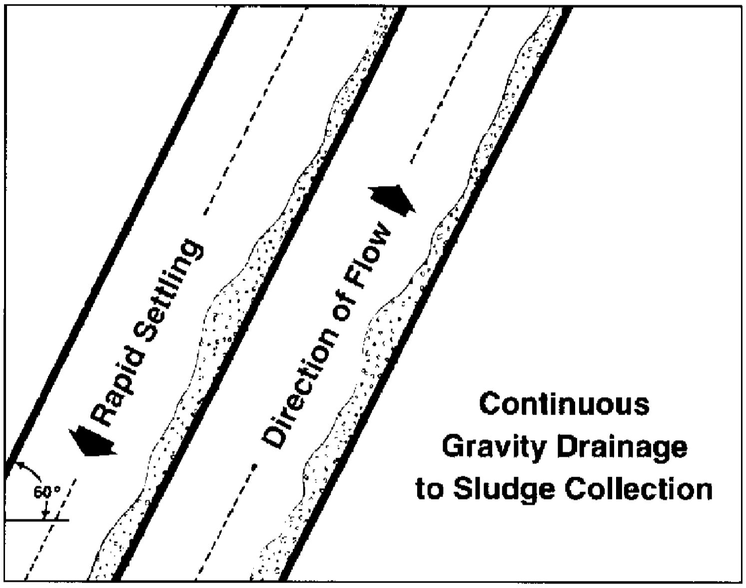
The advantages of tube settlers can be illustrated by an example. In a two-inch-diameter tube, the farthest distance a particle must settle is two inches, from the top of the tube to the bottom. If the particle's settling rate is one inch per minute, it will only take two minutes for the particle to reach the bottom of the tube. In contrast, if the same particle were to settle in a 6-foot tank, it would take 72 minutes for it to reach the bottom of the tank. Consequently, the detention time can be reduced from hours to minutes or more importantly, the surface loading rate can be increased dramatically without impairing the effluent quality.



The Microfloc® Trident® Adsorption Clarifier™, showing its three modes of operation. Courtesy of USFilter/Microfloc® Products.



The Adsorption Clarifier™ at Coffman Cove, Alaska, in clarifier flush mode, is visible in the lower left-hand corner. Water is flowing out of the clarifier, over the weirs, and into the launder channel to the filter on the right.



Flow directions in tube settlers inclined at a 60° angle in a clarifier. Rapid clarification results from reduced settling distance and laminar flow conditions. Courtesy of USFilter/Microfloc® Products.

Inclined-Plate Settlers

The design of the inclined-plate type of clarifier is based on the same shallow-depth sedimentation concept as tube settlers. However, flow is not introduced at the bottom of the basin, but enters at or near the top and is then directed downward through a series of parallel plates. The City of Petersburg uses the Lamella® clarifier, which is the trademark name for the inclined-plate clarifier by the Parkson Corporation.

SLUDGE DISPOSAL

Water treatment wastes may form at several different locations in the treatment plant. Sedimentation basins, or clarifiers, and filters accumulate residuals during operation. Sludge must be regularly removed from a sedimentation basin so that problematic currents do not stir it up and cause it to remix with the rest of the water. Sludge that collects in the bottom of a sedimentation tank is made up of organic and inorganic substances, which may or may not be easily disposable according to current environmental regulations.

In the past, sludge was often discharged to lakes and streams without treatment. This is no longer allowed under current environmental laws because of the harm these materials can cause to the receiving water bodies. If hazardous chemicals or pathogenic microorganisms are present, the sludge may need to be transported to a wastewater treatment plant for processing. The sludge also must be carefully handled to avoid health risks to personnel. The supernatant may be returned to the inflow of the water treatment plant to be reprocessed.

Dewatering

Dewatering is important to reduce the volume of the sludge. Typically raw sludge removed from the bottom of the tank is only 0.1 to 2.0 percent solids. The continuous mechanical process of scraping it toward the drain hole can help to consolidate it. After collection, the sludge is dried out by some means to reduce its volume, and thus, the expense of its disposal. Dewatering systems include sludge lagoons, sand drying beds, and the use of mechanical equipment such as vacuum filters, centrifuges, or filter presses.

The choice of a dewatering system depends on the type and volume of sludge to be dewatered. Alum sludge is the most common type formed in conventional systems because alum is the coagulant most frequently used to remove turbidity. Alum sludge is difficult to dewater because the water molecules are chemically bound to the aluminum hydroxide floc. Before dewatering with mechanical means, alum sludge may be pretreated by stirring in a sludge thickener. A polymer is often added to enhance this process, causing the floc particles to break apart so that the bound water may escape, allowing the solids to settle. Pretreating with a sludge thickener may concentrate sludge to as much as 5 percent solids by weight, and subsequent mechanical dewatering may result in a sludge that is 20 percent solids by weight.

Tank Cleaning

Most modern sedimentation basins are equipped with automated scrapers to remove the sludge or move it to a hopper from which it can be easily pumped. Usually tank cleaning is not done very often if automated machinery removes the sludge continuously. However, it is good practice to totally drain, scrub down, and disinfect the inside of the tank annually. This process also allows the tank and mechanical components of the scraper mechanism to be inspected so potential problems can be identified and avoided.

Disposal

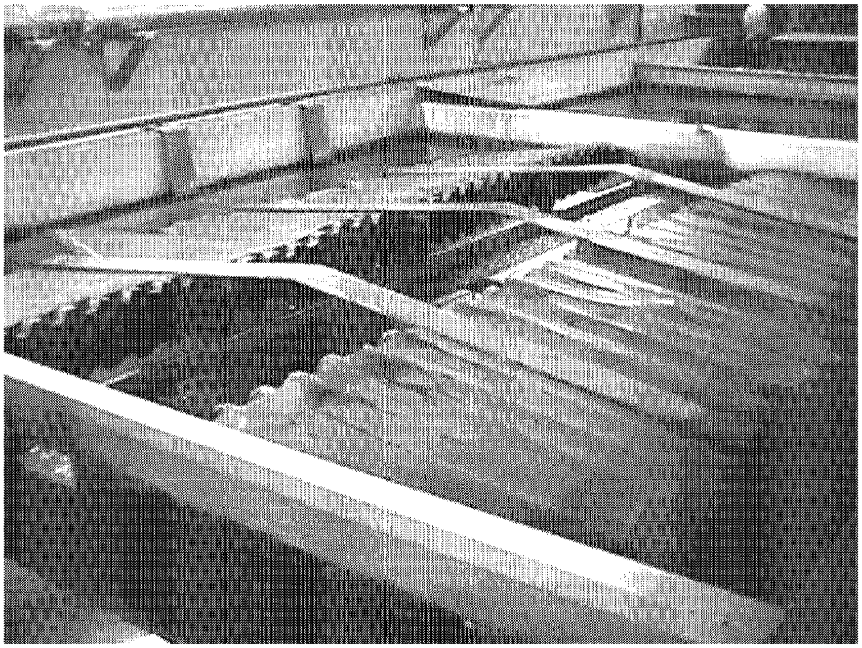
Sludge is sometimes disposed directly to the sewer system, or may be land-filled after being completely dried. Sludge that doesn't contain hazardous substances may even be used in agricultural applications. Federal regulations specify how and what kinds of sludge can be disposed of and where, and a permit is required for disposal.

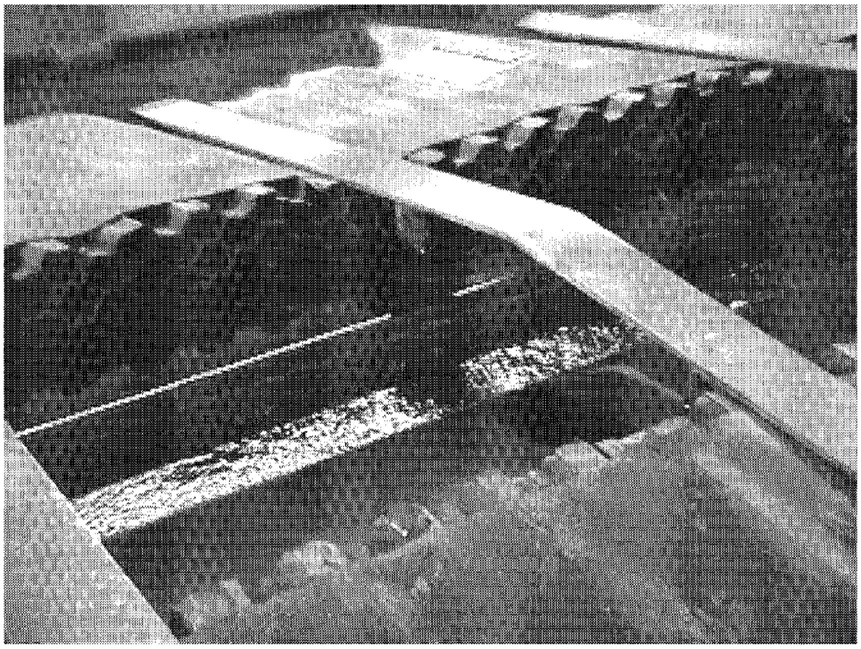
UNIVERSITY OF ALASKA FAIRBANKS

At the University of Alaska Fairbanks (UAF) water treatment plant, the sedimentation basin is actually a type of upflow clarifier, with a honeycomb arrangement of hexagonal tube settlers submerged in the 6-foot tank at an angle of 15°. The water flows from the flocculators over the effluent weirs and is then channeled downward to flow into the bottom of the sedimentation tanks. As the water travels upward through the settling tubes, the force of gravity causes even the lighter particles of floc to settle out in the tubes. As more and more particles of floc settle onto the bottom of the settling tubes, they begin to act like a net, trapping other particles of floc. The water continues up and flows over the sedimentation tank weirs down into the filters. During routine backwashing of the filters, the operator hoses down the settling tubes and the walls of the sedimentation tank with a hard spray of domestic water.

OPERATIONS MONITORING

The primary indicator of sedimentation basin performance is turbidity. The turbidity of both the raw water and the sedimentation basin effluent should be tested at least three times a day, and more frequently if water quality is changing rapidly. In general, the turbidity of the effluent from the basins should be no more than 10 nephelometric turbidity units, to prevent overloading the filters. If insufficient turbidity is being removed, it may be that the problem is in one of the previous treatment processes. However, insufficient detention time in the sedimentation basin may be one reason for poor sedimentation performance.





Above: The sedimentation basin at the University of Alaska Fairbanks. Tube settlers are submerged in the basin at a 15° angle. Below: Detail of the hexagonal tube settlers in their honeycomb arrangement inside the sedimentation basin.

Tracer Studies

Tracer studies can provide useful information about clarifier performance and can be completed on site fairly easily. Generally, tracer studies are done using a chemical such as fluoride or salt that can be measured accurately at low concentrations. The concentrated tracer solution is introduced at the inlet of the tank and is measured at various times at the outlet.

Time-concentration curves can be plotted with the use of tracer dyes to see how closely the actual transport time matches the theoretical detention time for the sedimentation basin. Different characteristics of the water being treated and the suspended particles being removed can affect this relation and include the following:

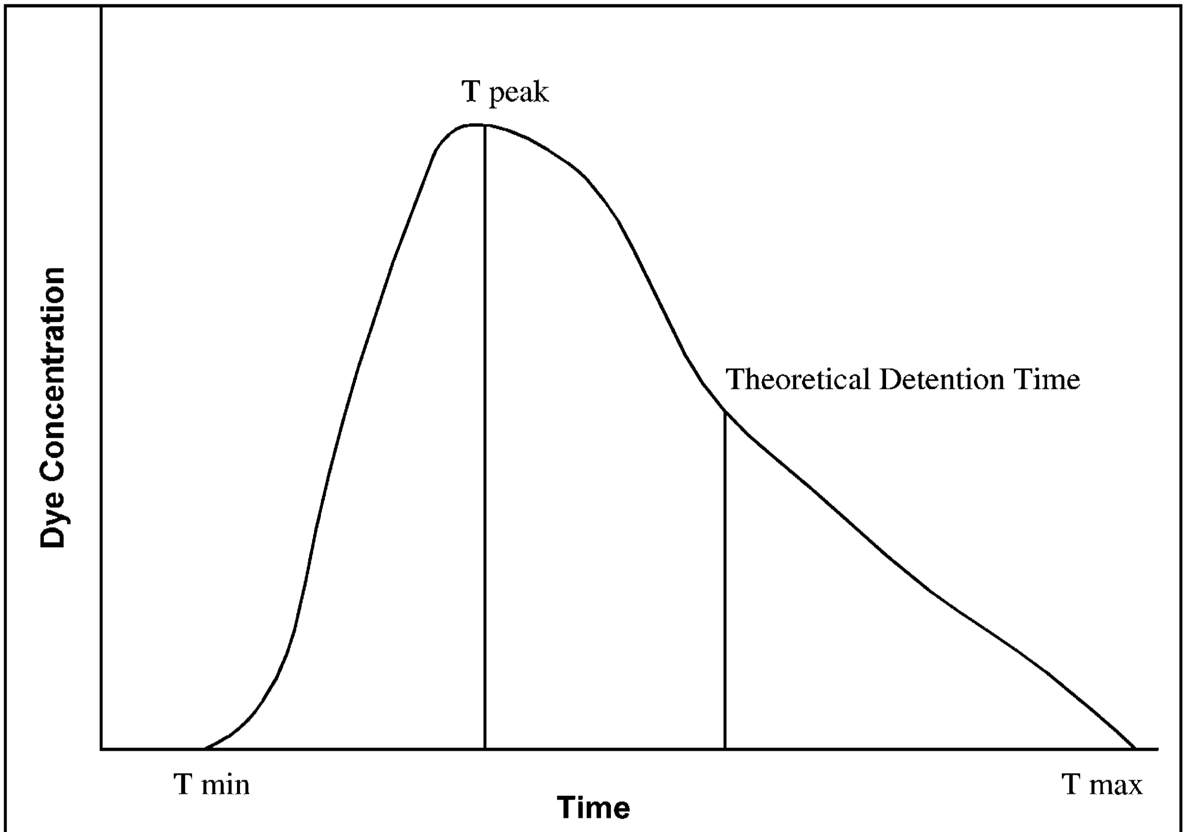
- **temperature of the water** – temperature stratification could cause stratification of current flow in the tank, and low temperatures tend to slow the rate of particle settling
- **specific gravity (density) of the particles** – higher-density particles have higher settling rates. Particle density may depend on several factors, including the coagulant being used.

Seasonal changes can affect the time-concentration curve. Moreover, if the time-concentration curve is not easily reproducible, it might mean that the sedimentation basin needs some fine-tuning or modifications.

Evaluation of Tracer Studies

If the tracer study indicates that the performance of the clarifier is far from ideal, the operator can systematically evaluate various structures and components of the clarifier. For example:

- Uneven overflow weirs can cause poor distribution of water within the basin, impairing settling.
- Poor inlet design can result in density currents; installation of a perforated baffle or target baffle can minimize this problem.
- To improve overall basin performance, tube settlers can be retrofit into the basin at minimal cost.



Time-concentration curve, showing the time dye tracer first appears at the effluent, T min, the time the last dye tracer is detected at the effluent, T max, the time of peak dye concentration, T peak, and the theoretical detention time of the sedimentation basin. The less the difference between T peak and the theoretical detention time, the closer the basin approaches its ideal performance.

SAFETY AND MANAGEMENT

As with all processes in water treatment, the sedimentation process has safety and management issues that are important for the operator to consider.

Safety Considerations

Sedimentation basins should be equipped with hand rails to prevent falls into the tanks; life rings should be provided in case someone does fall in. Walkways and bridges between basins should also have hand rails. Surfaces inside basins may be slippery from solids residues and care should be taken not to slip when working inside empty basins. Electrical and mechanical safety procedures should be followed when working around sludge-removal equipment. Chemicals and other constituents of sedimentation basin sludge may be caustic and toxic, requiring special care and **personal protective equipment** in its handling. Lastly, if tanks are cleaned and maintained manually, confined space procedures may be required.

Record Keeping

Records of sedimentation basin performance should be carefully maintained so that operational problems may be quickly identified and eliminated. Surface and weir loading rates, turbidity values, sludge volumes, time-concentration test results, and any operating problems and corrective actions taken all should be recorded in the plant operating logs. Because sedimentation operates in conjunction with coagulation and flocculation, these records should be maintained together.

Regulations

Requirements of the Surface Water Treatment Rule may have an impact on sedimentation tank design, because some older basins were designed without consideration of dead water spaces. In order to increase their detention times and meet the new turbidity standards, such basins may need to be modified, perhaps retrofitted with tube settler modules.

The Water Pollution Control Act Amendments of 1972 require a water treatment facility to obtain a National Pollution Discharge Elimination System (NPDES) permit before discharging water treatment wastes. Under the NPDES rules, operators must monitor the water quality of the discharge stream, including such parameters as pH, suspended solids, metals, biological oxygen demand, turbidity, temperature, and chlorine residual. In Alaska, water treatment wastes may not be discharged to any receiving body of water that supports aquatic life.

REVIEW QUESTIONS

1. What is the purpose of sedimentation? ______________________________
____

2. Sedimentation basins that incorporate the horizontal flow of water can generally be classified as:
   a. ______________________________
   b. ______________________________

3. What are the four zones found in a conventional sedimentation basin?
   a. ______________________________
   b. ______________________________
   c. ______________________________
   d. ______________________________

4. A problem caused by poor baffle design in a sedimentation basin is
____

5. What are three parameters that will affect the critical settling velocity in a sedimentation basin?
   a. ______________________________
   b. ______________________________
   c. ______________________________

6. Define “surface loading rate”: ______________________________
____

7. A circular sedimentation basin with a diameter of 20 feet has a flow rate of 0.3 MGD. What is the surface loading rate?

8. If the clarifier in question 7 were being used for turbidity removal after coagulation with ferric sulfate, is the calculated surface loading rate within acceptable limits?
   a. yes
   b. no

9. Calculate the weir loading rate for the clarifier in question 7.

10. Is the weir loading rate in question 9 within acceptable limits for water treatment sedimentation basins?
    a. yes
    b. no

11. Solids-contact basins are also called ______________________________.

12. One way to improve shallow sedimentation basin efficiency is with the use of ____________________________ or ____________________________.

13. What is the term for the process that decreases sludge volumes before disposal? ________________________________

14. One method for testing the performance of a clarifier is a ____.

15. Multiple choice: What is the acronym for the type of permit required by the 1972 amendments to the National Water Pollution Control Act for the discharge of water treatment plant waste?
    a. SWTR ___________
    b. NPDES ___________
    c. ADEC ___________
    d. CWA ___________

Chapter 9

Filtration

Operations Monitoring

Turbidimeters
Particle Counters
Head Loss Indicators
Rate-of-Flow Controller

Safety and Management

Safety Considerations
Record Keeping
Regulations

Review Questions

Chapter 9 – Filtration

INTRODUCTION

Filtration is the oldest form of water treatment; records dating back thousands of years mention filtration of water through charcoal or sand and gravel. In the 1600s, it was recognized that filtering water through pebbles or sand could improve its appearance and the health of its consumers. Indeed, the success of filtration can be measured by a decline in the typhoid fever death rate in Cincinnati after filtration was installed in the early 1900's. Before filtration, the typhoid death rate was 50 to 150 per 100,000; after filtration was installed in 1907, the typhoid death rate declined to 11 per 100,000. After chlorination was installed in 1910, the typhoid death rate declined to only 0.4 cases per 100,000.

In most of today's water treatment plants, filtration is an integral step to remove turbidity and to reduce microbial risks. The Surface Water Treatment Rule (SWTR) requires that public water supplies utilizing a surface source provide filtration to remove pathogenic microorganisms from drinking water. In addition, the SWTR requires that filtration provide a **2-log removal** (99 percent) of *Giardia lamblia* cysts.

Filter design and operation will become even more challenging when the new Enhanced SWTR goes into effect on January 1, 2002, for large systems that serve more than10,000 people. Under the ESWTR the combined filter effluent turbidity requirement for most filtration systems is proposed to be lowered from 0.5 to 0.3 nephelometric turbidity units (NTU) in 95 percent of the samples taken each month, and maximum turbidity limits may be set for individual filters. The maximum contaminant level (MCL) for turbidity may be reduced from 5 NTU to 3 NTU for any one sample. In addition to the required limits, the American Water Works Association recommends water treatment systems work toward a filtration quality goal of 0.1 NTU.

THE FILTRATION PROCESS

The purpose of filtration is to remove any remaining turbidity and floc from the water following coagulation, flocculation, and sedimentation. Filtration is a combination of physical, chemical and biological processes, and is accomplished by passing the water through layers of filter media, most commonly sand, **anthracite coal**, **garnet**, and gravel. Filter media may also consist of **granular activated carbon** (GAC), **diatomaceous earth (DE)**, or filter fabrics such as cellulose or other artificial fibrous media.

Filtration Mechanisms

The mechanisms involved in the filtration process are sedimentation onto the filter media, straining, adsorption, and biological filtration. Additionally, the flow of water through the filter media provides for additional flocculation of particles, further enhancing chemical precipitation. The particles to be removed may actually be much smaller than the pores in the filter media, especially when the filter is at the beginning of a filtration cycle and the filter media has not adsorbed much material. In addition to these mechanisms, filtration can be enhanced by the addition of chemical filter aids.

Sedimentation

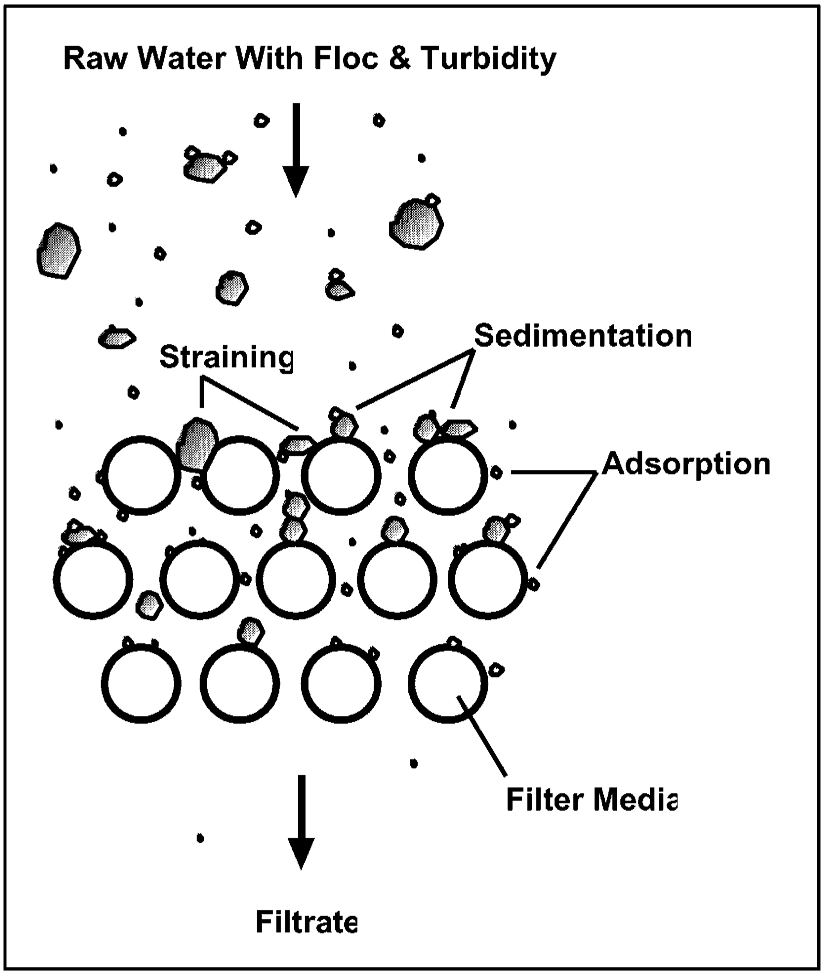
Some particles will settle on the surface of the filter and accumulate in a layer. This layer becomes an additional filter layer, removing even smaller particles as they reach the upper layer of the filter.

Straining

Particles that are small enough to enter the upper layers of the filter, but that are larger than the average pore size of the filter medium will be strained out. As this material fills the larger voids between the particles of filter medium the turbidity removal efficiency improves. This process continues until the pressure differential between the top of the water column above the filter media and the filter outlet on the bottom becomes excessive. This pressure differential is referred to as **head loss**.

Adsorption

One of the most important filtration mechanism is adsorption, which removes particles much smaller than the spaces between grains of filter media. The removal mechanism is adhesion onto the surface of the grains of filter media through which they pass. Adsorption works similarly to the chemical reactions at work in the coagulation and flocculation process. Indeed, some coagulation and flocculation continues inside the filter media. The surface charges on the turbidity particles cause them to stick to the grains of filter media. As more particles adhere to the filter media, they become part of the media, creating additional surfaces for trapping and adsorbing suspended solids from the water. Adsorption is discussed in greater detail in Chapter 12.



Mechanisms of filtration.

Biological Filtration

The formation of a biological film consisting of bacteria, protozoans, algae, and other organic matter on the surface of filter media can be an important and efficient filtration mechanism. In slow sand filters this type of biological film is the primary removal mechanism. It efficiently removes other bacteria and protozoans, organic matter, and turbidity. In addition, biological filtration can remove nutrients such as nitrate and phosphate.

Chemical Filter Aids

In some water treatment facilities, a chemical filter aid, typically a nonionic polymer, is applied to the filter inlet water. A polymer filter aid reinforces the bonds between the filtered particles and enhances the adsorptive properties of the filter media. This helps to maintain the integrity of the floc and keep it from breaking up as it passes through the filter. When the floc holds together it can be filtered more effectively, allowing for longer filter runs and less frequent backwashing. The required dosage of a polymer used as a filter aid is usually less than 0.2 milligrams per liter (mg/L) but the precise amount must be determined by actual use. Too much polymer may cause excessive particulate matter to stick to the upper part of the filter, causing rapid head loss, whereas an inadequate polymer dosage may allow turbidity to break through the filter before terminal head loss is reached.

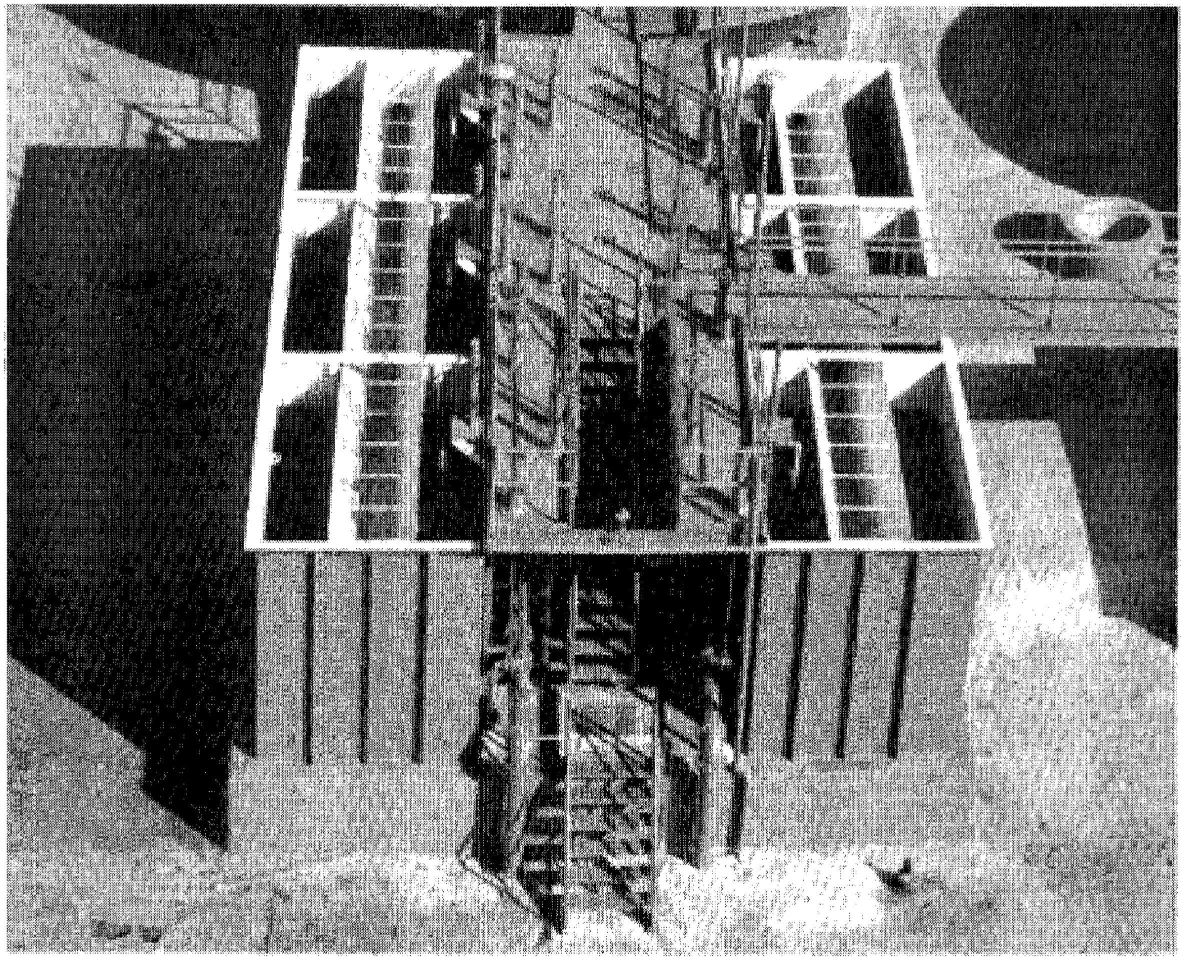
FILTRATION METHODS

A variety of filtration methods are approved for use under the Surface Water Treatment Rule. These encompass all of the commonly used systems in Alaska, along with several other types of filters that are just being introduced in new Alaskan water treatment systems.

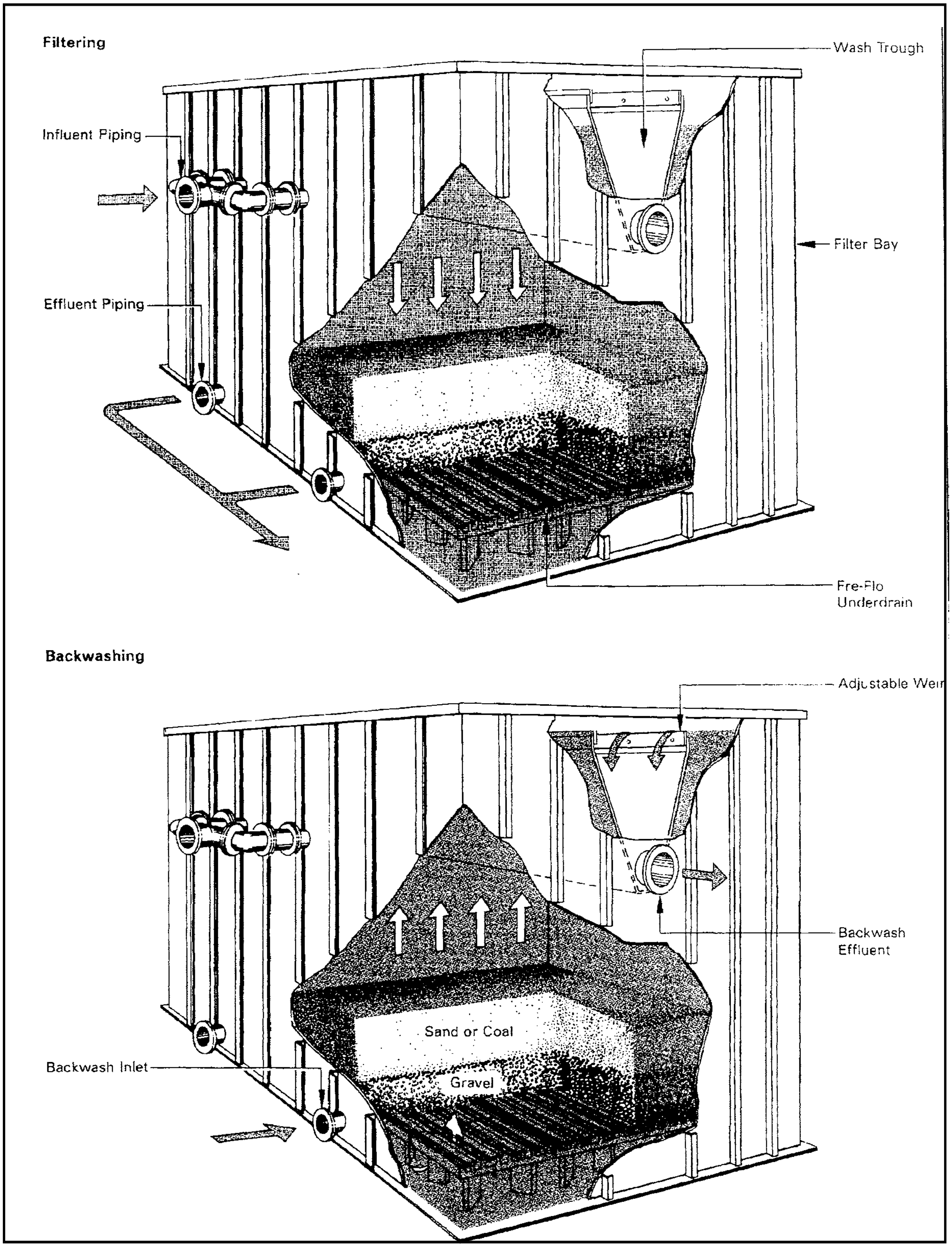
Conventional Filtration

Conventional filtration is a common configuration used both historically and in modern water treatment systems such as the Ship Creek Water Treatment Plant in Anchorage and the GHU Water Treatment Plant in Fairbanks. In conventional filtration, water entering the filters has completed the steps of coagulation, flocculation, and sedimentation. It must then be filtered to remove any remaining turbidity, floc, microorganisms, and chemical precipitates. Rapid gravity sand or mixed media filters are typically used in conventional filtration systems. The performance standard set by the Alaska Department of Environmental Conservation (ADEC) for conventional filtration systems is 0.5 NTU.

A rapid gravity filter is a tank with layers of filter media composed of sand or a combination of anthracite coal, sand, garnet, and gravel. Granular activated carbon (GAC) also may be used as a filter medium in these systems. Water passes through the filter media under the force of gravity and collects in an underdrain system. For maintenance, the filter must be backwashed between filter runs to flush and clean the surfaces of the grains of filter media and to clear turbidity and floc from the voids within the material. An underdrain system is used to collect the filtered water and disperse backwash water into the filter.



Outside top view of a packaged gravity filter. Courtesy of Infilco Degremont, Inc.



Schematic cutaway diagram showing the flow through the packaged gravity filter during regular filtration and backwash modes. Courtesy of Infilco Degremont, Inc.

Direct Filtration

Direct filtration is another common filtration method in which the sedimentation process is eliminated and water flows directly into the filter with or without the flocculation step. Because of this, direct filters can only tolerate low levels of turbidity or the filter run length becomes too short, requiring frequent backwashing.

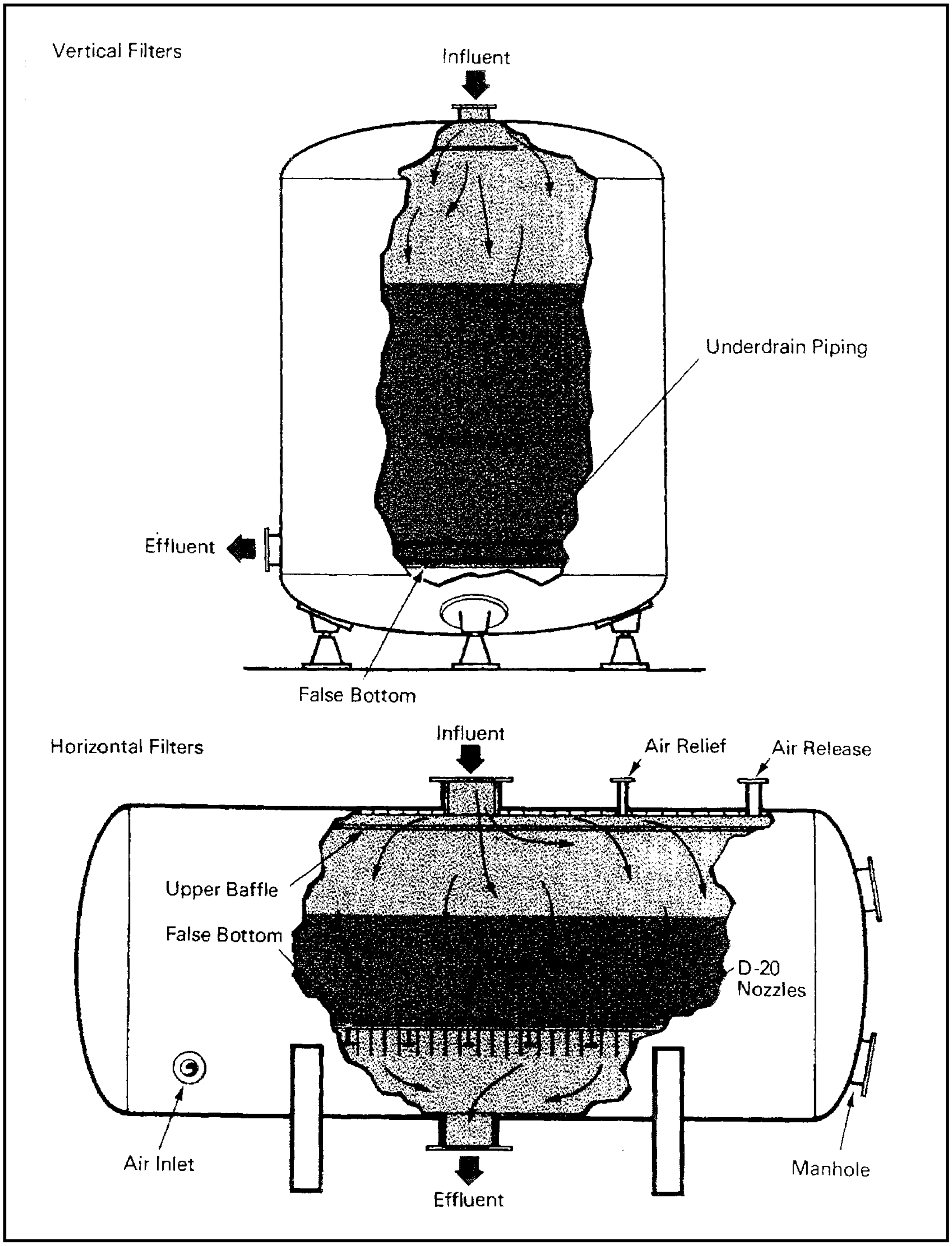
Direct filtration can incorporate either gravity or pressure filters, but usually pressure filters are used for direct filtration. Pressure filtration is similar to gravity filtration but the water is forced through the filter under pressure. Direct filtration systems are used extensively in Alaska for low turbidity water. Media used in direct filtration is essentially the same as in conventional rapid sand or mixed media filters. As for conventional filtration, the performance standard set by the ADEC for direct filtration systems is 0.5 NTU.

Slow Sand Filtration

Slow sand filtration, an older type of filtration, generally is not used for water with high turbidity or color, and is not as common in the United States as rapid gravity filtration. Slow sand filters are also a type of gravity filter. The sand filter media is usually quite fine, with an effective size of 0.20 to 0.30 millimeters (mm). The filtration rate is typically 50 to 100 times slower than conventional rapid sand filters. Thus, slow sand filter systems require a large amount of surface area to process the same volume of water as a smaller rapid gravity filter system would.

In a slow sand filter, chemicals are usually not applied to pretreat the water. Rather, the material filtered out of the water forms a **schmutzdecke**, a surface mat of suspended matter and microorganisms, that becomes part of the filtration medium. Slow sand filters in essence have a biologically active filter media, a technology that is gaining acceptance in the U.S. water treatment industry. These filters require continuous operation submerged under 3 to 5 feet of water to prevent the biological schmutzdecke from drying out and dying. In freezing climates, slow sand filters are usually housed to prevent ice from building up on the surface of the filters. In areas with mild climates and relatively inexpensive land, slow sand filters represent a cost effective solution.

Slow sand filters are cleaned by scraping off the top 1 inch of sand, rather than by backwashing. After several cleanings, new sand is added to restore the filter bed to its original depth. When a slow sand filter is first started up after cleaning, the filtered water is filtered to



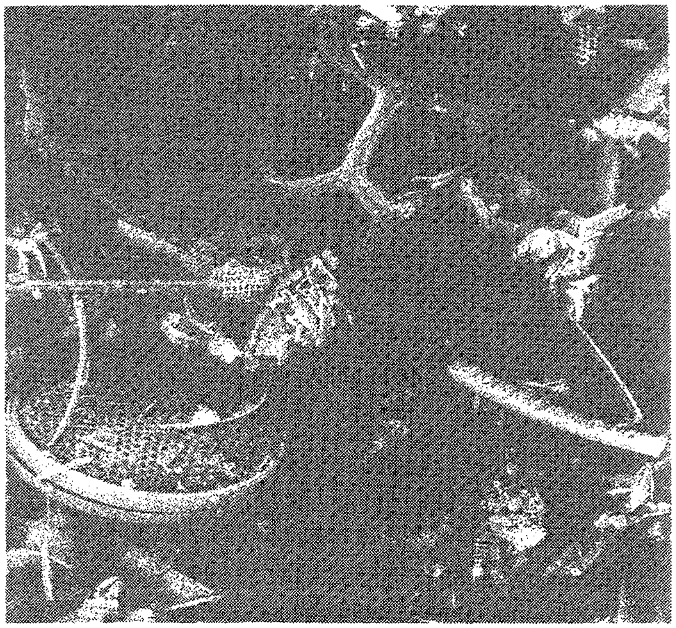
Vertical and horizontal pressure filter designs. Courtesy of Infilco Degremont, Inc.

waste for as much as two days until a new schmutzdecke develops. Because the amount of sand requiring replacement can be substantial, the cost of replacement media must be factored into the planning.

A new slow sand filter installation was recently commissioned in the City of Wrangell in Southeast Alaska, and is the first large, modern facility of this design in Alaska. Because the schmutzdecke is so efficient at removing *Giardia*, slow sand filters are afforded a higher filtrate turbidity standard of 1 NTU for 95 percent of the samples taken in one month, double the 0.5-NTU standard for surface water sources under the SWTR.

Diatomaceous Earth

DE filters were first used by the U.S. Military during World War II to control outbreaks of amoebic dysentery. The material used is almost pure silica, mined and processed from deposits of fossil **diatoms**, which are microscopic aquatic plants. Large deposits of DE are mined in the western United States. DE filters can be operated as either pressure or vacuum filters, and are commonly used in Alaska to filter swimming pool water.



Photomicrograph, at 1,000x magnification, of fossil diatoms and fused diatom fragments that make up the Standard Super Cel® grade of Celite® diatomaceous earth filter medium. Courtesy of Schneider Filtration Systems.

In this type of filter, the DE is added to the water to form a slurry, which then forms a **precoat** on the filter element. This precoat acts as the filter medium that strains out turbidity particles from the water. Additional DE is added continuously as a **body feed** during the filter run. After the run is completed, the filter cake is washed from the filter and discharged to a sludge lagoon for disposal.

One of the few operational controls available to the operator of DE filters is the selection of the grade of DE to use. Different grades of DE have different particle size distributions and, therefore, different filtering properties. Typically, the finest grade of DE offers superior particle size exclusion properties, but has the highest rate of head loss development. Information on DE filtration and on the selection of DE filter media may be found in AWWA Manual M30.

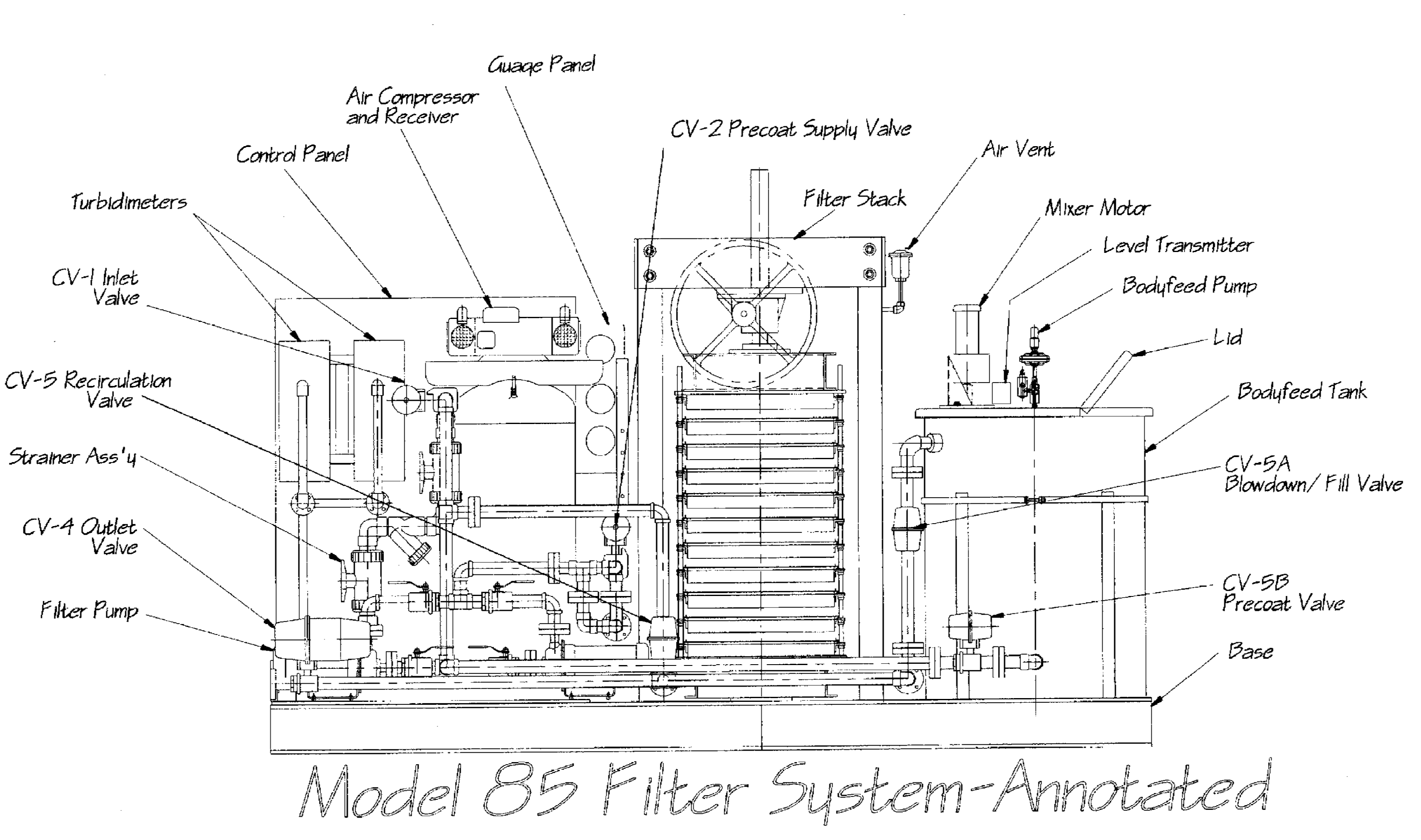
Recently, the Village of Quinhagak received the first modern installation of a DE filter in Alaska. Like slow sand filters, DE filters are so efficient at *Giardia* removal that monthly filter effluent turbidity standards are set at 1 NTU for 95 percent of the samples taken, rather than the current 0.5 NTU for surface water sources.

Alternative Filtration Devices

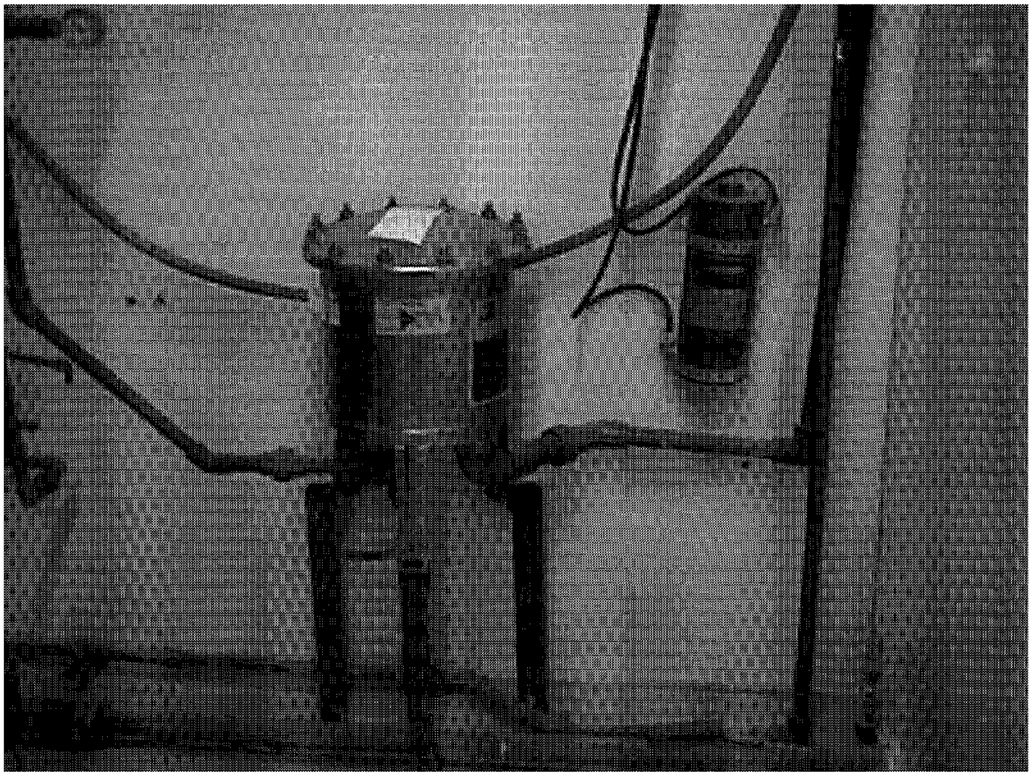
Alternative filtration devices include any that are not conventional, direct, slow sand, or DE. This includes high-rate sand filters, membranes (discussed in Chapter 13), and cartridge and bag filters.

Cartridge and bag filters are widely used in small potable water systems in Alaska. Many private homes use cartridge filters to filter well water. For public systems, cartridge filters are considered alternative water treatment systems. The device proposed for use must be approved by the ADEC, and must appear on the ADEC Drinking Water Program's "Listing of Approved Alternative Filtration Devices to Meet the SWTR for Use in Public Water Systems," which is periodically updated.

A cartridge filter system may consist of several cartridges set up in series, each with a plastic or fiberglass housing containing a fibrous or charcoal filter material. Different types of filter material are designed to remove particles of different sizes, and each is rated according to whether it removes suspended particles, rust, color, or microorganisms. In such a system, the filters are typically arranged with the coarser filter materials first in the series and the finest, such as the *Giardia* filter, at the end. The series of filters may be held in a single housing or may be individually arranged. For larger installations, multiple cartridge filter housings, holding several cartridges, are used to process higher flows.



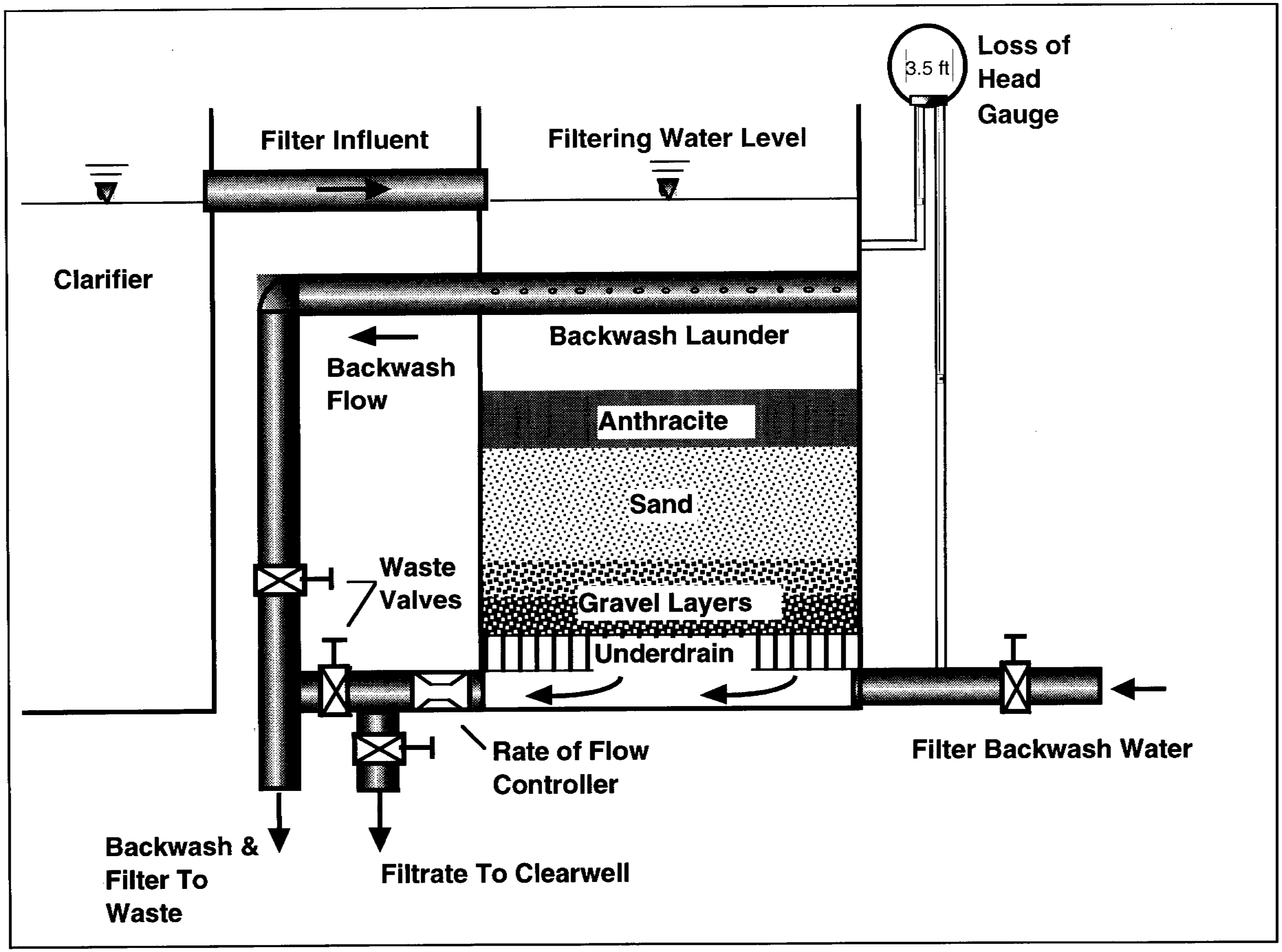
The Schneider Filtration Systems Model 85 diatomaceous earth filter system installed at Quinhagak, Alaska. This type of installation usually uses the Super Cel® Celite® grade of diatomaceous earth filter medium pictured on page 9-9. Courtesy of Schneider Filtration Systems



Housing for multiple cartridge filters.

FILTER DESIGN

A typical gravity filter design includes a concrete or steel box to hold the layers of filter media, an underdrain system, nozzles for surface wash and bed agitation, and wash water troughs to channel the backwash water away to waste. A head loss monitoring system and rate-of-flow controllers are also necessary to ensure efficient filter operation. The following simplified diagram shows the major components of a conventional gravity filter:

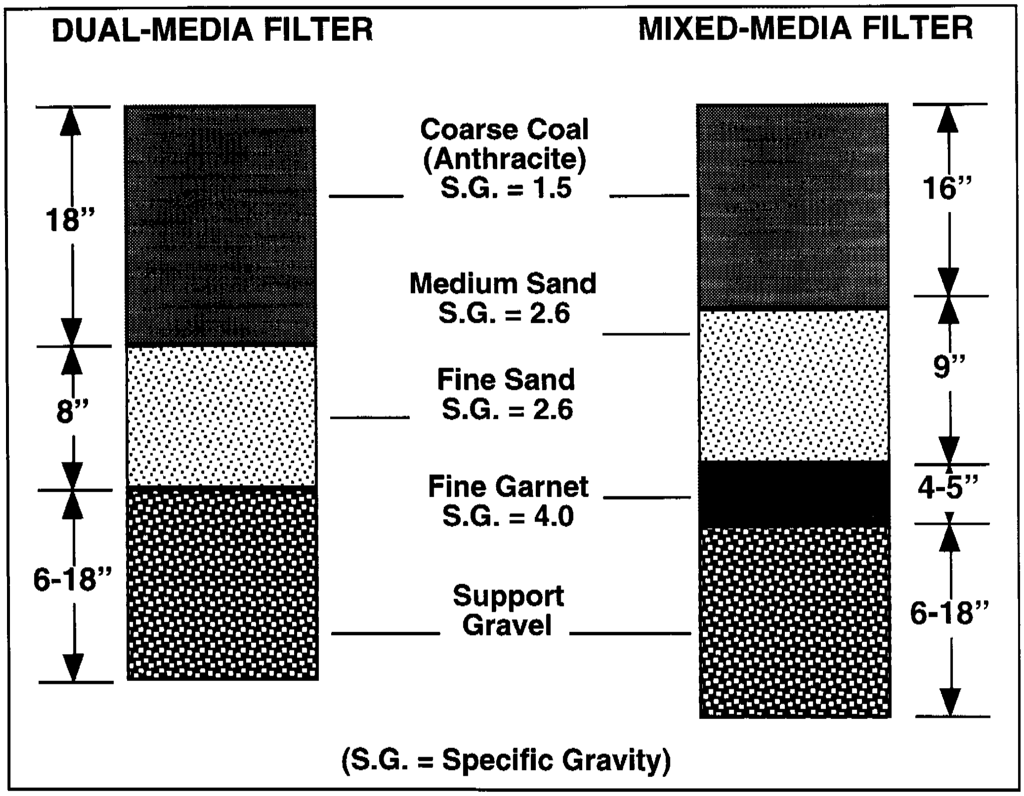


Basic gravity sand filter valving arrangement.

Filter Media

The filter medium chosen for a system depends on the volume of water being processed, the system being used, and the raw water characteristics. The characteristics that are important in a good filter medium are hardness, density, size, porosity, and uniformity of size. It is also important that the material not be easily dissolvable and that it will not react with any chemicals added to the water during earlier treatment processes.

The filter media may be ungraded, uniformly graded, or arranged with the pore size or coarseness either increasing or decreasing. For example, if anthracite coal is used, it will be placed on top of the filter bed providing a more coarse media to capture larger particles first. This allows the finer particles to penetrate more deeply into the bed utilizing a greater volume of the bed to capture and store particles and thus increasing the length of the filter run. If too many of the fines are trapped on the surface of the filter bed, it will clog much more quickly and result in a short filter run. Slow sand filters use a single grade of sand, which retains all solids of different sizes in the upper layers of the filter, forming the schmutzdecke.



Filter media configurations.

Depending on the type of underdrain system installed, gravel may be used as the support bed for the filter medium or media. Gravel under the filter prevents sand from entering the underdrain system and helps to evenly distribute the backwash water across the bed. Many modern filter underdrain systems do not require a gravel base, and support the sand or other filter media directly. Some of the most common filter media used are anthracite coal, filter sand, garnet sand, GAC, and DE. The following table compares some basic design characteristics of various types of filter media:

FILTER DESIGN CHARACTERISTICS

Filter Type	Media	Size, mm	Specific Gravity	Layer Depth, in.	Flow	Flow Rate, in gpm/ft^2
Slow Sand	fine sand	0.2	2.6	36 - 48	gravity - downward	0.05 - 0.13
Rapid Sand	coarse sand	0.35 - 1.0	2.6	24 - 36	gravity - downward	2 - 5
Dual Media	anthracite sand	0.9 - 1.2 0.4 - 0.55	1.4 - 1.6 2.6	18 - 24	gravity - downward	4 - 5
Mixed Media	anthracite sand garnet	0.9 - 1.2 0.4 - 0.55 0.2	1.4 - 1.6 2.6 4.2	16.5 9 4.5	gravity - downward	5
Diatomaceous Earth	diatomite	0.005 - 0.125		1/16 - 1/8	pressure or vacuum	0.5 - 5.0
Pressure	variable				pressure, any direction	2 - 4

mm, millimeters; in., inches; gpm/ft^2, gallons per minute per square foot
Source: *Filters and Filtration, a Rural and Small Water Systems Training Guide*, A. Steed, J. Shands, B. Carroll, 1992.

Filters that deviate from the above specifications may be considered alternative filtration devices. Utilities proposing to use alternative filtration devices must demonstrate to the ADEC that the device can achieve the required 2-log removal of *Giardia lamblia* cysts.

Anthracite Coal

Anthracite coal is a highly porous and lightweight material that is crushed and graded to be slightly larger-grained than filter sand. As noted above, anthracite is placed at the top of the filter bed to trap the larger pieces of floc while smaller particles penetrate deeper into the filter media, allowing longer filter runs before particles begin to break through into the filter effluent. Anthracite has a much lower specific gravity than filter sand, so it stays on top of the filter bed during backwashing. Care must be taken that backwash rates are not so high as to lose the grains of anthracite with the outgoing wash water. Operators should monitor the backwash to waste stream to guard against excessive media loss.

Filter Sand

Filter sand is specially manufactured for use in water filtration and is designed to be hard, chemically stable, and of uniform size. Different types of filter sand may be field-tested to see which ones work best in a particular filter system. If the filter sand is too coarse, it will not effectively remove suspended particles; if it is too fine, it will slow the flow of water and require more frequent backwashing. The specifications listed by manufacturers for filter sand are grain size, size distribution, shape, density, hardness, and porosity.

Two parameters used to describe a filter sand are **effective size** and **coefficient of uniformity**. The effective size (d_{10}) is the diameter of the smallest opening that will allow 10 percent by weight of the sand to pass through it. Thus, if 10 percent by weight of the grains in a bag of filter sand will pass through a hole 1 mm in diameter, and the rest of the grains are too large to pass through the hole, then the effective size of the sand is 1 mm.

The coefficient of uniformity is a measure of the size range of the sand. It is measured by the ratio of the sand-grain diameters that make up 60 percent and 10 percent by weight (d_{60}/d_{10}). The closer the coefficient of uniformity is to 1, the more uniform the size of the grains. In general, the more uniform the size of the sand grains, the slower the buildup of head loss.

Another parameter sometimes used in describing filter media is d_{90}. The d_{90} media diameter refers to the sieve size that retains 10 percent of the media and passes 90 percent.

Garnet Sand

Garnet sand is made up of base metal silicates that are harder and more dense than the material in the regular sand. Although the grains of garnet sand are generally smaller than regular filter sand, they tend to stay at the bottom of the filter because of their greater density.

Granular Activated Carbon

GAC may be used in rapid gravity filters for the removal of tastes and odors or hazardous organic compounds. It has superior adsorptive properties because of its high relative surface area: one pound of GAC has a surface area of 150 acres. However, GAC loses its effectiveness after a period of several years, and then must be either regenerated or replaced with a new medium.

Diatomaceous Earth

DE is a powdery siliceous material that is mined from deposits of fossil diatoms. It is used in specialized DE filters, as discussed above, and has the disadvantage of producing large amounts of sludge that require disposal.

Greensand

Glauconite, or manganese, **greensand** is a specialized filter medium most commonly used to remove iron and manganese. This filter medium incorporates a combination of oxidation and adsorption, along with simple filtration, to remove these metals. Greensand grains have a smaller diameter than silica sand, so head loss can build up quickly under heavy loading. Adding a layer of anthracite over the greensand can increase the length of filter runs. Manganese greensand filters for iron and manganese removal are discussed in Chapter 11.

FILTER BACKWASHING

Backwashing is the process of cleaning the filters by reversing the flow of water through them. The water used for backwashing is usually filtered water and should represent a small percentage of the plant's production. Filter backwash should not exceed 5 percent of the daily production of the water treatment plant under the worst case conditions, and ideally should be no more than 2 to 4 percent of daily production. If this level of water use is exceeded, the operator should thoroughly evaluate the operation and equipment to determine the cause of the problem and correct the excessive waste of water.

Backwash Flow Rates

Sufficient water flow must be provided during backwash to achieve **fluidization** of the filter bed. This means that the flow of water must be sufficient to lift all of the filter media, including the upper layer of fine gravel, so that it can become agitated enough to clean it.

Conversely, the flow rate must not be so great that the media is removed with the backwash water. The amount of water required to backwash various types of media depends on the size and density of the medium. The following table shows minimum backwash fluidization velocities required for sand and anthracite according to the size of the particles:

MINIMUM BACKWASH FLUIDIZATION VELOCITIES

d_{90} size, mm	Required Backwash Rate at 25 °C (gpm/ft^2)	
	Anthracite	Sand
2.83	37.0	--
2.38	30.0	--
2.00	24.0	41.0
1.68	20.0	33.0
1.41	15.7	27.0
1.19	12.5	21.0
1.00	9.9	16.4
0.84	8.4	12.6
0.71	7.0	9.0
0.60	--	6.3
0.50	--	5.4
0.42	--	4.0

d_{90}, size rating for granular media indicating that 90% of the media grains have diameters smaller than this number; gpm/ft^2, gallons per minute per square foot
Source: *Water Treatment Plant Design for the Practicing Engineer*, R.L. Sanks, 1980.

Calculate the backwash pumping rate required to backwash a tank 15 square feet (ft^2) in area if the desired backwash rate is 20 gallons per minute per square foot (gpm/ft^2).

20 gpm/ft^2 x 15 ft^2 = 300 gpm

A means of confirming the backwash rate is to measure the **rate of rise**. By measuring the rate at which the water rises on the walls of the filter basin, the operator can determine whether the backwash rate is adequate for complete fluidization of the media.

Calculate the rate of rise (in inches per minute) required to accomplish the backwash rate calculated in the previous example.

Known: Backwash rate = 300 gpm; area of basin = 15 ft^2

First, determine gallons per inch of water in the basin:
15 ft^2 x 1 foot depth x 7.48 gallons/cubic foot ÷ 12 inches = 9.35 gallons per inch

Rate of Rise = 300 gpm ÷ 9.35 gallons per inch = **32.09 inches per minute***
(*round this quantity to 32 inches per minute)

Backwash Water Temperature

The temperature of the backwash water influences its density and subsequent lifting capacity for bed fluidization. Warmer water is less dense, requiring a higher flow to achieve the same fluidization energy as colder water. The following table shows the correction factor that the backwash flow rate should be multiplied by relative to 25 °C:

BACKWASH RATE TEMPERATURE CORRECTION FACTORS

Temperature, °C	Multiply 25 °C value by
30	1.09
25	1.00
20	0.91
15	0.83
10	0.75
5	0.68

Source: Sanks, R.L., *Water Treatment Plant Design for the Practicing Engineer*, Ann Arbor Science Publishers, Inc., 1980.

Backwash Water Recycling

After backwashing the backwash water is often recycled back to the headworks of the plant for reprocessing, or may be discharged to a wastewater system or outdoor settling pond. Backwash water, particularly from surface water treatment plants, has been found to be a concentrated source of microbial contaminants such as *Giardia* cysts and *Cryptosporidium* oocysts. A new Federal "Filter Backwash Rule" is being developed that may restrict recycling of filter backwash water to prevent recycling of these microbial contaminants to the treatment system.

Backwash Initiation

Backwashing is done whenever the filter reaches a certain loss of head, **turbidity breakthrough** or an increase in particle counts, or after a specified time period in which the filters become fouled. Backwashing can be actuated by an automatic monitoring system using any of these variables. For example, a common monitoring system will include on line turbidity monitors and head loss sensors. When either preset turbidity limits or head loss reaches a maximum pressure differential (usually in the range of 6 to 10 feet) between the inlet and outlet of the filter, the backwash cycle is initiated automatically. Alternatively, backwash can be initiated by a timer, flow meter, or manually when the operator has determined that it is time to clean the filters.

Bed Expansion

Bed expansion, the expansion of the media during backwashing, is an important parameter to determine if the backwash rate has been set correctly. Most filter operational guidelines recommend a bed expansion of 15 to 20 percent to ensure the media is being adequately cleaned while not being lost from the filter by excessive backwash flow. This is particularly problematical for light filter media such as anthracite or GAC. Bed expansion can be calculated by measuring the distance in inches between the top of the filter and the surface of the media before backwashing, then again while the backwash is in progress. A percentage formula is used to calculate the result as shown in the following example:

$$\text{Filter Bed Expansion (\%)} = \frac{(A - B) \times 100\%}{\text{Depth of Media}}$$

Where:
A = Distance from top of filter tank to media before backwash
B = Distance from top of filter tank to expanded media during backwash

Example:
A = 20 inches
B = 15 inches
Media Depth = 30 inches

$$\textbf{Filter Bed Expansion} = \frac{(20 - 15)}{30} \times 100\% = \mathbf{16.7\%}$$

In the above example, the bed expansion is acceptable. If the bed expansion is not within the recommended design range, then the backwash flow rate should be adjusted and the bed expansion recalculated until the correct rate is established.

Some filter designs use a high-pressure (greater than15 pounds per square inch) water source for filter backwashing. A pressure reducing valve (PRV) on the backwash line must be installed to reduce the backwash water pressure sufficiently to avoid disrupting the filter media. This practice is risky because a failure of the PRV could result in mixing the media and support gravel, necessitating removal and regrading of the filter media.

Air Binding

Shortened filter runs and destratification of filter media can result from an air bound filter. Filter feed water may be saturated with dissolved oxygen, carbon dioxide or other dissolved gases, such is common with cold water in Alaska. During filtration, as the filter builds up head loss and the water begins to warm up, reducing the solubility of the dissolved gases, gas bubbles may begin to accumulate inside the filter media. Head loss builds up rapidly as the media voids become filled with gas, necessitating frequent backwashing. During backwashing the entrained gas is released, often disrupting the filter media.

Air binding can be minimized by maintaining at least 5 feet of water above the surface of the unexpanded bed. When a filter is operated to a head loss that exceeds the head of water over the top of the media, air will be released. More frequent backwashing may provide some limited relief for this problem. Some operators “probe” their filters with rods or other tools to release the gas bubbles during filtration. This procedure is not recommended because it forces open channels through the filter media that allow turbidity to pass through the filter. During spring, when surface water sources begin to warm up, air binding can become particularly troublesome.

Surface Wash

In conjunction with backwashing, agitation of the filter bed surface is necessary to fully clean the media. Filter **surface wash** is accomplished by the use of water or air surface scour nozzles that direct a strong stream of water or air onto the surface of the filter bed during backwashing. The surface wash usually is started before bed expansion so that encrusted material on the surface is broken up first, allowing better mixing during backwashing.

Air Scour

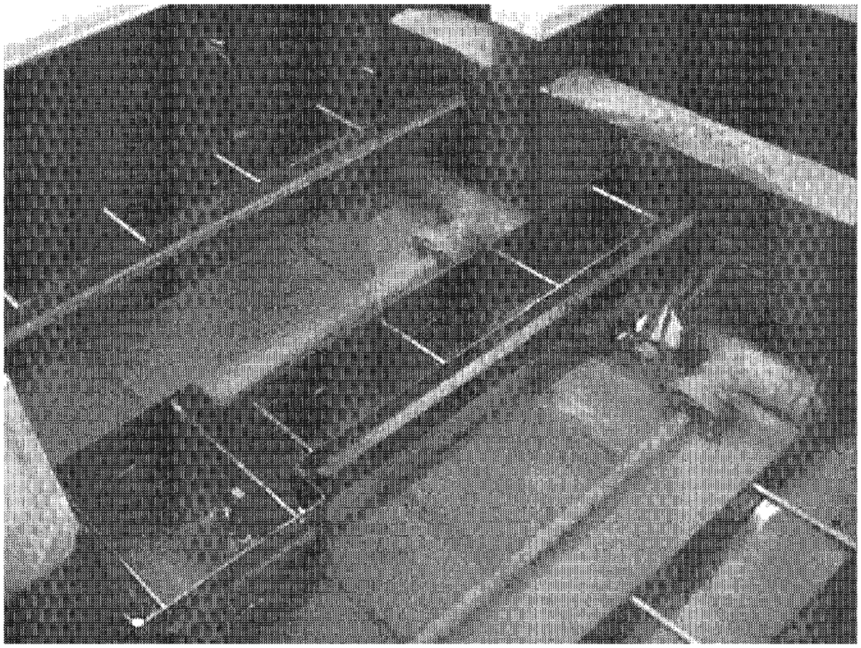
A common means to enhance filter media cleaning is the addition of an **air scour** system consisting of a low-pressure air blower that discharges into the backwash line at the point of entry to the filter underdrain. Air scour typically is done during the early stage of filter backwashing, either before bed expansion or during a low-rate initial backwash flow in filters with dual backwash rate pumping systems. The volume of air delivered to the media is controlled to allow effective agitation of the media without disruption of the media layers.

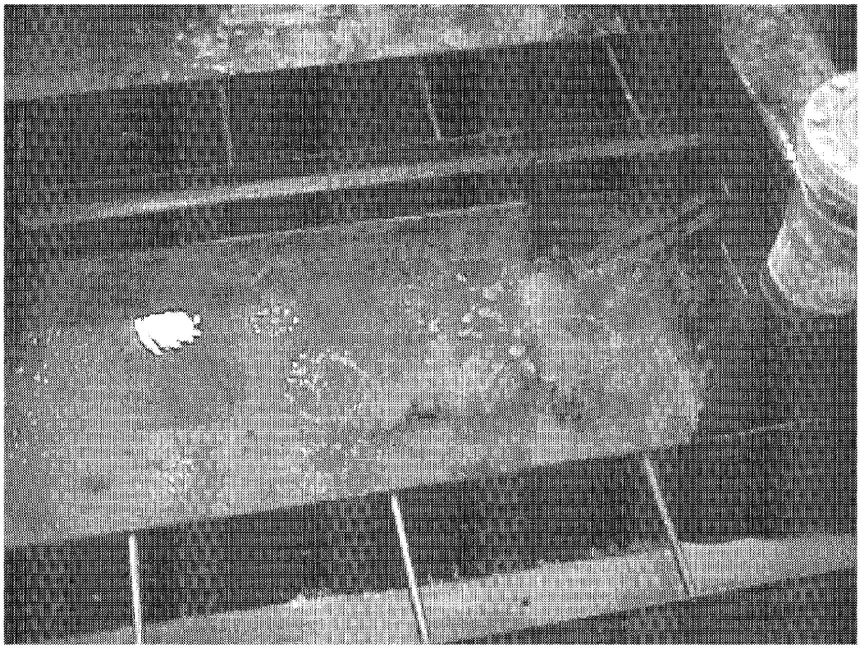
Filters can be seriously damaged by uncontrolled slugs of air introduced during backwashing. The impact of the air can overturn the support gravel and mix it with the media. If this occurs, the filter media and support gravel will have to be removed, regraded, and restratified by hand. Sources of unwanted slugs of air during backwashing include stuffing box leakage in a rate-of-flow control valve if the valve and valve operator are placed above the hydraulic gradient of the filter. Another possible source is air leakage in stuffing boxes in a surface wash system. Both of these problems can be minimized by maintaining stuffing boxes at elevations below the hydraulic gradient of the filter when the filter run is in progress.

Mudballs

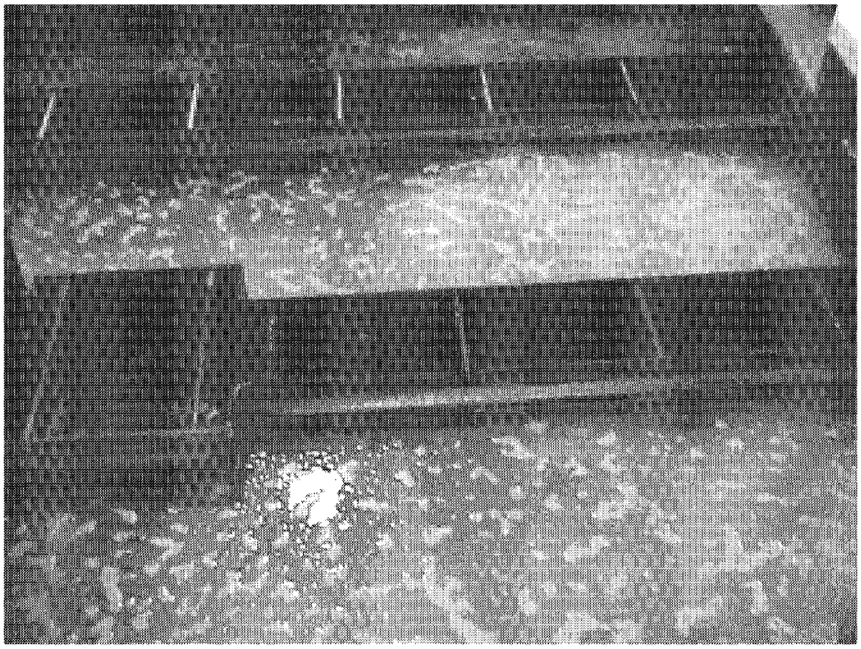
Regular and thorough backwashing is critical to avoid a build up of **mudballs** inside the filter media. Mudballs are masses of floc, turbidity, and filter media that can build up inside the media when backwash flow rates are too low. Mudball formation often begins as an artifact of overdosing coagulants or flocculants, which leaves unreacted chemicals in the filter feed water. The highly charged coagulants or flocculants then bind with the filter media rather than with turbidity in the water, ultimately forming small globs that can grow to be the size of a marble.

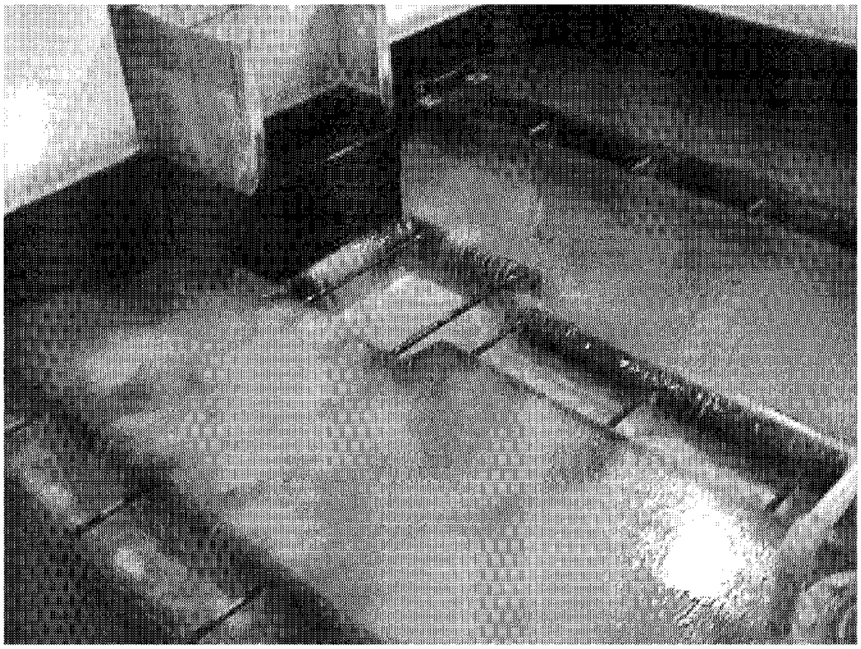
Mudballs are usually heavier than the lighter media layers and will migrate downward during media stratification as backwashing is being completed. As the mudballs migrate deeper into the media, they continue to grow and interfere with the passage of water through the filter. Premature head loss and turbidity breakthrough result from the formation of large quantities of mudballs. Operators should check for mudballs by coring the filter media with a section of pipe or by digging down into the media with a spade or small shovel. Mudballs can be readily identified by sifting the media with a fine screen.





Filter backwashing sequence at the Golden Heart Utilities water treatment plant, Fairbanks, Alaska.
Top: view of filter before backwashing, showing the wash-water troughs.
Bottom: backwash initiation with water beginning to rise through the filter.





Continuation of backwashing sequence at Golden Heart Utilities.
Top: water continuing to rise up through the filter.
Bottom: backwash water overflowing into the wash-water troughs.

To correct a mudball problem, the chemical dosages in the coagulation and flocculation steps should be checked to ensure that excess chemicals are not being used. In addition, short circuiting or other problems in a clarifier may be allowing excess floc to enter the filter. Thorough backwashing with proper surface wash and air scour will help to minimize mudball formation.

Filter Cracking

Filter cracking is the formation of cracks in the filter media when the media become overly compacted and dry out. Filter cracks look like cracks in the mud at the bottom of a dried up lake bed and are caused by infrequent backwashing. The cracks provide conduits through which turbid water may flow directly to the effluent without proper treatment, thus decreasing the efficiency of the filter.

Filter Rinsing and Ripening

After backwashing, the filter is rinsed by channelling the effluent to a waste collection container and then possibly back to the headworks of the plant. This **filtering to waste** process continues until the turbidity in the effluent reaches an acceptable level. This can take anywhere from 2 to 20 minutes, depending on the type of filter and media and the treatment processes that preceded filtration. The elevated turbidity in the filter effluent immediately following backwashing is caused by filtered material that remains in the bed after backwashing and to the relatively high flow rates through the filter upon resuming flow through the clean filter.

Filtering to waste enhances **filter ripening**, an important process to optimize filter performance. However, in many plants lengthy periods of filtering to waste may not be affordable. Increasing the time between the end of backwashing and placing the filter back into service is another way to maximize filter ripening. A filter that is left out of service for four hours after backwashing will produce a higher-quality effluent than a filter that is placed back into service immediately after backwashing[1].

Polymer Addition During Backwash

The addition of polymers or other filter aids to the backwash water can reduce the initial turbidity spikes during filter ripening. Polymer addition to the backwash water also can extend

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[1] "Optimizing Your Plant's Filter Performance," Nick Pizzi, *Opflow*, American Water Works Association, Volume 22, No. 5, May 1996.

filter operation before breakthrough occurs. Polymer should be added during the first 5 to 7 minutes of the backwash cycle. At a dosage of 0.1 to 0.15 mg/L, polymer addition has been shown to reduce the initial turbidity breakthrough by one half[1].

CITY OF WRANGELL, ALASKA

The City of Wrangell, Alaska, recently commissioned a new water treatment plant with a capacity of 1.3 million gallons per day (MGD). The new plant uses two filter systems: a roughing filter and a slow sand filter. These filtration methods are complemented by pH adjustment, ozonation, and chlorination. Because of the large surface area requirements of slow sand filters, the plant site occupies about 1½ acres. This plant is the first of its kind in Alaska.

The raw water in Wrangell is highly acidic, the color of tea, and high in organics and suspended particles. The surface water source originates in the muskeg of the Tongass rain forest. The water use in Wrangell was three times the national average, because residents would run the water to try to clear out the suspended solids. The high acidity of the water leached copper from pipes and turned laundry green.

The previous water treatment system consisted only of disinfection by chlorination, with no filtration. The chlorine residual in the distribution system was 5 mg/L, ten times the current level. In spite of the high organic content, the formation of disinfection by-products was not a major problem, most likely because of short contact time before distribution. Testing for trihalomethanes consistently yielded concentrations below the current MCL of 0.1 mg/L.

The new system, which went on line in July 1999, was made possible by grants from ADEC and the Alaska Department of Administration. Upgrading the water treatment facility was necessary to bring it into compliance with the provisions of the Surface Water Treatment Rule, which requires filtration of surface water supplies to remove pathogenic microorganisms. A Bellingham-based company, Wilson Engineering, provided preliminary plans and pilot tested several alternatives for water treatment efficiency and cost effectiveness before recommending the alternative now in use in Wrangell.

Opposite, foldout: plan and sectional process flow schematics of the City of Wrangell's new water treatment plant. Courtesy of Wilson Engineering and Greg Scheff and Associates.

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[1] *Technologies for Upgrading Existing or Designing New Drinking Water Treatment Facilities*, U.S. Environmental Protection Agency, 1990.

pH Adjustment, Ozonation, and Chlorination

The first treatment at Wrangell's new facility is pH adjustment with a dosage of 8 mg/L of soda ash to raise the pH to 7.4. After pH adjustment, ozone is added to oxidize the organic material in the water. Ozone is applied at a dosage of 10 mg/L into a contactor with a contact time of 10 minutes. After filtration, the treated water is dosed with approximately 1.5 mg/L of sodium hypochlorite generated on site with a hypochlorite generator, providing 0.5 mg/L chlorine residual in the system.

Roughing Filters

In the pilot tests, minerals in the water reacted with the ozone to form floc in amounts that would require frequent scraping of the schmutzdecke in the slow sand filter. For this reason two roughing filters were added to reduce the load to the slow sand filters. Each roughing filter has 4 feet of 4- to 8-mm fine gravel media with 2 feet of supernatant freeboard over the top of the media layers. Each of the roughing filters has a surface area of 16 by 27 feet, or 432 ft^2, and will process 900 gpm at a flow rate of about 1.15 gpm/ft^2.

Slow Sand Filters

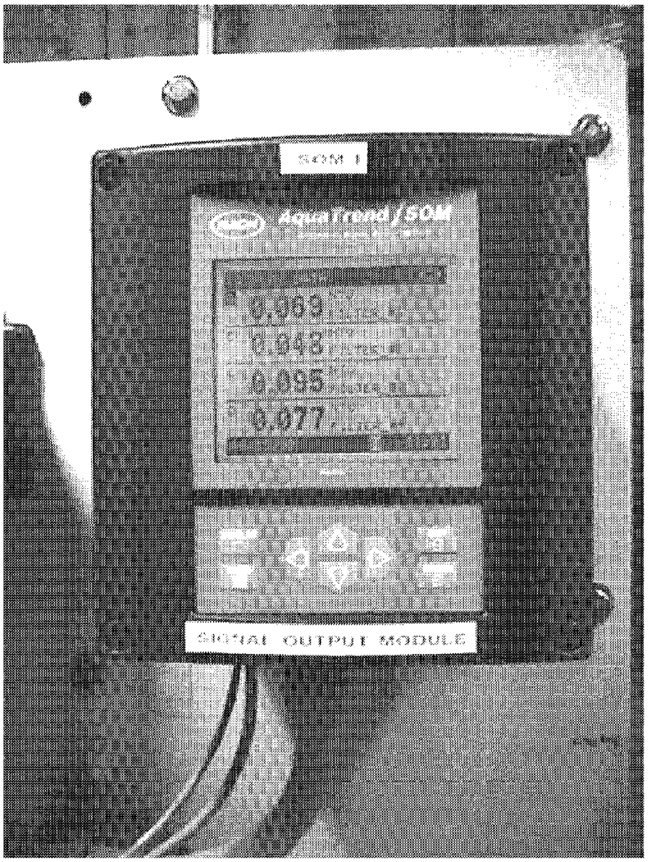
The Wrangell water treatment facility has four slow sand filters, each with a surface area of 3,000 ft^2 and a flow rate of 0.1 gpm/ft^2. These filters are designed to produce 1.3 MGD with three filters operating at one time. The filters have 3.5 feet of filter sand, and will operate with 6.5 feet of supernatant freeboard above the sand layer. The finished water is chlorinated and stored in a 424,000-gallon clearwell.

OPERATIONS MONITORING

In monitoring the filtration process, the plant operator must be aware of several parameters: turbidity, flow rate, and head loss. In addition, a particle counter is a valuable tool for monitoring filter operations. Abrupt or unexpected changes in any of these parameters could indicate operating problems. Generally, turbidity, head loss, or particle counts are used to determine when the filter is ready to be backwashed.

Turbidimeters

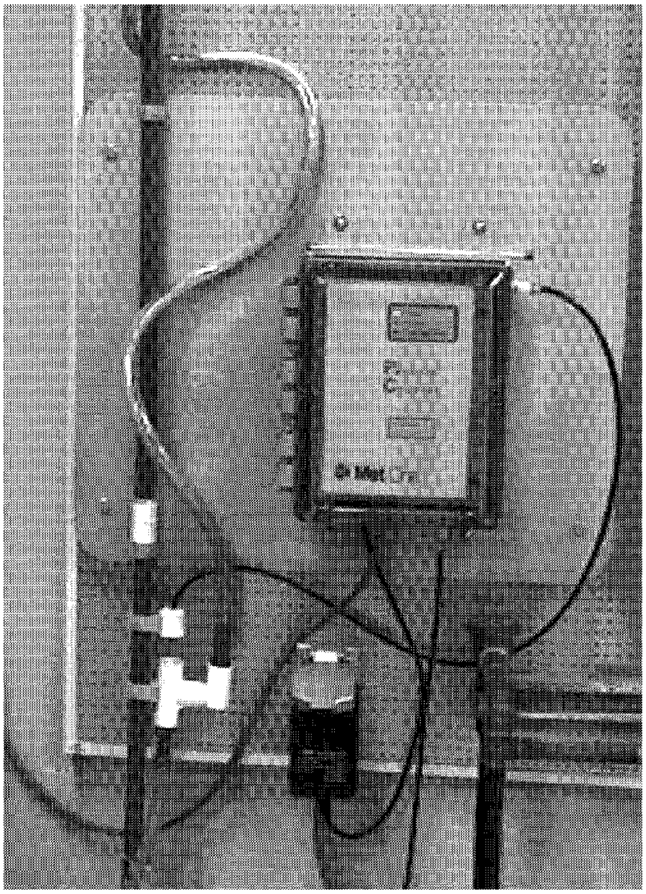
An on-line turbidimeter is essential for continuous monitoring of filter effluent turbidity. This should also be compared with the raw water turbidity, to assess any effects of changes in the raw water conditions. A predetermined maximum turbidity value, such as 0.1 NTU should be set as the goal for the filter effluent, and any exceedances of this value indicate that the operator should evaluate possible operational problems. Excessive turbidity in the filter effluent could arise from problems in the coagulation process, such as incorrect chemical dosage or inadequate flash mixing. The problem could also be in the filtration process itself, possibly caused by improper filter aid dosage, inadequate backwashing, or problems with the filter media.



Hach Aquatrend® Interface datalogger, Ship Creek Water Treatment Facility, Anchorage, Alaska. This instrument records data from the on-line turbidimeters and particle counters that monitor the four filters at the treatment plant.

Particle Counters

On-line particle counters provide a rapid means of counting particles in the water in selected size ranges. Both influent and effluent sensors are normally provided, with the effluent from each filter being separately monitored as is done with turbidity. It is becoming increasingly common to continuously monitor both turbidity and particle counts at the same time because these two parameters provide different but complementary information about the water quality. Common particle size ranges monitored in filtration systems are 2 to 5 microns (μm) (approximately the size of *Cryptosporidium* oocysts), 5 to 15 μm (the size of *Giardia* cysts) and greater than 15 μm. Particle counters are sufficiently sensitive to detect fine particle breakthrough even before a turbidimeter begins to register any change.



An example of an on-line particle counter.

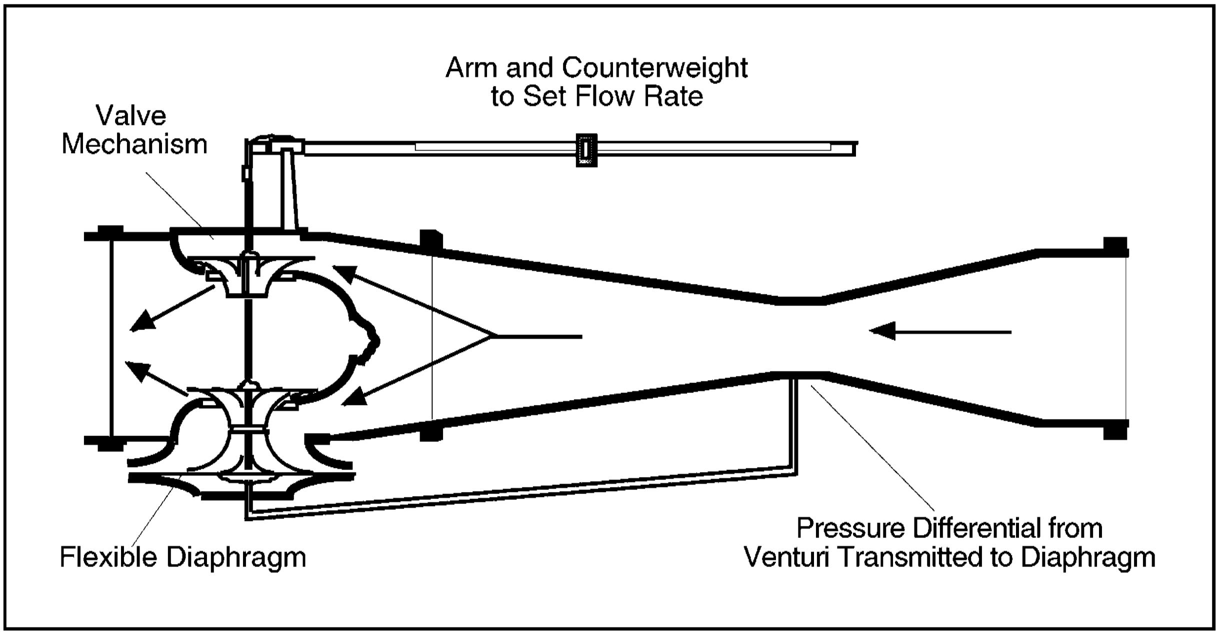
Head Loss Indicators

A head loss indicator in the filtration system will monitor the steady buildup of head loss in the filter and alert the operator to excessive head loss, which may be caused by air binding in the filter or too rapid flow of water through the filter media. Head loss indicators are essentially a pressure differential measurement system reading in feet of head. As the head loss builds, the pressure differential is increasing. At a predetermined level, the filter must be backwashed.

If premature head loss is problematical, one "quick fix" for sand filters is to add about 6 inches of anthracite coal to the surface of the media. This will increase the filter run and loading rate and usually improves the filter effluent quality. As the length of the filter run increases, less backwash water is needed to clean the filter.

Rate-of-Flow Controller

The flow rate of water through the filter should be maintained at a consistent level. If the flow rate is too high or too low, the result could be turbidity and particle breakthrough or air binding of the filter, respectively. A rate-of-flow controller is a device that will regulate the flow of water through the filter and help avoid such problems.



An example of a rate-of-flow controller.

SAFETY AND MANAGEMENT

As with any water treatment process, filtration has its own set of safety and management concerns. Record-keeping practices are especially important, because long-term information is an irreplaceable tool for tracking and trouble shooting operational problems.

Safety Considerations

Hand rails should be installed to prevent falls into the filters. Life rings or poles also should be available for quick rescue should an operator fall into a filter. Filter tankage is generally considered to be a confined space, so entry for maintenance purposes should follow appropriate confined space entry guidelines.

In addition, work areas could become slippery and personnel should be careful to avoid slips and falls. Polymers used as filter aids are slippery, and containers found to be leaking should be repaired or replaced as soon as possible.

Record Keeping

Preparation and maintenance of filtration records is an important operational responsibility. ADEC requires certain types of filtration records, particularly filter monitoring data from surface water treatment systems to be reported monthly. Filter records should include influent and effluent turbidity monitoring, filter flow rates, head loss data, filter aid dosages, backwash logs and other operational notes.

Utilities should develop and maintain standard log forms that are used by all operators. This information can be computerized by inputting the data onto a form on a spreadsheet or data base program. In more automated filter systems, a SCADA (supervisory control and data acquisition) program may provide automatic data logging. Regardless of the type of computerized data management system in use, it is important to provide both electronic backup files and hard copy (printed) data. Printed data forms should be signed and dated by the lead operator or shift supervisor to certify that the data are accurate and representative of the electronic files.

Regulations

The SWTR provisions of 1986 require that surface water sources be filtered and disinfected, in effect providing two "barriers" to microbial contamination. Under the SWTR, filtration must achieve a 2-log removal of *Giardia lamblia* cysts, and filtration and disinfection combined must provide at least a **3-log removal** (99.9 percent) of *Giardia lamblia* cysts and at least a **4-log removal** (99.99 percent) of viruses. Different filtration systems are rated on their ability to achieve various log removal levels.

The following formula is used to calculate log removal from filter particle count data:

$$\text{Log removal} = \left|\log_{10}\left(\frac{100 - \%\ \text{removal}}{100}\right)\right|$$

Example: Particle counts (5-15 μ) of filter influent = 12,500/ml

Particle counts (5 -15 μ) of filter effluent = 125/ml

$$\textbf{\% Removal} = \frac{(12{,}500/\text{ml} - 125/\text{ml})}{12{,}500/\text{ml}} \times 100\%$$

$$= \mathbf{99\%}$$

$$\textbf{Log Removal} = \left|\log_{10}\left(\frac{100-99}{100}\right)\right|$$

$$= |\log_{10} 0.01|$$

$$= |-2.0| = \mathbf{2.0}$$

Log removals for various types of filtration systems are provided in the *Alaska Drinking Water Procedures Manual*, ADEC, 1993. The expected log removals for filtration systems and required additional inactivation from disinfection are shown in the following table:

EXPECTED LOG REMOVALS FOR DIFFERENT FILTRATION METHODS AND MINIMUM ADDITIONAL INACTIVATION RECOMMENDED

Filtration Type	Expected Log Removals		Recommended Additional Log Inactivations with Disinfection	
	Giardia lamblia	Viruses	*Giardia lamblia*	Viruses
Conventional	2.5	2.0	0.5	2.0
Direct	2.0	1.0	1.0	3.0
Slow Sand	2.0	2.0	1.0	2.0
Diatomaceous Earth	2.0	1.0	1.0	3.0

An Enhanced SWTR is being developed at this time under the requirements of the 1996 Safe Drinking Water Act Amendments that will require even more stringent removals and effluent turbidity limits. Also, a filter backwash recycle rule is being developed that will affect the reuse of backwash water. Operators should be aware of the new rule developments because their facilities will be directly affected by them when they are ultimately adopted by the ADEC in Alaska. Sources of information on rule development are the American Water Works Association, the ADEC, and the U.S. Environmental Protection Agency.

REVIEW QUESTIONS

1. What is the purpose of filtration?
   ____

2. List four filtration mechanisms:
   a. ____
   b. ____
   c. ____
   d. ____

3. What is the difference between conventional and direct filtration?
   ____

4. The most common type of filter vessel used for direct filtration is a
   ____

5. Slow sand filters have filtration rates _______ to _______ times slower than rapid sand filters, and use a biological slime layer called a _______________ as the primary filtration mechanism. Another name for this type of filtration mechanisms is _______________ filtration. ADEC allows a turbidity standard of ________ NTU for slow sand filters because of their efficiency in removing ________________ .

6. Diatomaceous earth filters use a slurry of fine siliceous media added to the filter initially as a ___________________________ and then continuously as a ____ during the filter run. The ADEC standard for DE filters for surface water sources is ________ NTU.

7. What are five types of filter media?
   a. ____
   b. ____
   c. ____
   d. ____
   e. ____

8. Two parameters used to specify filter sand are:
   a. ____
   b. ____

9. What is the purpose of backwashing?
   ____
   How is it done?
   ____

10. Sufficient water must be provided to effect proper bed ___________________. If the media used is relatively light such as anthracite coal the backwash flow rate should be ___________ than for heavier media such as garnet sand. For

relatively cold backwash water (5° C), the backwash flow rate should be only __________% of the backwash flow rate used at 25 °C.

11. List five methods for determining when to initiate a filter backwash cycle:
    a. ____
    b. ____
    c. ____
    d. ____
    e. ____

12. Calculate the expansion of a filter bed from the following data:
    Distance from top of filter tank to unexpanded bed = 24 inches
    Distance from top of filter tank to expanded bed = 10 inches
    Filter media depth = 36 inches

13. Is the bed expansion calculated above within an acceptable range?
    ____

14. What is a possible result of this level of bed expansion?
    ____
    ____

15. How can air binding be minimized?
    ____

16. An unacceptable practice to release air from filters that can impact filter effluent turbidity is
    ____.

17. Two mechanical methods to improve the efficiency of filter backwashing are
    ____ and
    ____.

18. Mudballs are made up of ____________, ____________ and ____________.
    One of the major causes of mudball formation is
    ____.

19. How does an operator determine the length of the filter rinse (filter-to-waste) cycle?
    ____

20. The SWTR requires _____-log removal of ________________

and _____-log removal of _________________.

21. Calculate the log removal of a filter from the following data:
    a. Particle counts (5-15µ) of filter influent = 22,000/ml
    b. Particle counts (5-15µ) of filter effluent = 110/ml

Chapter 10

Softening

Alkalinity Tests
Total Hardness Tests
Magnesium Tests
Carbon Dioxide Tests
pH Tests
Jar Tests
Langelier Saturation Index Determination
Possible Operating Problems

Safety and Management

Safety Considerations
Record Keeping
Regulations

Review Questions

Chapter 10 – Softening

INTRODUCTION

The primary purpose of water softening is to reduce the content of dissolved minerals to minimize scale formation. **Softening** may be necessary if the water source has a high concentration of dissolved minerals, commonly known as **hardness**. Typically, only groundwater sources contain sufficient hardness to warrant softening. The minerals that cause hardness contain soluble **divalent metallic cations**, most commonly calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. Other metal ions may also contribute to hardness, but usually not to a significant extent. The dissolved bicarbonate salts of calcium and magnesium ($Ca[HCO_3]_2$ and $Mg[HCO_3]_2$), and to a lesser extent, calcium and magnesium carbonates ($CaCO_3$ and $MgCO_3$) and magnesium sulfate ($MgSO_4$) can form thick deposits on the interior walls of pipes and other system components. A common problem is that this type of scale functions as an insulator on hot water heating elements, increasing energy used and ultimately causing failure of the elements. Hardness in water is also objectionable to customers because soap reacts with the calcium or magnesium in the water, leaving a sticky film and making it necessary to use more soap in showering, dishwashing, and clothes washers. In addition, certain industries are not able to use water containing appreciable hardness.

Public acceptance of hardness varies from one community to another, and because hardness is not considered a health issue, the ways in which utilities address hardness vary. Moreover, in recent years, detergents and soaps have been developed that do not react with hardness.

In many geographical areas, especially those using groundwater sources, hardness may be a problem. In these areas, water treatment plants may use softeners to remove hardness from water before delivery to customers. Because of the added expense, some systems with hard water may not include softening in their treatment process, and sometimes individual homes and businesses in such areas will install their own softeners. One of the benefits of water softening is the incidental removal of iron and manganese, and ion exchange softening has proven effective at removing radium, barium, and strontium.

HARDNESS

Total hardness may be expressed in terms of calcium hardness plus magnesium hardness. Using this distinction, all calcium compounds, including $CaCO_3$, $Ca(HCO_3)$, calcium sulfate ($CaSO_4$), and calcium chloride ($CaCl_2$), contribute to the calcium hardness component. All compounds containing magnesium make up the magnesium hardness component.

Alternatively, hardness may be expressed in terms of carbonate versus noncarbonate hardness, in which total hardness is the sum of the two. Using this distinction, the calcium and magnesium carbonates and bicarbonates are considered to contribute to carbonate hardness, whereas the other salts of calcium and magnesium, such as sulfate and chloride, contribute to the noncarbonate hardness component. When hard water is boiled, CO_2 is driven off, increasing the pH of the water and causing calcium and magnesium carbonates to precipitate out of the water. This forms the scale deposits on tea kettles. Noncarbonate hardness cannot be removed or precipitated from water by heating or boiling.

Regardless of its source, hardness in water is expressed in terms of milligrams per liter as calcium carbonate ($CaCO_3$). The conversion from concentrations of calcium and magnesium ions to hardness in milligrams per liter as $CaCO_3$ is derived from their relative atomic and molecular weights. The atomic weights of Ca, C, and O are 40.08, 12.01, and 16.0, respectively. Thus:

The molecular weight of $CaCO_3$ is $40.08 + 12.01 + 3(16.0) = 100.09$

To determine the equivalent concentration of $CaCO_3$ from the concentration of calcium ions in the water, the calcium concentration is multiplied by the ratio of the molecular weight of $CaCO_3$ and the atomic weight of Ca, which is:

$$100.09 \div 40.08 = 2.497 \text{ (round to 2.5)}$$

To determine the equivalent concentration of $CaCO_3$ from the concentration of magnesium ions in the water, the magnesium concentration is multiplied by the ratio of the molecular weight of $CaCO_3$ and the atomic weight of Mg, which is:

$$100.09 \div 24.31 = 4.117 \text{ (round to 4.1)}$$

Thus, the hardness contributed by calcium and magnesium ions in a water may be expressed by the following formula:

$$\text{Hardness, in milligrams per liter as } CaCO_3 = 2.5\ [\text{Ca, mg/L}] + 4.1\ [\text{Mg, mg/L}]$$

Calculate the hardness in milligrams per liter as $CaCO_3$ of a water with a calcium concentration of 132 mg/L and a magnesium concentration of 15 mg/L.

Hardness = (132 x 2.5) + (15 x 4.1) = **391.5 mg/L as $CaCO_3$**

Alkalinity is expressed in the same way as hardness, and the carbonate hardness and alkalinity of a water are the same quantity. The total hardness may also then be expressed as the alkalinity plus the noncarbonate hardness. On the basis of total hardness measurement, water may be classified as soft, moderately hard, hard, and very hard. These classifications by no means illustrate the possible extremes; water from wells in the Denali area is 1,500 milligrams per liter (mg/L) as $CaCO_3$ in total hardness.

HARDNESS RATING SCALES		
Classification	mg/L as $CaCO_3$[1]	mg/L as $CaCO_3$[2]
Soft	<50	0-60
Moderately hard	50-150	60-120
Hard	150-300	120-180
Very hard	>300	>180

1 According to Sawyer, C.N., 1960, *Chemistry for Sanitary Engineers*, McGraw-Hill Publishing Company, New York
2 According to Briggs, J.C., and Ficke, J.F.,1977, *Quality of Rivers in the United States, 1975 Water Year*, USGS Open-File Report 78-200, Reston, Virginia

Another expression of hardness concentration that is rarely used today, other than in ion exchange softening, is grains per gallon, or more simply, **grains**, where 17.1 mg/L as $CaCO_3$ equals 1 grain. Typically, the exchange capacities of resins used in ion exchange are expressed in kilograms per cubic foot of media.

Two common types of processes are used for removing hardness from water: **precipitation** and **ion exchange**. Membrane separation technology, discussed in Chapter 13, can also be used as a softening method.

SOFTENING BY PRECIPITATION

Several different chemicals may be used in the precipitation softening method, depending on the type of hardness and other raw water characteristics. In precipitation, the hardness-causing calcium and magnesium carbonates or bicarbonate salts are converted to insoluble forms that can be removed by sedimentation and filtration. After precipitation, the solids are removed by sedimentation and filtration. Precipitation softening is usually included in the conventional treatment process, either as or in addition to the primary coagulation method.

Lime Softening

One of the classical softening methods is **lime softening**. Lime softening works by precipitation of hardness-causing chemicals, such as calcium bicarbonate ($Ca[HCO_3]_2$, out of the water. It is used if the water contains very little or no magnesium hardness. Lime ($Ca[OH]_2$) added to the water reacts with the ($Ca[HCO_3]_2$ and causes the precipitation of $CaCO_3$ by the following equation:

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2CaCO_3 + 2H_2O$$

For the $CaCO_3$ precipitate to form, the pH of the water must be adjusted to 9.4. If the water contains a high concentration of CO_2, the pH may need to be raised or additional lime added to remove the excess CO_2 and stabilize the $CaCO_3$. Because excess CO_2 in water will react with lime, it is sometimes more economical to aerate the water to remove some of the CO_2 before adding lime.

Two kinds of lime are used in lime softening: hydrated lime ($Ca[OH]_2$, also called slaked lime) and quicklime (CaO, also called unslaked lime). Quicklime is hydrated by rapid mixing with water before adding to the water to be treated. This reaction is **exothermic**, requiring care in handling.

Lime–Soda Ash Softening

If a component of noncarbonate hardness is present in the water, the use of both lime and soda ash (sodium carbonate, Na_2CO_3) is necessary. The soda ash provides carbonate ions for the formation and precipitation of $CaCO_3$. Soda ash substitutes carbonate ion (CO_3^{2-}) for sulfate ion (SO_4^{2-}), forming sodium sulfate, or for chloride ion (Cl^-), forming common table salt, as illustrated in the following two examples:

$$CaSO_4 + Na_2CO_3 \rightarrow CaCO_3 + Na_2SO_4$$

$$CaCl_2 + Na_2CO_3 \rightarrow CaCO_3 + 2NaCl$$

Lime softening and lime–soda ash softening are typically done in what is known as the single-stage process, in which both chemicals are added at the same time.

Excess-Lime Treatment

If the magnesium hardness exceeds about 40 mg/L, additional lime may be used in addition to the lime–soda ash process to raise the pH to 10.6 and precipitate the magnesium out of the water as magnesium hydroxide ($Mg[OH]_2$).

Excess-lime softening may be performed in single or double-stage processes, but is more effective in the double-stage process, in which the excess lime is added first to raise the pH enough to precipitate $Mg(OH)_2$ and then Na_2CO_3 is added. Another variation of the excess-lime treatment is called split treatment, in which some of the water bypasses the excess-lime treatment and is later mixed back in with the softened water to avoid over-softening (very soft water is usually corrosive). This method also requires a smaller amount of chemicals.

Caustic-Soda Treatment

Caustic soda (sodium hydroxide, NaOH) will remove both carbonate and noncarbonate hardness from water and may be used in place of lime or soda ash. Its advantages are that it produces less sludge and is easier to handle than lime, but it has the disadvantages of being more expensive and increasing the total dissolved solids in the finished water. Neither excess-lime nor caustic-soda treatments are used for softening in Alaskan water treatment operations.

Coagulant Addition in Lime Softening

To enhance the formation of a more settleable floc from the fine particles of calcium and magnesium precipitates, a polymer or other type of coagulant may be added to the water during the lime softening process. This helps to enhance sedimentation and provide for longer filter runs after lime softening.

Recarbonation

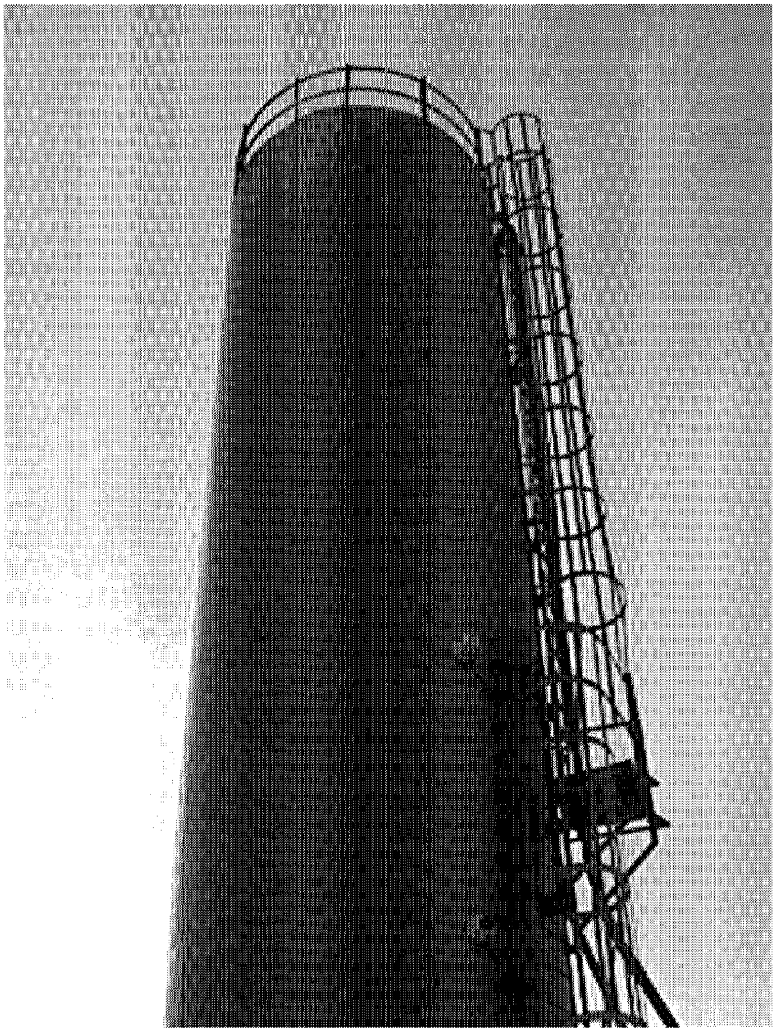
Softening produces an unstable water with an excessively high pH. Such water has an objectionable taste, fouls filter sand, and causes scale to form in pipes and valves. To eliminate these problems, CO_2 is added. **Recarbonation** is the process of adding CO_2 to the water to stabilize the pH and react with excess lime or supersaturated $CaCO_3$ to produce $Ca(HCO_3)_2$. Recarbonation requires about 15 to 30 minutes of detention time, and is usually performed in a basin designed just for this process, after sedimentation and before filtration. The CO_2 may be produced on site by burning a natural gas or propane flame under water, or may be purchased in the form of dry ice or liquid. Regardless of how the CO_2 is obtained, good ventilation is essential to prevent the buildup of hazardous concentrations of CO_2 or carbon monoxide gas in low areas in the treatment plant. Liquid CO_2 significantly reduces operations and maintenance problems characteristic of the recarbonation process.

Rapid Mixing, Flocculation, Sedimentation, and Filtration

The concepts, procedures, and equipment used in the rapid mixing, flocculation, sedimentation, and filtration steps of the lime-softening process are essentially the same as those used in conventional treatment, discussed in Chapters 7, 8, and 9. When lime is added to form a solution, it must be continuously mixed to keep it in suspension. This is because it is a slurry and does not completely dissolve in concentrated solutions. Coagulants may be added to help build heavier floc from the fine chemical precipitates formed in lime softening. The sedimentation step is important for removing the insoluble precipitates of calcium and magnesium carbonates and hydroxides. Because of the large quantities of sludge produced by lime softening, inadequate sedimentation may allow the calcium and magnesium precipitates to seal the spaces between grains of filter media, shortening filter runs and making thorough backwashing more difficult.

CHEMICAL STORAGE AND FEED EQUIPMENT

Because of the large quantities of chemicals required for lime softening, the chemical storage containers must have large capacities. The Golden Heart Utilities (GHU) water treatment plant in Fairbanks, Alaska, uses a 5,000-cubic-foot (ft^3) silo to store its supply of pulverized quicklime. The silo is supplied by 3,000-ft^3 railcar loads, and the quicklime is fed to the top of the silo by a hose and pump.



The 5,000-cubic-foot lime silo, Golden Heart Utilities, Fairbanks, Alaska.

The quicklime is channelled through a hopper at the bottom of the silo. The hopper is equipped with an agitator to keep the quicklime flowing. The hopper supplies two chemical feed lines that carry the quicklime to the lime slaker, a unit that mixes the quicklime with water to produce hydrated, or **slaked**, lime. The quicklime is easily slaked because it dissolves readily in the water. Slaking is an exothermic reaction, meaning it produces heat, so care must be taken when working near the active lime slaker. From the slaker the hydrated lime is pumped as a slurry through a hose to one of the treatment plant's clarifiers.

DETERMINING CHEMICAL DOSAGE

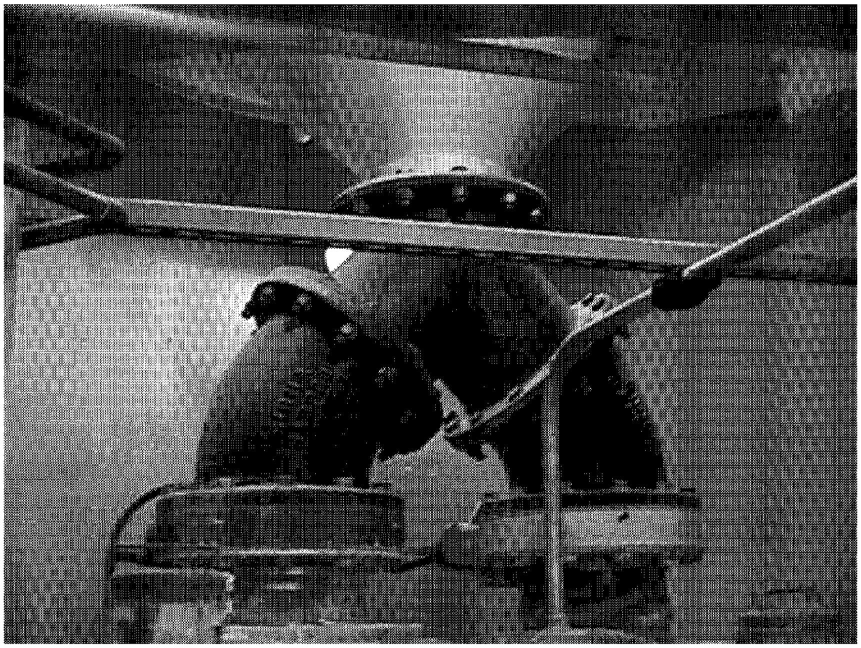
Two approaches for determining the lime dosage needed to remove hardness from water are (1) calculations based on a chemical analysis of the raw water, or (2) jar testing to determine the optimal dosage in small-scale simulation of the softening process.

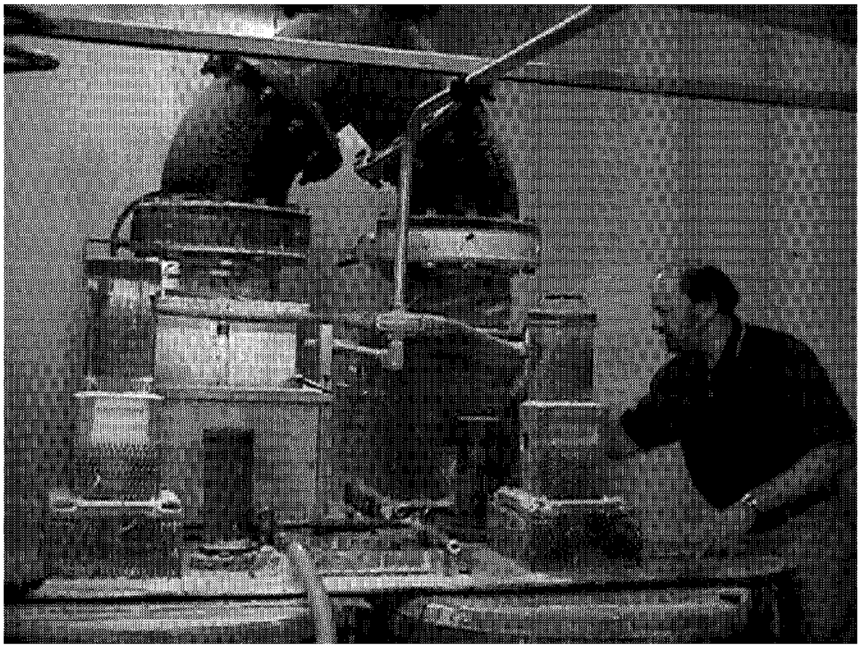
Dosage Calculations

Dosage calculations use the molecular weight equivalents in milligrams per liter of the dissolved CO_2, alkalinity, the components of carbonate and noncarbonate hardness in the water, and of the lime and soda ash needed to react with them to remove hardness. The percent purity of the lime and soda ash must be entered into the calculations. For step-by-step procedures used in calculating lime dosage, see Ken Kerri's field manual, *Water Treatment Plant Operation*, Volume II, Chapter 14, and the American Water Works Association's *Basic Science Concepts*, Chemistry Chapter 7.

Jar Testing

Although calculations may establish the approximate amounts of chemicals needed, the best way to estimate chemical dosage requirements is the jar test. Jar testing can determine the optimal lime dosage for hardness removal while also allowing manipulation of other parameters such as addition of soda ash and polymers or other coagulants. The jar test is a simulation of the actual plant conditions, allowing a "hands-on" assessment of different combinations of chemical dosages. Another advantage of the jar test is that it may show that a smaller amount of lime will do the job even if a larger amount was determined through calculation and that larger amount would increase the hardness removal by a negligible amount. The negligible benefit may not justify the added expense of using more lime.





Top: quicklime hopper at bottom of lime silo feeding two lines to the chemical mixers at Golden Heart Utilities, Fairbanks.

Bottom: operator at right tends chemical feed station that includes two lime slakers (tubs in bottom front of photo).

Determining Chemical Feed Rate

Once the chemical dosage is determined by jar testing, the chemical feed rate can be adjusted according to the plant flow rate. This is the same chemical feed rate formula used in the coagulant dosing discussed in Chapter 7:

$$\text{Chemical Feeder Setting (lbs/day)} = \text{Flow (MGD)} \times \text{Lime Dosage (mg/L)} \times 8.34\ \text{lbs/gal}$$

Where
lbs/day = pounds per day,
MGD = million gallons per day, and
lbs/gal = pounds per gallon.

If, for example, the jar test determined that the lime dosage should be 100 mg/L, and the plant flow rate is known to be 2 MGD, then the chemical feed rate is determined by the following equation:

$$\text{Chemical Feeder Setting} = 2\ \text{MGD} \times 100\ \text{mg/L} \times 8.34\ \text{lbs/gal}$$

or

$$\text{Chemical Feeder Setting} = 1{,}668\ \text{lbs/day}$$

As mentioned in Chapter 7, translation from the jar test to the full-scale treatment plant requires careful monitoring because the plant conditions cannot be duplicated exactly in the small-scale containers. Monitoring the finished water hardness, pH, turbidity, and other characteristics will help the operator make adjustments for optimal results.

ION EXCHANGE SOFTENING

Because dissolved minerals dissociate into charged ionic particles in water, they can be removed or neutralized by other ions. Ion exchange processes incorporate a material called **resin** to exchange a hardness-causing ion for an ion that does not cause hardness. In ion exchange softening, two Na^+ ions are substituted for each Ca^{2+} or Mg^{2+} ion. The sodium is from the salt ($NaCl$) that is used to regenerate the resin.

As opposed to lime-softening facilities, ion exchange facilities are less expensive to set up and require less space, can be operated by automatic control and require minimal staff monitoring, and the chemical used in the process, salt, is much less hazardous to store and handle. In ion exchange softening, the water hardness is reduced to nearly zero, which makes the water highly corrosive. Raw water may be mixed with the softened water to achieve any level of hardness desired.

For smaller water utilities, ion exchange systems are a common alternative to lime and soda-ash softening processes. Many Class B and small Class A water treatment plants in Alaska use small ion exchange systems on groundwater supplies. A common use in the Interior and South Central Alaska is hardness and iron and manganese removal.

Ion Exchange Facilities

The materials and equipment used in ion exchange softening include the ion exchange material, or resin; the ion exchange chemical, most commonly salt, and containers to store it in; the ion exchange unit; and brine-feeding equipment for regeneration of resin.

Water softeners and bags of rock salt for resin regeneration at a Fairbanks business establishment.

Ion Exchange Resins

Several types of materials may be used as an ion exchange resin. **Zeolites**, long chain-like silicate minerals, were commonly used in the past because they contain vast networks of open spaces to take up ions from the water. Today it is more common to use synthetic zeolites and organic polymers, known as polystyrene resins, because their quality is more easily controlled and they have greater ion exchange capacities.

Salt

Salt (NaCl) is mixed with water to form a brine solution that is used to regenerate the ion exchange resin after it has exchanged all its sodium ions for calcium and magnesium. The salt is usually in pellet or rock form, and may be stored either in the bags from the supplier or in the tanks that will be used to mix the brine. The salt used in water softening must meet the standards for purity and be approved by a Federal or State regulatory agency, as described in Chapter 7, in the section, "Approval of Additives to Potable Water."

Ion Exchange Units

The units used to house the ion exchange process look similar to pressure filters, but they must be coated with a protective lining to guard against corrosion. The main components of an ion exchange unit are the hard-water inlet, soft-water outlet, wash-water inlet and collector, brine inlet and distribution system, brine and rinse-water outlet, rate-of-flow controllers, sampling taps, an underdrain system, and graded gravel for support of the resin. The units may be either upflow or downflow in design. The size of the unit depends on the flow volume of the system and the hardness of the raw water. The recommended minimum depth for the resin bed is 24 inches.

Brine-Feeding Equipment

Salt pellets are mixed with water into a saturated solution that is maintained in a brine tank. A plastic suction line draws brine into the softener during the regeneration cycle. The equipment used for feeding the highly corrosive brine must be a special plastic or other corrosion-resistant material.

Ion Exchange Process

In ion exchange softening, hardness often is expressed in terms of grains per gallon, or more simply, **grains**, as opposed to milligrams per liter as $CaCO_3$ in lime softening. The relation between grains and milligrams per liter is 1 grain equals 17.12 mg/L or 0.142 pound per 1,000 gallons, or 7,000 grains equals 1 pound per gallon. The quantity of salt used to make the brine ranges from 0.25 to 0.45 pound for every 1,000 grains of hardness removed. The process of ion exchange softening involves four different cycles:

1. softening cycle
2. backwash cycle
3. regeneration cycle
4. rinse cycle

Softening Cycle

In the softening cycle, hard water is fed to the top of the ion exchange unit until the effluent hardness reaches about 1 to 5 mg/L. The time this takes depends on the ion exchange capacity of the resin and the size of the unit. The chemical reactions occurring during softening depend on the hardness-causing chemical being removed. In the following equations, *X* stands for the ion exchange material:

Carbonate hardness:

$$Ca(HCO_3)_2 + Na_2X \rightarrow CaX + 2NaHCO_3$$

$$Mg(HCO_3)_2 + Na_2X \rightarrow MgX + 2NaHCO_3$$

Noncarbonate hardness:

$$CaSO_4 + Na2X \rightarrow CaX + Na_2SO_4$$

$$CaCl_2 + Na_2X \rightarrow CaX + 2NaCl$$

$$MgSO_4 + Na_2X \rightarrow MgX + Na_2SO_4$$

$$MgCl_2 + Na_2X \rightarrow MgX + 2NaCl$$

Backwash Cycle

After the resin has exchanged all its sodium ions for calcium and magnesium ions, it must be regenerated. Before regeneration, however, the resin must be backwashed with treated water to loosen it and release any materials that may have precipitated from the water, such as oxidized iron. The backwash should be adequate to expand the resin bed by 50 percent of its compacted depth.

Regeneration Cycle

During the regeneration cycle, salt brine is washed over the resin bed. The resin releases its hard-water ions to solution in exchange for a fresh supply of sodium ions (Na^+). As the Na^+

from the NaCl attaches to the resin, the displaced Ca^{2+} and Mg^{2+} are removed as $CaCl_2$ and $MgCl_2$, with Cl^- ions from the NaCl. The duration of this process must be adequate to restore full ion exchange capacity to the resin. This requires a contact time of about 20 to 30 minutes. The brine waste is then discharged as wastewater.

Rinse Cycle

After regeneration, a thorough rinse is applied to the resin bed to remove any unused salt. Rinsing is done first with hard water and then with treated water. This process uses about 20 to 35 gallons of water per cubic foot of resin.

Blending Hard and Soft Waters

Because the ion exchange process reduces the hardness of the water to zero, the softened water may be blended with raw water to achieve the desired level of hardness. This is somewhat subjective, but it can reduce the corrosivity of ultra-soft water.

MEMBRANE SOFTENING

Membrane separation technology is increasingly being used as a water-softening method. The Denali Princess Hotel, Denali National Park, Alaska, uses a 100,000-gallon-per-day membrane softening system, with no other chemicals added except membrane cleaning chemicals and antiscalants to prevent membrane fouling. The process at the hotel achieves 90 percent removal of hardness (90-95 percent membrane rejection), producing finished water with a total hardness of 100 to 150 mg/L as $CaCO_3$. Although this water is still considered moderately hard to hard, it has at most only a tenth of the hardness of the raw water (1,500 mg/L as $CaCO_3$). Membrane separation is discussed in detail in Chapter 13.

RESIDUALS HANDLING

As with the sedimentation and filtration processes in conventional treatment, softening by precipitation creates lime sludge, and the ion exchange process produces wastewater with a high salt content. Sludge dewatering may reduce the expense of disposal. The expense of disposing of brine may make ion exchange a less than cost-effective option. Because of the large quantities of lime sludge produced during lime softening, clarifiers used in this process are usually equipped with automated sludge removal scrapers and pumps. Dealing with residual sludge and wastewater is discussed in Chapter 8.

SOFT WATER PROBLEMS

Some problems are associated with the softening of water, depending on the process used. The two common problems that may occur with water softening are increased corrosivity of the finished water, and elevated sodium concentrations from the ion exchange process.

Corrosion

Water that is overly softened may be highly corrosive, damaging pipes, pumps, other distribution system components, and household plumbing fixtures. The corrosivity is due to its inability to deposit even a thin protective layer of $CaCO_3$ inside pipes. Increased corrosivity can cause leaching of metals from pipes, causing elevated iron, lead, and copper concentrations. Provisions of the lead and copper rule regulate lead and copper in drinking water, and corrosion control measures may be necessary to correct high concentrations of these metals.

Health Concerns

Elevated sodium concentrations produced by ion exchange softening may cause concern for people with high blood pressure or heart disease. However, the minor increase in the sodium content of the water over the raw water concentrations is negligible compared with the amount of sodium ingested in food.

The U.S. Environmental Protection Agency has not established a maximum contaminant level for sodium in drinking water, but, in accordance with the recommendations of the American Heart Association, the EPA does suggest a maximum level of 20 mg/L, to protect the “at-risk” population. The secondary maximum contaminant level for sodium in drinking water is 250 mg/L.

Potassium chloride can be used for regenerating ion exchange softeners, leaving potassium in the water instead of sodium. This alternative is slightly more expensive but better for the public health.

GOLDEN HEART UTILITIES, FAIRBANKS, ALASKA

The GHU water treatment plant supplies water to the city of Fairbanks. GHU's total plant production averages 3.3 MGD. The raw water comes from four groundwater wells, with only one or two wells operating at any one time. The raw water problems at GHU include iron, manganese, and hardness. The concentrations of these constituents in the raw water are 3.5 to 6 mg/L iron, 0.7 to 0.8 mg/L manganese, 140 to 220 mg/L total hardness as calcium carbonate (with an average value of about 180 mg/L), with 40 mg/L as $CaCO_3$ of the total hardness contributed by magnesium and the rest by calcium.

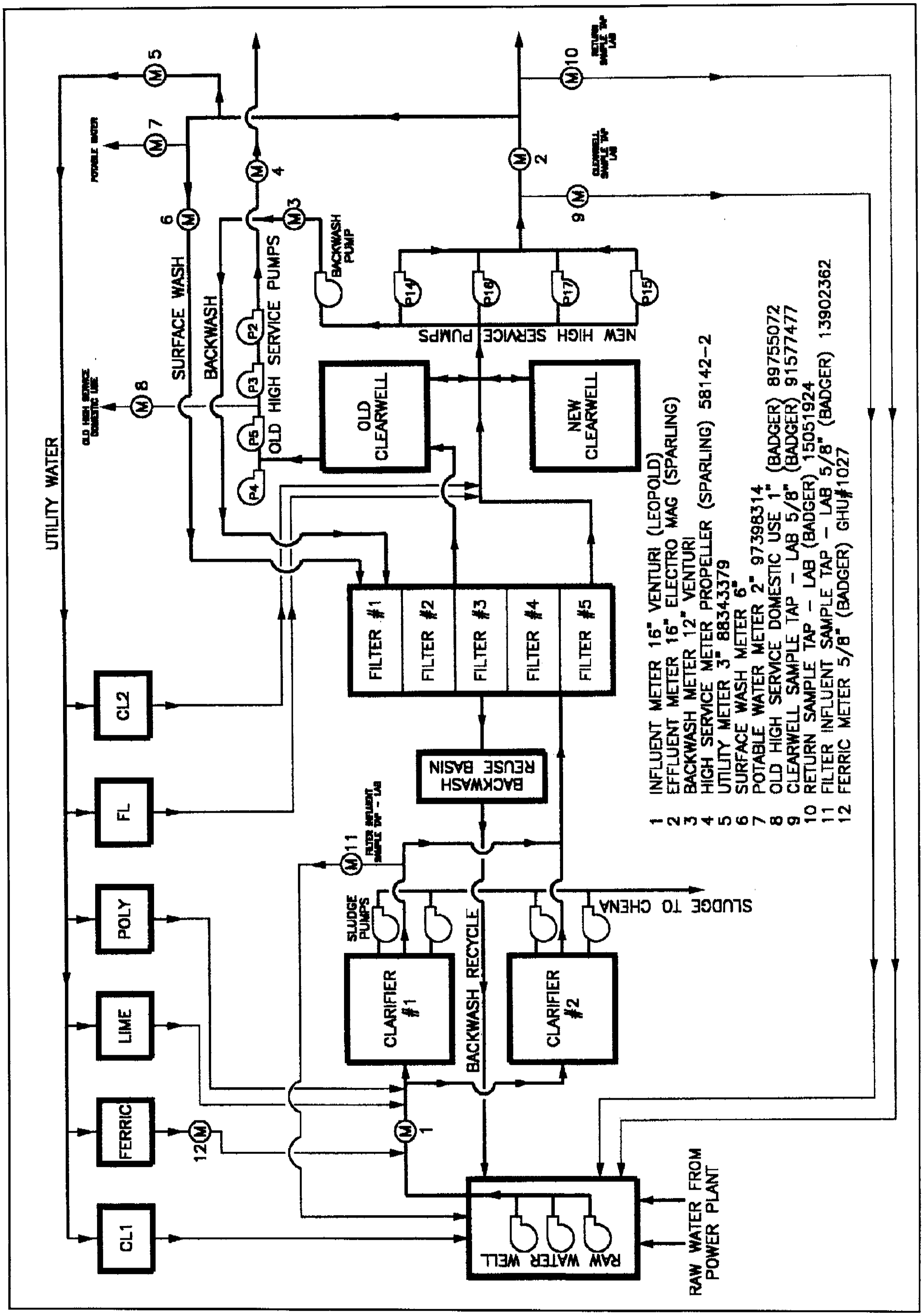
Before the addition of lime to the water at GHU, the water is prechlorinated to oxidize some of the iron. For many years, ferric sulfate ($Fe_2[SO_4]_3$) was used as a coagulant at GHU, but the operators discovered that the water contained adequate iron to react with the lime and form good floc. Thus, the softening process at GHU is conventional treatment. The hydrated lime previously used was replaced with quicklime because of its lower cost and easier storage. The lime dosage used at GHU is 100 mg/L, and the total volume used is about 1,000 to 2,000 lbs/day.

Calculate the chemical feeder setting in pounds per day for the Golden Heart Utilities water treatment plant.

Known: Plant Flow Rate = 3.3 MGD; Lime Dosage = 100 mg/L

Feeder Setting = 3.3 MGD x 100 mg/L x 8.34 lbs/gal = **2,752.2 lbs/day**

A nonionic polymer is added with the slaked lime to enhance coagulation and floc formation. The lime and polymer are mixed into the water as they flow into one of two upflow clarifiers. A 90,000-gallon clarifier is used in winter and a 160,000-gallon clarifier in summer. After mixing and settling of suspended solids in the clarifiers, the water is fed to one of five dual-media filters. The filter media consist of a 16-inch top layer of anthracite underlain by 8 inches of sand. Three grades of gravel underlie the media for support. The finished water from GHU has a hardness of 140 to 150 mg/L as $CaCO_3$.



Process flow schematic of the Golden Heart Utilities water treatment plant, Fairbanks, Alaska.

OPERATIONS MONITORING

The two softening processes discussed in this chapter differ greatly in complexity. Lime softening is complex and requires several different control tests. These include alkalinity tests, total hardness tests, carbon dioxide tests, pH tests, jar tests, and the **Langelier saturation index** determination. Conversely, ion exchange softening is a relatively simple process and requires only total hardness tests, the Langelier saturation index determination, and chloride tests to make sure rinsing is adequate after resin regeneration.

Alkalinity Tests

Alkalinity tests provide information needed for calculating dosages of both lime and soda ash. In general, the total alkalinity is equal to the carbonate hardness, so that if the total alkalinity and total hardness are known, the noncarbonate hardness can be calculated by subtracting the total alkalinity from the total hardness.

The three types of alkalinity to be tested for include hydroxide alkalinity, carbonate alkalinity, and bicarbonate alkalinity. The speciation of alkalinity is pH dependent, with hydroxide alkalinity only appearing above pH 8.3. Thus, hydroxide alkalinity rarely comes into consideration in measurements of natural waters.

Alkalinity may be determined by titration to a pH endpoint. The two levels of alkalinity titration are known as phenolphthalein alkalinity and total alkalinity. Both tests may use a color-change end-point indicator or a pH meter. Phenolphthalein has a titration endpoint of pH 8.3, to determine hydroxide alkalinity, and the total alkalinity test has a titration endpoint of pH 4.5. For very low alkalinities, the sensitivity of the titration may be adjusted by titrating an additional 0.30 pH unit past the pH 4.5 endpoint. The table below shows the relations between the different species of alkalinity, as determined by phenolphthalein and total alkalinity titrations.

ALKALINITY RELATIONS			
Result of Titration	Hydroxide Alkalinity as $CaCO_3$	Carbonate Alkalinity as $CaCO_3$	Bicarbonate Alkalinity as $CaCO_3$
P = 0	0	0	T
P < 1/2 T	0	2P	T - 2P
P = 1/2 T	0	2P	0
P > 1/2 T	2P - T	2(T - P)	0
P = T	T	0	0
Key: P, phenolphthalein alkalinity; T, total alkalinity			

Alternatively, if the pH, total alkalinity, temperature, and total mineral content are known, each of the forms of alkalinity and the free CO_2 can be determined by referring to a nomographic chart. The details of these tests are provided in a separate reference, *Standard Methods for the Examination of Water and Wastewater*, 19th Edition, published jointly by the American Public Health Association, the American Water Works Association, and the Water Environment Federation. Additional information concerning alkalinity testing and its application to chemical dosage calculations may be found in *Basic Science Concepts and Applications*, by the American Water Works Association.

Total Hardness Tests

Tests for total hardness indicate the need for softening and provide information about the effectiveness of the treatment process. The hardness of both raw and finished waters should be tested. The total hardness test results are combined with those for alkalinity to calculate carbonate and noncarbonate hardness, which in turn are used to calculate the dosage of lime and soda ash needed. The method most commonly used for determining hardness is to calculate it from the results of separate calcium and magnesium analyses, as shown on pages 10-2 and 10-3.

Magnesium Tests

Magnesium testing is used to determine the amount of magnesium in the water. If magnesium hardness in the water is more than 40 mg/L as $CaCO_3$, excess lime may be necessary to reduce the magnesium levels and prevent scale formation in water heaters and boilers.

Carbon Dioxide Tests

The carbon dioxide test determines the concentration of free carbon dioxide in the water. This helps in calculating the lime dosage needed to soften raw water, and in determining whether recarbonation of softened water will be necessary. As mentioned above, the free CO_2 concentration can be determined by referring to a nomographic chart, providing the pH, total alkalinity, temperature, and total mineral content are known.

pH Tests

Measurements of the pH of the water should be made throughout the lime softening process. The water's pH is an important factor in the precipitation of both calcium carbonate and magnesium hydroxide. After these compounds have been precipitated out of the water at pH levels of 9.4 and 10.6, respectively, the pH may be stabilized by recarbonation to more neutral levels.

Jar Tests

As previously described, the jar test is an excellent way to model actual plant conditions and process performance by testing a number of independent variables. Jar testing is described in detail in Chapter 7.

Langelier Saturation Index Determination

The Langelier saturation index is used to determine the stability of the finished water after softening, to ensure that neither corrosivity nor scale will be a problem. The Langelier saturation index should be determined daily. The determination is made by the following equation:

$$LI = pH_{actual} - pH_s$$

Where

LI is the Langelier index,

pH_{actual} is the measured pH of the water, and

pH_s is the theoretical pH at which the water will be saturated with calcium carbonate.

If the LI equals zero, the water is considered stable. The Langelier index is discussed in detail in Chapter 16.

Possible Operating Problems

Because lime softening is more complex than ion exchange softening, it has more potential problems associated with it. Magnesium-hydroxide scale potential and unstable water may be detected by magnesium tests and Langelier saturation index determination. The tests described above will help the operator monitor the softening process, with aberrations in test results indicating less than optimal process performance and the need to take corrective action.

Another problem that may arise in lime softening is the precipitation of excess calcium carbonate, which may shorten filter runs, sometimes even making it necessary to replace underdrain systems and filter media, and create thick deposits in pipes, restricting flow. This problem may be corrected by increasing mixing or detention times, recarbonating the water, or by adding a sequestering agent such as sodium hexametaphosphate to keep the calcium carbonate in solution.

In ion exchange softening, some potential problems include resin breakdown; iron, turbidity, organic color, and bacterial slime fouling of resin; and unstable water. Oxidation by chlorine is one of the main causes of resin breakdown, and may be managed by removing excess chlorine after prechlorination. Iron oxide in moderate amounts can usually be removed from the resin bed by proper backwashing, but if iron levels are excessive, pretreatment for iron removal will help prolong the life of the resin. Sodium sulfite or similar reducing compounds can be added to the brine to help remove iron from the resin. Resin fouling by turbidity, organic color, and bacterial slime may be manageable by backwashing, but if their concentrations are high, complete conventional treatment may be necessary before softening to preserve the resin. Blending raw and softened water is often used after ion exchange softening to stabilize the water and prevent corrosion.

SAFETY AND MANAGEMENT

Safety is a far greater issue in lime softening than in ion exchange softening, but record keeping is important in any treatment process. Regulations indirectly pertaining to softening are those that deal with corrosion and secondary contaminant levels.

Safety Considerations

Care must be taken when handling the caustic chemicals involved in lime softening processes. In addition to the hazards of contact with skin or eyes, some of the chemicals may react exothermically with each other. Lime, soda ash, and carbon dioxide are all substances to be treated with respect, and personal protective equipment should be worn at all times when handling caustic chemicals. In addition, the operator must be familiar with first aid procedures in case of accidental skin or eye contact with lime or soda ash. Carbon dioxide gas is heavier than air and if allowed to collect in low areas of the treatment plant, can pose an asphyxiation hazard.

The equipment used in lime softening may have moving parts, such as in a lime slaker, and the operator must take care not to reach into a mixing unit while it is operating. As in other conventional treatment processes, basins and filters should be equipped with hand rails to prevent falls into the units.

Record Keeping

The records that should be maintained daily in the lime softening process include the following:

- quantities of chemicals fed
- chemical feeder settings
- amount of water treated per day
- hardness, alkalinity, and magnesium and calcium concentrations of raw and finished water
- free carbon dioxide in raw water
- the pH of the raw water, treated water, and at stages in the process that are critical to chemical reactions

- amount of sludge pumped to disposal
- dosage calculations and results of jar tests
- depth of the sludge blanket and results of settling tests if a solids-contact basin is used

In ion exchange softening, daily records include the following:

- hardness, alkalinity, and calcium and magnesium concentrations
- pH of the raw and treated water
- amount of water treated in each softening cycle
- amount of backwash water, rinse water, and brine used
- amount of salt added to the storage tank

In both treatment processes, these records will help with operational monitoring, troubleshooting, and ordering chemicals. The statistical data that may be derived from these records may be useful in compiling the annual Consumer Confidence Reports now required from all public water supply facilities.

Regulations

No Federal regulations apply directly to water softening. However, the process may affect a utility's compliance with the Lead and Copper Rule because of the corrosivity of soft water.

REVIEW QUESTIONS

1. What are the major components of hardness in water?
   a. ____
   b. ____

2. What are the two common types of water-softening processes?
   a. ____
   b. ____

3. What are two different categorizations for hardness in water?
   a. ____________________ and ____________________
   b. ____________________ and ____________________

4. When is it necessary to add soda ash to the lime-softening process?
   a. ____
   b. ____

5. Name two calcium compounds that contribute to noncarbonate hardness.
   a. calcium __________________ b. calcium ____________________

6. Another term for slaked lime is _________________________, and another term for unslaked lime is _____________________________________.

7. Matching: match each chemical formula with the letter of its common name:

_____$Mg(HCO_3)_2$	a. sodium hydroxide
_____$NaOH$	b. quicklime
_____CaO	c. magnesium sulfate
_____$CaCO_3$	d. calcium carbonate
_____$MgSO_4$	e. magnesium bicarbonate

8. Recarbonation is a process used to stabilize _____________ and react with excess _____________ in lime-softened water. The most common method of recarbonation adds _______________ from a natural gas or propane burner.

9. What treatment process steps are common to both lime softening and conventional treatment?
   a. _________________________ b. _________________________
   c. _________________________ d. _________________________

10. What are two ways to determine the correct lime dosage in lime softening?
    a. ____
    b. ____

11. If a treatment plant's daily production is 4 MGD of water, and the chemical feeder setting is at 3 tons of lime per day, what is the lime dosage?

12. What is the common name and chemical symbol of the cation that substitutes for calcium and magnesium in the ion exchange softening process?

    ____

13. True or False: ion exchange softening has more safety hazards associated with it than lime softening.

    True ________

    False ________

14. What softening process is most affected by the pH of the water?

    ____

15. What problem may be identified by a Langelier index determination, and compliance with which ADEC regulation could be affected by it?

    ____

    ____

Chapter 11

Iron and Manganese Treatment

Chapter 11 – Iron and Manganese Treatment

INTRODUCTION

Although no evidence suggests that humans can be harmed by drinking water containing iron and manganese, these substances contribute to some of the most serious problems ever to confront the waterworks operator. Excessive iron and manganese in water causes numerous operational and aesthetic problems. Oxidized iron and manganese precipitate out of the water and deposit onto pipes and other system components. If a sudden surge in demand occurs, perhaps from the opening of a fire hydrant, the deposits may become dislodged and cause metal precipitates and discolored water to flow from customers' taps, a phenomenon known as a "red water" event.

Water containing iron and manganese fosters the growth of microorganisms in the water system. Some iron and manganese bacteria, also referred to as **crenoforms**, are *Crenothrix*, *Gallionella*, *Sphaerotilus*, and *Leptothrix*, with *Crenothrix* being the most common. These bacteria that thrive on iron and manganese can form bacterial slimes on distribution system components and plumbing fixtures that can reduce flow capacity through pipes, clog meters and valves, add further discoloration and objectionable tastes and odors to the water, and increase chlorine demand. Iron bacteria also are associated with corrosion of distribution system components.

Oxidized iron discolors water yellow to red, and manganese can turn it black, either of which is highly objectionable to customers, especially when it stains plumbing fixtures and laundry. Moreover, water containing iron and manganese gives a metallic taste to beverages made with it. If the source water contains a high concentration of iron and manganese, specialized treatments may be necessary to remove them. Because of the potential damage these two contaminants can cause, secondary maximum contaminant levels (SMCLs) of 0.3 milligrams per liter (mg/L) for iron and 0.05 mg/L for manganese have been established by the U.S. Environmental Protection Agency (EPA). The American Water Works Association suggests limits of 0.05 mg/L for iron and 0.01 mg/L for manganese for an "ideal" quality water for public use.

Iron and Manganese in Natural Waters

The earth's crust is approximately 5 percent iron and 0.1 percent manganese, with greater concentrations in the mantle and core. Iron is the fourth most abundant element; only oxygen, aluminum, and silica are more abundant than iron. When rain percolates down through the soil, it can lose dissolved oxygen to microorganisms that use the oxygen to oxidize and decompose organic matter. In this process carbon dioxide (CO_2) is produced. CO_2 in groundwater forms carbonic acid, lowering the pH and dissolving the iron in the soil. If manganese is present, it usually occurs along with iron, but at lower concentrations. Iron and manganese are two of the most common contaminants found at unacceptable levels in drinking water supplies, and Alaskan waters are no exception.

Only the divalent (+2) and trivalent (+3) states of iron are found in the aqueous environment. Ferrous iron (Fe^{2+}) is the soluble form of iron and ferric iron (Fe^{3+}) is the insoluble, or oxidized, form. Iron can be complexed with naturally occurring acids from organics, or with naturally occurring silicates, phosphates, and polyphosphates. Complexed iron is stable, so oxidation, agglomeration, precipitation, and filtration are reduced or prevented.

Manganous manganese (Mn^{2+}) is the soluble form of this metal, and manganic (Mn^{3+}) is the insoluble, or oxidized, form. However, manganese is most often removed by oxidizing it to its quadrivalent (+4) state as MnO_2. Manganous manganese is more difficult to remove than ferrous iron because it requires a higher pH and greater chemical quantities to convert it to its insoluble form.

The occurrence of iron and manganese in water supplies is usually limited to wells. However, some impounded surface-water supplies may have seasonal iron and manganese problems. It is rare to find either in flowing streams of normal pH. In Alaska, the natural occurrence of iron and manganese is widespread, with concentrations as high as 110 mg/L for iron and 10 mg/L for manganese reported from wells in the Yukon-Kuskokwim region.

Arsenic, Hydrogen Sulfide, and Sulfates

Contingent removal of arsenic is another benefit of iron and manganese removal. If arsenic is present in the water, it may be complexed with iron or manganese and incidentally removed along with those metals. The level of arsenic removal in greensand filters in Alaskan treatment applications has ranged from about 33 percent to 67 percent of the raw water arsenic concentration. Like iron and manganese, arsenic oxidizes from arsenite (+3) to arsenate (+5), from a soluble to a filterable precipitate form. In addition, it may be adsorbed onto iron floc and removed that way as well. Alternatively, arsenic may be treated with specialized greensand media designed for arsenic removal. Activated alumina also is used to remove arsenic from water.

Hydrogen sulfide (H_2S) and sulfates respond to aeration and oxidation in a way similar to iron and manganese. H_2S is easily removed by aeration, as described in Chapter 6, or may be removed by chemical oxidation along with iron and manganese. If H_2S and sulfates are present, they may interfere with oxidation by reacting with the oxidizing chemical, increasing chemical use during iron and manganese removal.

Treatment Options

The principal iron and manganese treatment methods are precipitation and filtration, ion exchange, and sequestration. Other processes that may be used to remove excess iron and manganese from water are lime softening, coagulation, and membrane separation.

OXIDATION AND PRECIPITATION

Excess iron and manganese can be oxidized and precipitated out of water by aeration or chemical oxidation. Fe^{2+} and Mn^{2+} are much more soluble than Fe^{3+} and Mn^{3+}. Thus, their removal usually depends on oxidation to these less soluble forms. The relative insolubility of Fe^{3+} and Mn^{3+} over the entire pH range of interest in municipal water treatment is the key to their removal by oxidation. However, the oxidation of iron and manganese is much improved by higher pH and temperature.

Oxidation by Aeration

Theoretically, 1 mg of oxygen will oxidize 7 mg of iron; 1 mg of oxygen oxidizes 1.5 mg of manganese. The following chemical reaction represents oxidation of iron using aeration only:

$$2Fe^{2+} + {}^{1}/_{2}O_2\ (aq) + 5H_2O \rightarrow 2Fe(OH)_3\ (s) + 4H^{+}$$

Oxidation by aeration of manganese (requires a minimum pH of 9.5) is shown below:

$$Mn^{2+} + {}^{1}/_{2}O_2\ (aq) + H_2O \rightarrow MnO_2\ (s) + 2H^+$$

Aeration is discussed in greater detail in Chapter 6.

Oxidation by Chlorination

Chlorine is sometimes used as the chemical oxidant. Lime may be added to raise the pH and facilitate iron and manganese oxidation and precipitation. The Golden Heart Utilities water treatment plant chlorinates the water before lime softening; this process adequately oxidizes and precipitates the iron and manganese from the water. The oxidation of iron using chlorine (hypochlorous acid) is expressed by the following chemical reaction:

$$2Fe^{2+} + HOCl + 5H_2O \rightarrow 2\ Fe(OH)_3\ (s) + Cl^- + 5H^+$$

The following reaction represents oxidation of manganese using chlorine (as hypochlorous acid):

$$Mn^{2+} + HOCl + H_2O \rightarrow MnO_2\ (s) + Cl^- + 3H^+$$

Oxidation with Potassium Permanganate

Potassium permanganate ($KMnO_4$) is a strong oxidant that may be used alone or with chlorine. One of the advantages of using $KMnO_4$ is that no harmful disinfection by-products, such as trihalomethanes will be formed. In addition, $KMnO_4$ is a low-strength disinfectant. Oxidation of iron using permanganate is shown below:

$$3Fe^{2+} + MnO_4^- + 7H_2O \rightarrow 3Fe(OH)_3\ (s) + MnO_2\ (s) + 5H^+$$

Oxidation of manganese using permanganate is represented by the following chemical reaction:

$$3Mn^{2+} + 2MnO_4^- + 2H_2O \rightarrow 5MnO_2\ (s) + 4H^+$$

Oxidation with Ozone

Ozone has been used for years in Europe, and increasingly in the U.S., usually in combination with chlorine. Oxidation of iron using ozone is shown below:

$$2Fe^{2+} + O_3\ (aq) + 5H_2O \rightarrow 2Fe(OH)_3\ (s) + O_2\ (aq) + 4H^+$$

Manganese oxidation using ozone is shown below:

$$Mn^{2+} + O_3\ (aq) + H_2O \rightarrow MnO_2\ (s) + O_2\ (aq) + 2H^+$$

Chemical Dosages

The amount of chemical required depends on whether iron or manganese is being removed. If they are being removed in combination, or if H_2S is present, a greater amount of chemical, perhaps in some combination, will be required. Adjustment of the pH can optimize chemical oxidation. At a pH of 7.5 to 8.0 the oxidation of iron is almost instantaneous, whereas manganese requires a higher pH. The amounts of the different oxidants required to remove1 mg of iron or manganese are shown below.

AMOUNT OF OXIDANT REQUIRED TO OXIDIZE IRON AND MANGANESE

Oxidant	Amount to oxidize 1 milligram, in milligrams	
	Iron	Manganese
oxygen	0.14	0.29 (at pH 9.5)
chlorine	0.64	1.3
potassium permanganate	0.94	1.92

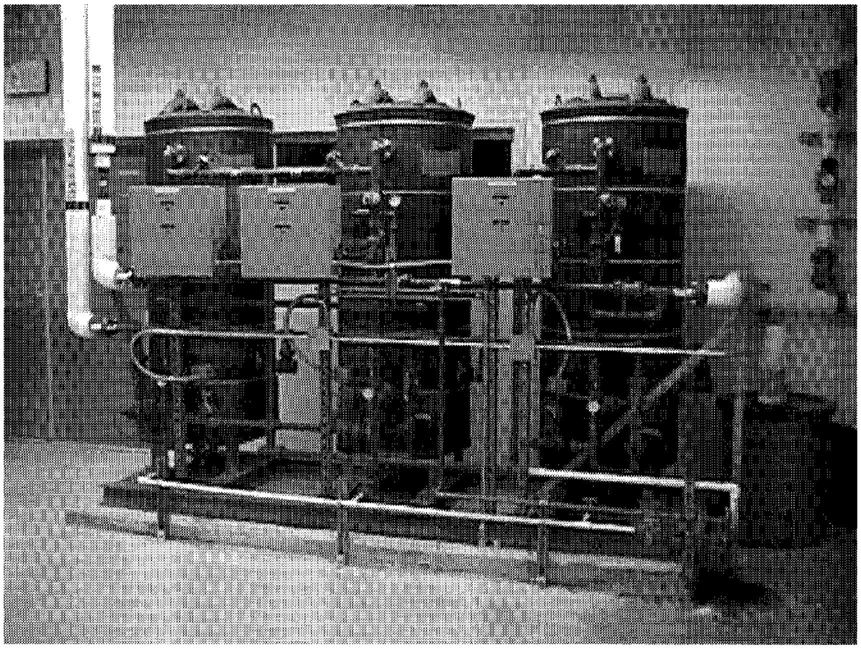
Filtration

After the iron or manganese precipitate forms, it is removed either by conventional or direct filtration using either standard granular media filters or specialized manganese **greensand** filters. Greensand filters incorporate adsorption and chemical oxidation in addition to physical filtration. These filters are especially helpful in removing manganese, which requires a higher pH and greater quantities of chemical oxidants than iron does to be converted to its insoluble form. H_2S is particularly consumptive of chemical oxidants, and is effectively treated by chlorine and permanganate oxidation in combination with manganese greensand filtration. In general, if the solids concentration is less than 5 mg/L, direct filtration without sedimentation may be used. However, if the solids content is greater than 5 mg/L, sedimentation should be provided first to remove as much precipitate as possible and avoid excessive filter backwashing.

MANGANESE GREENSAND FILTERS

The use of manganese greensand filters is a standard Alaskan water treatment method. Because of the high concentrations of iron and manganese in Alaskan groundwater supplies, this treatment is used in groundwater systems throughout the state.

Manganese greensand filters are much like any other pressure filter, but use a special medium called greensand. Manganese greensand is derived from the mineral glauconite, which is treated with manganous sulfate and potassium permanganate to produce a medium with both ion exchange and adsorptive properties. In the early part of this century, glauconite greensand was used in sodium ion exchange softening systems. Greensand in such applications has since been replaced with synthetic ion exchange resins with seven times the ion exchange capacity, but greensand has been adapted as a specialized oxidizing filter medium in iron and manganese removal. Manganese greensand consists of pellets of stabilized glauconite with a coating of active manganese oxide. Each cubic foot of manganese greensand has the capacity to remove 0.09 pounds of iron and manganese.



The water treatment plant at the Federal Aviation Administration facility in Bethel, Alaska. The two columns on the left are manganese greensand filters, and the one on the right is a granular activated carbon contactor.

$KMnO_4$ is used in greensand filters to oxidize the iron and manganese in the filter bed and to reactivate the greensand filter medium. A layer of anthracite coal (minimum 15 to 18 inches) is commonly placed over the greensand (15 to 24 inches) to serve as a roughing filter and preserve the special medium. If large amounts of iron floc are produced upstream from the greensand filter, sedimentation should be provided to settle out the large particles before the water enters the filter, to avoid fouling the filter bed.

In the manganese greensand filter, several different processes occur simultaneously. First, the filter medium traps particles as the water passes through it; second, the greensand is an adsorptive medium to which particles will adhere; and third, chemical oxidation through reactions with the $KMnO_4$ continues to form iron and manganese precipitates that also are filtered. Chlorine is often used in conjunction with $KMnO_4$ to help oxidize iron and manganese since chlorine is a less expensive chemical.

OXIDANT CHEMICAL FEED FORMULAS FOR IRON AND MANGANESE REMOVAL WITH MANGANESE GREENSAND	
Oxidant	Formula
Cl_2 and $KMnO_4$	mg/L Cl_2 = mg/L Fe mg/L $KMnO_4$ = 0.2 x mg/L Fe + 2 x mg/L Mn
$KMnO_4$ only	mg/L $KMnO_4$ = 1 x mg/L Fe + 2 x mg/L Mn

Cl_2, chlorine; $KMnO_4$, potassium permanganate; Fe, iron; Mn, manganese; mg/L, milligrams per liter

A Simplified View of a Manganese Greensand Filter in Operation

To help understand how the greensand filter works, consider the greensand material to be a giant sponge that soaks up potassium permanganate from the water that flows through it. With permanganate in the sponge, any iron that comes through the sponge is oxidized and retained in the sponge. As the iron is removed, the permanganate is used up. If more permanganate than iron goes through the filter, the sponge eventually becomes full of permanganate and pink water results. If more iron than permanganate goes into the sponge, eventually all the permanganate is used up and the iron begins to attach to the sponge. This causes the manganese that is attached to the greensand to be released into the water.

Manganese Greensand Regeneration

After processing a specific volume of water, depending on the concentrations of iron, manganese, and H_2S being removed, the manganese greensand will have lost its removal capacity. At this point, it is necessary to regenerate the greensand medium. Manganese greensand filters may be regenerated by two different methods: **continuous regeneration** (CR) and **intermittent regeneration** (IR).

Continuous Regeneration

Most greensand filters in Alaska operate in the CR mode. In CR, excess $KMnO_4$ is added continuously to the water being treated before it reaches the filters. This oxidizes and precipitates the iron, manganese, and H_2S while maintaining a constant excess concentration of permanganate in contact with the filter media. This constant $KMnO_4$ bath oxidizes any remaining soluble constituents within the filter bed and regenerates the greensand medium.

If soluble iron and manganese begin to break through into the filtrate, the dosage of $KMnO_4$ will need to be increased. Determining the appropriate feed quantity can be determined by increasing it until the filter effluent takes on a pink color. This means $KMnO_4$ is breaking through the filter and that an excess concentration has been attained. At this point the $KMnO_4$ feed rate should be cut back just until the filter effluent is no longer pink. Until this adjustment is complete, the filter effluent should be filtered to waste.

Once neither $KMnO_4$ nor manganese are present in the filtered water, the $KMnO_4$ injection pump can be set to provide the excess needed for constant regeneration of the greensand. A general rule for permanganate dosage is to have a slight purple color in the water going to the filter. This can be checked by sampling the water in a white styrofoam cup for contrast. To determine if the dosage is right, let the cup sit for 3 to 5 minutes. The purple color should slowly disappear over this period until almost no purple color is left. The dosage can be adjusted until these results are achieved.

The removal capacity of manganese greensand in CR mode is about 500 to 700 grains per square foot of bed area, depending on the $KMnO_4$ demand (or dosage), where 1 grain equals 17.1 mg/L. Flow rates for CR operation should be between 2 and 5 gallons per minute per square foot (gpm/ft^2)

In a CR system, the filter bed is backwashed periodically to restore its volume and flush out particulate matter. The backwash flow rate should be sufficient to provide a bed expansion of 40 percent. The length of filter runs between backwashes depends on the concentrations of iron and manganese in the raw water. Estimating the backwash frequency for a particular system is illustrated by the following example:

Calculate the filter run length for a water containing 1.7 mg/L iron and 0.3 mg/L manganese at a 4 gpm/ft^2 operating rate, using only $KMnO_4$ as an oxidant:

$KMnO_4$ Dosage = (1 x mg/L Fe) + (2 x mg/L Mn)*
= (1 x 1.7) + (2 x 0.3) = 2.3 mg/L
or 2.3/17.1 = 0.13 grains/gal (gpg)

at 700 grains/ft^2 loading ÷ 0.13 gpg = 5,385 gal/ft^2

at 4 gpm/ft^2 operating rate, 5,385 gal/ft^2 ÷ 4 gpm/ft^2 = 1,350 minutes
1,350 min ÷ 60 min/hour = 22.5 hours

Thus, the **backwash frequency should be 20 to 24 hours.**

*from the table on page 11-7

Intermittent Regeneration

In IR, which works best for water with a maximum combined iron and manganese concentration of 10 to 15 mg/L and a maximum sulfide concentration of 2 to 5 mg/L, the filter bed periodically is drained and washed with $KMnO_4$. The quantity of $KMnO_4$ required to regenerate a filter bed is about 1.5 ounces per cubic foot of manganese greensand. Normally, the water treatment plant operator monitors for iron and manganese breakthrough or terminal head loss (maximum pressure drop through the filter) to determine backwash intervals. These intervals generally will remain constant unless the raw water concentrations of iron and manganese fluctuate. If H_2S also is being removed, it will deplete the filter medium much faster, requiring more frequent regeneration. The optimal contact time for regeneration is about 30 to 40 minutes.

As with other types of filters, greensand filters require regular backwashing. $KMnO_4$ regeneration is applied after backwashing, and the filter bed is then thoroughly rinsed.

ION EXCHANGE

Ion exchange methods, discussed in detail in Chapter 10, can remove iron and manganese along with calcium and magnesium. Ion exchange as a method of iron removal is only cost-effective if the iron concentration in the water is less than 5 mg/L and the iron in the water is in soluble form. If the water contains oxidized iron precipitate it may foul the resin bed and decrease system efficiency.

SEQUESTRATION

Sequestration is another iron and manganese treatment method that is appropriate only if the iron and manganese concentration in the water is less than 1 or 2 mg/L. Sequestration does not remove iron and manganese from water, but keeps it in solution so it does not precipitate out to clog pipes and discolor the water. However, because the iron remains in solution, it can still cause bacterial slimes to form on system components, and at high enough concentrations can still impart a metallic taste to the water. Sequestration works by the addition of polyphosphates or sodium silicates to the water before it is exposed to the air or other oxidants such as chlorine. This may require injection near the well head. Because polyphosphates lose their effectiveness when heated to temperatures commonly associated with home water heaters, the use of sequestering agents is rare in municipal water systems. If used, polyphosphate dosages should not exceed 10 mg/L because phosphorous can stimulate biological growths in the distribution system.

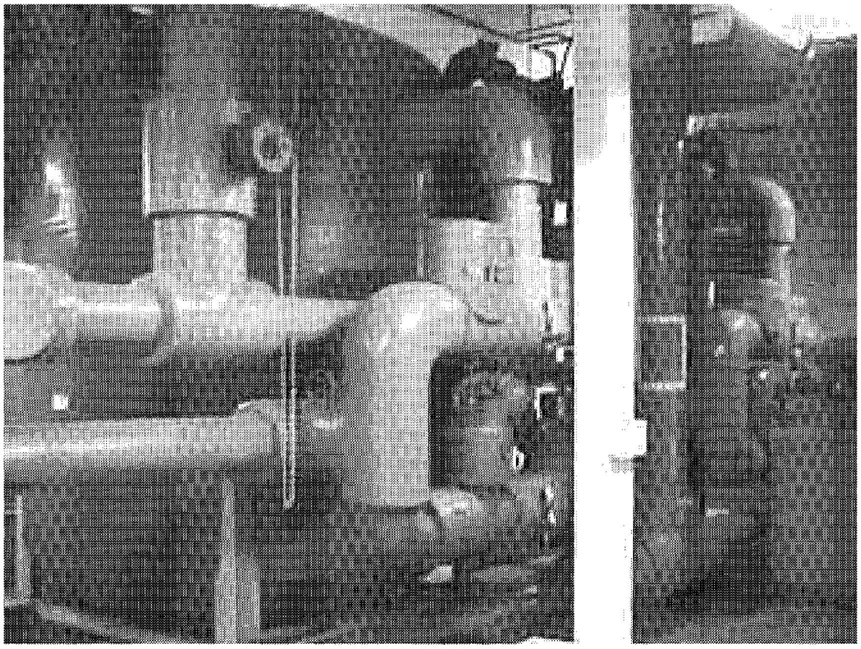
ALTERNATIVE TREATMENT OPTIONS

Lime softening, coagulation, and membrane separation are discussed in detail in separate chapters of this manual. Iron and manganese may be removed during lime softening because of the increase in pH, depending on the length of contact time allowed. Lime may also be added to increase the pH during other iron removal processes. During conventional coagulation, particulate iron can be caught up in floc formation. Iron may be rejected by membranes during the membrane separation process, but usually must be sequestered to prevent deposition on the membrane. Polyphosphates are often used as the sequestering or “antiscalant” compounds, binding iron (and manganese) which is then flushed out in the brine reject stream. This process is done in some situations as a by-product of low-pressure membrane softening.

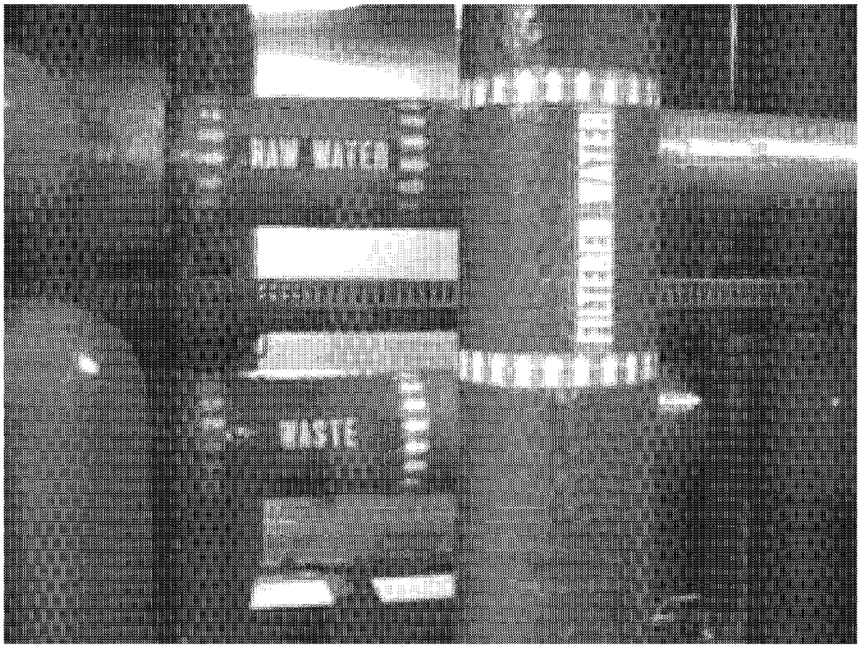
CITY OF NORTH POLE, ALASKA

The City of North Pole, Alaska, uses a continuous regeneration manganese greensand iron filter. The well water is dosed with $KMnO_4$ to enhance oxidation and filter-media adsorption of iron and manganese before the water enters the treatment plant.

The dominant plant process is direct, greensand filtration designed to remove iron and manganese. The filters are two 8-foot-diameter pressure greensand filters, each of which has a hydraulic loading rate of approximately 2.7 gallons per minute per square foot. The iron and manganese concentrations in the raw water are approximately 0.3 mg/L and 0.8 mg/L, respectively, at a pH of 7.2. The media in the filters consists of 20 inches of anthracite overlying 20 inches of greensand. Potassium permanganate is dosed at a rate of 2.5 mg/L and is the only oxidant used. The filters are taken out of service for two hours each day for backwashing, which uses about 30,000 gallons of filtered water, or about 10 percent of the plant capacity. The finished water has iron and manganese concentrations of 0.1 mg/L and 0.05 mg/L, respectively, and a pH of 8.0.



Vertical 8-foot-diameter pressure greensand filters at the North Pole Utilities water treatment plant.



The filter piping gallery at the North Pole Utilities water treatment plant is color coded to indicate raw water influent, filtered water effluent, and backwash water.

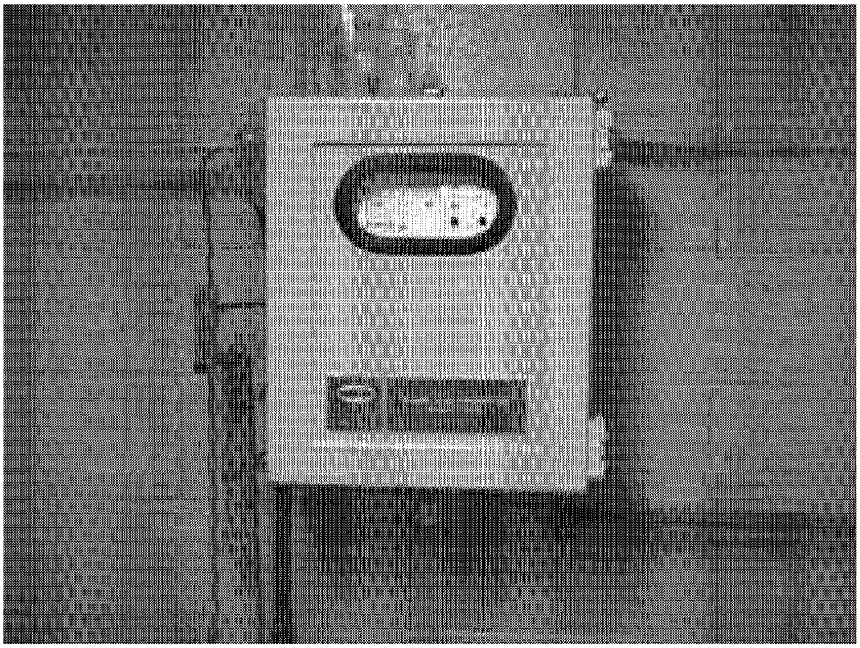
OPERATIONS MONITORING

Although the iron and manganese concentrations in the raw water should be monitored periodically, they typically remain constant. This allows the water plant operator to automate much of the process without having to make adjustments to chemical concentrations unless flow rates or other factors in the plant operation change. If arsenic, H_2S, and sulfate are being removed along with iron and manganese, their concentrations also should be monitored.

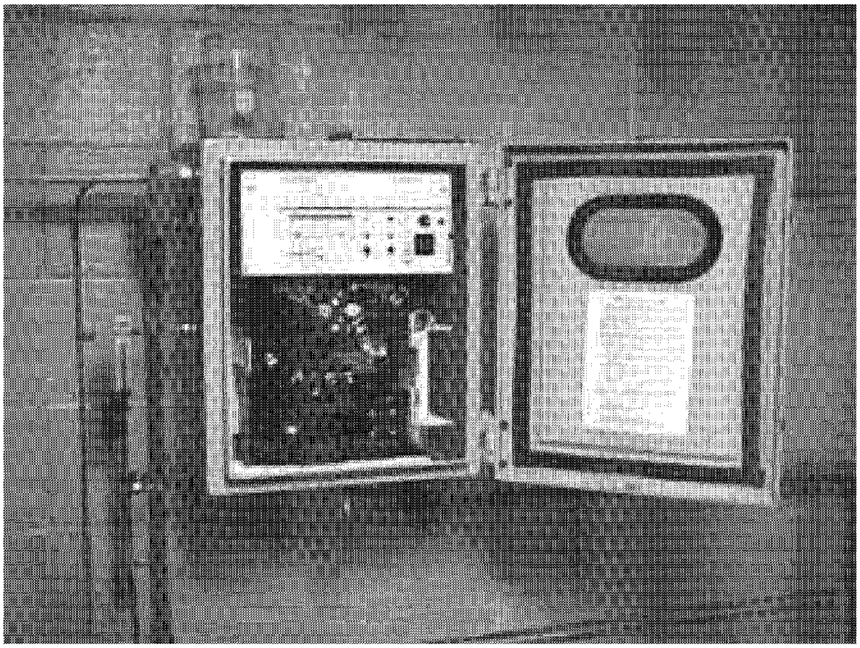
The concentration of chemical oxidant or sequestering agent being fed should be monitored continuously, to ensure the system is not under- or overdosed. The filter effluent should be monitored to make sure any remaining iron or manganese is being kept in solution.

Possible Operational Problems

One operational problem that arises when using $KMnO_4$ for iron removal is “pink water” breakthrough, which is caused by an overdose of permanganate. If black water is present in the filter effluent, the $KMnO_4$ dose may be too low to efficiently oxidize and remove manganous manganese. A $KMnO_4$ monitor is a colorimeter that indicates the concentration of $KMnO_4$ in the water by the concentration of the purple color. In this way the operator will immediately see any changes in the concentration and make the appropriate adjustments.



An example of a $KMnO_4$ monitor.



$KMnO_4$ monitor, internal view.

Another problem that sometimes arises is the organic complexing of iron, which can interfere with greensand and ion exchange treatment. At Bethel, Alaska, this problem was overcome by the addition of a low dosage of a nonionic polymer. Others have used a low alum dose to correct this problem.

SAFETY AND MANAGEMENT

As with any water treatment process, the removal of iron and manganese involves safety and administrative considerations. Some of the main points are covered below.

Safety Considerations

Any of the chemical oxidants used in the removal of iron and manganese from water will support combustion. They all burn skin and permanganate will stain skin and clothes brown. As with most chemicals, it is important to use caution and to wear personal protective equipment and clothing when handling them.

Record Keeping

If iron and manganese removal is one of the treatment plant's processes, the following records should be maintained by the treatment plant operator:

- results of periodic raw water analyses to track changes in the iron and manganese concentrations
- concentration and volume of the oxidizing or sequestering chemical being fed
- detention time provided between oxidation and sedimentation
- concentration of any supplemental chemicals added to improve sedimentation
- sedimentation time provided
- length of filter runs
- quantity of water treated
- results of periodic analysis of distribution system samples for iron and manganese concentration
- notes on distribution system flushing to control discolored water
- any customer complaints of discolored water

Regulations

No maximum contaminant levels (MCLs) have been established for iron and manganese in drinking water, because they have not been shown to pose a health risk to consumers. However, because of the aesthetic problems associated with iron and manganese in public water supplies, secondary maximum contaminant levels (SMCLs) have been set at 0.3 mg/L for iron and 0.05 mg/L for manganese. These SMCLs, however, are unlikely to be monitored unless the regulatory agency receives numerous customer complaints.

Constituents that may be present along with iron and manganese, and incidentally removed with them or removed by other specialized processes, are arsenic, H_2S, and sulfate. Arsenic has been shown to be carcinogenic at high concentrations in drinking water and is regulated by Federal and State public health and environmental agencies. The current MCL for arsenic in drinking water established by the EPA is 50 micrograms per liter or parts per billion (ppb). This is anticipated to be reduced to between 2 and 20 ppb. The World Health Organization has set a maximum acceptable concentration for arsenic of 10 ppb.

H_2S is not a health hazard in drinking water at the concentrations usually present. In fact, the water would become unpalatable before harmful levels could be reached. The SMCL for sulfate in drinking water is 250 mg/L.

REVIEW QUESTIONS

1. What is the chemical name and valence state for the soluble form of iron?

   ____

2. What is the chemical name and valence state for the precipitate form of manganese?

   ____

3. Why are iron and manganese objectionable in public water supplies?
   a. ______________________________
   b. ______________________________
   c. ______________________________

4. What are three common methods of iron and manganese removal?
   a. ______________________________
   b. ______________________________
   c. ______________________________

5. The process of chemically binding ferrous iron and manganous manganese with phosphate to prevent precipitation is called ______________________.

6. Name two chemicals used in the oxidation of iron and manganese.
   a. ______________________________
   b. ______________________________

7. A) Calculate the dosage rate for a manganese greensand filter using both chlorine and $KMnO_4$ as oxidants, and with a raw water iron concentration of 3.2 mg/L and a manganese concentration of 0.15 mg/L.

   B) What should this filter's backwash interval be if the filtration rate is 3 gpm/ft^2 and the manganese greensand media has a capacity of 600 grains of $KMnO_4$ per square foot loading?

8. List two methods of greensand regeneration and indicate where the $KMnO_4$ is dosed.
   a. ____
   b. ____

9. The SMCLs for iron and manganese are:
   Iron _____ mg/L
   Manganese ______ mg/L

10. What is the cause of pink water breaking through into a water distribution system, and how is it remedied?

Chapter 12

Adsorption

Chapter 12 – Adsorption

INTRODUCTION

Adsorption is a process that is incorporated into different types of filtration systems, and is principally used for the removal of organic substances from water. Many organic compounds present in water can cause taste and odor problems. Moreover, colloidal organic matter present as **color** in water may react with chlorine during disinfection to form harmful **disinfection by-products** (DBPs) such as **trihalomethanes** (THMs) and **haloacetic acids**, which have been shown to be carcinogenic. The adsorption process also is being used to remove the fuel additive **methyl tertiary butyl ether (MTBE)**, which recently has become a widespread drinking water contaminant. Adsorption is the process of removing organics by adhesion, whereby the colloidal particles adhere to an adsorptive medium.

Origin of Organics in Water

Organic (carbon-containing) material is present in nearly all natural waters. It dissolves into the water from soil, vegetation, and animal matter. Such organic substances present in water are referred to as **natural organic matter** (referred to as "NOM" by design engineers). Increasingly, **synthetic organic chemicals** (SOCs) are present at unacceptable levels in water, flowing with runoff from farmlands where pesticides and fertilizers are used, and also from industrial chemicals that may spill or be dumped into surface waters. In general, surface water will have greater concentrations of organic material than groundwater, but organics may be found in either system, particularly if underground injection wells are used for waste disposal or if surface wastes percolate into the soil. The organics of concern in water treatment fall into the following categories:

- **Class I**: organic compounds that cause taste, odor, and color problems
- **Class II**: SOCs such as pesticides, herbicides, fertilizers, and industrial chemicals, some of which have maximum contaminant levels (MCLs) set by regulatory agencies
- **Class III**: humic and fulvic acids, commonly referred to in water treatment as **precursors**, which can react with disinfectants to form DBPs
- **Class IV**: DBPs, which form by chemical reaction with disinfectants

(Source: *Water Treatment*, American Water Works Association, 1995)

TREATMENT OPTIONS

Several treatment options are available for controlling organics in water, including source protection, aeration, and coagulation and sedimentation. Of course, the best way to protect drinking water supplies is to remove undesirable constituents before the water enters the treatment plant, but this is not always possible. Aeration is effective for the removal of volatile organic compounds, as discussed in Chapter 6. Coagulation followed by sedimentation is also an effective method of removing color from water by agglomerating the microscopic particles together into larger floc particles that will settle out of the water.

Sometimes not all of the organics present as color can be removed by conventional coagulation, and it may be necessary to provide for either enhanced coagulation or adsorption before the water proceeds to disinfection and distribution. In such cases, adsorption is often the preferred process for more effective organics removal. In addition, adsorption can be used as part of a simplified direct-filtration treatment system, particularly for low-turbidity surface water or groundwater with low iron concentrations.

MTBE Removal

The Clean Air Act of 1990 required that areas of the country with certain air-quality problems use reformulated gasoline with an increased oxygen content. The addition of MTBE to gasoline proved to cause more problems in groundwater supplies than it solved in air quality. Because MTBE is highly soluble in water, it does not adhere to soil well and has a tendency to move into water much more quickly than other components of gasoline. Today many groundwater supplies in the United States are contaminated by MTBE that has leaked from underground fuel tanks. Concentrations of MTBE as low as 20 parts per billion (ppb) can make drinking water unfit for consumption because of foul taste and odor.

Some metropolitan areas have been hit extremely hard. For example, the city of Santa Monica, California, has had to shut down seven of its groundwater wells that supplied 50 percent of its drinking water because of MTBE concentrations as high as 600 ppb. It is estimated that it will cost the city $150,000,000 to develop alternative water sources, not including the cost of remediation and treatment of the contaminated wells. Kilometer-scale plumes of MTBE in the subsurface have been tracked in several urban areas of the United States. The larger metropolitan areas of Alaska have also been affected by MTBE groundwater contamination.

Currently, the American Water Works Association is asking for increased funding for remediation of MTBE contamination, recommending that Congress appropriate at least $100,000,000 for priority cleanup of leaking underground storage tank sites contaminated by MTBE. Calgon Carbon Corporation has developed a new activated carbon product called Filtrasorb® that is designed to remove MTBE consistently and predictably from water. Filtrasorb® incorporates a proprietary design, based on pore size and pore energy, that specifically targets the capture of MTBE. As the MTBE contamination problem increases in metropolitan areas of the country, the use of adsorption with activated carbon as a drinking water treatment also will likely increase.

ADSORPTION AND FILTRATION

In adsorption, organic contaminants are attracted and adhere to an adsorbent material by a combination of complex physical and chemical processes. One of the most important features of a good adsorbent is a large surface area in proportion to its volume. The greater the surface area, the more sites available on the medium to which organic particles may adhere.

In water treatment systems where continuous organics removal is required, adsorption can be applied in the filtration process. The only difference between a filter using adsorption and other granular-media filters is the type of filter medium. The most common filter medium used for adsorption is **granular activated carbon** (GAC).

Granular Activated Carbon

The driving principle behind adsorption is a large amount of surface area for particle adhesion, which is present in GAC. Just one pound of GAC, which looks somewhat like tiny bits of pumice (porous volcanic rock), has a surface area of 150 acres. GAC is produced by exposing carbon to high temperatures in the presence of steam. This process of “activation” opens pores and cracks in the carbon, providing the large surface area. Eventually, the activated carbon is rendered inactive after it has adsorbed its maximum capacity of organic contaminants.

Another important consideration is that GAC also removes chlorine residual, and will lose capacity quickly in the presence of chlorine. This limits the use of prechlorination in water treatment plants that use GAC. On the other hand, when GAC is used, chlorine demand will decrease significantly in the finished water, resulting in fewer DBPs and requiring a lower dosage in post chlorination.

In a GAC filter, the GAC may be placed in a layer over anthracite or sand, or may be used in place of these other media. Thus, the GAC serves as both a filter and an adsorbent. The recommended bed depth for GAC is about 24 inches, so if GAC is added to an existing installation, the wash-water troughs may need to be raised to provide enough room for this. GAC usually is best laid in the filter bed in a slurry, to minimize the generation of dust. Once the GAC has been laid in place, the filters should be backwashed before use to remove trapped air and fine particles of carbon. It is important to have two filters available, so that when one is being backwashed or recharged the other can continue to operate.

Contact Time

An important limiting factor on the effectiveness of GAC as an adsorptive filter medium is known as the **empty bed contact time** (EBCT). This is the length of time the water is in contact with the GAC as it passes through the filter bed. The EBCT is determined by the volume of the bed divided by the flow rate through the filter. The volume is calculated as the depth of the bed multiplied by the area of the filter compartment. Most GAC filters are operated at a filtration rate similar to that used in regular rapid sand filters, about 2 gallons per minute per square foot. This generally provides an EBCT of about 7.5 to 9 minutes, which is usually adequate to remove most organic compounds. In a conventional-style GAC filter, the operator generally has control only over the depth of the GAC bed. The deeper the bed, the greater the EBCT, and subsequently, the longer the life of the GAC.

GAC Filter Backwashing

GAC filters are backwashed in the same way as regular filters, but the backwash rate must be lower to prevent the loss of media to the wash-water troughs. This is because the density of GAC is about 1.4 grams per cubic centimeter (g/cm^3), as opposed to 2.65 g/cm^3 for regular filter sand. Because some media loss is inevitable, the depth of the filter bed should be checked periodically, and GAC added when needed to bring the bed back to its optimal depth. The backwashing must be adequate to expand the filter bed by about 50 percent. The manufacturer can provide recommendations for the proper backwash rate for their product.

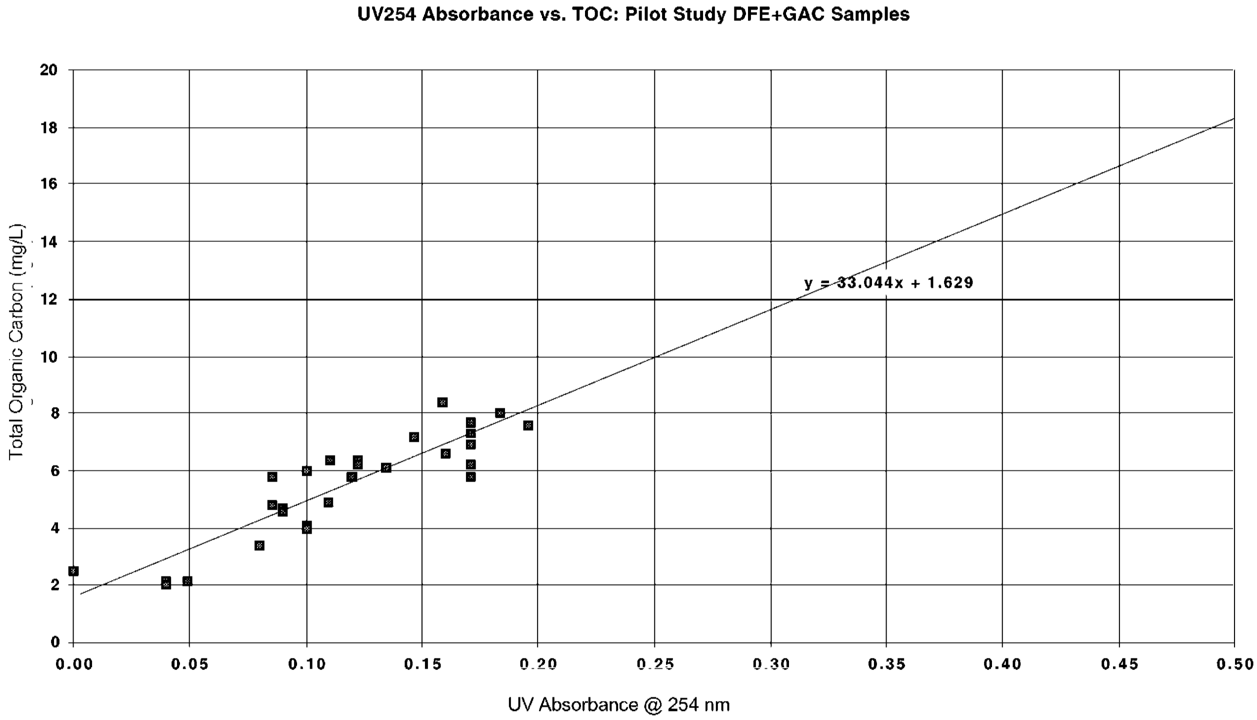
Along with backwashing, a surface wash should be incorporated to prevent the formation of mudballs on the surface of the GAC. The surface wash should be done after draining the filters and begun before backwashing to break up any surface mat that may prevent the backwash water from effectively washing through the filters. The backwash interval may be determined by terminal headloss of the filter, or may be a preset length of time based on experience.

GAC Regeneration

Once all of the surfaces of GAC are covered with adsorbed molecules, it loses its adsorptive capability. Depending on the concentration and type of organics to be removed from the water, the GAC filter medium may have a life of several months to three or four years. A GAC filter used to remove SOCs will be spent much faster than a filter removing a similar concentration of mainly taste-and-odor-causing organics. When the GAC medium is finally spent, it must be either reactivated or discarded and replaced. GAC regeneration is done by heating the carbon in a regeneration furnace at 1,500 to 1,700 °F. In Alaska, it usually is more cost-effective to replace than to regenerate GAC.

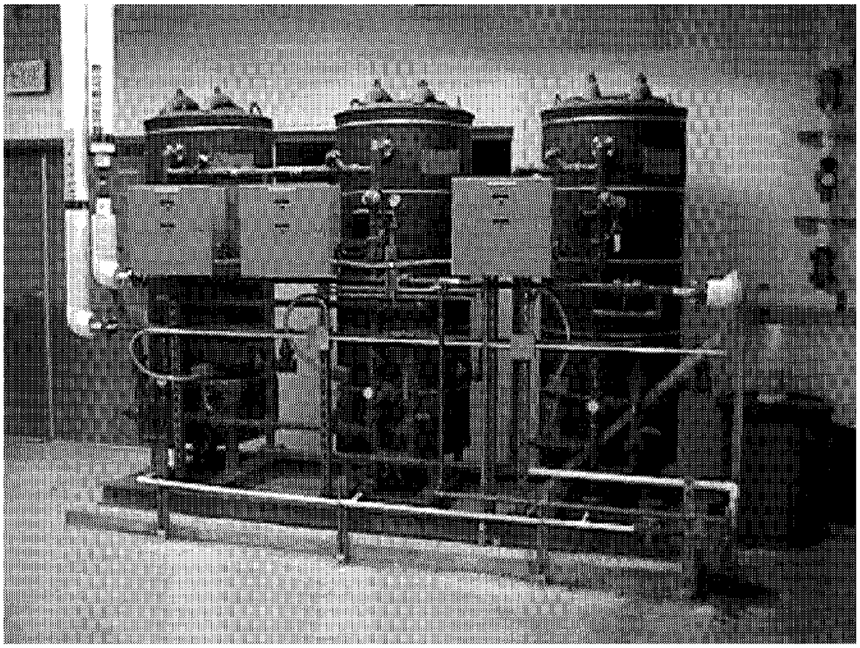
When organic contaminants begin to break through the filter into the effluent, the GAC is losing its adsorptive capabilities. This is a gradual process, so plenty of time is available for GAC replacement in one filter while the second continues to operate. Technically, GAC is considered spent when the organics concentration in the effluent is equal to that of the influent into the filters. However, this usually will allow the contaminant concentration in the finished water to rise beyond the MCL. It is recommended that the water treatment operator establish a maximum cutoff concentration, well below the MCL for the target constituent, at which the filters will be shut down and the media replaced.

Organics breakthrough may be monitored by measurements of the **total organic carbon** (TOC) in the filter effluent. TOC testing is a complex instrumental procedure usually contracted out to a certified analytical laboratory. Ultraviolet (UV) absorption at 254 nanometers (nm) can serve as a surrogate for TOC monitoring to determine when a GAC filter needs to be regenerated. UV is a less expensive and more accessible analytical method that water treatment plant operators may use on site. An ultraviolet spectrophotometer with a range to 254 nm is required. In pilot tests at the Barrow Utilities and Electric Cooperative, Inc. (BUECI), in Barrow, Alaska, a close correlation was shown between TOC and UV measurements. In two different tests of direct-filtered and GAC-treated water, the coefficient of correlation between TOC and UV measurements was about 0.93. The tests also showed that GAC adsorption after direct filtration greatly enhanced the removal of organics from the water. However, pilot testing of nanofiltration (NF) membrane technology resulted in lowering the organics level to less than the detection limit, so NF is the system now in place at BUECI.



GAC Contactors

GAC contactors are specialized closed pressure filters that remove organics, especially SOCs and other DBP precursors from groundwater. The contactor is usually placed after the conventional treatment processes to preserve the life of the GAC. If floc or other large particles are allowed to reach the filters, they will shorten the useful life of the contactor.



GAC contactor (far right) at the Federal Aviation Administration water treatment facility in Bethel, Alaska. To the left of the GAC contactor are two manganese greensand filter columns.

The principal advantage of GAC contactors is that the EBCT can be designed into the system. The size and flow rate of the system can be designed through pilot tests using the actual raw water characteristics and plant conditions. GAC contactors are backwashed and the GAC regenerated or replaced along the same guidelines as open GAC filters.

ADSORPTION IN CONVENTIONAL TREATMENT

In addition to filtration, adsorption may be used during the conventional treatment steps of coagulation, flocculation, and sedimentation. This approach is generally used where the need for adsorption is not constant and the feed rate required may be higher or lower at different times.

Powdered Activated Carbon

Powdered activated carbon (PAC) is the same material as GAC but it is ground to a fine powder. PAC is fed as a slurry to the water before it enters the coagulation process. The PAC dosage needed generally is determined from jar tests. In Alaskan systems, PAC primarily has been used in wastewater treatment rather than in drinking water treatment.

If PAC is to be used, either dry feed or slurry feed can be used, but slurry feeders have been more common in Alaska. In slurry feed systems, vacuum extractors are used for removing PAC from bags and feeding it to a wetting system that draws the powder directly into a water stream. PAC slurry must be constantly mixed and is very abrasive to chemical feed pumps and centrifugal pump seals. Special chemical feed pumps adapted to increase flow when feeding slurries should be used. PAC must be handled with extreme care because of the large amounts of dust generated.

OPERATIONS MONITORING

When using GAC as a filter medium, it is important to operate the coagulation, flocculation, and sedimentation processes continuously to ensure the optimal removal of suspended matter before the water reaches the filters. This is especially important in preserving the usefulness of GAC contactors. Filter rates through the filters should be carefully controlled and regular backwashing should be practiced to maximize the benefits of using GAC. The operator must monitor the influent and effluent organics levels regularly to assess process effectiveness and to know when it is time to replace the filter media.

Bacterial Growth in GAC

One problem particular to GAC filtration, whether in regular filters or GAC contactors, is that bacteria may grow rapidly on the filter within the filter bed. The bacteria feed on the organic compounds adsorbed onto the GAC. In some cases, the bacteria count may be higher on the filter effluent than the influent. Because GAC also adsorbs chlorine, attempts to control bacterial growth by chlorinating the water ahead of the filters is not effective. Interestingly, the presence of bacterial populations in the GAC filter bed can actually enhance adsorption of organics, because the bacteria break the compounds down into simpler molecules that are more easily adsorbed by the GAC. Some treatment plants use heavily chlorinated water in backwashing GAC filters to control bacterial growth in the filters, but the most important consideration is that disinfection must be sufficient to destroy the bacteria before the water enters the distribution system.

SAFETY AND MANAGEMENT

PAC is one of the most dangerous powders the operator will be exposed to in a water treatment plant. The two main problems are dust and the potential fire hazard. As with all water treatment processes, records of the GAC or PAC adsorption process should be maintained daily. The water treatment plant operator must keep current on changing regulations covering organics in water and the removal of DBP precursors.

Safety Considerations

Because of the large amounts of fine dust involved, the use of PAC is messy and dangerous. This is one of the reasons PAC adsorption is not a popular practice in most water treatment plants. Personal protective equipment should include a dust mask, gloves, apron or full coveralls if possible, and goggles. Shower facilities should also be provided for workers if they get dirty from handling the powder. Extended use without proper safety equipment will result in the water treatment equivalent of black lung from coal mining. The dust also may combust if ignited by a flame.

Activated carbon should be stored in a clean, dry, fireproof place, with plenty of room between rows of bags for personnel access. Smoking should not be permitted in the storage area or while handling activated carbon. The storage area should be kept clear of dust and flammable materials, and equipped with carbon dioxide fire extinguishers. Activated carbon may burn even in areas without much oxygen because of the oxygen contained within the porous medium. Electrical equipment operating near a PAC storage area should be explosion-proof and protected from the dust.

Although GAC also is capable of producing dust, it is only a fraction as messy as PAC. GAC generally is easier to handle and does not pose the level of fire hazard that PAC does.

Record Keeping

Records of GAC filter and contactor operation should include the following:

- hours of filter operation, used for calculating the volume of water processed
- monthly measurements of the GAC bed depth to monitor for loss of filter medium
- dates of backwashing and GAC replacement
- results of tests for organics concentration, color, and odor in raw and finished water

Regulations

Most of the regulations pertaining to adsorption are concerned with DBPs. The Surface Water Treatment Rule mandates that naturally occurring organic matter be removed to acceptable levels from surface water to avoid the formation of DBPs during disinfection. MCLs for THMs and other DBPs must not be exceeded. In addition, groundwater that may be affected by surface water may need to pass minimum requirements for concentrations of SOCs such as pesticides percolated down from surface runoff.

REVIEW QUESTIONS

1. Adsorption works by a process of
   ____
2. List two treatment objectives that use adsorption
   a. ______________________________
   b. ______________________________
3. Why is the removal of organics from drinking water before disinfection with chlorine or ozone important?
   ____
   ____
   ____
4. List two regulatory requirements that are pertinent to the use of adsorption in water treatment
   a. ______________________________
   b. ______________________________
5. What are two common types of activated carbon?
   a. ______________ b. ______________
   Which is the most commonly used in water treatment in Alaska?
   ____
6. What property gives activated carbon its treatment capacity?
   ____
   How is it "activated"?
   ____
7. Why is it important that backwash rates for GAC filters be lower than for regular filters?
   ____
8. True or False: Taste-and-odor-causing organic compounds deplete GAC filter media faster than synthetic organics.
   True ________
   False ________
9. What are two methods for monitoring organics breakthrough in GAC filter effluent?
   a. ______________________________
   b. ______________________________
   Which one is more easily practiced on site?
   ____

10. Define the following acronyms:

SOC ____

THM ____

GAC ____

PAC ____

MTBE ____

TOC ____

Chapter 13

Membrane Separation

Chapter 13 – Membrane Separation

INTRODUCTION

The future of water treatment may very well reside in the world of **membrane separation**. Membrane technology is advancing rapidly, with performance and endurance improving and costs declining. Membrane separation technology provides the water system designer with a process that can be used to engineer water treatment plants for removal of specific sizes of molecules, even if they are dissolved in the water.

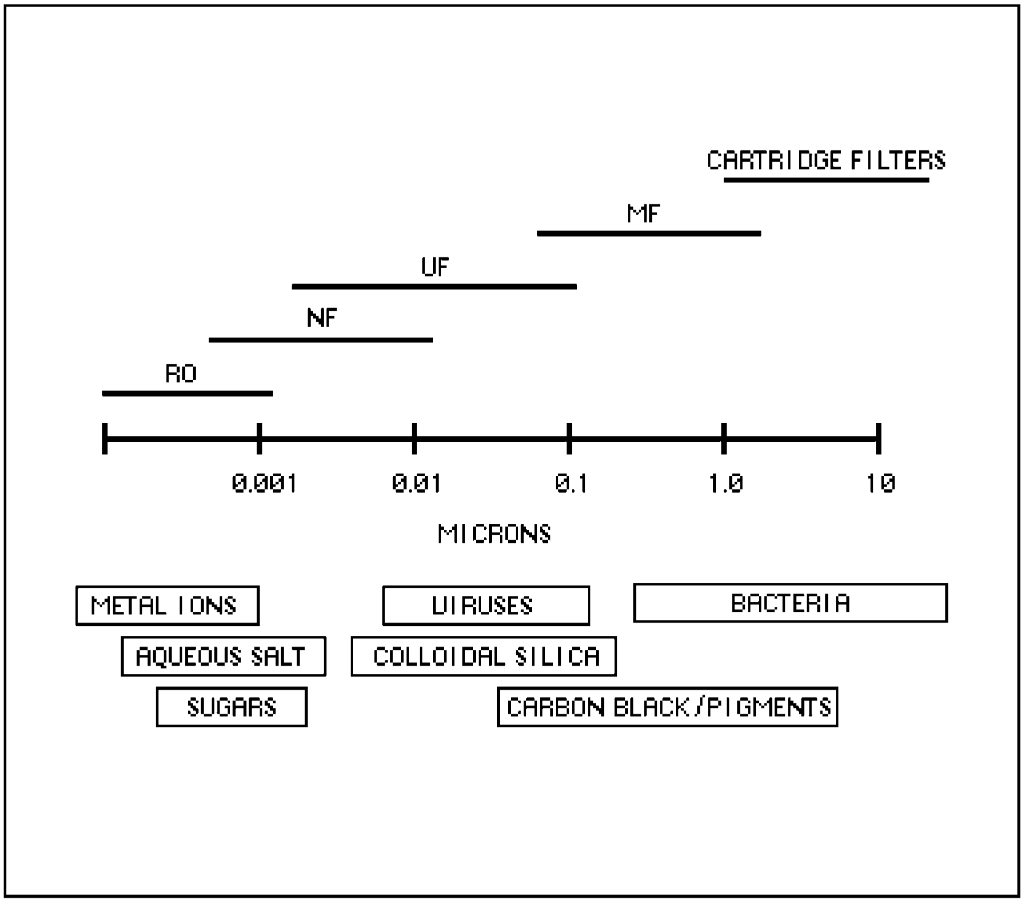
Membrane processes include many different alternatives, including **microfiltration** (MF), **ultrafiltration** (UF), **nanofiltration** (NF) and **reverse osmosis** (RO). The common component of all of these is a semipermeable membrane with different separation or rejection capabilities for various particles or dissolved ions in water.

PRINCIPLES OF MEMBRANE SEPARATION

Conventional filtration with sand, anthracite, or other relatively coarse media only removes particles 1 micron (µm, one millionth of a meter) or larger in size. Conventional ion exchange treatment, such as salt-regenerated softeners, simply trades ions, exchanging two sodium ions for each calcium or magnesium ion. Membrane softening, by comparison, removes the calcium and magnesium by forcing the water through a membrane at high pressure. The membrane allows water molecules to pass, but rejects the dissolved calcium and magnesium ions.

One common application of membrane treatment is RO desalination of seawater in which enough dissolved salt is removed to make the water potable. UF and NF are emerging as usable technologies to remove hardness and large organic molecules that produce color and that may form disinfection by-products in treated water.

Membranes can easily be fouled, however, because of the extremely fine porosity and physical structure of the membranes. If the water is not pretreated properly to reduce the propensity to deposit scale or prevent the growth of biofilm, the performance will decline rapidly.



Size separation capabilities for the different types of membranes.

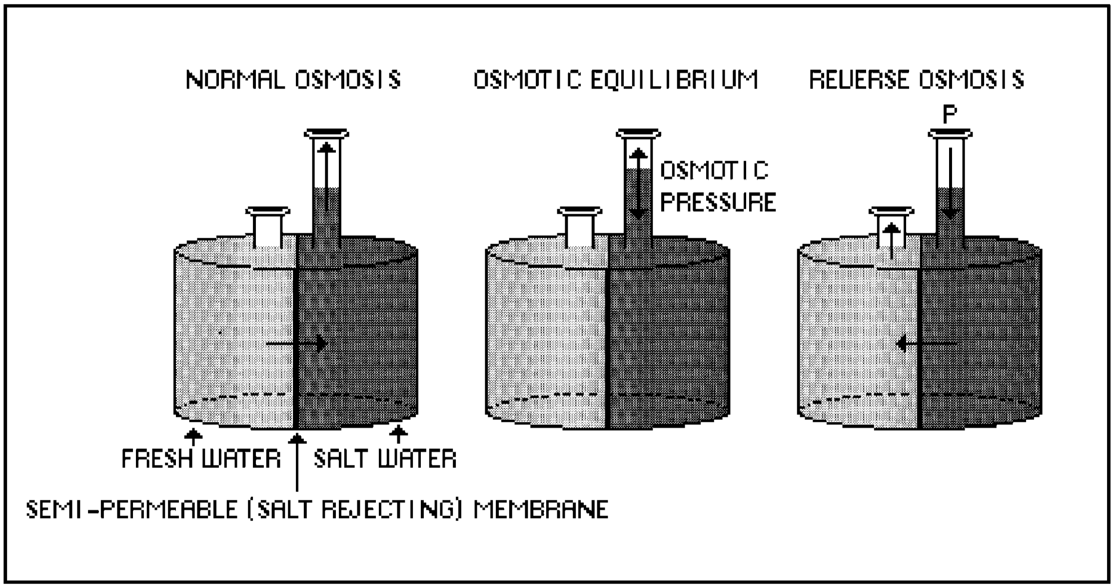
Membrane Separation - Basic Theory

Microfilters are true particle filters that are being used as prefilters for more sensitive membrane processes such as NF or RO. Microfilter membranes are manufactured to a selective pore size ranging from 0.1 to 2.0 µm.

Ultrafilters, which are less porous than microfilters, are designed to remove only higher molecular-weight materials such as large organic molecules that cause color in water. The porosity of UF membranes is selectively designed to remove substances up to a particular **molecular weight cutoff**.

Nanofilters are a type of semipermeable membrane slightly more permeable than RO membranes. Nanofilters can selectively remove larger dissolved molecules while allowing smaller ones to pass through.

Osmotic pressure is the result of different concentrations of dissolved ions (salt) in water trying to reach equilibrium. In normal osmosis, fresh water tends to flow into the saltwater side of the vessel through the semipermeable membrane. The pressure generated in this attempt to reach equilibrium in salt concentration is measured as the height of the column of water extending above the container, which equals 0.431 pounds per square inch (psi) per foot of elevation. The greater the difference in salt concentration, the higher the osmotic pressure.

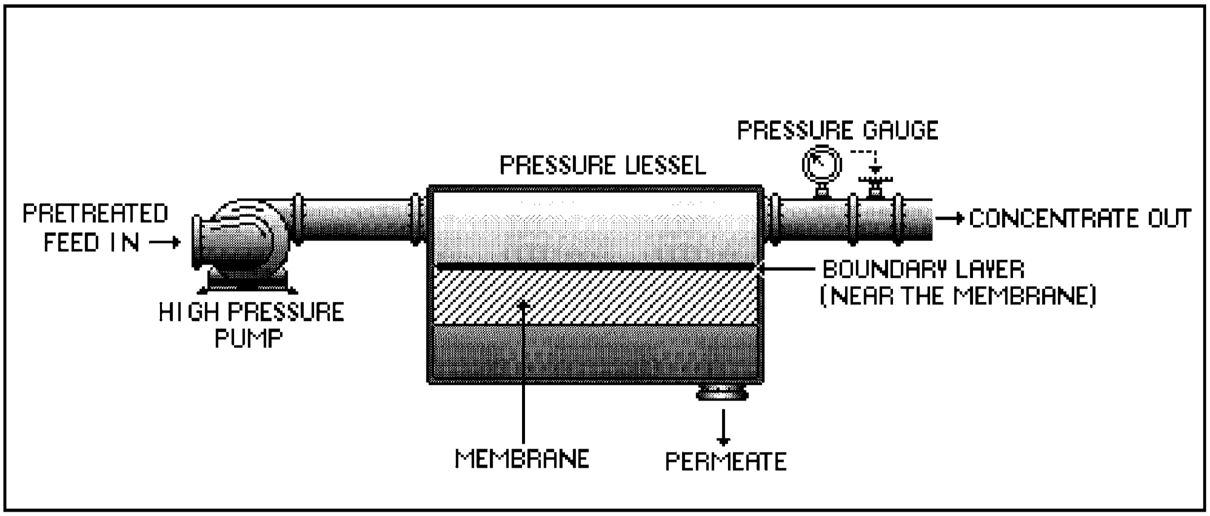


Basic theory of osmosis and reverse osmosis.

In RO, sufficient pressure is applied to the higher concentration side to overcome the osmotic pressure and push the fresh water through the membrane, leaving the salt behind. RO membranes provide the highest salt removal efficiency of the major types of membranes available.

Membrane Terminology

Essentially, the membrane system consists of a high-pressure pump that feeds pretreated water to a pressure vessel containing a semipermeable membrane. Water molecules are forced through the membrane and become clean **permeate**, while the remaining salt is rejected as a concentrate or reject stream for disposal. At the surface of the membrane is a layer of high dissolved-ion concentration called the **boundary layer**. The boundary layer is important in understanding how fouling occurs, since it is in this layer that very high concentrations of foulants are exposed directly to the surface of the membrane.



Basic membrane separation terminology.

Flow through a membrane system is referred to as **flux**, the gallons per minute that flow through each square foot of membrane. The primary forces that influence the flux in membrane systems are pressure, concentration, temperature, and pH. These are referred to as the "driving forces," and have the following effects:

- **Pressure** - the higher the applied pressure the greater the flux. Sufficient pumping pressure needs to be applied to initially overcome the osmotic pressure, then to provide extra pressure to drive the fresh water out of the salty water.
- **Concentration** - the higher the salt concentration, the greater the pressure needed to desalinate that solution. As the concentration increases, the flux will decrease without additional pumping pressure.
- **Temperature** - membrane flux is a function of temperature. The optimal temperature range for most desalination membranes is approximately room temperature. At lower temperatures, the flux declines significantly.

- **pH** - each type of membrane has an effective pH range in which it can operate. A pH that is too high or too low may damage the membrane, and in some cases actually dissolve it.

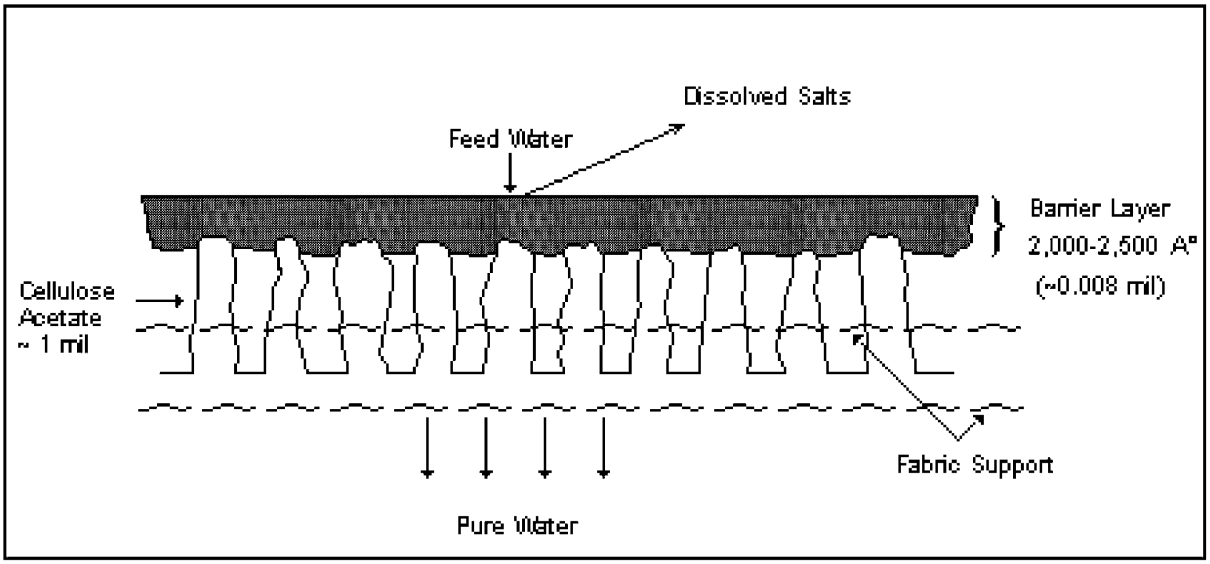
Good operational practice for membrane systems means maintaining each of the above driving force factors in the optimal range.

Separation efficiency defines what percentage of salt is rejected, and is calculated using a percent removal formula:

$$\text{Separation Efficiency} = \frac{\text{(Feed Concentration - Permeate Concentration) x 100\%}}{\text{Feed Concentration}}$$

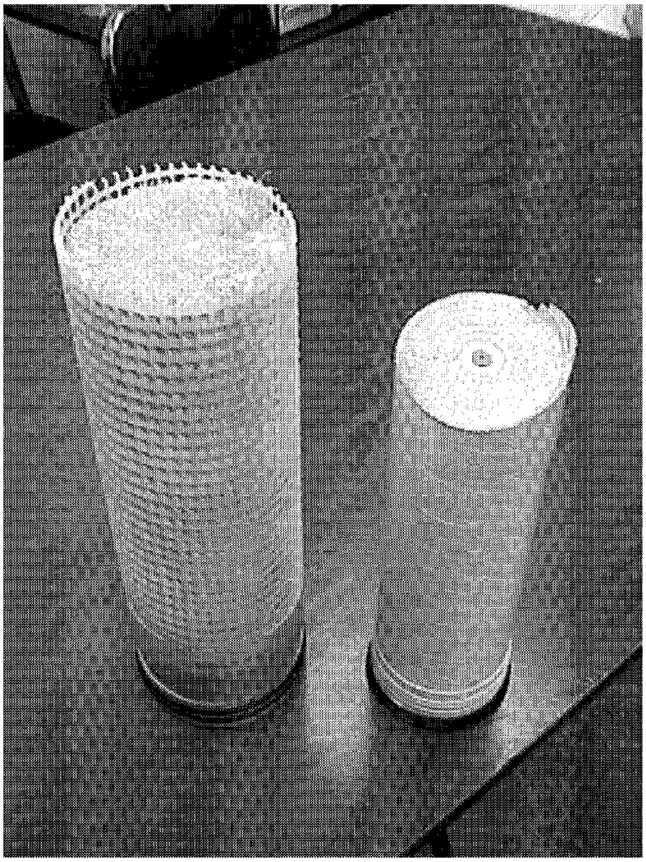
Membrane Structure

The most common materials used to construct water treatment membranes are cellulose acetate and polyamide-composite materials. New materials with improved resistance to chemicals such as chlorine are being developed. Membrane sheets are manufactured as thin films of these materials cast onto a support fabric.

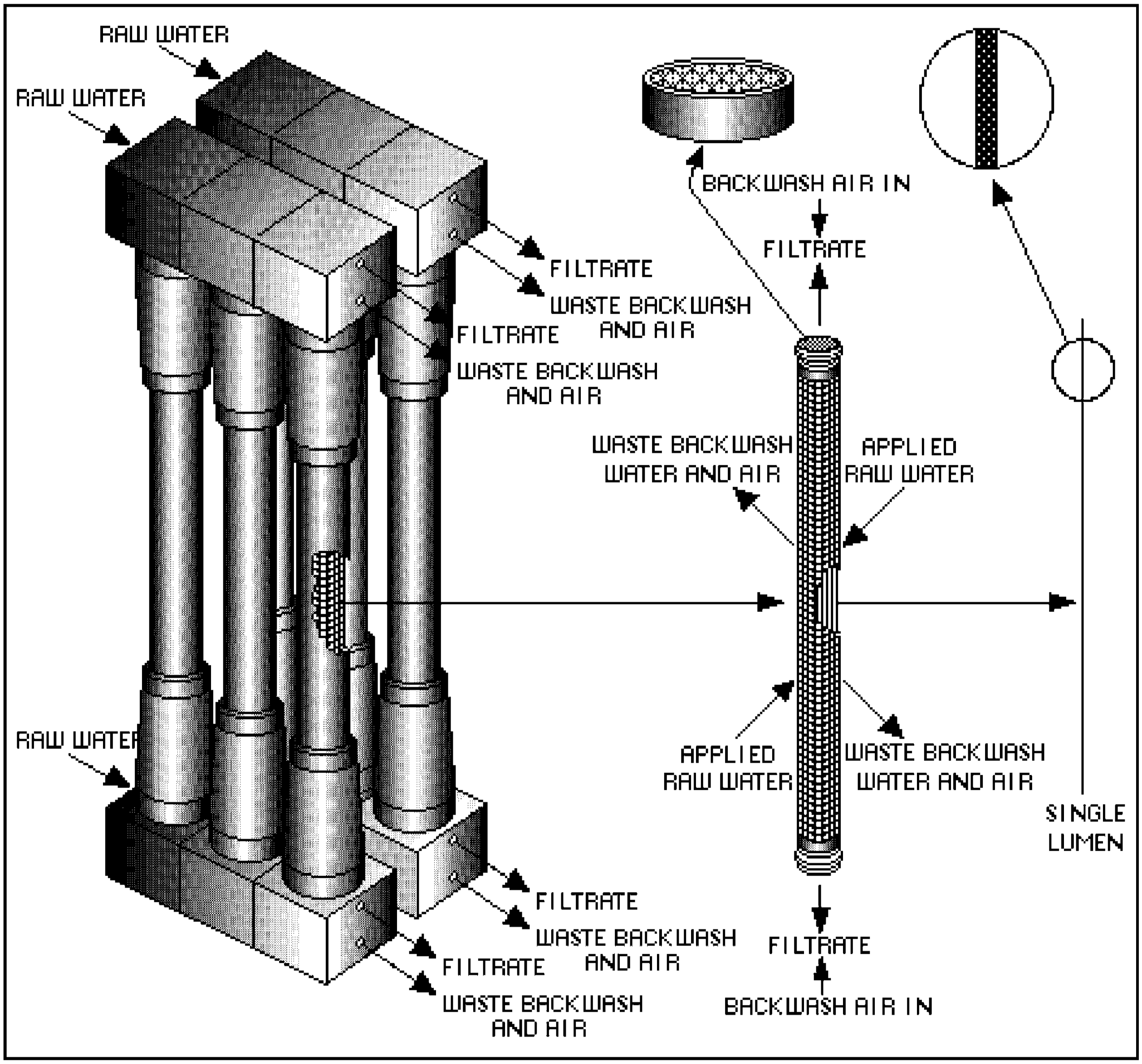


Membrane structure: the barrier layer is between 2,000 and 2,500 Angstroms in thickness (~0.008 mil); the layer of cellulose acetate is about 1 mil in thickness.

Membranes are available in a variety of designs. MF membranes are designed as bundles of fine fibers with tiny pores called **lumen**. One type of RO membrane, the hollow fiber permeator, is also produced in a fiber bundle form.

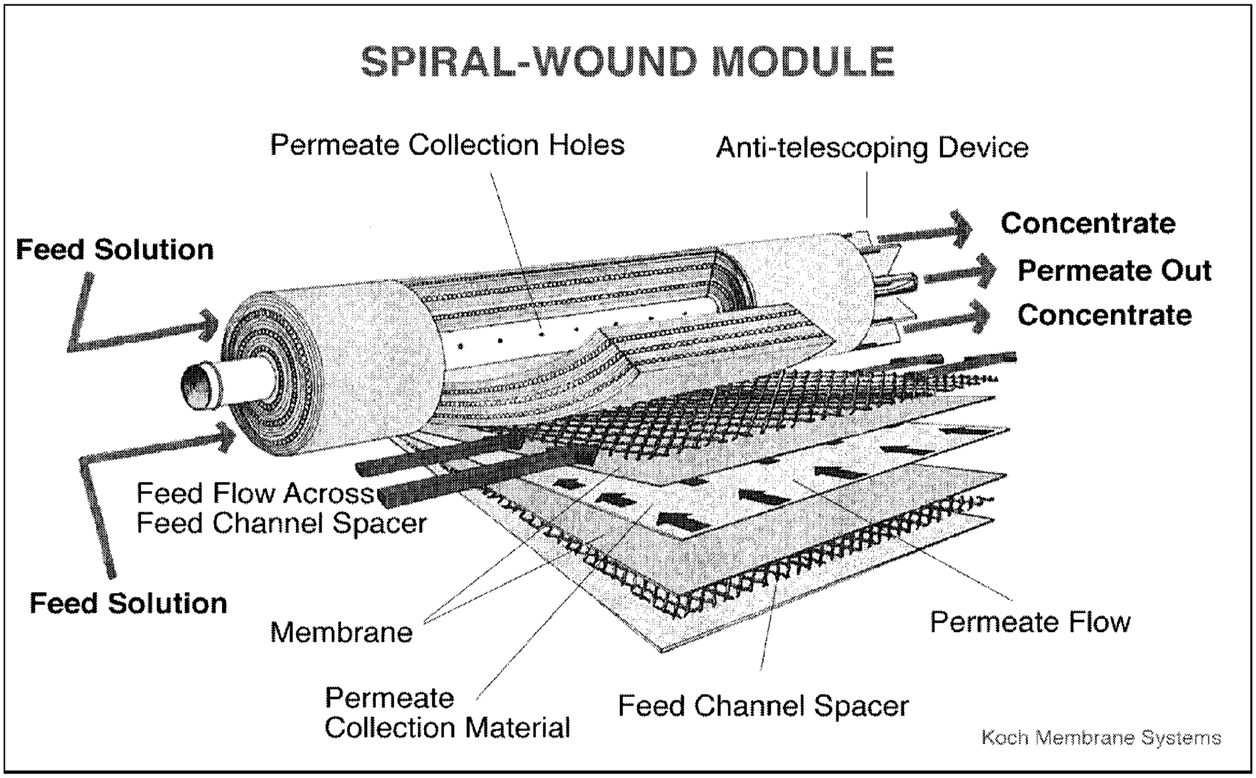


Microfilter lumen bundle (left) provides the 0.2-µm separation of particles from the raw water. The spiral-wound nanofilter permeator (right) then removes dissolved organic matter that would otherwise form disinfection by-products after chlorination.

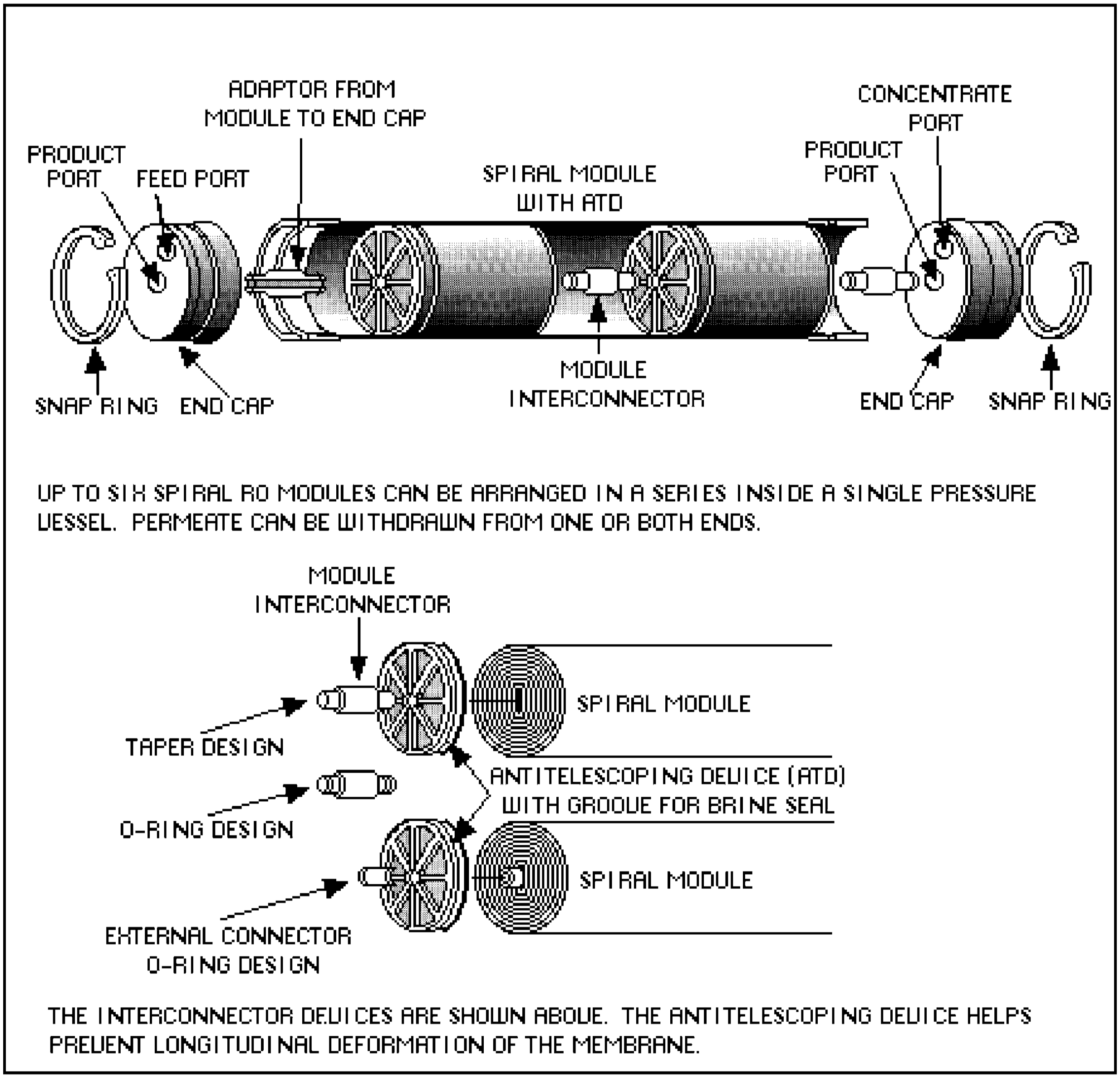


Detail of microfilter components, showing the flow of raw water, air, wastewater, and filtrate through the filter.

Most other membranes are formed in sheets, which are rolled into tubes or stacked in plates. Two membranes are usually rolled together with a spacer between them used to distribute the feed water, and additional collection spacers on the outsides to collect permeate. The spacers are commonly made of plastic mesh material. This rolled, or spiral-wound module configuration is the most common. The membrane modules are sealed in a pressure vessel, and locked into place with o-rings or gaskets to prevent seepage around the outside of the membrane bundle. Multiple modules can be placed in a single pressure housing to increase capacity. Spiral-wound membranes are more tolerant of fouling than hollow fiber units because of the relatively high feed water flow rates that pass through the spacers. However, more permeate production per unit volume of membrane is possible with hollow fiber units.



An example of spiral-wound membrane structure, courtesy of Koch Membrane Systems.



UP TO SIX SPIRAL RO MODULES CAN BE ARRANGED IN A SERIES INSIDE A SINGLE PRESSURE VESSEL. PERMEATE CAN BE WITHDRAWN FROM ONE OR BOTH ENDS.

THE INTERCONNECTOR DEVICES ARE SHOWN ABOVE. THE ANTITELESCOPING DEVICE HELPS PREVENT LONGITUDINAL DEFORMATION OF THE MEMBRANE.

Detail of spiral-wound membrane components.

TYPES OF SYSTEMS AND APPLICATIONS

Membrane systems are available in a variety of sizes and permeabilities. Thus, each type of membrane has different applications.

Microfiltration

Microfilters are used to treat either filtered or unfiltered source water. They have pore sizes ranging from 0.1 to 2 μm. The pressure required to operate microfilters is relatively low, less than 100 pounds per square inch gauge (psig), compared to other types of membranes, since microfilters primarily are removing particles like bacteria and turbidity. MF is often used as a pretreatment system for other membrane processes. It is also becoming a practical option for replacement of conventional rapid sand filters. One advantage of MF units is that the porosity is sufficiently fine that protozoan contaminants such as *Giardia* and *Cryptosporidium* can be positively removed.

Ultrafiltration

Ultrafilter pore sizes range from 0.002 - 0.1 μm, which removes virtually all microorganisms and even some larger molecules such as those that produce organic color. Driving pressure requirements range from 25 to 175 psig as a result of the finer pore size, and the pretreatment requirements are more restrictive than microfilter units. Typically, ultrafilters only treated water filtered by another process such as a microfilter or a sand filter. In one modern application, a French company has patented a treatment process that uses UF to filter water that has been dosed with powdered activated carbon (PAC). The PAC adsorbs organic molecules, and is completely removed by the UF membranes.

Nanofiltration

NF units require driving pressures ranging from 75 to 200 psig. With pore sizes ranging from 0.001 - 0.02 μm, nanofilters actually remove larger molecules including organic acids that cause color and produce disinfection by-products. NF is also referred to as "membrane softening" because of the high rejection rate for divalent ions such as calcium and magnesium. A popular combination is microfiltration/nanofiltration (MF/NF), which provides an effective pretreatment removing particles and a finishing treatment to remove organic matter and even the smallest microorganisms.

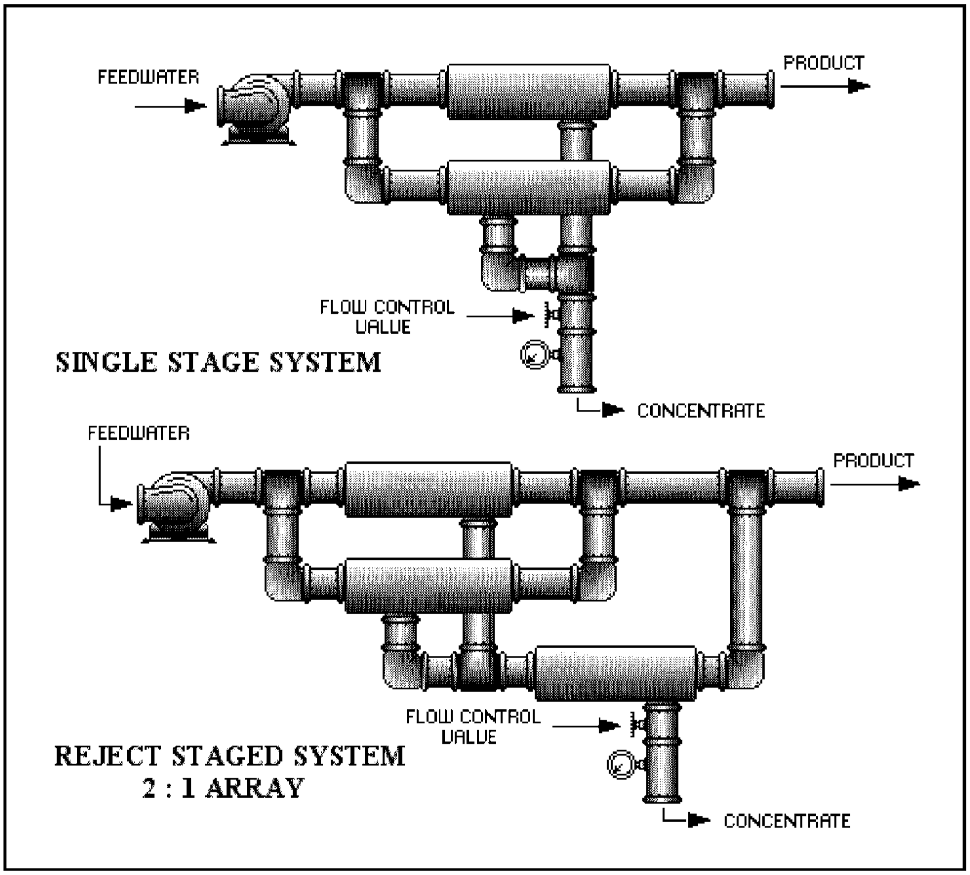
Reverse Osmosis

Pore sizes of <0.001 μm (<1 nm) allows this class of the membrane to remove even the smallest of dissolved ions or salts. RO units have been used for desalination of seawater and brackish water, and for the production of "ultrapure" water for industrial applications including high purity boiler feed water.

Microchip and pharmaceutical manufacturers also use ultrapure water, which can be created by cycling permeate through several stages of RO membranes. RO units require very high pressure because of the very fine membrane porosity, and the higher osmotic pressures of saline water. RO driving pressures start at 120 psig, and are around 400 psig for treating brackish water, with about 5,000 milligrams per liter (mg/L) total dissolved solids (TDS), and 900 - 1,100 psig for desalination of seawater, with about 35,000 mg/L TDS.

System Configurations

Membrane systems can be configured in a variety of arrangements depending on the desired result. Some configurations can produce more volume by treating the reject water through a second stage, thus recovering some of the water that would otherwise be rejected.



Reverse osmosis system configurations, showing single and double-stage systems.

WATER QUALITY CONSIDERATIONS AND PRETREATMENT

Each type of source water has different characteristics that need to be considered when a membrane system is selected. Also, different types of membranes have specific pretreatment requirements that must be considered when a particular quality of source water is to be treated. To ensure that an appropriate level and type of protection is being applied, the membrane supplier should review pretreatment equipment and chemical selections.

Numerous proprietary chemicals are available from membrane manufacturers and other companies in the membrane support service business. Each chemical is formulated for a specific function and for a particular type of membrane. It is important that the right chemicals be employed and that the dosages and point of application be correct. It is also important to obtain current Material Safety Data Sheets and other handling and safety information on proprietary chemicals. This information will describe what personal protective equipment should be used and how the chemicals can be safely stored and handled.

Surface Water Sources

Surface water supplies can experience significant changes in water quality in a very short period of time. Contaminants that have a potential to affect membrane performance include particulates, biological materials including live microorganisms, and a variety of inorganic and organic constituents. Some surface water, such as brackish water with a high mineral content, can also form mineral scales on membrane surfaces.

Surface water pretreatment often involves coagulation, flocculation, sedimentation, and filtration before membrane treatment. In some plants, MF units are used to replace the conventional treatment train. It is also common to include a disinfection step to reduce bacteria levels to prevent membrane biofouling. Biofouling manifests itself as a sudden increase in feed water pressure with a reduction in flux, usually across the first stage of the membranes where the bacteria tend to grow rapidly. Microbiological growths are enhanced where large surface areas are available, such as in membranes and the spacers used to channel feed water between the membranes.

One serious problem with disinfection of membranes is that many types of membranes degrade rapidly in the presence of oxidizing chemicals such as chlorine or ozone. UV light may be a more practical disinfectant in such situations. Also, chloramination (feeding combined chlorine residual) has proven to be successful in limiting bacterial growth while protecting chlorine-intolerant membranes.

Groundwater Sources

Groundwater supplies tend to have more consistent quality, but usually a higher mineral content than surface waters. Mineral scale formation is often a key design factor for membrane configuration and pretreatment of groundwater supplies. Common treatment to control mineral scales includes the addition of acids or sequestering agents such as sodium hexametaphosphate.

Iron and manganese are also problem foulants for membranes. In some cases, conventional iron filtration using manganese greensand filters has been used to control iron fouling. A comprehensive list of groundwater well test parameters is used to determine the proper pretreatment for membrane systems (see table on the following page). The data from this analysis also can be used to determine permeate quality and predict membrane performance.

Seawater Sources

Seawater sources can be either surface water or water produced from wells submerged into the seafloor. When seawater desalination systems are located in estuaries or immediately offshore from the mouths of rivers, the salt concentration and turbidity levels can change rapidly during tidal changes and periods of significant river discharge, such as at spring thaw and major rainfall events. Rapid turbidity increases in the feed water can overwhelm the pretreatment system and result in membrane fouling. Salt concentration fluctuations can result in changes in the flux through the membranes.

<table>
<tr><th colspan="4">COMPLETE GROUNDWATER WELL TEST PARAMETERS</th></tr>
<tr><th colspan="2">Primary Inorganic Contaminants</th><th colspan="2">Secondary Contaminants</th></tr>
<tr><th>Constituent</th><th>Symbol or Formula</th><th>Constituent</th><th>Symbol or Formula</th></tr>
<tr><td>Antimony</td><td>Sb</td><td>Aluminum</td><td>Al</td></tr>
<tr><td>Arsenic</td><td>As</td><td>Chloride</td><td>Cl</td></tr>
<tr><td>Barium</td><td>Ba</td><td>Color</td><td></td></tr>
<tr><td>Beryllium</td><td>Be</td><td>Copper</td><td>Cu</td></tr>
<tr><td>Cadmium</td><td>Cd</td><td>Corrosivity (Langelier Index)</td><td>L.I.</td></tr>
<tr><td>Chromium</td><td>Cr</td><td>Fluoride</td><td>F</td></tr>
<tr><td>Cyanide</td><td>Cn</td><td>Foaming Agents</td><td></td></tr>
<tr><td>Fluoride</td><td>F</td><td>Iron</td><td>Fe</td></tr>
<tr><td>Mercury</td><td>Hg</td><td>Manganese</td><td>Mn</td></tr>
<tr><td>Nickel</td><td>Ni</td><td>Odor</td><td></td></tr>
<tr><td>Nitrate</td><td>NO_3^-</td><td>pH</td><td></td></tr>
<tr><td>Nitrite</td><td>NO_2^-</td><td>Silver</td><td>Ag</td></tr>
<tr><td>Selenium</td><td>Se</td><td>Sodium</td><td>Na</td></tr>
<tr><td>Thallium</td><td>Tl</td><td>Sulfate</td><td>SO_4^{2-}</td></tr>
<tr><td colspan="2"></td><td>Total Dissolved Solids</td><td>TDS</td></tr>
<tr><td colspan="2">Volatile Organic Chemicals (EPA 524.2)</td><td>Zinc</td><td>Zn</td></tr>
<tr><td colspan="4"></td></tr>
<tr><th colspan="4">Other Parameters to Complete an Ion Balance</th></tr>
<tr><td>Magnesium</td><td>Mg^{2+}</td><td>Strontium</td><td>Sr^{2+}</td></tr>
<tr><td>Potassium</td><td>K^+</td><td>Phosphate</td><td>PO_4^{3-}</td></tr>
<tr><td colspan="4"></td></tr>
<tr><th colspan="4">Other Miscellaneous Parameters</th></tr>
<tr><td>Silica</td><td>Si</td><td>Carbon Dioxide</td><td>CO_2</td></tr>
<tr><td>Turbidity</td><td></td><td>Total Organic Carbon</td><td>TOC</td></tr>
</table>

EPA, Environmental Protection Agency
Source: State of Alaska Drinking Water Regulations

OPERATION AND MAINTENANCE CONSIDERATIONS

As in any other type of water treatment plant, the performance and durability of membrane treatment systems are a function of proper care by trained and motivated operations personnel. Membrane systems have certain special requirements, however, which need to be addressed.

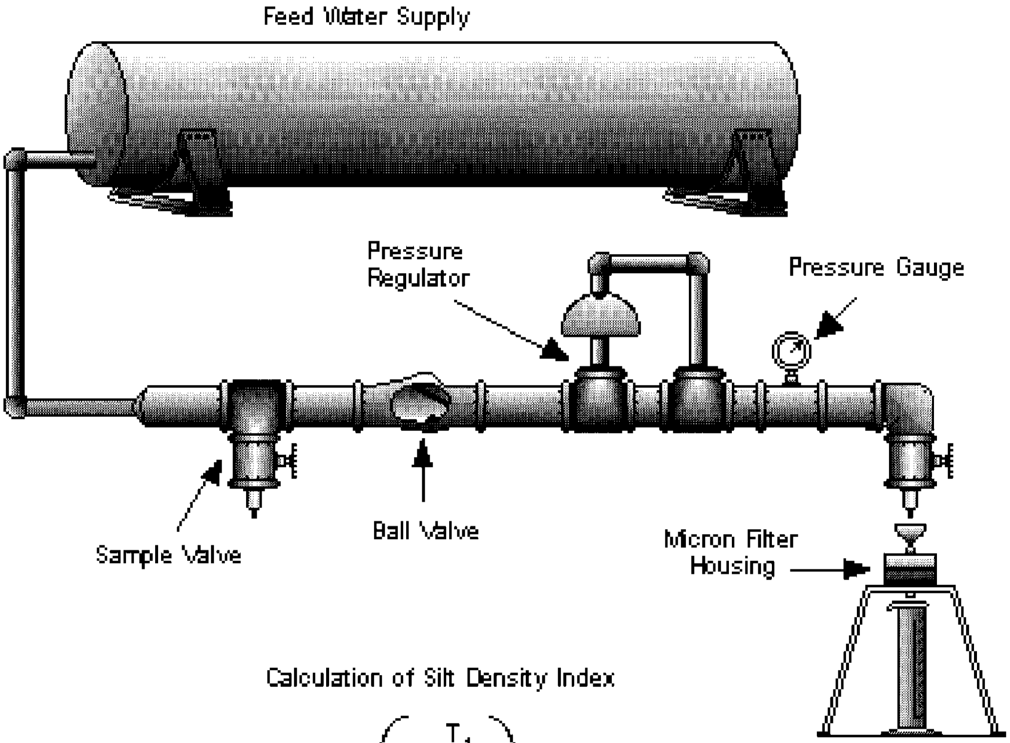
Operating Parameters

Monitoring parameters for membrane system operations include flow, pressure, temperature, and salt content in the feed water, and permeate at each stage of the process and in the reject brine stream. Salt concentration is measured using conductivity meters. Monitoring is usually done daily or once per shift, or continuously with on-line instruments for larger installations. Data from on-line instruments can be transmitted to a computer terminal, allowing an operator to monitor the system or several systems remotely.

In addition, it is useful to determine the potential of a water supply to foul membranes. A special test developed for this purpose is the Silt Density Index (SDI) test. The SDI test is run on the RO feed water, usually once per day or once per shift. The SDI test compares the amount of time it takes to collect a fixed amount of water filtered through a 0.45-µm membrane filter initially, then again15 minutes later. The 0.45-µm membrane filter is a standard lab filter used in bacteria tests.

In essence, this test measures the fouling potential of the feed water supply on fine-porosity membranes, in this case the bacteria filter. The result is an SDI number, which can be compared with other SDI data. Manufacturers of membranes use SDI as a pretreatment criterion. A maximum SDI of no more than 3 is recommended to protect hollow fiber membranes, while spiral wound membranes can usually tolerate SDI values of up to 5.

In addition to the operating parameters, pretreatment chemical levels and dosage rates should be confirmed daily and stock solutions prepared as needed. All data related to chemical preparation and addition should be recorded on the operations log.



Calculation of Silt Density Index

$$SDI = \frac{100\left(1 - \frac{T_1}{T_f}\right)}{T_t}$$

T_1 = INITIAL TIME REQUIRED TO COLLECT 500 ml.

T_f = TOTAL TIME, USUALLY 15 MINUTES.

T_t = TOTAL TIME REQUIRED TO COLLECT 500 ml AFTER TOTAL TEST TIME.

Apparatus for determining the silt density index.

Membrane Cleaning

If the membranes become fouled, it may become necessary to clean them. Operations personnel must be aware of system conditions that signal when cleaning is necessary. Some of these operational "signals" are:

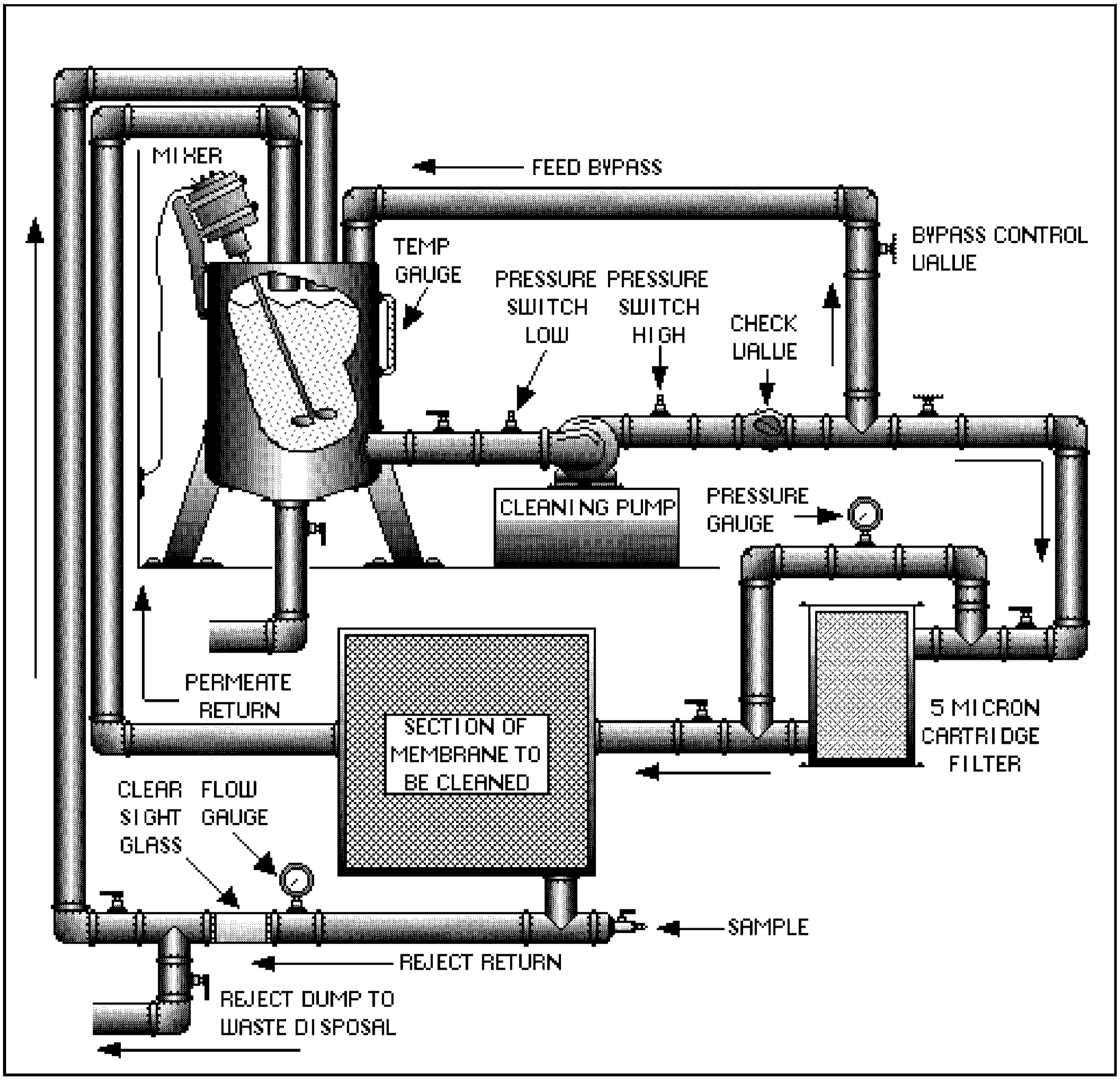
- salt passage increases by 15% or more
- individual pressure module pressure drop increases by 20% or more
- feed pressure requirements increase by 20%
- product flow drops or increases by 5% or more
- reject flows change by 5%

Most large systems are equipped with a chemical cleaning skid, referred to as a "clean in place" or CIP skid by some manufacturers. The purpose of the CIP system is to provide a means to mix cleaning chemicals safely and at the proper concentrations, and to circulate the solutions through the membranes. The manufacturer should provide a procedure for cleaning which may include some combination of the following chemicals:

- citric acid or other mild acids to remove scales
- detergents to remove oil films and organic chemical deposits
- biocides such as sodium metabisulfite, which are designed to protect the membrane while removing bacteria
- alkaline chemicals to remove certain types of foulants or to adjust the pH following an acid cycle
- clean water rinse

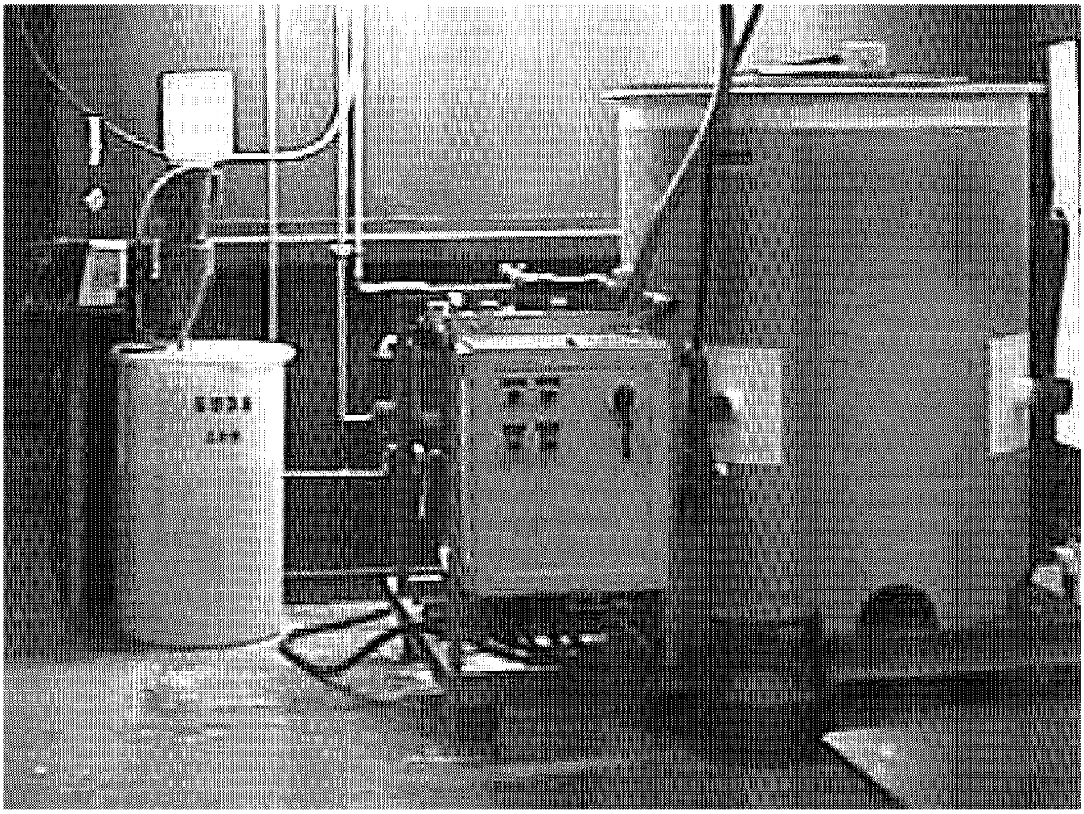
The membrane cleaning procedure description should include solution mix strength for each chemical, point of addition to the membranes, length of time of circulation or soaking, and the proper sequence of chemical addition and rinse cycles. Information on proper disposal of spent solutions should also be provided.

The interval between membrane cleanings is a function of the type of fouling and the results of the monitoring data. Increase in pressure across the membranes, loss of flux or degradation of permeate quality are all parameters that may be used to determine cleaning intervals. Membranes may not recover 100 percent of their initial performance after cleaning, and will likely lose some of their capacity or efficiency over time. Eventually, they will need to be replaced. A typical life span for membranes operating full time is about 3 years. Membrane life can be reduced by excessive fouling, or extended by good pretreatment and careful operation.



Cleaning system skid, showing the principal components and flow paths.

An important job for the membrane system operator is troubleshooting. Careful observation of the membrane performance over time will provide useful information to help identify the source of problems. In the event that a membrane becomes irreversibly fouled, it is possible to have the membrane analyzed by the manufacturer or a supplier of membrane treatment chemicals. This procedure is referred to as an "autopsy" and literally involves dissecting the membrane and examining it closely to determine the cause of failure.



Membrane cleaning system skid at the Barrow Utilities and Electric Cooperative, Inc., Barrow, Alaska.

Membrane Storage

If membranes are taken out of service for an extended period, it is common to "pickle" them in a preservative solution so bacteria do not degrade them. Again, the manufacturer should be consulted for a proper formulation for this. Frequently, the pickling solution will be the same chemical as is used as a biocide in the cleaning cycle.

For long storage times such as over winter, the membranes may be removed from the pressure vessels and stored in the pickling solutions in separate packaging. This can be a risky operation, since all of the o-rings and gaskets have to be removed and ultimately replaced carefully to avoid damage. Leakage around these seals results in poor permeate quality.

Concentrate Disposal

In all membrane systems, some percentage of the feed water will be rejected as brine for disposal. That percentage depends on the number of stages being used and the temperature and other driving force conditions. Disposal of concentrated brines is one of the limiting factors in membrane system operations, because a wastewater disposal permit may be required if a convenient point of disposal to a sewer system is not available. Even if a sewer system is available, brine reject may not be acceptable under limitations of the pretreatment requirements for that sewer system. Part of the planning process in membrane installations is to identify an acceptable means of brine reject disposal.

Usually, if either a discharge permit or pretreatment authorization to discharge to a sewer is obtained, there will be some monitoring required. The plant operator usually does this, often reporting the flow and test data as determined by the permit. That data will likely have to be collated monthly or according to some other routine cycle and reported to the agency in charge of that program. In some cases, it has been possible to obtain a permit to discharge otherwise clean reject water with slightly elevated salinity directly to the outfall of a wastewater treatment plant. For desalination plants, it is common practice to return the saline reject stream to the ocean away from the raw feed water intake structure.

EXAMPLES OF APPLICATIONS IN ALASKA

Membrane technology is finding a place in Alaskan water treatment applications. Much has been learned from some of the early applications, and much more will be gained in the future from additional work on the peculiarities of water-quality problems in cold regions. Following are brief outlines of several case histories of membrane systems in Alaska.

Membrane Softening Plant

Groundwater in the Denali Park area and other parts of the northern foothills of the Alaska Range has unusually high hardness levels. Values as high as 1,500 mg/L as $CaCO_3$ are not uncommon, and result in heavy scale deposition, particularly in hot water piping and boilers. In some cases, the sulfate and other dissolved ion levels are so high that the water has a salty or otherwise distinctly unpleasant taste. Even when treated with a conventional salt-regenerated softener, the final water has so many dissolved ions that it makes lousy coffee.

In the mid-1990's, Princess Tours commissioned the pilot testing, design and installation of a 100,000-gallon-per-day (gpd) low-pressure membrane softening plant at their Denali Park Hotel. The first installation, which used feed water pretreated with manganese greensand filters, was destroyed in a fire. A replacement unit of the same capacity was constructed, which drew feed water from two wells closer to the Nenana River which had better quality water.

In the new installation, the pretreatment was reduced to carbon dioxide gas removal, cartridge filters and antiscalant chemical conditioning. The system is a two-stage system that recovers nearly 75 percent of the feed water, and reduces the hardness by 90 percent to a nearly ideal level of about 100 mg/L as $CaCO_3$. The feed pressure is approximately 250 psig and the membranes are cellulose acetate spiral wound type. Initially, the system was intended to have the RO elements removed and pickled for winter storage, but they are now stored in place in the pressure vessels in the winter.

Brackish Water Desalination

Barrow Utilities & Electric Cooperative, Inc. (BUECI) draws their raw water supply from the Isatkoak Reservoir, an old tidal basin on the edge of the Chukchi Sea. The reservoir was developed using a series of overflow dams backing the water level up above sea level and allowing the basins to fill with snow melt each spring. The quality of the reservoir water remained brackish, however, with mid-winter TDS levels as high as 5,000 mg/L under the ice cover.

In the late 1970's BUECI installed a small 2-stage RO system using Du Pont Hollow Fiber® permeators rated at about 36,000 gpd. Feed water was conventionally treated with coagulation, flocculation, sedimentation, and filtration. The RO system was able to reduce the treated water TDS levels to potable quality, although frequent cleanings were necessary to maintain the membrane performance.

In the early 1980's BUECI commissioned an upgrade to the RO system, improving the pretreatment system and expanding the capacity to 150,000 gpd, which made this the largest membrane plant in Alaska. Again, Du Pont Hollow Fiber® permeators were the membranes of choice, and a two-stage arrangement was used.

This system ran well for more than ten years, but slowly the feed water quality changed in the reservoir. Over a period of several years, BUECI intentionally pumped the more saline brine out from under the ice layer in late winter and allowed the Isatkoak Reservoir to refill with snow melt water. By the early 1990's the TDS level of the reservoir was less than the Alaska Department of Environmental Conservation's secondary maximum contaminant level of 500 mg/L even in the winter. The RO units continued to be operated, however, to reduce the concentration of organic matter in the feed water that was forming disinfection by-products in the finished chlorinated water.

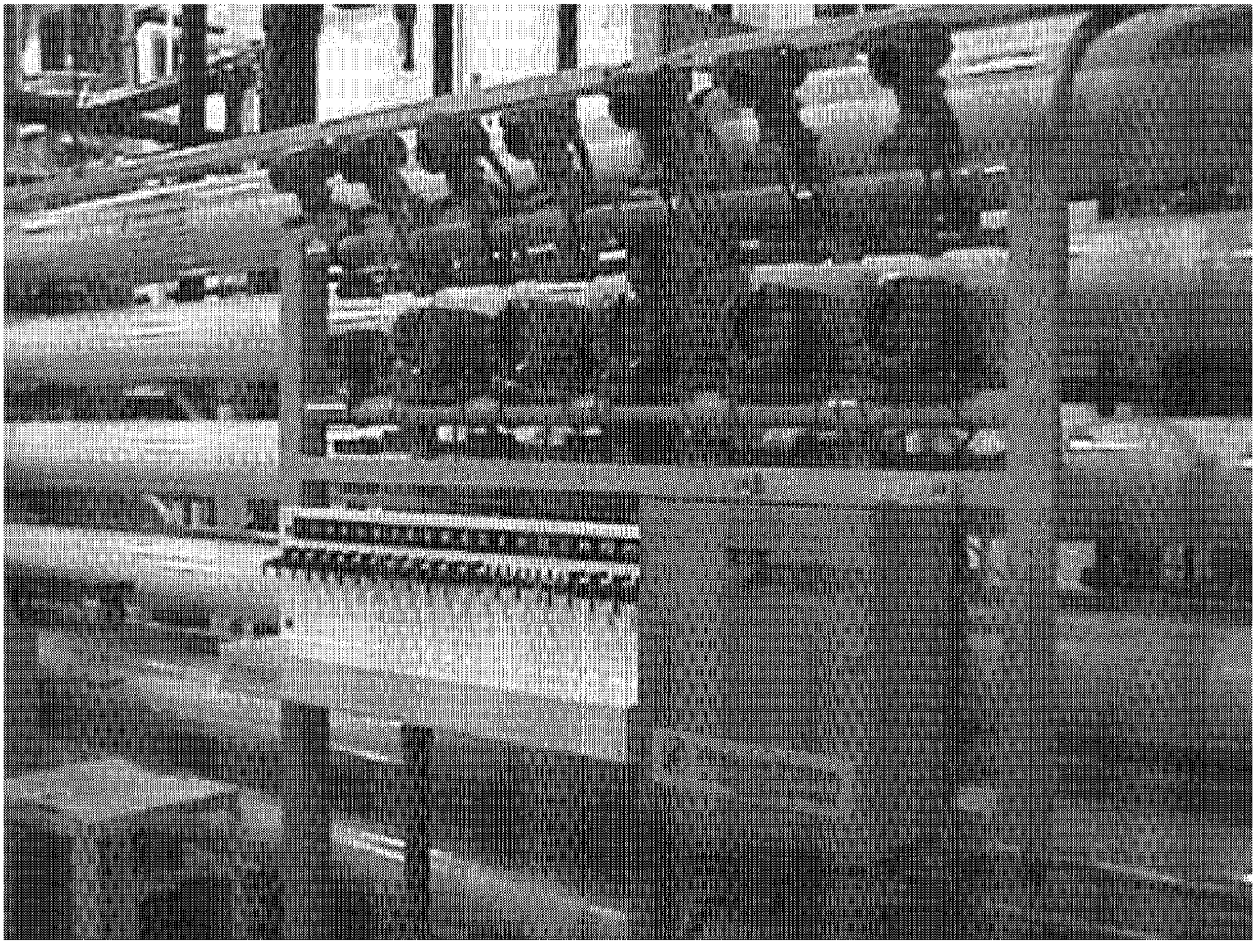
Removal of Natural Organic Matter

In the mid 1990's BUECI began a series of pilot tests to upgrade the design of the RO system to more effectively treat the new, lower TDS quality of water from the Isatkoak Reservoir. An innovative 40-gallon-per-minute (gpm) system was installed that relied on microfiltration rather than conventional treatment to treat the raw water, and low-pressure nanofilters to remove the organic color. This small MF/NF unit provided a means to demonstrate the new technology and to temporarily supplement the production of water for the rapidly growing community of Barrow.

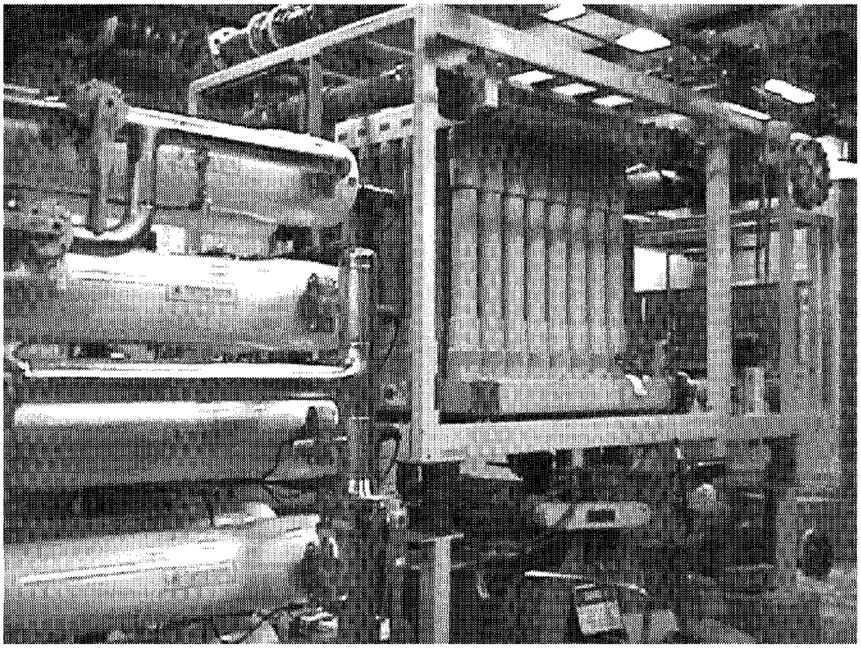
The unit was configured in a 3-stage array, which provided more than 85 percent recovery of the feed water as permeate. Several types of NF membranes were tested to determine the optimal configuration, and ultimately a single brand was selected for long-term use. An antiscalant was added after the MF units to sequester scale-forming chemicals in the water and preserve the NF unit life.

A severe biofouling problem occurred in the first stage of the NF units. The problem was solved with the addition of a chloramine feed station just after the MF units. Bacteria counts declined rapidly after chloramine addition was started and the rapid increase in pressure differential ceased. At the peak of the biofouling incident, the membranes were being cleaned every two weeks. Now, membrane cleaning only takes place a few times per year.

A 240-gpm (about 345,000 gpd) MF/NF system was recently installed at BUECI to completely replace the older treatment system. This system has also become the prototype for similar MF/NF systems being installed in six other North Slope villages with similar water-quality problems.



Nanofilter module monitoring equipment at BUECI. Rows of pressure and conductivity sensors display readouts from each stage of the nanofilter array. Sample ports from each pressure vessel are in the lower center left. This system allows the operators to determine the individual performance of each pressure vessel in the system.



BUECI nanofilters (left) and microfilters (right). Note the stainless steel interconnect piping on nanofilter array.

Microfilter backwash separation tank at BUECI

Seawater Desalination

Several RO desalination plants have been developed for use by the North Slope oil industry. BP owns the largest of these, a 144,000-gpd 3-stage unit, on Endicott Island just offshore from the mouth of the Sagavanirktok River. The rapidly fluctuating water quality during spring thaw and heavy wind conditions created high-turbidity conditions which prematurely fouled the normally tolerant spiral wound, thin-film composite membranes. BP upgraded the pretreatment system, providing a highly automated coagulant addition and settling system using a lamella plate clarifier ahead of the sand filters. That addition solved the feed water problem and has allowed many years of successful operation.

Arsenic Removal

One of the more difficult contaminants to remove from groundwater is arsenic. Many of the deep wells in Southcentral and Interior Alaska contain some arsenic. Membrane treatment has proven reasonably successful for single and multiple residential treatment. Small, commercially manufactured package RO units are routinely being used to remove arsenic, and in a few cases, nitrate from well water.

Pretreatment is usually a challenge with these smaller systems, so they are often installed as a point-of-use system at kitchen sinks, using water that has been pretreated with a softener or an iron filter. In these smaller units, only water being used for direct consumption or cooking is treated with the RO units.

REVIEW QUESTIONS

1. True or False: Different types of membranes can remove various types of contaminants from water including colloidal particles, organic color, hardness and salt.
   True_______
   False________
2. Osmotic pressure is the result of different ____________________________ of ____________________________ in water trying to reach equilibrium.
3. In reverse osmosis, ____________________________ is applied to a salty solution to extract fresh water.
4. Four types of membranes are ____________________________ , ____________________________ , ____________________________ , and ____________________________ .
5. Four "driving forces" in membrane operations are ______________________ , ____________________________ , ____________________________ , and ____________________________ .
6. Microfilters are made of bundles of porous tubes called __________________.
7. Dissolved organic matter that can react with chlorine to form disinfection by-products can be removed by ____________________________ or ____________________________ membranes.
8. Desalination of seawater is accomplished with __________________________ membranes and high-pressure pumps.
9. To protect membrane systems, specific ____________________________ requirements must be considered for each type of source water.
10. Surface water source contaminants that can affect membrane performance include ____________________________ , ____________________________ , ____________________________ , and ____________________________ .
11. Sudden pressure increase in the feed water to a membrane treating surface water can be caused by ____________________________ .
12. True or False: Chlorine can be used to disinfect all types of membranes.
    True _________
    False __________
13. True or False: Groundwater usually has a higher mineral content than surface water.
    True _________
    False __________

14. Mineral scales on membranes can be treated with ____________________ or ____________________ .

15. Monitoring parameters for membrane systems include __________________ , ___________________ , ___________________ , and ___________________ .

16. To determine the fouling potential for membranes, a ____ test can be run on the feed water.

17. List four types of chemicals that may be used for cleaning membranes:
    a. _______________________ b. _______________________
    c. _______________________ d. _______________________

18. To determine what caused a membrane to fail, an ___________________ can be performed by a membrane manufacturer or treatment chemical supplier.

19. Disposal of the concentrated reject stream may require a wastewater permit
    True _______
    False ________

20. Four types of water treatment applications using membranes are:
    a. ____
    b. ____
    c. ____
    d. ____

Chapter 14

Disinfection

Other Disinfectants

Ozone
Bromine and Iodine
Ultraviolet Radiation
Hypochlorite Generators

Safety

Self-Contained Breathing Apparatus
Emergency Repair Kits
Changing Cylinders
Safety Procedures

Management

Total Coliform Sampling
Record Keeping
Regulations

Review Questions

Chapter 14 – Disinfection

INTRODUCTION

Cholera and typhoid epidemics were common before the advent of the **disinfection** of water supplies. Even today, lack of disinfection of water supplies is a significant public health problem in much of the developing world, resulting in large populations being continuously afflicted by a variety of waterborne diseases. The American Water Works Association's "Water for People" technology outreach program estimates that some 40,000 people die every day from waterborne diseases throughout the world. The victims are mainly the very old and very young. Until the early 1900's when boiling water by soldiers became a common practice, virulent typhoid outbreaks frequently killed more soldiers during wars than combat did.

History

One of the earliest uses of disinfection was an attempt to treat the water supply from London's Broad Street Well in 1850 with "chloride of lime," a powdered hypochlorite chemical. A cholera outbreak had been traced to this well, helping to establish the science of waterborne disease transmission by microorganisms. By the turn of the 20th century chlorine was used as a disinfectant in water supplies to prevent the transmission of pathogenic organisms. In 1897, bleach solution was used to disinfect water mains in Maidstone, England, following a typhoid outbreak.

Chlorine became widely used once its disinfecting power was established. It continues to be used today because of its wide range of advantages including effectiveness, ease of mixing with water, simple dosage control, low cost, and, most importantly, a residual can be maintained in water treated with chlorine. As a result chlorine is by far the most commonly used disinfectant in municipal water supplies.

The first continuous use of chlorine as a disinfectant in water treatment is believed to have been in Middelkerke, Belgium, in 1902. The process used both ferric chloride as a coagulant along with calcium hypochlorite. In 1903 in the town of Ostende, Belgium, chlorine was generated on site and used in the disinfection of the treated water.

Through the late 1800's a variety of electrolytic methods were devised which converted salt into an active form of a chlorine disinfectant. The research was done by a number of individuals and was used in both water and wastewater treatment. It is interesting to note that as we begin the 21st century many large facilities are reverting back to the electrolytic method of chlorine generation to avoid problems with storage of large quantities of chlorine gas.

The first notable use of chlorination in the United States was in 1908 in Chicago at the Bubbly Creek filter plant. The raw water contained sewage and high levels of bacteria. Chloride of lime was added to the raw water 7 hours before filtration, resulting in a dramatic decrease in the incidence of *E. Coli* cases. Also in 1908, chlorination was installed at the Jersey City water supply.

In 1900 the death rate in the United States from typhoid fever was 36 per 100,000 people, or approximately 25,000 deaths that year. With the introduction of disinfection the death rate dropped to 20 per 100,000 in 1910, and 3 per 100,000 in 1935. By 1960 there were less than 20 deaths from typhoid fever in the entire United States. Over time the practice of chlorination for the disinfection of water supplies became better understood and was implemented widely to prevent waterborne diseases such as typhoid fever, gastroenteritis, and amoebic dysentery.

WATERBORNE DISEASES

The goal of disinfection is to inactivate disease-causing, or **pathogenic**, organisms. Protection of public health is one of the most important tasks of the water operator and the careful and appropriate level of disinfectant dosage is the most critical task in accomplishing this goal.

Pathogenic organisms, by definition, spend part of their life cycle in the intestinal tract of warm-blooded mammals, including humans. As a result, pathogenic organisms are designed in such a way that they survive well inside the intestinal tract, an environment which is often acidic, and always **anaerobic**. Because pathogenic organisms prefer anaerobic conditions, they generally do not survive well in aerobic, or oxidizing, conditions.

The anaerobic nature of pathogenic organisms makes it possible to achieve potable drinking water through simple disinfection rather than sterilization. Sterilization is the complete killing of all living things. Conversely, disinfection refers to the destruction or inactivation of pathogenic organisms. Because pathogenic organisms do not survive well in oxidizing environments they are more susceptible to chlorination and other forms of disinfection than aerobic organisms. This allows water treatment facilities to use far less oxidizing disinfectant chemicals than would otherwise be required.

In most cases, pathogenic organisms do not survive long outside of the body. However, many viruses can survive for hours or days, and many protozoans can form cysts that protect the organism during a dormant phase until it is ingested. For these reasons, it is important to properly disinfect drinking water.

Typhoid Fever

The bacterium that causes typhoid fever, *Salmonella typhi*, resides only in the intestinal tract of humans and has been the causative agent for more sickness and death in North America than any other waterborne pathogen. *Salmonella typhi* can live for many months in frozen environments. If these bacteria infect an individual, the urine and feces from that person will contain the bacteria and will contaminate any drinking water supply it comes in contact with. Individuals who have recovered from typhoid fever may continue to carry the bacteria for the rest of their lives. In the 19th century in North America, death rates from typhoid fever rose to more than 300 deaths per 100,000 people. Now, with the use of disinfectants in water treatment, typhoid outbreaks are rare or nonexistent.

Cholera

The bacterium that causes cholera, *Vibrio cholerae*, has been established in India since 400 B.C. The organism spread outside of India after 1817 as human travel increased around the globe. In 1831 it reached Britain, where cholera caused the deaths of 21,000 people. The organism is easily killed by disinfection and has been virtually eliminated where good hygiene and water treatment are practiced.

Amoebic Dysentery

The protozoan that causes amoebic dysentery, *Entamoeba histolytica*, can survive as a cyst for long periods inside the intestinal tract, lie dormant, and then reinfect with no warning. While rather resistant to disinfection, requiring 10 milligrams per liter (mg/L) of chlorine for a **contact time** of 1 hour, it is easily removed by filtration because of its large size. Water can only be contaminated if it comes in direct contact with human feces.

Shigellosis

The bacteria genus *Shigella* has many varieties that cause gastroenteritis. While rarely fatal, shigellosis will cause intestinal disorders such as nausea, vomiting, diarrhea, abdominal pain, and fever. An outbreak of shigellosis occurred in the community of Barrow, Alaska, in 1979 when untreated lake water was carried in contaminated water trucks to individual homes.

Salmonellosis

The genus *Salmonella* is a group of bacteria that also cause gastroenteritis. One specific type, *Salmonella typhi*, was discussed earlier and is the cause of typhoid fever. However, many other varieties also can cause gastroenteritis and intestinal distress.

Giardiasis

The flagellated protozoan ***Giardia lamblia*** is spread by human feces but can be carried by pets and wildlife. The disease giardiasis is often referred to as "beaver fever" as it is believed that beavers contribute to its spread even in pristine watersheds. *Giardia* is the most commonly reported human intestinal parasite in the United States and England. Between 1971 and 1985, 92 waterborne disease outbreaks affecting nearly 25,000 people were reported in the United States. Giardiasis lasts as long as two weeks and can be quite debilitating, with symptoms such as stomach cramps, nausea, and diarrhea. Outbreaks tend to occur because of breakdowns in chlorination equipment, inadequate chlorination, or deficiencies in the treatment process.

The solution to giardiasis is to provide adequate water treatment with filtration and disinfection. *Giardia* exists during part of its life cycle in a vegetative or reproductive state called a "trophozoite." It can also exist in a dormant, resting state as a cyst that can survive for long periods of time and is resistant to typical disinfection practices. The cysts can be as small as 5 microns (μm) in width, and the trophozoites as long as 15 μm.

The Surface Water Treatment Rule (SWTR), embodied in the 1986 Safe Drinking Water Act (SDWA) Amendments and adopted in 1989 by the U.S. Environmental Protection Agency (EPA), specifically targeted *Giardia*, requiring all surface water sources to be filtered and disinfected. **Three-log** (99.9%) **removal** requirements for *Giardia* were established in the SDWA Amendments and in the SWTR.

Cryptosporidiosis

Cryptosporidium parvum, the protozoan that causes cryptosporidiosis, is another flagellated protozoan with a vegetative trophozoite stage and a dormant cyst stage. *Cryptosporidium* may be as much as 720 times more resistant to chlorination than *Giardia.* The cyst stage, called an oocyst because of its nearly circular shape, is half the size of a *Giardia* cyst and has a very tough cyst wall that can protect the organism for several years in the environment. This makes the organism more difficult to remove by filtration and more difficult to disinfect.

Cryptosporidiosis is a debilitating gastrointestinal disease with no known cure. Numerous outbreaks in the United States and England have been reported over the past 15 years, including the largest waterborne pathogen incident in modern history. In 1993 in Milwaukee, Wisconsin, 400,000 residents contracted cryptosporidiosis from a water treatment plant that reported only two minor turbidity incidents following heavy rain events. This represented a 25 percent rate of infection in the general population; 5,000 people were hospitalized and more than 100 people died. All of the fatalities were immunosuppressed individuals. In healthy individuals, the disease runs its course in about one to two weeks, but once infected, a person may remain a carrier for life.

Infected humans produce very large quantities of infectious trophozoites, up to 10,000,000 per gallon of feces. In the SDWA Amendments of 1996, *Cryptosporidium* is the targeted organism for an Enhanced Surface Water Treatment Rule being developed now. Disinfection methods proven to be effective against *Cryptosporidium* include ozone and chlorine dioxide. Both *Giardia* and *Cryptosporidium* are very difficult to detect in water samples, and it is even more difficult to assess the viability of the cysts and oocysts. Both of these parasitic protozoans have been detected in surface waters in all regions of Alaska.

Legionnaire's Disease

Legionnaire's disease is a pneumonia-like illness which was first documented in a hotel in Philadelphia, Pennsylvania, in 1976 during an American Legion convention. The cause of Legionnaire's disease is the bacterium *Legionella*, which often thrives in the hot-water systems of hospitals or hotels where the temperature is maintained below 140 °F. *Legionella* can be inactivated with conventional disinfection practices, and was also a targeted organism in the original Surface Water Treatment Rule in the 1986 SDWA Amendments. **Four-log** (99.99%) **removal** was established for *Legionella.*

Gastroenteritis Caused by Other Bacteria

Many other microorganisms can cause gastroenteritis in humans. The most important of these are described below.

The toxigenic bacterium *E. coli* is responsible for the well-known travelers' disease known as Montezuma's Revenge. The disease lasts for about 5 days and results in severe dehydration, which can cause death if not treated. Other symptoms include abdominal cramps, nausea, headache, vomiting, and fever. Toxigenic *E. coli* is one of the few forms of coliform bacteria that is pathogenic.

An outbreak of gastroenteritis caused by the *Campylobacter* bacterium affected about 2,000 people in Sweden in 1980 and 3,000 people, or 19 percent of the population of Bennington, Vermont, in 1978. In both cases, the disease was traced to the water mains although coliform tests did not indicate contamination. However, when the chlorination dosage was increased and a public notice to boil water given, no further cases of this disease were reported.

Pseudomonas aeruginosa is a common soil bacterium that can cause gastroenteritis, particularly in newborn babies. Previously considered to be nonpathogenic, *Pseudomonas* can grow in filter systems. In addition to gastroenteritis, *Pseudomonas* can infect mucous membranes, frequently causing rashes and other skin irritations in users of recreational waters carrying this bacterium. With the advent of antibiotics, many new strains of *Pseudomonas* have developed with increasing virulence over time.

Another problematic bacterium that is relatively resistant to chlorination, particularly chloramination, is the mycobacterium. *Mycobacterium avium* complex produces severe infections in immunosuppressed individuals, such as chemotherapy and AIDS patients. Tuberculosis is caused by another, non-waterborne form of *Mycobacterium.*

Polio

Although it is not certain whether the polio virus is a waterborne pathogen or not, it was thought at one time to be transmitted by drinking water. A vaccination program has made the occurrence of polio very rare.

Hepatitis A

Hepatitis is an acute viral inflammation of the liver that produces fever and gastrointestinal distress. While rarely fatal, the disease has been spreading throughout the globe. Adequate disinfection can prevent transmission in water supplies.

New Study of *Helicobacter pylori*

The Anchorage offices of the Centers for Disease Control are currently studying the bacterium *Helicobacter pylori* in rural Alaska. Researchers at Penn State University in Harrisburg have correlated the presence of *H. pylori* in private well water to stomach ulcers and possibly two types of cancers in people drinking the water. *H. pylori* apparently is more resistant than *E. coli* to disinfection, and may be able to survive for extended periods in distribution system pipes. The precise mechanism of transmission has not been determined, but *H. pylori* has been isolated in stool samples and dental plaque; a fecal-oral route of transmission is suspected.

DISINFECTION METHODS

Boiling

Boiling water is an effective way to disinfect drinking water. Most organisms, including *Giardia* cysts and *Cryptosporidium* oocysts, will be inactivated by a few minutes of a full "rolling" boil. Because of the expense of fuel associated with heating water, boiling is only practiced as an emergency or field measure for disinfection and is not used by water treatment plants. Because of its effectiveness, however, if contamination is found in a drinking water supply, a "boil water" notice should be announced to the public until the system has been proven safe. Boiling water can disinfect water from lakes and streams while camping.

Ultraviolet Radiation

Ultraviolet (UV) **radiation** at a wavelength of 254 nanometers (nm) is becoming more popular as a disinfectant for water supplies. UV radiation is in the spectrum of radiation that includes visible light: short-wavelength, high-energy UV and long-wavelength, low-energy infrared. The high energy level of UV gives it the ability to penetrate the organisms in the water and damage their ribonucleic and deoxyribonucleic acids (**RNA** and **DNA**, respectively). DNA is the chemical code that controls all biological functions of the organism including reproduction. Without viable DNA, an organism cannot reproduce, and is therefore not capable of causing infection.

The degree of disinfection depends on the ability of the UV light to penetrate the water. It is important that the turbidity of the water be low enough to allow full penetration of UV light.

Chemical

A variety of chemicals may be used for disinfection in water supplies, most of which are classified as oxidants. An oxidizing chemical is one that strongly attracts electrons from other materials in the water. When a molecule or atom is oxidized it loses an electron, which can change its properties dramatically. For example, molecules in the membranes or cell walls of microorganisms can be altered so that they cannot perform their necessary functions. These functions may include transportation of ions or food and wastes in and out of the cell. Without these functioning molecules, bacteria may no longer be viable and are considered inactivated, or disinfected.

Another result of chemical oxidation is the oxidation of iron in water. Iron in groundwater is usually in a reduced, or Fe^{2+} state. Because this form of iron is water soluble, groundwater can often contain high quantities of iron. When iron is oxidized during treatment, it loses an electron and is transformed to the ferric form with a +3 charge. This form of iron is not soluble in water and will precipitate out of solution.

Thus, the process of chemical disinfection does more that just disinfect pathogenic organisms. It also controls taste and odors, removes color, and oxidizes metals, furthering the process of precipitation and removal.

Various chemicals can be used for disinfection including:

- chlorine gas
- sodium hypochlorite
- calcium hypochlorite

- ozone
- chlorine dioxide
- chloramines
- bromine
- iodine
- mixed oxidants

CHLORINATION

As discussed previously, one of the first uses of chlorine for disinfection purposes was the use of **hypochlorite**, or chloride of lime, in 1850 to disinfect a water supply in London after a cholera epidemic resulted from sewage contamination. Although chlorine was originally used as a bleaching agent for textiles, it was not until the beginning of the 20th century that it became widely used as a disinfectant for water supplies

Types of Chlorine Disinfectant

Three types of chlorine compounds are commonly used for disinfection:

- chlorine gas
- calcium hypochlorite
- sodium hypochlorite

Chlorine Gas

Chlorine gas is the elemental form of chlorine. It is transported and stored in compressed gas cylinders as a liquid. Gas-phase chlorine is maintained in a space above the liquid. As chlorine gas is drawn out of the tank more liquid evaporates to replace the gas maintaining a nearly constant pressure until the liquid is gone.

Chlorine gas is classified as an inhalation hazard necessitating numerous safety protocols with which the utility and its operators must comply. When inhaled, chlorine gas will react with water to form hypochlorous and hydrochloric acid in the mucous membranes inside the nose, throat, and lungs, causing tissue damage. Chlorine gas is an excellent disinfectant since it is an extremely reactive oxidant.

Calcium Hypochlorite

Calcium hypochlorite, or $Ca(OCl)_2$, is a white powder that contains 67 to 70 percent chlorine. The remainder of the dry powder is lime (CaO). The powder is dissolved in water to make a stock solution that is decanted (liquid separated from the solid lime residue) and injected into the water for disinfection. It is sold under trade names such as HTH® (High Test Hypochlorite), Perchloron® or Pittchlor®.

Sodium Hypochlorite

Sodium hypochlorite has a chemical formula of Na(OCl) and is delivered as a liquid. Typical household bleach is 5.25 percent chlorine by weight, whereas sodium hypochlorite for industrial purposes ranges from 9 to 15 percent active chlorine.

Disinfection Chemistry

The following chemical reactions occur when chlorine gas is dissolved in water:

$$1)\ Cl_2 + H_2O \leftrightarrow HOCl + H^+ + Cl^-$$

$$2)\ HOCl \leftrightarrow H^+ + OCl^-$$

In the first reaction, chlorine and water form **hypochlorous acid** (HOCl) and **hydrochloric acid** (HCl). Hypochlorous acid then establishes **equilibrium** with hypochlorite ion (OCl^-), with the concentration of either form being dependent on the pH of the solution. Notice that a chlorine molecule contains two chlorine atoms. Only one of those atoms actually ends up in the reactive form. The other ends up as the chloride ion part of hydrochloric acid.

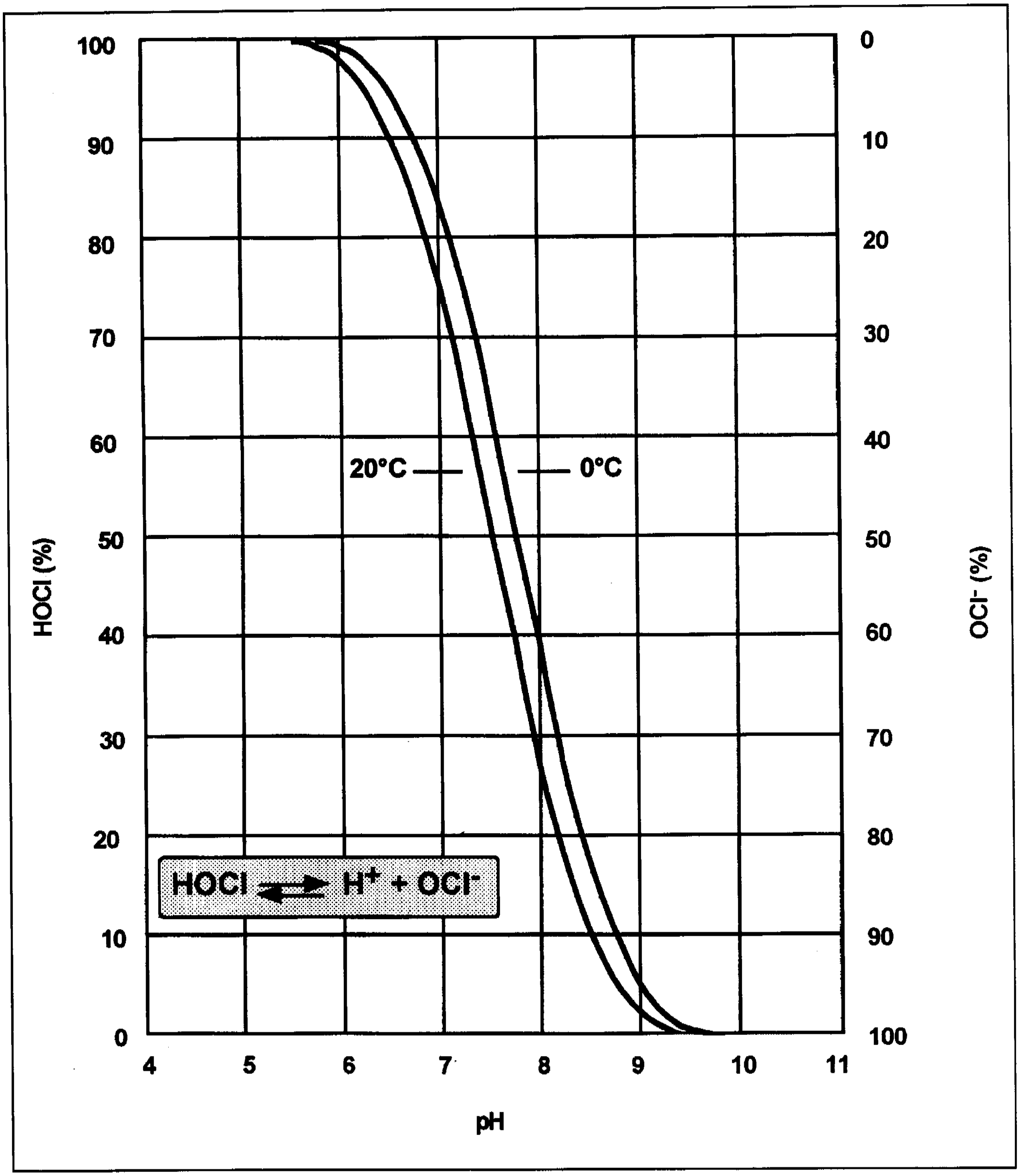
When either calcium or sodium hypochlorite is used as the disinfectant, hypochlorous acid and either lime [$Ca(OH)_2$] or sodium hydroxide (NaOH) are produced.

$$3)\ Ca(OCl)_2 + 2\ H_2O \rightarrow Ca(OH)_2 + 2\ HOCl$$

$$4)\ Na(OCl) + H_2O \rightarrow NaOH + HOCl$$

Free Chlorine Residual

Hypochlorous acid and hypochlorite ion together make up what we call **free chlorine residual**. Notice that the reaction arrows go in both directions in equations 1 and 2 above. This indicates that the reaction will proceed in either direction until it reaches equilibrium, with the final concentrations being a function of the pH of the solution. At high pH levels, hypochlorite ion predominates, whereas at low pH hypochlorous acid is the dominant form.



Distribution of hypochlorous acid (HOCl) and hypochlorite ion (OCl^-) at various pH levels.

An important consideration is that HOCl is about 100 times more powerful a disinfectant than OCl^- is. Therefore, free chlorine residual is a stronger disinfectant at lower pH. At pH 7.5 both forms are present in approximately equal amounts. It is not always convenient to control the pH optimally for disinfection. Factors such as coagulant effectiveness and corrosion control also require consideration of pH levels.

Combined Chlorine Residual

Hypochlorous acid can now react further with other chemicals present in the water. An important compound present in water is ammonia, derived from amino acids that are the building blocks of protein molecules in all biological systems. In addition to ammonia, organic chemicals that can also react with HOCl are often present. Compounds formed from the reaction of chlorine and ammonia are called chloramines; compounds formed from chlorine and organic molecules are called chloroorganics. The formation of three types of chloramines are shown in equations 5-7, and equation 8 shows a generic chloroorganic reaction.

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

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

7) $NHCl_2 + HOCl \rightarrow NCl_3 + H_2O$ (trichloramine formed)

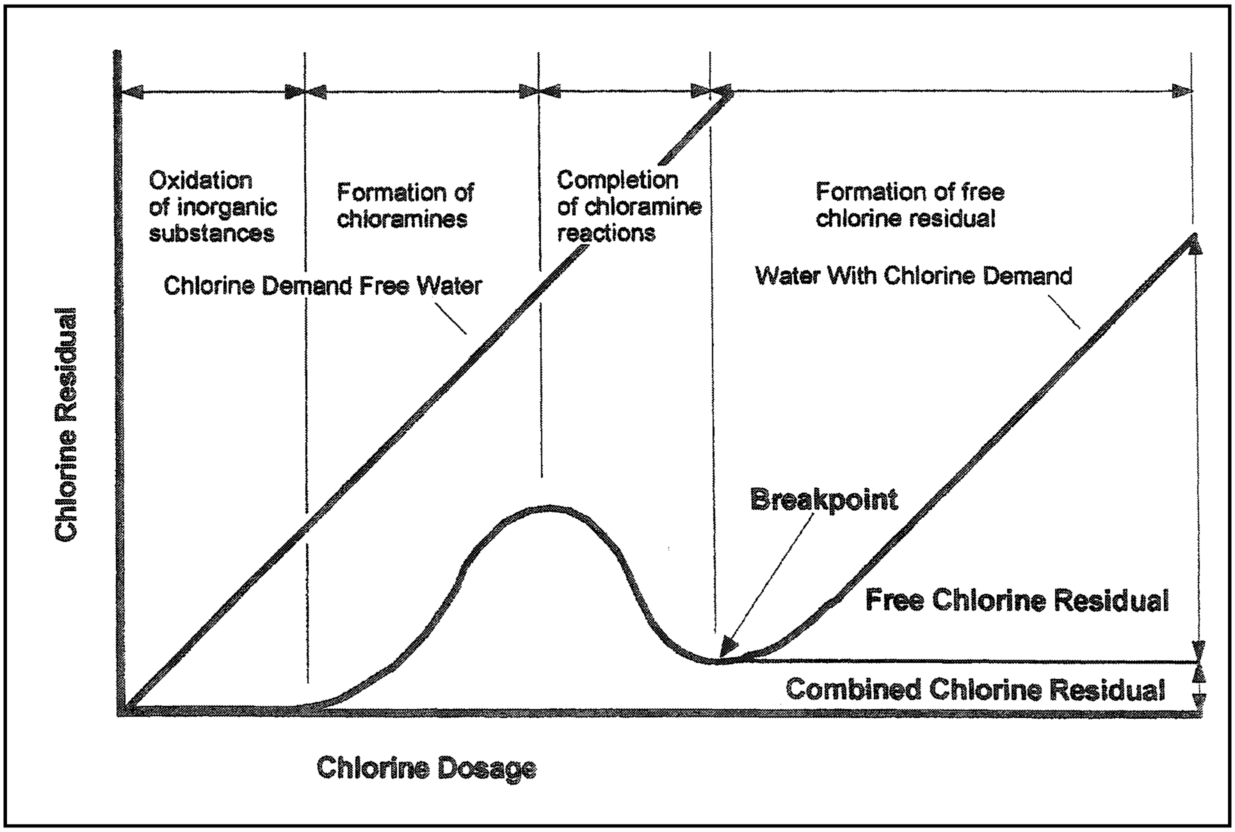
8) $\text{Organics} + HOCl \rightarrow \text{Org-Cl} + H_2O$

The total of all of the chloramines and chloroorganics is referred to as **combined chlorine residual**. As disinfectants, the chloramines are not as strong as hypochlorous acid. The relative disinfecting power for the various forms of free and combined chlorine residual is:

Chemical	Formula	Effectiveness relative to HOCl
Hypochlorous acid	HOCl	1
Hypochlorite ion	OCl^-	1/100
Trichloramine	NCL_3	~1/80
Dichloramine	$NHCl_2$	1/80
Monochloramine	NH_2Cl	1/150

Total Chlorine Residual

The total of the concentrations of free chlorine residual and combined chlorine residual is called **total chlorine residual**. The formation of combined and free chlorine residual is shown graphically in the following figure, in which the vertical axis is the measured total residual and the horizontal axis is the total amount of chlorine added.



Comparison of chlorine residual formation in chlorine demand-free water and water with a significant chlorine demand.

1. **Phase 1:** Demand

When chlorine is initially added to water a measurable chlorine residual may not form. This is because the chlorine is consumed by materials in the water such as microorganisms and unoxidized, or reduced, iron and manganese. A **demand** is being exerted on the chlorine, consuming it and preventing the formation of a measurable residual.

2. **Phase 2:** Formation of Combined Residual

   After this initial demand is met, the total residual increases slowly as the chlorine reacts with amines and organics to form combined residual. The chlorine residual that forms in this phase is combined residual, comprising chloramines and chloroorganic compounds.

3. **Phase 3:** Destruction of Combined Residual

   In the next phase of the breakpoint curve, the measured residual actually declines as more chlorine is added to the water. The additional chlorine reacts with the combined residual, forming compounds with more chlorine atoms such as dichloramines and trichlroamines. As a result, the measured total residual decreases until these reactions are complete. The end of Phase 3 is termed **breakpoint**.

4. **Phase 4:** Free Chlorine Residual

   At the breakpoint all of the combined residual has formed; any chlorine added after the breakpoint immediately becomes free residual because there is nothing left for the chlorine to react with. After breakpoint the increase in chlorine residual is equal to the amount of chlorine added. This is the key definition of breakpoint.

As discussed previously, free chlorine residual is the strongest form for efficient disinfection, so a free residual should be achieved before placing the water in the distribution system. State regulations require a minimum disinfectant residual of 0.2 mg/L at the point of entry to the distribution system and a measurable trace at the farthest points in the system. It is preferable that this residual be in the form of free chlorine residual.

Just before the breakpoint, unpleasant odors may form. Once a free residual is achieved beyond breakpoint, these odors will dissipate. Sometimes this will occur in storage or in the distribution system as the free chlorine residual is used up and the total residual declines back to the breakpoint level. Operators find that maintaining a higher initial free chlorine residual often will help prevent odor formation. Some operators have noticed this problem after a heavy demand for water has been exerted on the system and stagnant water in a large storage tank is drawn into the system.

Effectiveness of Chlorination

The factors most critical to the success of chlorination are the chlorine concentration, C, and the length of time the organisms are in physical contact with the disinfectant, or **contact time**, T. The destruction or inactivation of organisms is directly proportional to the product, C x T, commonly referred to as **CT**, expressed as milligram-minutes per liter (mg-min/L). Thus, if the chlorine concentration is decreased, the contact time will have to be increased to achieve the same level of disinfection. Combined chlorine residual will require a longer contact time than free chlorine residual; if the contact time between chlorination and customer use is short, free residual will be required to provide adequate disinfection.

The temperature and pH of the water also are important considerations for the effectiveness of chlorination. At lower temperatures, the inactivation of bacteria tends to be slower than at higher temperatures. The water treatment operator should keep a record of water temperature; changes in temperature will necessitate adjustments to the chlorine dosage used for disinfection. As mentioned previously, the pH of the water also affects the chlorination process because it determines the ratio between HOCl and OCl^-. The pH of the water should be checked regularly; if pH is being maintained at higher levels for corrosion control, the chlorination dosage will have to be adjusted accordingly.

Values of CT can be calculated using a formula or may be determined from a set of tables provided in the Alaska Department of Environmental Conservation (ADEC) regulations (18 AAC 80.660). These tables are designed for various temperature, pH, and chlorine residual concentrations, for log removals from 0.5 to 3.0. Log removals refer to the percent removal or inactivation of a targeted organism, where one log equals 90 percent, two logs equal 99 percent, three logs equal 99.9 percent, and so on.

For *Giardia* removal, three logs is the required level of treatment. For surface water systems that do not filter, all three logs of removal must be provided by disinfection. Therefore, high chlorine residuals or long chlorine contact times, or both, are required to achieve the necessary level of treatment.

Example Calculation: Refer to Table J, p. 156, ADEC Regulations (18 AAC 80.660) for CT values for inactivation of *Giardia* cysts by free chlorine residual at 0.5 °C or lower.

Calculate the required detention time, T, in minutes, required for a 3-log removal, where: temperature = 0.5 °C, pH = 7.0, and free chlorine residual, C, is 0.6 and 1.0 mg/L

$CT_{required}$ = 200 mg-min/L for C = 0.6 mg/L; 200 mg-min/L ÷ 0.6 mg/L = 333 minutes

$CT_{required}$ = 210 mg-min/L for C = 1.0 mg/L; 210 mg-min/L ÷1.0 mg/L = 210 minutes

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Superchlorination and Dechlorination

Before the understanding of breakpoint chlorination (1939), water systems commonly practiced **superchlorination** to destroy tastes and odors caused by chlorination. The water was then dechlorinated to achieve a lower residual. Some bottled water companies dechlorinate by passing the water through carbon filters to produce water free of chlorine residual. Superchlorination is a common practice to disinfect new or repaired water mains, treatment plants, storage tanks, or wells. The resulting superchlorinated water must be dechlorinated before disposal to avoid violating wastewater disposal regulations.

Dechlorination is the practice of removing chlorine from the water using one of several methods, most commonly granular activated carbon or sulfur compounds.

Granular Activated Carbon

Granular activated carbon will effectively remove chlorine residual from water. As noted above, this is a common treatment practice used in the bottled water industry and is also common in point-of-use treatment systems installed on kitchen taps.

Sulfur Compounds

The sulfur compounds used for dechlorination include sodium thiosulfate, sodium bisulfite, and sodium metabisulfite.

Sodium Thiosulfate. This compound is most often used for the dechlorination of water in coliform sample bottles. A small amount of sodium thiosulfate is added to the sample bottles before they are sterilized. When a chlorinated sample for bacteria is collected, the sodium thiosulfate removes the chlorine to prevent further contact time during transport to the laboratory.

Sodium Bisulfite / Sodium Metabisulfite. These chemicals are typically used in smaller systems. They rapidly destroy reactive chlorine compounds and turn into bisulfate compounds.

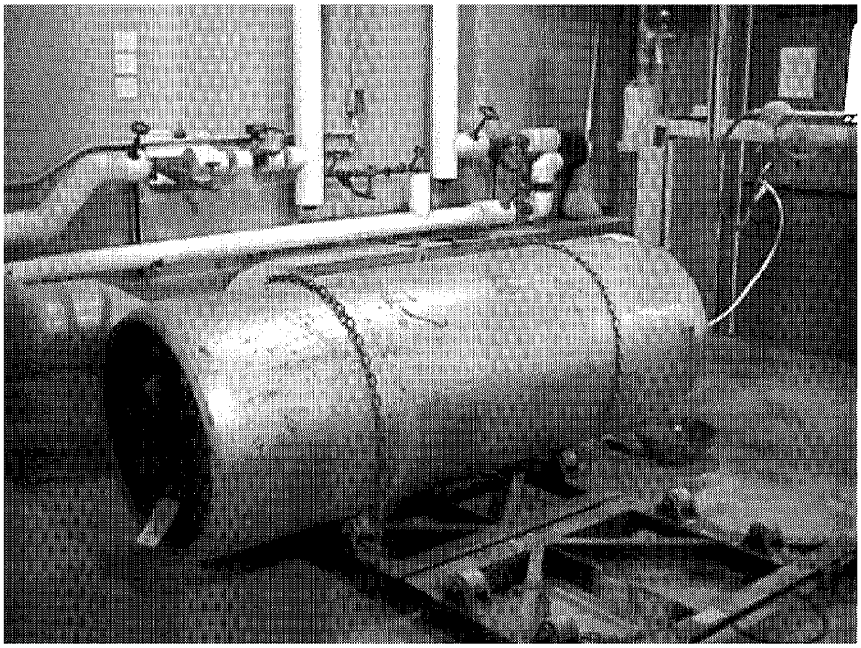
CT VALUES FOR INACTIVATION OF *GIARDIA* CYSTS BY FREE CHLORINE AT 0.5°C OR LOWER (milligram-minutes per liter)

Chlorine Concentration (mg/L)	pH ≤ 6						pH = 6.5						pH = 7.0						pH = 7.5					
	Log Inactivations						Log Inactivations						Log Inactivations						Log Inactivations					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
≤ 0.4	23	46	60	91	114	137	27	54	82	109	136	163	33	65	98	130	163	195	40	79	119	158	198	237
0.6	24	47	71	94	118	141	28	56	84	112	140	168	33	67	100	133	167	200	40	80	120	159	199	239
0.8	24	48	73	97	121	145	29	57	86	115	143	172	34	68	103	137	171	205	41	82	123	164	205	246
1	25	49	74	99	123	148	29	59	88	117	147	176	35	70	105	140	175	210	42	84	127	169	211	253
1.2	25	51	76	101	127	152	30	60	90	120	150	180	36	72	108	143	179	215	43	86	130	173	216	259
1.4	26	52	78	103	129	155	31	61	92	123	153	184	37	74	111	147	184	221	44	89	133	177	222	266
1.6	26	52	79	105	131	157	32	63	95	126	158	189	38	75	113	151	188	226	46	91	137	182	228	273
1.8	27	54	81	108	135	162	32	64	97	129	161	193	39	77	116	154	193	231	47	93	140	186	233	279
2	28	55	83	110	138	165	33	66	99	131	164	197	39	79	118	157	197	236	48	95	143	191	238	286
2.2	28	56	85	113	141	169	34	67	101	134	168	201	40	81	121	161	202	242	50	99	149	198	248	297
2.4	29	57	86	115	143	172	34	68	103	137	171	205	41	82	124	165	206	247	50	99	149	199	248	298
2.6	29	58	88	117	146	175	35	70	105	139	174	209	42	84	126	168	210	252	51	101	152	203	253	304
2.8	30	59	89	119	148	178	36	71	107	142	178	213	43	86	129	171	214	257	52	103	155	207	258	310
3	30	60	91	121	151	181	36	72	109	145	181	217	44	87	131	174	218	261	53	105	158	211	263	316
	pH = 8.0						pH = 8.5						pH ≤ 9.0											
≤ 0.4	46	92	139	185	231	277	55	110	165	219	274	329	65	130	195	260	325	390						
0.6	48	95	143	191	238	286	57	114	171	228	285	342	68	136	204	271	339	407						
0.8	49	98	148	197	246	295	59	118	177	236	295	354	70	141	211	281	352	422						
1	51	101	152	203	253	304	61	122	183	243	304	365	73	146	219	291	364	437						
1.2	52	104	157	209	261	313	63	125	188	251	313	376	75	150	226	301	376	451						
1.4	54	107	161	214	268	321	65	129	194	258	323	387	77	155	232	309	387	464						
1.6	55	110	165	219	274	329	66	132	199	265	331	397	80	159	239	318	398	477						
1.8	56	113	169	225	282	338	68	136	204	271	339	407	82	163	245	326	408	489						
2	58	115	173	231	288	346	70	139	209	278	348	417	83	167	250	333	417	500						
2.2	59	118	177	235	294	353	71	142	213	284	355	426	85	170	256	341	426	511						
2.4	60	120	181	241	301	361	73	145	218	290	363	435	87	174	261	348	435	522						
2.6	61	123	184	245	307	368	74	148	222	296	370	444	89	178	267	355	444	533						
2.8	63	125	188	250	313	375	75	151	226	301	377	452	91	181	272	362	453	543						
3	64	127	191	255	318	382	77	153	230	307	383	460	92	184	276	368	460	552						

These chemicals are commonly used to dechlorinate water used for superchlorination of pipes and other treatment appurtenances.

Gas Chlorination

Chlorine gas is an strong oxidant, and will support combustion although the gas is not flammable. Chlorine is an inhalation hazard and will form strong acids when in contact with water, including fluids in the respiratory tract and lungs. It is 2.5 times heavier than air and will settle to the bottom of the room if a leak occurs. It has a pungent odor and a greenish yellow color and can be fatal at a concentration of 0.1 percent, or 1,000 parts per million (ppm), in air if breathed directly. When chlorine evaporates from liquid phase to the gas phase, it expands to 460 times its original volume. Chlorine gas equipment and safety procedures are strictly regulated.



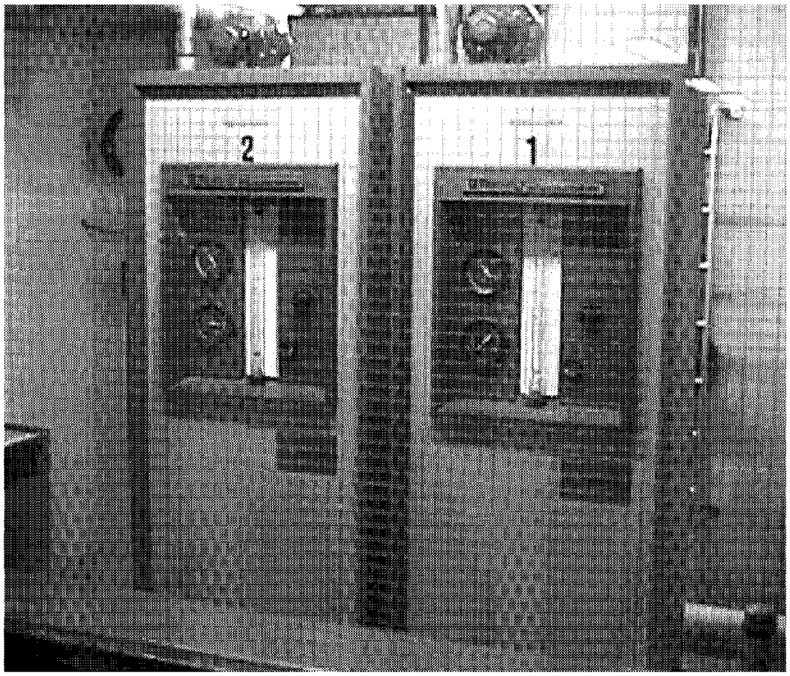
Ton chlorine gas container, Golden Heart Utilities, Fairbanks, Alaska.

Chlorine Gas Facilities

Gas chlorine is used in Alaska in 100-pound and 150-pound cylinders, and 1-ton containers. The chlorine gas above the liquid phase maintains a constant pressure of 85 pounds per square inch (psi) at 70 °F until no more liquid remains in the cylinder. Except for ton containers, chlorine cylinders should be stored in an upright position and be chained two-thirds of the way up the tank (and at the bottom in earthquake areas), and should always be handled with a hand truck with the bonnet in place.

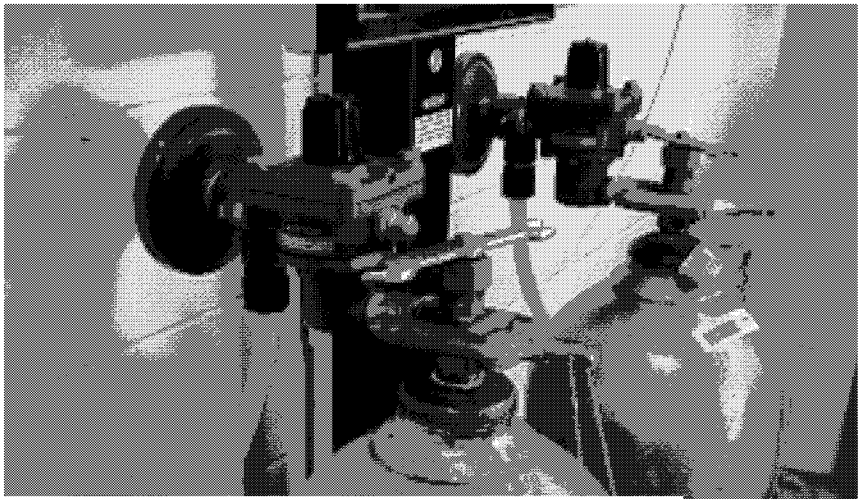
Fusible Plugs. To prevent explosive release in the event of fire, all chlorine cylinders are equipped with a fusible plug designed to melt at temperatures between 158 and 164 °F.

Chlorinators. Chlorinators feed chlorine gas into water through a device called an injector. In the injector, a vacuum is created as water is pumped through a restricted section inside the injector, causing a vacuum regulator to open on the cylinder. In the event of a loss of vacuum due to loss of water pressure in the injector or from a leak in chlorine feed lines, diaphragms inside the chlorinator will close stopping the flow of chlorine gas. Chlorinators come in various sizes and may be either wall mounted, floor mounted or cylinder mounted.



Wallace and Tiernan V-Notch gas chlorinators metering chlorine gas from ton containers at the Ship Creek Water Treatment Facility, Anchorage, Alaska.

Diffusers. A diffuser is a section of pipe that disperses the chlorine solution into the water. A properly designed diffuser ensures that the chlorine is uniformly and efficiently mixed with the water.



Above: 150-pound cylinder gas chlorination facility, showing chlorine scales and automatic switchover that allows one cylinder to be in use while a second is on standby.

Upper right: Note the wrench on the cylinder valve.

Right: Gas chlorine controls; left to right: chlorine gas detector, chlorinator with rotameter, and injector.

Scales. The consumption of chlorine gas can be measured directly by a set of scales. Different types of scales are available for horizontal ton containers and vertically mounted 100- and 150-pound cylinders. Chlorine usage can be determined by the following formula:

$$\text{Chlorine Feed Rate (lbs/day)} = \text{mg/L} \times \text{MGD} \times 8.34 \text{ lbs/gallon}$$

Where mg/L = chlorine dosage = (chlorine demand + chlorine residual), and MGD = water system flow in millions of gallons per day, and 8.34 lbs/gallon = weight of water. Thus, for a chlorine dosage of 5 mg/L and a plant flow rate of 2.5 MGD:

$$\text{Chlorine Feed Rate} = 5 \text{ mg/L} \times 2.5 \text{ MGD} \times 8.34 \text{ lbs/gallon} = 104.25 \text{ lbs/day}$$

In the above example, the most efficient storage unit would most likely be a ton container, which would allow at least two weeks between container changes.

Risk Management Plans

In 1999, changes in Federal air quality regulations began to require the development of **risk management plans** at any facility storing more than 2,500 pounds of chlorine gas on site. These plans proved to be costly to develop and required a lengthy process of public involvement and disaster planning for the possibility of a catastrophic chlorine release. Because most water treatment plants using ton containers normally store one or more reserve containers on site in addition to the primary container on line, this new rule resulted in many utilities reconsidering their policies regarding on-site storage of gas chlorine.

Some utilities opted to discontinue using gas chlorine, not wanting to engender potential negative public relations or to pay for expensive risk management plans. For those who continued to use chlorine gas, some adopted the policy of maintaining only a single ton container on site with several 150-pound cylinders as a backup supply. An unfortunate consequence of this practice is that transport of chlorine gas ton containers for delivery, often through heavily populated areas, has become more frequent because fewer containers are stored on site at any time.

Chlorine Room

When gas chlorine is used, a secure room must be constructed, sealed off from the rest of the treatment facility and with doors that open only to the outside. The room must be equipped with ventilation intake ducts at the floor that discharge to a **scrubber** containing sodium hydroxide. The ventilation system must be able to evacuate the entire air volume of the chlorine room within 4 minutes. In the event of a spill, chlorine gas is mixed with water and sodium hydroxide to form sodium chloride and water (salt water), thus neutralizing the spilled chlorine gas. The chlorine room must also be equipped with corrosion-proof electrical equipment, a chlorine gas detector typically located near the floor vents, and an alarm system.

Hypochlorination

Hypochlorination involves the addition of solutions of sodium or calcium hypochlorite to water for disinfection. As discussed previously, sodium hypochlorite (NaOCl) is available commercially as a liquid solution and calcium hypochlorite [$Ca(OCl)_2$] as a dry chemical. These chemicals are strong oxidants and are hazardous when handled in concentrated form. It is important that hypochorites be stored in a dry cool environment and away from fuel sources that may react with these strong oxidants.

Sodium Hypochlorite

Sodium hypochlorite is sold as bleach in a 5.25-percent concentration in retail stores and in 12- to 15-percent concentration as a commercial bleach and disinfectant solution. Sodium hypochlorite can be fed neat (undiluted) from the shipping container or it can be diluted in water in a solution tank to make a lower-concentration feed solution. It should be kept out of the sun and away from sources of heat to minimize degradation of the chemical. A 12- to 15-percent solution will lose approximately 2 to 4 percent of the reactive chlorine every month. Exposure to sunlight further accelerates the deterioration rate.

Sodium hypochlorite is a corrosive liquid and an oxidizer, and should be labeled as such. If it comes in contact with the skin or eyes the victim should flush with running water for 15 minutes. Small spills can be cleaned up with vinegar or soaked up with sand or other absorbents.

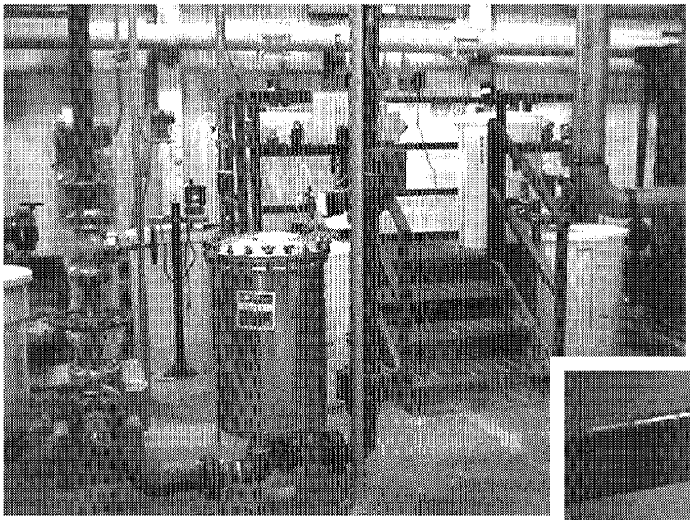
Calcium Hypochlorite

Calcium hypochlorite, or chlorinated lime, should also be kept cool and dry. A small amount of moisture can cause spontaneous combustion of the chemical or a hardening of the powder. Calcium hypochlorite will deteriorate at a rate of 3 to 10 percent per year. The dry powder must be mixed in water to prepare a stock solution. After a period of mixing, the solution is allowed to settle to separate the inert lime from the feed solution.

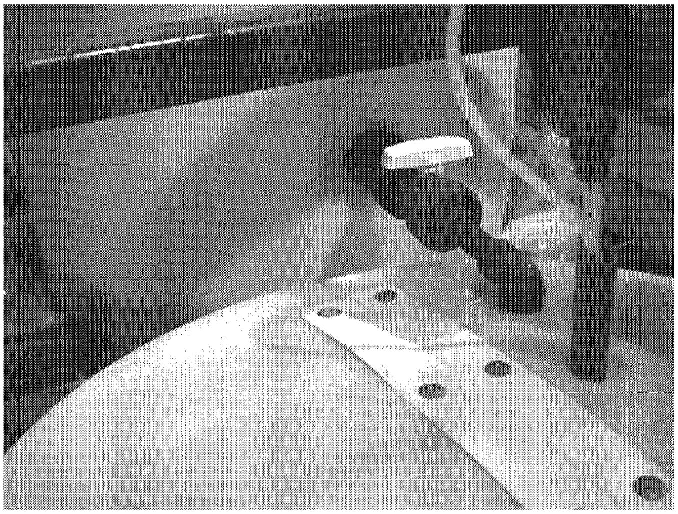
Calcium hypochlorite is a strong oxidant and should be stored in a suitable location, away from fuel sources. Calcium hypochlorite solutions are corrosive and should be handled with the same precautions as sodium hypochlorite solutions.

Equipment

A hypochlorination system consists of a solution tank, chemical mixer, and a chemical feed pump. For calcium hypochlorite, a decant tank can also be used. Typically, a 25- to 50-gallon corrosion-resistant tank is used for the diluted stock solution; although as noted above, sodium hypochlorite can be pumped neat, directly from the shipping container. The same type of tank can be used for both the decant and solution tanks for a calcium hypochlorite chemical mixing system. In a decant arrangement, the mix tank is usually placed on a stand above the feed tank. The mix tank is equipped with a mixer and a tap with a valve, 6 to12 inches above the bottom of the tank. After mixing and settling, this tap is used to decant the supernatant from the mix tank to the feed tank, leaving the settled lime in the mix tank (see photos). A separate drain line is used to remove accumulated lime.



Hypochlorination feed station at Barrow Utilities and Electric Cooperative, Inc. Chlorine decant tanks are on the landing, and the feed tanks are on floor level.



Close-up view of the chlorine decant tank and supernatant transfer into feed tanl

Chemical metering is done with a positive displacement injection pump, most often a diaphragm-type pump in Alaska. Two common brands of diaphragm metering pumps widely used in Alaska are Liquid Metronics, Inc. (LMI Pumps), and Wallace and Tiernan. These pumps can be set to deliver a precise volume of solution either manually or in response to electronic pacing signals from a flow meter or process logic controller. These pumps normally have two controls, diaphragm speed and stroke length, each set as a percentage of full capacity. For example, if the pump is set with a stroke length of 75 percent (0.75) and a speed of 60 percent (0.60), the total output is calculated as a percentage of the pump capacity. For a 4-gallon-per-hour (gph) pump the output would be calculated as:

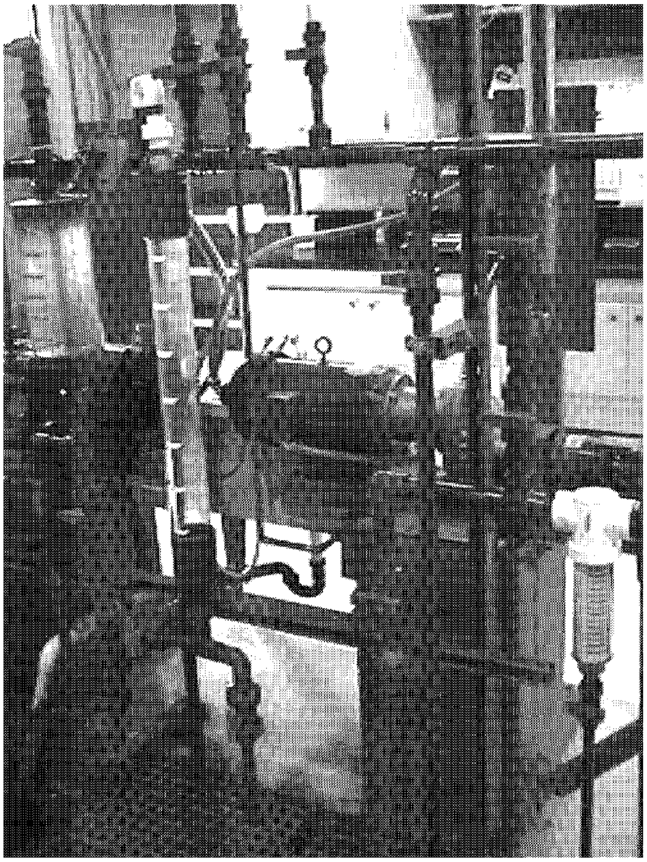
$$\text{Speed x Stroke x Pump Output} = 0.75 \text{ x } 0.60 \text{ x } 4 \text{ gph} = 0.45 \text{ x } 4 \text{ gph} = 1.8 \text{ gph}$$

To convert to milliliters per minute (ml/minute), multiply by 3,785 ml/gallon and divide by 60 minutes per hour:

$$(1.8 \text{ gph x } 3{,}785 \text{ ml/gallon}) / 60 \text{ minutes/hour} = 113.6 \text{ ml/minute}$$

The output of the chemical feed pump can be checked with a **drawdown cylinder** attached to the suction side of the feed pump and calibrated in milliliters. The cylinder is filled with the stock solution and the milliliters drawn out of the cylinder per minute measured with a timer. Drawdown cylinders need to be valved to allow the feed pump to draw from either the solution tank or the chlorine gas container.

The feed pump suction line should be equipped with a strainer to protect the diaphragm and check valves from particles in the stock solution, particularly with calcium hypochlorite. Also, the suction line is usually equipped with a foot valve to help maintain prime when the pump is off. The foot valve may include a ceramic weight to keep the suction line in the solution. Also, the solution tank can be equipped with a section of rigid plastic pipe that holds the solution line in place, particularly when the tank is equipped with a mixer. The suction line is usually made of non-corrosive polyethylene.



Drawdown cylinders on the ferric sulfate chemical metering station at the Ship Creek Water Treatment Facility, Anchorage, Alaska.

A common configuration for the LMI pumps is with a special 4-in-1 valve, which has the following functions:

1. An anti-siphon prevents solution from being siphoned from the tank should the water line experience a significant drop in pressure.
2. Back pressure control maintains a minimum 25 psi pressure on the discharge side of the pump to maintain the accuracy of the volume delivered.
3. Pressure relief is provided if the discharge line is closed or if line pressure exceeds the safety rating of the pump. Under either condition, the valve will open and discharge fluid back into the tank.
4. Line depressurization prevents fluid from spraying onto the operator when starting repairs to the pump; the pressure can be relieved before disassembly.

Diaphragm and check valve rebuild kits are available from the pump manufacturers. At least one of these kits should be continuously maintained in the spare parts inventory at all times to service the feed pump. Also, spare suction and discharge line tubing should be available.

Chlorine Dioxide

Chlorine dioxide is typically produced on site and is a strong oxidant. It can be used in water with high levels of organic matter to minimize disinfectant by-product formation. Chlorine dioxide is not presently in use in Alaska.

Chloramination

Chloramination involves the addition of both hypochlorous acid and ammonia to form chloramines. As discussed above, chloramines are a form of combined residual with relatively weak disinfecting power. In 1983 the EPA approved the use of chloramines as a primary disinfectant, primarily because of the decrease in the formation of trihalomethanes and other **disinfection by-products** (DBPs) when ammonia is added upstream of the chlorine. Several utilities have selected alternate primary disinfectants while adding chloramines to maintain a persistent residual in the distribution system.

One application of chloramination that has been adopted in Alaska is in controlling the growth of biofilms on nanofilter membranes. First used by Barrow Utilities and Electric Cooperative, Inc., a hypochlorinator and ammonium sulfate solution feeder were combined to produce chloramines in microfiltered water being fed to a nanofiltration system. The chloramine feed resolved a difficult problem with biofilms that were prematurely fouling the nanofilter membranes. This adjustment to the system resulted in significantly improved run times between membrane cleanings. This technique is now being used on several other similar membrane systems treating arctic surface water supplies. Use of chloramines protects the membranes, some types of which are susceptible to chlorine oxidation, and provides disinfection without premature formation of DBPs.

OTHER DISINFECTANTS

In addition to chlorine, several different chemical and non-chemical disinfection options are available. The disadvantage of many of these is that they do not provide a disinfectant residual in the finished water. In such cases, the addition of a small amount of some variety of chlorine may be incorporated to provide this residual.

Ozone

Ozone (O_3) is one of the most powerful and effective oxidants available in the water treatment arsenal. It is very effective against all types of pathogenic microorganisms including viruses, bacteria and protozoans such as *Cryptosporidium* and *Giardia.* The main problem with ozone is the absence of a persistent residual in the distribution system. Many utilities have successfully combined the use of ozone as a primary disinfectant with chloramination for maintaining a chlorine residual in the distribution system.

Ozone has been widely used as a disinfectant in water treatment systems in Europe for nearly as long as chlorine. It is gaining acceptance in the United States because of its powerful disinfecting properties against pathogenic protozoans. Ozone may produce different types of disinfection by-products than chlorine. In the presence of trace levels of bromide, ozone may form bromate, a new DBP regulated under the Disinfectant By-Product Rule. Bromide commonly occurs in water supplies near the ocean where sea salt can be carried inland as spray or through infiltration into coastal wells.

Ozone also is useful for controlling taste, odor, and color because of its strong oxidant properties. It is also beneficial in preoxidation, reducing the amount of coagulant chemicals required and improving the efficiency of conventional filtration systems. One application that small ozonators are used for in Alaska is preoxidation of iron and manganese ahead of direct filtration through mixed-media filters. The new water treatment plant at the City of Wrangell uses ozonation ahead of its roughing and slow sand filters to oxidize and remove color, and to coagulate suspended solids to enhance their removal by the roughing filters.

The ozone generators and associated air compressors at the City of Wrangell Water Treatment Plant. Photo courtesy of the City of Wrangell Water Treatment Plant and Greg Scheff and Associates.

Ozone is very unstable and must be generated on site. It is manufactured by passing a high voltage across an air gap in which air or purified oxygen is flowing. This process emulates the formation of ozone by lightening or an arc welder. The ozone molecule is highly reactive, bluish in color, and has a pungent odor. It is highly toxic when inhaled at even very low concentrations. The 8-hour OSHA exposure standard is 0.1 ppm in air.

Bromine and Iodine

Neither bromine nor iodine is commonly used for disinfection of water systems in Alaska, although several small systems have used these disinfectants in the past. They can be used for disinfection of swimming pool or spa water or for temporary use as a disinfectant for drinking water. These chemicals are in the same family as chlorine, known collectively as the **halogens**. Indeed, the original group of DBP compounds, the trihalomethanes, comprises four chlorinated and brominated organic species. The chemistry of bromine and iodine is similar to that of chlorine in water, but these compounds tend to produce unpleasant tastes. Moreover, iodine is problematical for individuals with thyroid disease.

Ultraviolet Radiation

UV light is an alternative disinfectant which, when applied correctly, is an efficient germicidal method for disinfecting potable water. Ultraviolet light disinfects through disruption of the cellular DNA or RNA of viruses, bacteria, or protozoans, including *Cryptosporidium* and *Giardia*, preventing the cells of these pathogenic organisms from reproducing. UV is strongly absorbed by DNA and RNA at 254 nm, its predominant wavelength in water treatment systems.

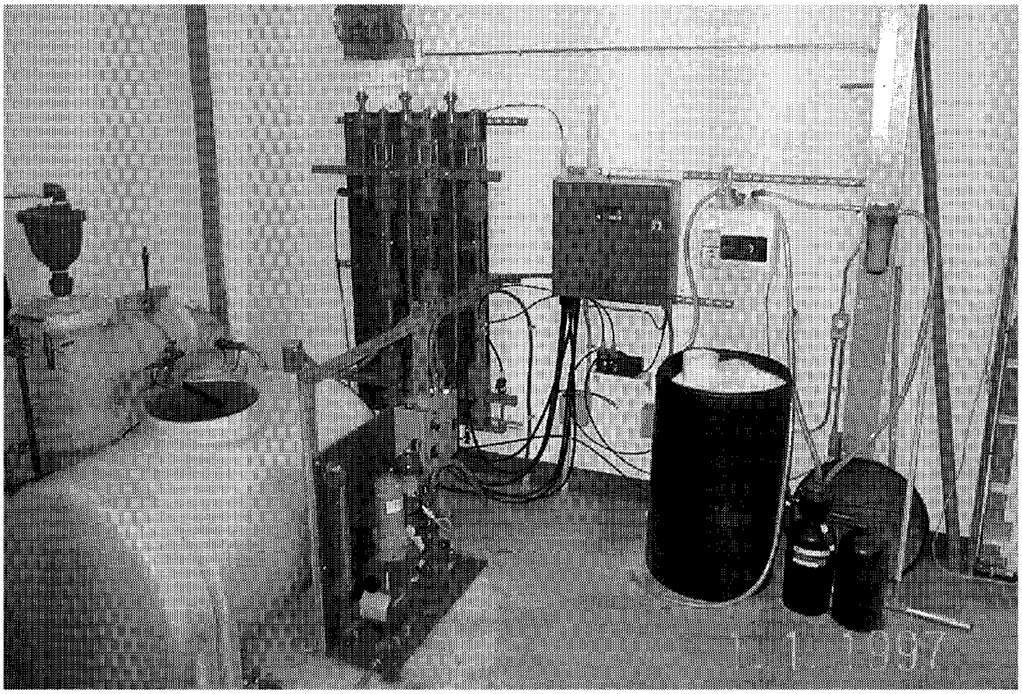
It is important that the water be very low in turbidity or the UV radiation will be adsorbed by the colloidal particles rather than by the cellular DNA and RNA. Like ozone, UV light does not leave a residual, so an additional disinfectant must be used to attain a measurable residual in the distribution system.

Hypochlorite Generators

On-site generation of hypochlorite from a salt solution and electricity is one method of producing chlorine for disinfection purposes. The Alaskan Cities of Wrangell and Coffman Cove use Clor-Tec™ hypochlorite generators to form a 0.8-percent sodium hypochlorite solution from a diluted salt water brine. The basic reaction involved in the electrolysis of salt water to form hypochlorite is the following:

$$\text{NaCl (salt)} + \text{H}_2\text{O (water)} + 2e \rightarrow \text{NaClO (sodium hypochlorite)} + \text{H}_2 \text{ (hydrogen)}$$

The MIOX® Corporation has taken this technology an additional step and developed an on-site generator that is designed to produce a mixture of oxidants that act like ozone and chlorine dioxide in addition to hypochlorites. Several Alaskan treatment systems have recently converted to this method of disinfection, including the University of Alaska Fairbanks and Eielson Air Force Base. According to MIOX®, this type of mixed-oxidant generator produces an array of powerful primary disinfectants effective against all types of pathogenic microorganisms, including *Cryptosporidium*, provides a persistent residual for the distribution system, and produces fewer DBPs than either conventional chlorine or sodium hypochlorite systems.



Clor-Tec™ on-site sodium hypochlorite generation system at the City of Wrangell Water Treatment Plant. Photo courtesy of the City of Wrangell Water Treatment Plant and Greg Scheff and Associates.

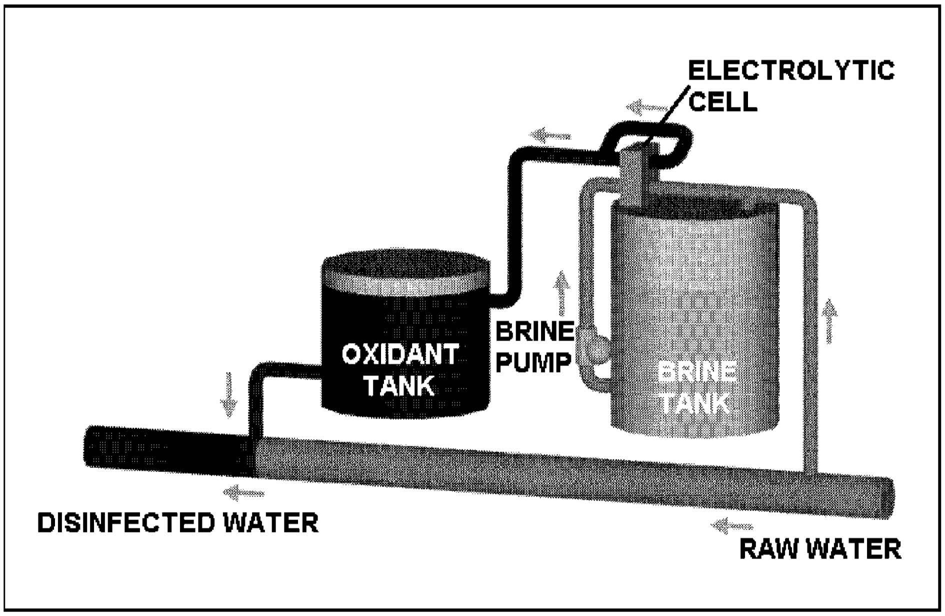
The catalytic reactions listed by MIOX® as possible at the anode of the electrolytic cell include:

$$2Cl^- \rightarrow Cl_2 + 2e^-$$
$$Cl_2 + H_2O \rightarrow HOCl + Cl^- + H^+$$
$$HOCl + H_2O \rightarrow ClO_2 + 3H^+ + 3e^-$$
$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$
$$O_2 + H_2O \rightarrow O_3 + 2H^+ + 2e^-$$

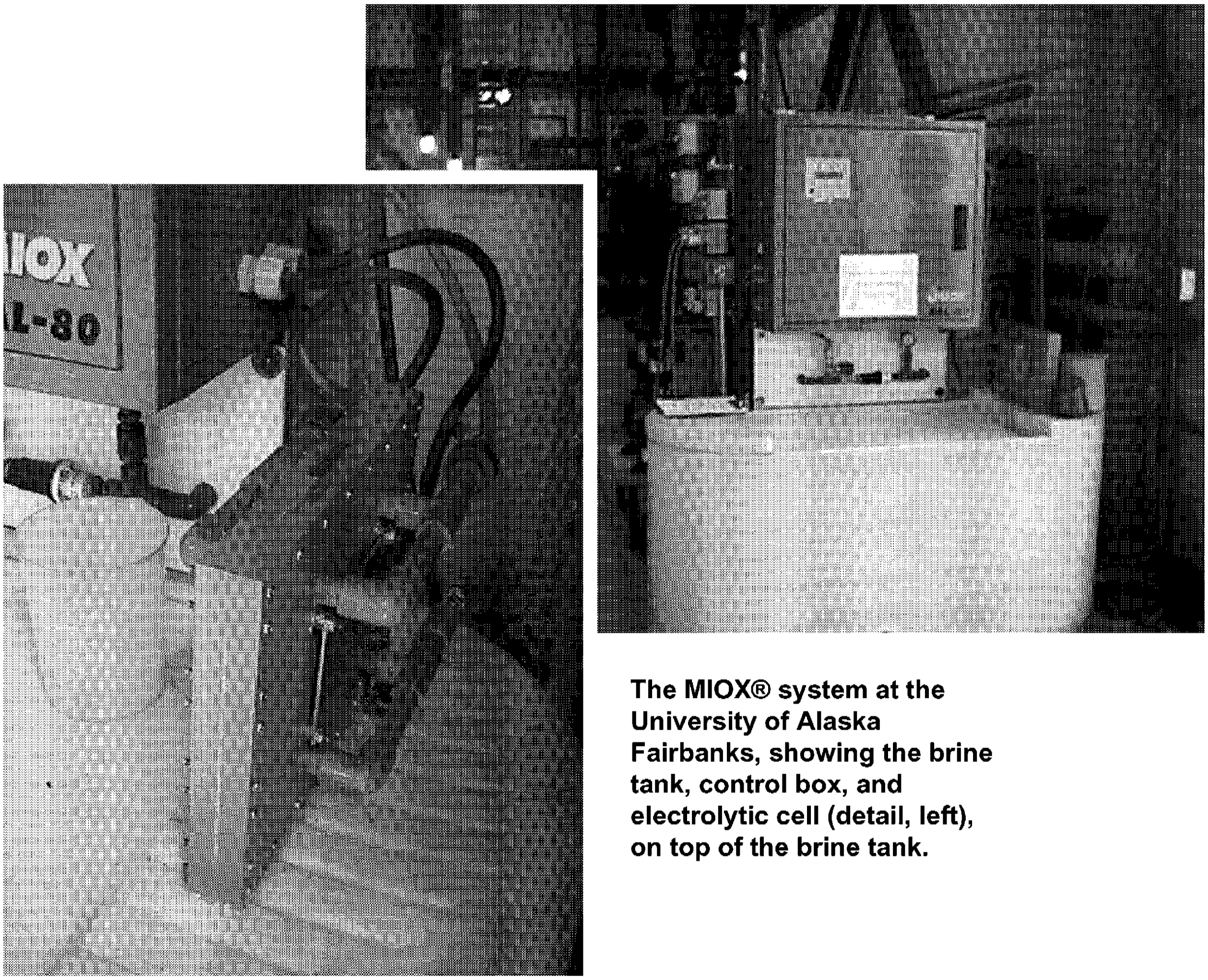
The major electrolytic reaction at the cathode is electrolysis of water:

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

An important advantage of the mixed-oxidant system is that the feed stock chemical is common salt (sodium chloride). Training in the operation of these systems is included during installation, and they are becoming increasingly popular as retrofit systems for large gas chlorine facilities. Replacing the gas chlorine system avoids the consequences and expenses of developing risk management plans for systems storing more than 2,500 pounds of chlorine gas on site.



General MIOX® system schematic, showing the main features. The mixed oxidants are produced by passing a salt (NaCl) brine through an electrolytic cell that catalyzes reactions between the sodium chloride and the raw water. Courtesy of the MIOX® Corporation.



The MIOX® system at the University of Alaska Fairbanks, showing the brine tank, control box, and electrolytic cell (detail, left), on top of the brine tank.

SAFETY

Chlorination system operators must be properly trained and equipped with the appropriate safety equipment to ensure safe operation of the facility. Excellent training programs with videos are available from the American Water Works Association and from the Chlorine Institute. Although the different types of chlorination involve different safety considerations, such as the safe handling of chlorination chemicals, the most hazardous application of chlorination is in gas chlorination. Therefore, gas chlorination is the dominant topic in this discussion of safety.

Self-Contained Breathing Apparatus

Self-contained breathing apparatus boxes just outside the gas chlorine room at the Golden Heart Utilities water treatment plant, Fairbanks, Alaska.

In gas-chlorine facilities, emergency self-contained breathing apparatus (SCBA) should be stored immediately outside the chlorine room. SCBA packs have a positive pressure full face mask that provides fresh air to the operator when in use. SCBA equipment must be approved for use by the National Institute of Occupational Safety, and only operators properly trained in its use and **fit tested** to ensure a proper seal of the face mask should use SCBA equipment. The SCBA air tank contains approximately 15 to 30 minutes of breathing air supply and should be inspected regularly.

Emergency Repair Kits

Emergency repair kits are used for stopping leaks in cylinders when they occur. The three repair kits typically used are the following:

- **Kit A**, for 100- and 150-pound cylinders
- **Kit B**, for1-ton cylinders
- **Kit C**, for tank cars and trucks

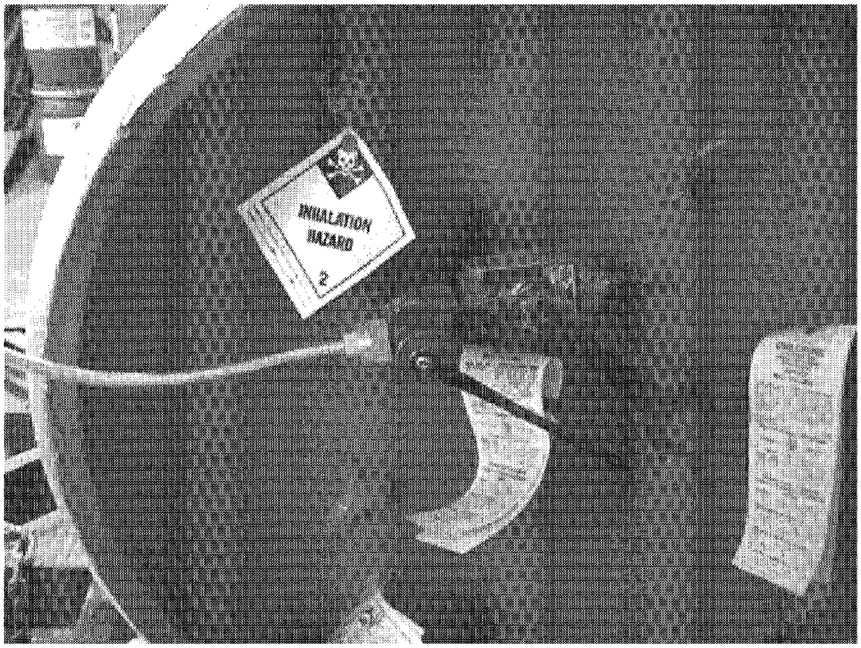
These repair kits contain equipment needed to repair leaks from a valve, cylinder sidewall, or fusible plug. Use of emergency repair kits also requires specialized training. Emergency kits should be inspected regularly to ensure they are intact and fully equipped. Parts used from emergency repair kits should be replaced promptly.

Changing Cylinders

Several specific requirements for changing chlorine cylinders should be followed. The device that attaches to the cylinder is called a **yoke**. A gasket made of lead or fiber that ensures a positive seal at the point of attachment must be replaced every time a cylinder is changed. Gaskets should never be reused.

Each type of cylinder is also designed to be opened with a specific type of wrench. The cylinder wrench for 100- and 150-pound cylinders is only 8 inches long, providing sufficient torque to open the cylinder valve but not enough to unscrew the valve assembly out of the top of the cylinder. Should the valve become stuck, using a “cheater bar” to lengthen the cylinder wrench handle could allow sufficient torque to loosen the entire valve assembly creating a hazardous chlorine leak.

Once a chlorine cylinder has been brought on line, the entire length of gas feed lines and fittings should be checked with a strong ammonia solution by dabbing a swab containing the solution or using an aspirator bottle “whiffing” ammonia vapor around the fittings and lines. If a chlorine leak is present, the ammonia vapors will react with the chlorine to form ammonium chloride gas, readily visible as a white cloud or smoke in the area of the leak. This procedure helps to ensure that all of the fittings are tight and that no leaks are present.



Close-up of top of ton chlorine gas container, showing wrench on control valve.

Safety Procedures

Utilities should prepare a written set of safety procedures for the operation of chlorine gas equipment. The plan should include:

- precautions for storing and handling cylinders
- procedures for connecting and disconnecting cylinders
- procedures to follow in case of a leak
- emergency procedures for a leak that threatens nearby areas
- first aid for chlorine exposure

MANAGEMENT

As with all water treatment processes, disinfection requires careful maintenance of records and knowledge of the applicable regulations. Thorough operational records are essential for adjusting the effective dosage of chemicals and for troubleshooting operational problems. Moreover, the disinfection practices and procedures followed in water treatment plants will evolve as new regulations pertaining to disinfection are developed and revised. In addition, a regular sampling program for coliform bacteria is required by State and Federal regulations.

Total Coliform Sampling

An important part of disinfection system management is monitoring, for disinfectant residual and related parameters such as temperature and pH, and for total coliform bacteria. Coliform bacteria is used as an indicator of possible contamination. As discussed in Chapter 2, "Drinking Water Regulations," a total coliform sample siting plan is required for public water systems and is one of the items checked during a sanitary survey. The plan should identify the locations from which routine bacteria samples will be collected throughout the water distribution system and where resamples are to be taken in the event of a positive result.

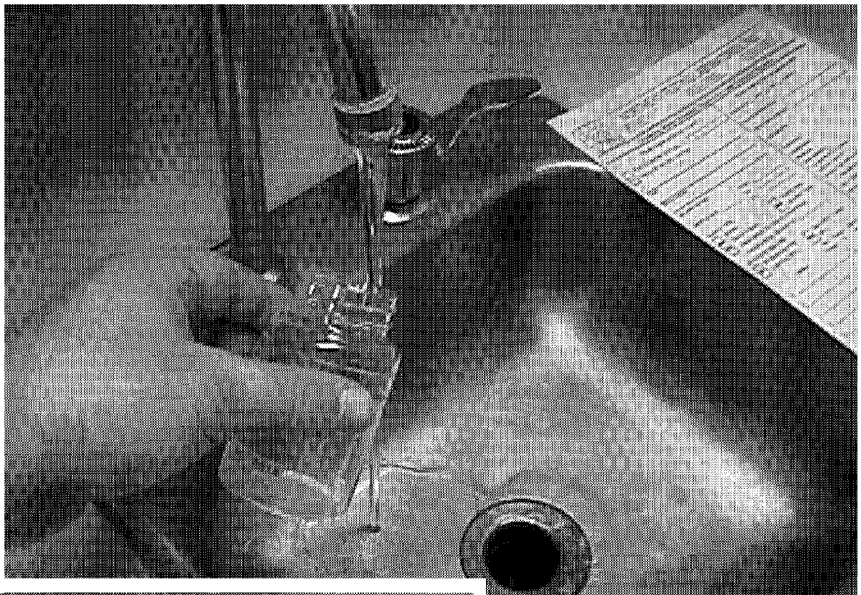
Total coliform samples must be collected carefully to ensure that no external contamination enters the sample. Swivel faucets and leaking faucets should be avoided, as should drinking fountains or taps with point- of-use water treatment devices on them. Moreover, aerators, strainers, and hose attachments should be removed from the faucet before sampling. The sample tap should be thoroughly flushed for at least several minutes, preferably until the sample temperature has stabilized.

The bacteria sample should be collected directly into the sterile bottle containing sodium thiosulfate for dechlorinating the sample. The bottle should be filled to just below the neck, with some space remaining to allow the sample to be mixed at the laboratory. The cap should be kept clean and replaced immediately upon collection. Once the sample bottle is sealed and associated paperwork is completed, the sample should be sent so that it arrives at a certified laboratory within 24 hours.

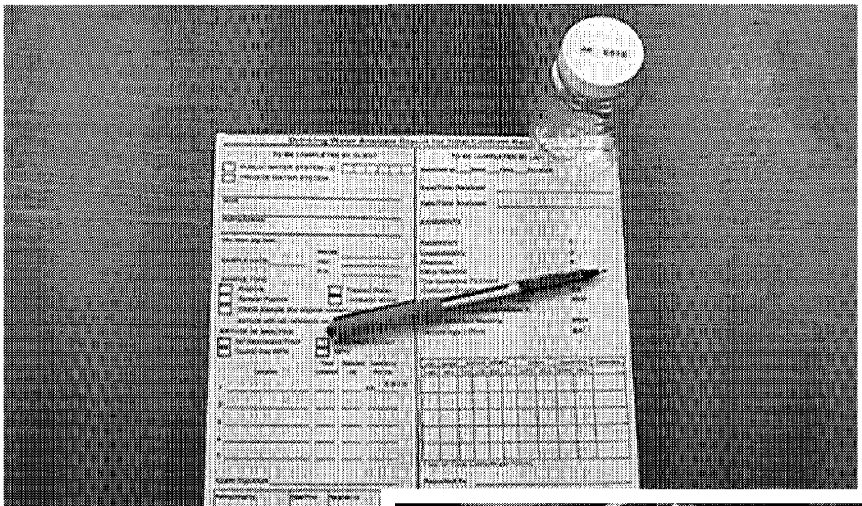
Record Keeping

The minimum record-keeping requirements for disinfection include the following:

- the type of disinfectant being used
- ordering information, including the names, addresses, and telephone numbers of manufacturers and suppliers, the type, size, and number of shipping containers, and the most recent costs of chemicals
- dosage rate, in milligrams per liter or pounds fed per day
- results of bacteriological tests
- results of daily chlorine residual tests (or tests of other disinfectant residuals)
- water temperature and pH
- daily notes on operational and mechanical problems or irregularities, emergencies, irregular test results, and explanations of these



Sterile total coliform sample bottle containing sodium thiosulfate dechlorinating agent (white powder in bottom of bottle). Note moderate flow rate from non-swivel tap.



Completed total coliform sample with air space above liquid level. The chain of custody form is ready to be filled out.

Completed total coliform samples with a positive (center left) and a negative (center right) sample in front.

Regulations

The SWTR, introduced in the Amendments to the 1986 SDWA and adopted in 1989 by the EPA, requires filtration, unless the facility can prove it has an exceptionally high-quality clear water, and disinfection of surface-water supplies and groundwater supplies that may be affected by surface water. The SWTR is the rule that specifically requires a 3-log (99.9%) removal of *Giardia* cysts and a 4-log (99.99%) removal of viruses. The Enhanced SWTR, introduced in the 1996 Amendments to the SDWA and currently in development, will target *Cryptosporidium*, and may require even higher log removal levels in the future.

To ensure adequate disinfection, the proper chlorine residual concentration must be maintained in the water distribution system. The ADEC regulations require a minimum disinfectant residual (interpreted as free chlorine residual) of 0.2 mg/L at the point of entry to the distribution system, and a detectable trace at the farthest points in the system. The regulations allow substitution of heterotrophic plate count (HPC) bacteria monitoring to confirm that a "trace" exists. The maximum allowable level is 500 HPC bacteria per milliliter to verify adequate disinfection in the distribution system.

In addition, in the near future, the 1996 SDWA Amendments will incorporate maximum residual disinfectant levels (MRDLs) for the following disinfectants:

Disinfectant	MRDL*
chlorine	4.0 mg/L
chloramine	4.0 mg/L
chlorine dioxide	0.8 mg/L

* Proposed Stage 1 Disinfectant/DBP Rule levels

REVIEW QUESTIONS

1. Two waterborne diseases that have historically been responsible for a large number of deaths throughout history are ______________________ and ______________________.

2. One of the earliest uses of chlorine for disinfection was in (year and location) ____.
   The first notable use of chlorination in the United States was in (year and location) _____________________________________.

3. Pathogenic microorganisms cause ______________________. Disinfection refers to killing or ______________________ of pathogens in water. Many disinfectants are (classification of chemical) ______________________, which are poisonous to anaerobic pathogens.

4. Two common pathogenic protozoans that can form protective cysts are:
   a. ______________________
   b. ______________________

5. Three general classes of disinfection methods are
   a. ___________________ b. ___________________ c. ___________________.

6. List 6 types of disinfectant chemicals based on chlorine chemistry:
   a. ______________________ b. ______________________
   c. ______________________ d. ______________________
   e. ______________________ f. ______________________

7. Show the 2-step chemical formula for chlorine gas mixing in water and label the components:

8. Powdered chlorine is also known as ______________________, and chlorine bleach solution is also known as ______________________.

9. Free chlorine residual is made up of ______________________ and _____________________. Which form of free chlorine residual is predominant at high pH? ______________________. Of the two forms of free chlorine residual, which is the strongest disinfectant? ______________________.

10. Combined chlorine consists primarily of what classes of compounds? ______________________ and ______________________.

11. Draw a picture of a breakpoint chlorination curve and label the following parts: breakpoint, free chlorine residual, combined chlorine residual.

12. Which form of chlorine is the weakest disinfectant, hypochlorous acid, hypochlorite ion, or monochloramine? ______________________.

13. CT stands for ______________________ times ______________________.
CT units are reported as ______________________.

14. The use of high concentrations of chlorine to disinfect pipes, tanks and wells is called ______________________.
Removal of chlorine residual is called ______________________.

15. List six properties of chlorine gas:
a. ______________________
b. ______________________
c. ______________________
d. ______________________
e. ______________________
f. ______________________

16. A water treatment plant using chlorine gas is treating 150,000 gallons of water per day at a dosage of 0.8 mg/L. How many pounds of chlorine gas are used per day?

17. If the above water plant is disinfecting with 12% sodium hypochlorite, how many pounds of NaOCl will be used per day.

18. To contain a chlorine leak, a ventilation system activated by a chlorine leak detector draws chlorine gas off the floor to a device called a ______________, which contains ______________________ to neutralize the chlorine gas. What final products are produced from the neutralization reaction? ______________________ and ______________________.

19. What is the output of a chemical feed pump in milliliters per minute feeding a hypochlorite solution with the following conditions:

    Maximum Pump Capacity = 2 gallons per hour
    Stroke Length = 80%
    Speed = 70%

20. To check the actual output of the chemical feed pump described above, what device would you use? ______________________

21. What form of chlorination will minimize the formation of disinfectant by-products? ______________________

22. True or False: Ozone is not effective against certain enteric viruses and protozoan cysts such as *Giardia* and *Cryptosporidium*.
    True _______
    False _______

23. List three halogens used as disinfectants:
    a. ______________________
    b. ______________________
    c. ______________________

24. UV radiation inactivates microorganisms at what wavelength?
    ____

25. One of the main problems with UV radiation is, like ozone, it does not leave a persistent disinfectant ______________________.

26. Mixed-oxidant systems generate a variety of disinfectants from ______________________ and ______________________.

Chapter 15

Fluoridation

Chapter 15 – Fluoridation

INTRODUCTION

In the early 20th century, a dentist in Colorado Springs recognized that his patients had fewer dental cavities than the general population. The reason was found to be the naturally high concentrations of fluoride ion in the drinking-water supply. Many water utilities now have a **fluoridation** program in place to promote better dental health in children. Fluoridation is accomplished by feeding fluoride chemicals to the water. If fluoridation is incorporated into water treatment, it is usually one of the last treatment processes the water undergoes before it enters the distribution system.

THE FLUORIDATION PROCESS

The optimal fluoride concentration in drinking water is determined on the basis of the average annual maximum air temperature of the location, because people drink more water in warm climates than in cold climates. In Alaska, the recommended fluoride dosage is 1.0 to 1.5 milligrams per liter (mg/L).

OPTIMAL FLUORIDE CONCENTRATIONS

Average Annual Maximum Daily Air Temperature (averaged over 5 years)		Recommended Limits of Fluoride Concentration, in milligrams per liter		
°F	°C	Lower	Optimal	Upper
53.7 and below	12.0 and below	0.9	1.2	1.7
53.8-58.3	12.1-14.6	0.8	1.1	1.5
58.4-63.8	14.7-17.6	0.8	1.0	1.3
63.9-70.6	17.7-21.4	0.7	0.9	1.2
70.7-79.2	21.5-26.2	0.7	0.8	1.0
79.3-90.5	26.3-32.5	0.6	0.7	0.8

Source: *Water Treatment*, American Water Works Association, 1995

Most surface water naturally contains only trace amounts of fluoride, but groundwater may have fluoride concentrations near the treatment level. Before starting a fluoridation program, the water utility should check the natural level of fluoride in the water. It is only necessary to add enough chemical to bring the level up to the optimum recommended by local health authorities. An excess of fluoride in water can cause a condition known as fluorosis, which results in mottled teeth. Severe fluorosis, resulting from fluoride concentrations higher than about 4 milligrams per liter (mg/L), can actually increase the occurrence of dental cavities. At extreme levels, over-fluoridation can cause severe health problems and even death. An extreme case of over-fluoridation did occur in a remote village in Alaska, apparently the result of a cross-connection between a raw water line and a fluoride saturator fill line. One fatality and dozens of hospitalizations resulted.

To achieve the maximum benefit from fluoridation, it is important that a constant level of fluoride be maintained in the water supply. A decrease of just 0.3 mg/L below the optimal concentration can reduce the benefit by two thirds, whereas an excess of 1.5 mg/L above the optimum can cause mottling of the teeth without providing significant added protection from cavities.

FLUORIDATION CHEMICALS AND DOSAGES

Several different chemicals are used for fluoridation. The American Water Works Association (AWWA) has developed standards for these chemicals that the operator may obtain by contacting AWWA. These standards are based on purity and chemical composition.

In determining chemical dosages, the fluoride concentration of the raw water must be taken into account. In some cases, the natural fluoride concentration may exceed the recommended levels. In such cases the water may be mixed with a water that has a lower than desired fluoride level, or the water may be defluoridated. The most common situation, however, is that in which the fluoride level of the water is increased to the desired level through fluoridation.

Fluoridation Chemicals

The table below shows the types of chemicals that may be used in fluoridation.

CHEMICALS USED FOR FLUORIDATION

Name	Chemical Formula	Form	Commercial Purity	Molecular Weight	Comments
sodium fluoride	NaF	white odorless powder or crystal	97-98%	42.0	the chemical most commonly used in Alaska for fluoridation; solubility is stable at different temperatures
sodium fluorosilicate	Na_2SiF_6	white to yellowish white crystalline powder	98-99%	118.1	the most inexpensive chemical used for fluoridation; solubility decreases with temperature
fluorosilicic acid	H_2SiF_6	colorless to light yellow fuming liquid	20-30%	144.1	highly corrosive acid; pH 1.0 to 1.5

Determining Chemical Dosage

Before fluoridating water, the fluoride concentration of the raw water should be checked. The fluoride added to the water should be only enough to bring the concentration up to the recommended level. The optimal dosage of fluoride is determined by the type of chemical, the percent purity of the chemical, the desired fluoride level, and the existing natural concentration of fluoride in the water.

The amount of fluoride in the compound also must be considered. For example, sodium fluoride (NaF) is composed of sodium (Na) with an atomic weight of 22.99 and fluorine (F) with an atomic weight of 19.0. Thus, the amount of F in NaF is:

$$\frac{F}{NaF} = \frac{19}{23 + 19} = 0.452 \text{ or } 45.2\ \%$$

The amount of fluoride in sodium fluorosilicate is 16.1 percent and in fluorosilicic acid, 13.2 percent.

Chemical treatment charts are provided by chemical manufacturers to determine the fluoride solution feed rate based on the percent strength of the solution and the plant flow rate. The charts are generally designed for a 1 mg/L dosage, so adjustments must be made for the natural fluoride concentration in the water, and the desired dosage. This determination follows the same basic formula as other chemical feed determinations. The basic formula is:

Chemical Feed Rate (lbs/day) = Dosage (mg/L) x Flow (MGD) x 8.34 lbs/gallon

Effect of Water Hardness on Fluoridation

The hardness of the water is an important consideration when determining fluoride dosage; hardness of less than 10 mg/L as $CaCO_3$ (see Chapter 10) probably does not pose a problem, but at higher hardness concentrations, fluoride can react with calcium and magnesium, forming calcium and magnesium fluorides that can precipitate from the water, creating scale deposits on plumbing fixtures.

If hardness in the water exceeds 75 mg/L as $CaCO_3$, the water should be softened before it is mixed with the fluoride chemicals. Because only the water used for mixing the fluoride chemicals needs to be softened, a household-size ion exchange softener installed ahead of the chemical solution mixer generally is adequate for the job.

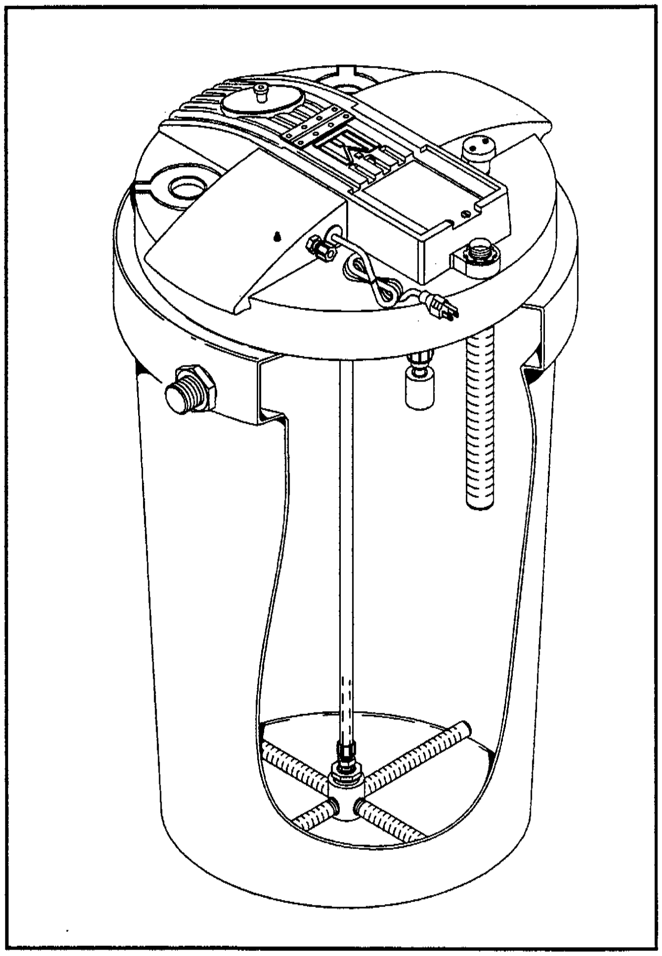
CHEMICAL FEED EQUIPMENT

Several different types of chemical feed equipment are available for adding fluoridation chemicals to water. The most common systems in small Alaskan utilities are upflow sodium fluoride saturators made by LMI Pumps. Several larger water operations use dry chemical feeders with mixing tanks to feed solutions of sodium fluorosilicate.

Upflow Fluoride Saturators

The fluoride saturator may be designed for an upward or downward flow of chemical solution, most commonly sodium fluoride. The upflow saturator is most commonly used in Alaska. The saturator maintains a 4 percent sodium fluoride solution, and feeds this to the finished water before it enters the distribution system. If water hardness is a problem, the saturator is connected to an upstream softener, usually a simple ion-exchange household-type unit.

The complete saturator package includes a tank, distributor tube assembly, and tank cover. The tank cover houses the mechanical components, including solenoid valve, syphon breaker, and liquid level switch. The cover also provides a suction tube strainer, recess for pump mounting and a hinged fill hatch cover. A push button light switch allows the operator to visually inspect the fluoride bed level.



Fluoride Saturator No. 28850, made by LMI Pumps.This is the type of fluoride saturator most commonly used in small Alaskan water treatment systems. Drawing courtesy of LMI Pumps.

The liquid level switch controls the solenoid valve operation to maintain the correct solution in the tank. The distributor tube assembly supplies fresh water to a bed of sodium fluoride at the tank bottom. Water is piped in through the distributor tubes and "flows up" through the bed of sodium fluoride crystals, dissolving the crystals to provide a saturated, 4-percent solution.

A metering pump can be mounted in the recess on the saturator cover assembly. Pumps may be selected either for constant water flow rate applications, or for operations requiring automatic output control. The pump's electronic circuit must be wired so that it stops pumping fluoride to the application point if the water flow stops. This is normally done using an in-line paddle switch.

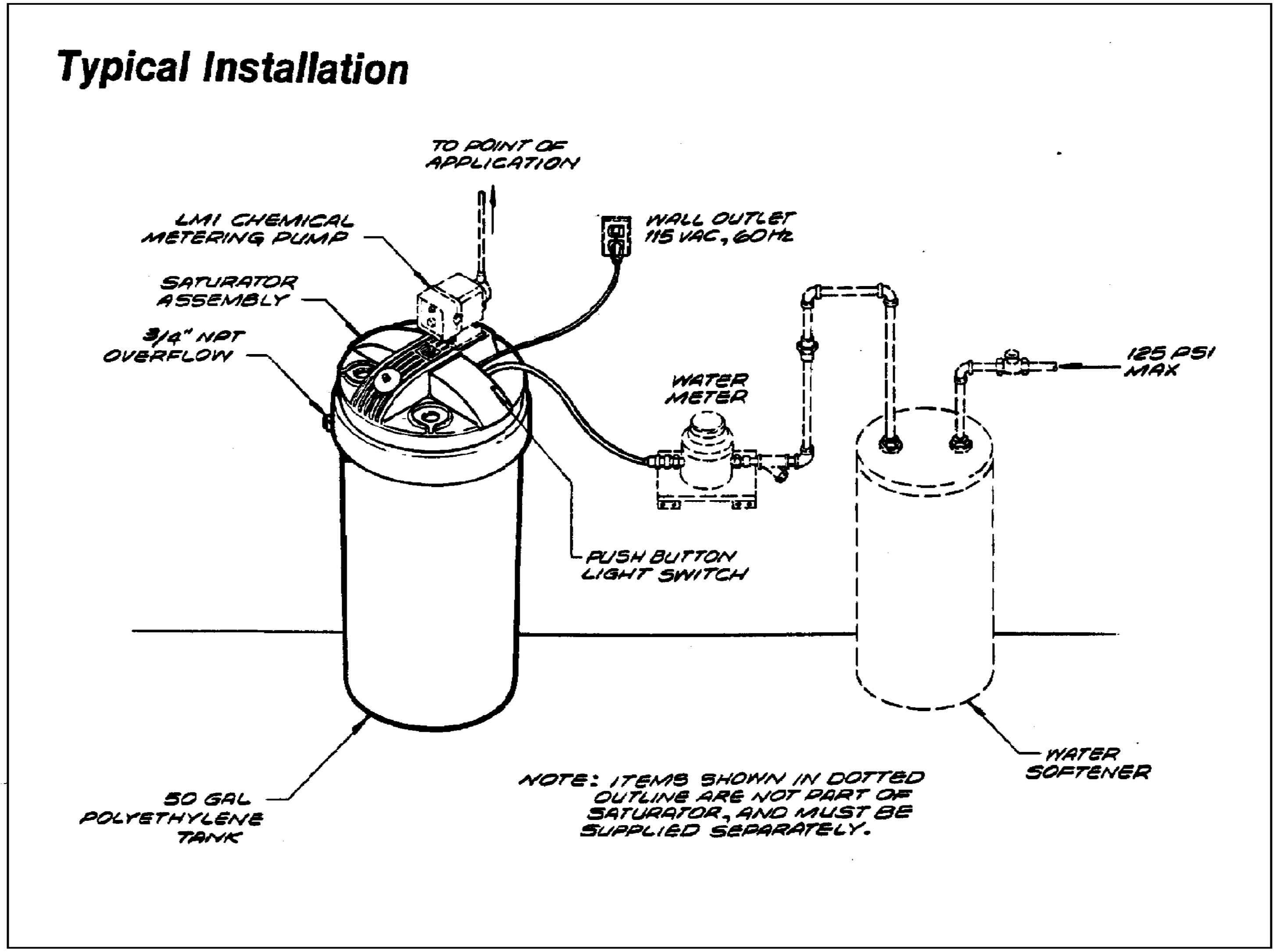
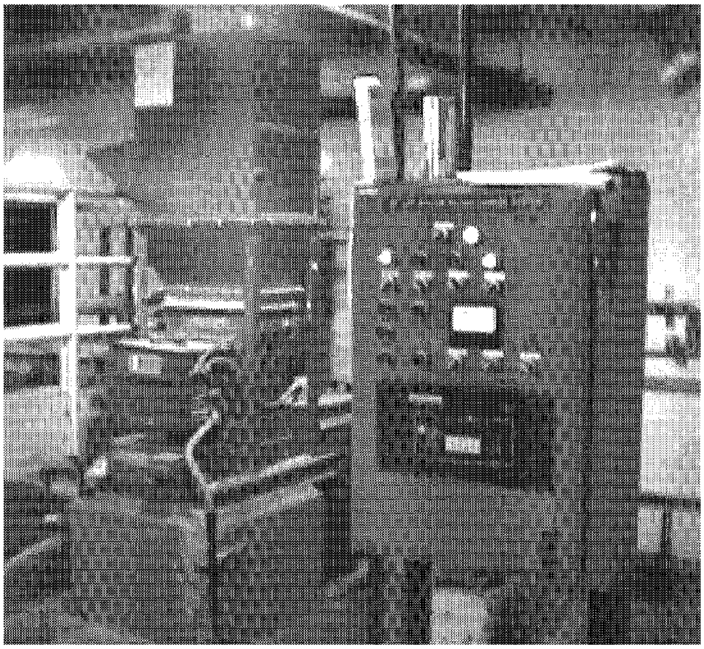


Diagram showing a typical installation of an LMI Pumps upflow fluoride saturator. Note water softener upstream from the saturator tank. Drawing courtesy of LMI Pumps.



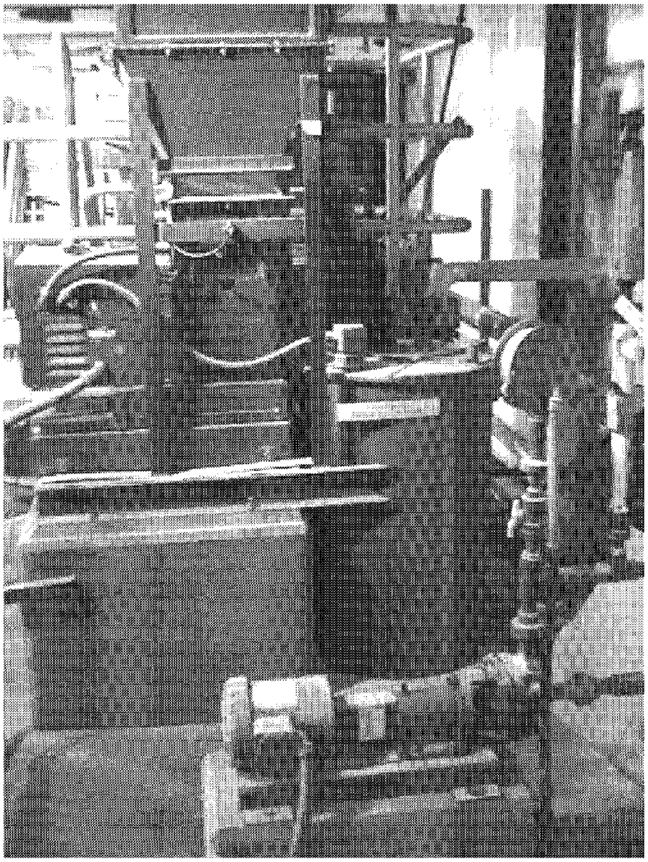
Dry chemical volumetric feeder and controls for feeding sodium fluorosilicate at the Golden Heart Utilities Water Treatment Plant in Fairbanks, Alaska.

Dry Chemical Feeders

The larger water treatment plants in Fairbanks and Anchorage fluoridate with sodium fluorosilicate using dry chemical feeders and chemical mixers.

At the Golden Heart Utilities water treatment plant, the raw water fluoride concentration is 0.2 mg/L. The water is dosed with an additional 1.0 mg/L to provide a total fluoride concentration in the finished water of 1.2 mg/L. Approximately 40 to 50 pounds per day of sodium fluorosilicate is fed to the finished water.

Side view of GHU's volumetric sodium fluorosilicate feeder and mixing tank. One of two chemical feed pumps for dosing fluoride to the finished water is in the foreground.



SAFETY AND MANAGEMENT

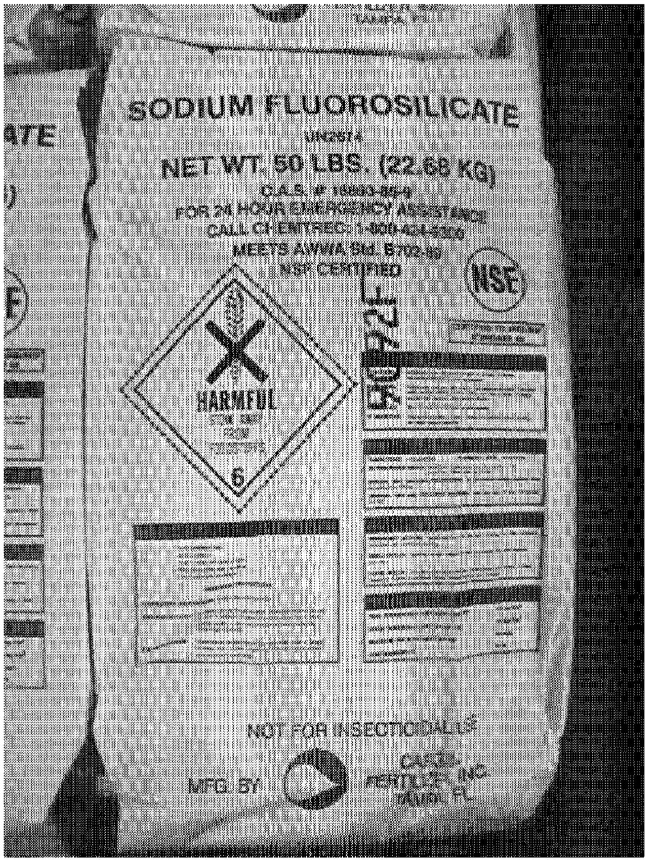
Because of the toxicity of excess fluoride and the hazards associated with handling some fluoride chemicals, safety and management are important considerations in fluoridation. The water treatment operator will need to monitor the fluoride concentration in the finished water daily, and ensure that proper records are maintained to track the process and its effectiveness. The U.S. Environmental Protection Agency has established a maximum contaminant level of 4 mg/L and the State of Alaska has set the secondary maximum contaminant level at 2 mg/L.

Safety Considerations

Fluoride chemicals are hazards to the respiratory tract if inhaled, causing severe irritation of mucous membranes of the upper respiratory tract, lung irritation, and bronchiospasms. Ingestion may cause abdominal pain, vomiting, diarrhea, excess salivation, thirst, perspiration and painful spasms of the limbs, and can be fatal in severe cases. Chronic exposure to high doses of fluorides can cause skeletal changes such as brittle bones, increased bone density, and increased calcification of ligaments and vertebrae. In addition, fluoride chemicals are irritants to skin and eyes.

When handling fluoride chemicals, it is important to consult the Material Safety Data Sheet (MSDS) for the particular chemical. The MSDS will list the type of personal protective equipment (PPE) necessary and emergency procedures in case of accidental over-exposure. In general, PPE should include a particulate respirator or self-contained breathing apparatus if the chemical is heated to decomposition. The work area should be well ventilated to avoid the accumulation of large quantities of fluoride chemical dust.

If dust is generated during handling, eye protection should be worn, and skin contact should be minimized by the use of gloves and other protective apparel. A safety shower and eyewash should be located conveniently to the work area. Workers should be sure to shower after handling, and to change clothes before going off shift to ensure they do not bring fluoride chemical dust home with them.



Sodium fluorosilicate in 50-pound bag at the GHU Water Treatment Plant. Note labeled warnings, emergency contact numbers, and stamp of approval of the National Sanitation Foundation (NSF).

Record Keeping

The records that should be kept documenting the fluoridation process at a water treatment plant are the following:

- amount of chemical fed each day
- daily measurement of fluoride concentrations in raw and finished water
- any operational problems

Regulations

No Federal or State regulations require the fluoridation of public water supplies. The decision of whether or not to fluoridate is made on the local level. However, new water system installations in Alaska funded by the U.S. Public Health Service are routinely equipped with fluoride saturators as a matter of the agency's national policy.

Systems that fluoridate are required to monitor and sample for fluoride at the entry point to the distribution system each day that water is served to the public. For fill-and-draw systems, fluoride is monitored and sampled each day that fluoride is added to the water when making water. The sampling results must be reported monthly to the Alaska Department of Environmental Conservation. The maximum contaminant level for fluoride in drinking water is 4.0 mg/L. The secondary maximum contaminant level is 2.0 mg/L. In Alaska, it is recommended that fluoride concentrations not be allowed to exceed 1.5 mg/L.

REVIEW QUESTIONS

1. What is the purpose of fluoridation?
   ____

2. What is the common fluoride dosage range recommended for Alaskan water treatment systems?
   ____

3. What are three chemicals, and their chemical formulas, commonly used for fluoridation of water supplies?
   a. ____
   b. ____
   c. ____

4. Which of these fluoridation chemicals is most commonly used in Alaska?
   ____

5. A system that produces 150,000 gallons per day of potable water has a fluoride concentration of 0.2 mg/L in its raw water. The desired fluoride concentration in the treated water is 1.3 mg/L. How many pounds of 97.5% pure NaF will be required per day to achieve the desired concentration?

6. What are the primary and secondary MCLs for fluoride?
   Primary: ____________________ Secondary: ____________________

7. ____________________ may interfere with fluoride chemical solubility.

8. What is the chemical feed system most commonly used for fluoridation in Alaska?
   ____
   What is the standard concentration of the stock solution in this system?
   ____

9. Fluoride is what type of hazard?
   ____

10. Typical personal protective equipment for mixing and handling fluoride chemicals includes:
   a. ____
   b. ____
   c. ____

Chapter 16

Corrosion Control Treatment

The Lead and Copper Rule

Maximum Contaminant Level Goals
Monitoring Requirements
Corrosion Treatment
Public Education
Reporting and Record-Keeping Requirements

Review Questions

Chapter 16 – Corrosion Control Treatment

INTRODUCTION

Corrosion of materials is a costly problem for the water industry and related industries. **Corrosive** water can have a devastating effect on water system appurtenances, and can dissolve toxic metals from distribution and plumbing fixtures. Other metals in system components also can be leached into the water, causing taste, odor, and staining problems. Some leached metals can form scale deposits in pipes, which can clog the distribution system and protect microorganisms from chlorine disinfection. This is one of the effects of **iron tuberculation**. Moreover, Federal and State regulations, specifically the **Lead and Copper Rule**, require water system operators to treat their water if lead and copper corrosion products are present in the water at elevated concentrations.

Several standard treatment methods are in use to control corrosion of water system components: pH and alkalinity adjustment, application of a protective calcium carbonate ($CaCO_3$) coating, and the addition of corrosion inhibitors and sequestering agents, such as phosphates or silicates.

EFFECTS OF CORROSION

Corrosion of water treatment and distribution systems has mechanical, operational, public relations, and public health implications including:

- increased head loss and pumping costs due to clogging of pipes from tuberculation
- loss of water and reduced water pressure due to holes created by pitting and subsequent damage to buildings and other structures from leaks
- increased frequency and cost of repairs to tanks, pipes, pumps, valves, and meters
- leaching of heavy metals such as copper and lead
- consumer complaints about taste problems, colored (red) water, and stains on laundry and fixtures

CORROSION THEORY

Corrosion is a complex phenomenon with multiple chemical, electrical, physical, and biological factors that affect both interior or exterior surfaces. A few basic concepts will help to describe the major principles of corrosion. Corrosion can be described as the deterioration of materials in the presence of water. Generally, the tendency is for a refined metal to revert back to an ore with a lower energy level. For example, steel can corrode to iron oxide (rust), which is one of the basic minerals mined to recover iron.

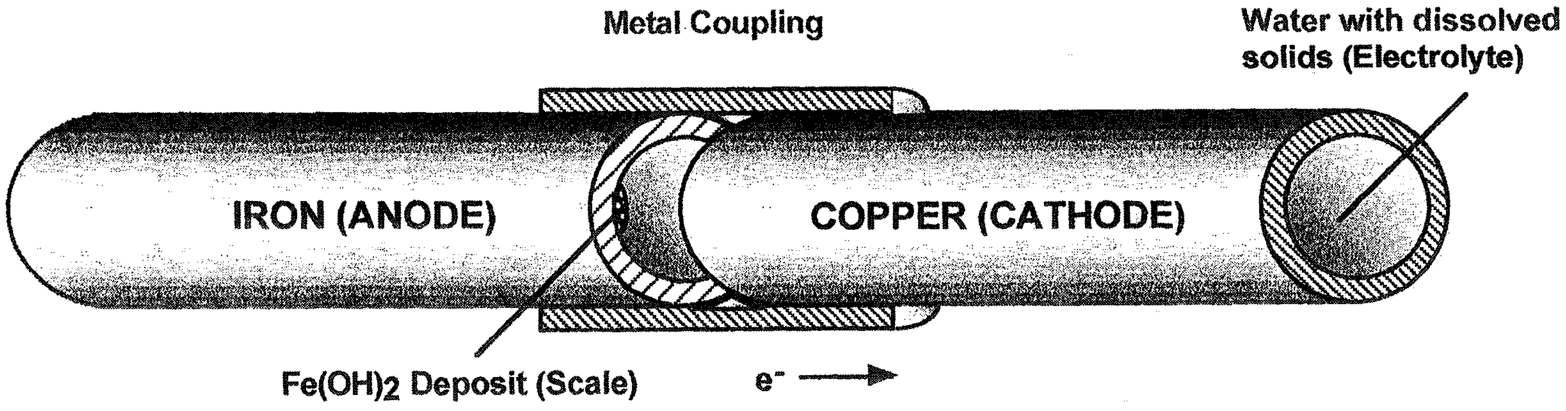
The Galvanic Cell

The corrosive deterioration of metal can be illustrated by an electrochemical system known as a **galvanic cell**. Essentially, the galvanic cell is a battery with the following components:

1. **Anode** – the location where metal erodes away and an electric current begins to flow. The anode must be connected to a cathode by a conductive material.
2. **Cathode** – the location where electric current leaves the metal and flows to the anode through the electrolyte, initiating chemical reactions in the water
3. **Electrolyte** – conductive solution of water and dissolved salts

The propensity for a particular metal to be anodic or cathodic depends on its position in the **galvanic series**. The higher the metal is on the list, the more noble or protected (more cathodic) it is. Any metal lower in the series will be anodic to any higher metal. The anodic metals are also referred to as base metals.

In the figure on the next page, a copper pipe is joined directly to a section of steel pipe. The galvanic series shows that steel will be the anode and copper the cathode in this galvanic cell. Iron will dissolve into the water in its ferrous (Fe^{2+}) state, and two electrons ($2e^-$) will flow to the cathode. At the cathode, two electrons leave the metal at the point of contact with the electrolyte (water) and react with hydrogen ions (H^+) in the water to form hydrogen gas (H_2). The hydrogen ions originate from the dissociation of water ($H_2O \rightarrow H^+ + OH^-$). The electrolyte is in contact with both the anode and the cathode, completing the circuit.



ANODE REACTIONS:

Iron is released to the water inside the pipe at the anode:

$Fe^{\circ} \rightarrow Fe^{++} + 2e^{-}$

The ionized iron reacts with water forming ferrous hydroxide:

$Fe^{++} + 2H_2O \leftrightarrow Fe(OH)_2 + 2H^{+}$

In the presence of oxygen, ferric hydroxide is formed:

$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$

CATHODE REACTIONS:

Hydrogen gas is produced by electrolysis:

$H^{+} + 2e^{-} \leftrightarrow H_2\uparrow$

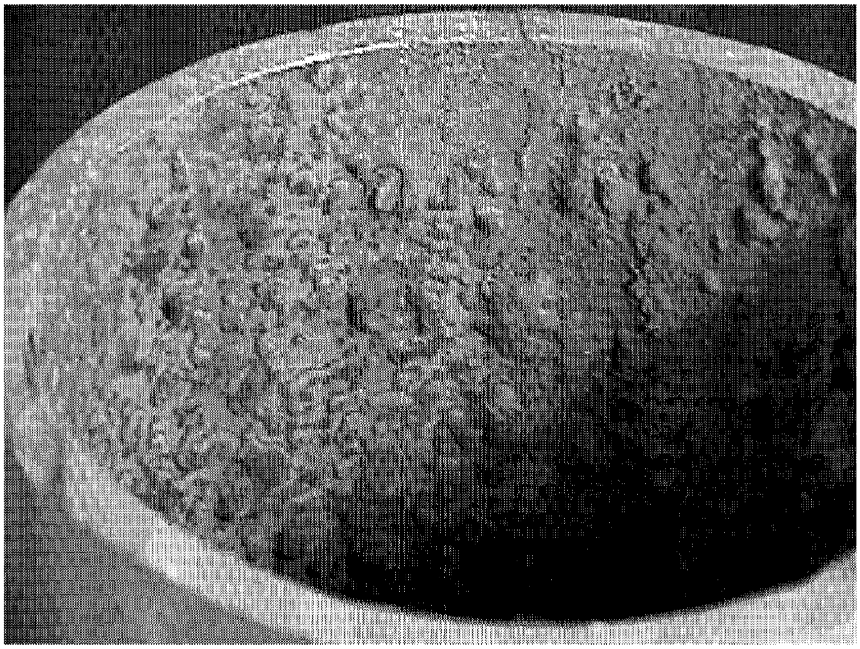
or, in the presence of oxygen, water is produced:

$H^{+} + 2e^{-} + O_2 \rightarrow H_2O$

An iron-copper galvanic cell, showing the anode and cathode reactions.

GALVANIC SERIES	
cathode, least active	gold
	graphite
	silver
	316 stainless steel
	304 stainless steel
	nickel (passive)
	silver solder
	titanium
	copper-nickel alloys
	bronze
	copper
	brass
	nickel
	tin
	lead
	50/50 lead-tin solder
	cast iron
	steel
	aluminum
	zinc
anode, most active	magnesium

At the anode, the dissolved iron may react with oxygen and water, forming a rust film consisting of layers of ferrous hydroxide [$Fe(OH)_2$] and ferric hydroxide [$Fe(OH)_3$]. This multi-layered rust deposit is called a **tubercule**, which can build up inside the pipe until the pipe is nearly choked off. During times of high flow rates, the tubercules may break loose, resulting in "red water" flowing from consumers' taps. As the rust coating on the pipe builds up it begins to cover and protect the anode, temporarily slowing the rate of corrosion. If the rust film is flushed away, the corrosion reaction begins again.



Iron tuberculation in a steel pipe.

The more active a metal is in the galvanic series, the greater its tendency to corrode. In addition, the greater the distance between two metals in the galvanic series, the greater the galvanic corrosion potential. Because of their active position in the galvanic series, zinc and magnesium often are used as sacrificial anodes to protect pipes and tanks. Sacrificial anodes in hot water heaters are typically made of an alloy of aluminum, magnesium, and zinc.

As can be seen in the galvanic series, when copper pipe and lead solder are in contact, the lead becomes the anode and will corrode. The toxicity of lead and its anodic properties to copper are the reason that lead has been banned for use in potable water systems by the Safe Drinking Water Act Amendments.

Another important feature of galvanic corrosion is the relative size of the anode and cathode. A large cathode will generate a high level of electrical potential. If that current is directed at a relatively small anode it will erode very quickly, resulting in what is called **pitting**. At high pitting rates, the wall of the tank or pipe may be completely penetrated in a relatively short time, forming pinhole leaks. This can occur within small flaws or scratches in the protective interior coating of a water tank.

One way to limit galvanic corrosion is to install dielectric fittings made of ceramic, plastic, or other nonconductive materials between dissimilar metals. Another approach is to attach sacrificial anodes to the tank wall and suspend them in the water inside the tank; the sacrificial anodes will dissolve first, protecting the steel.

PHYSICAL FACTORS INFLUENCING CORROSION

A variety of physical factors may increase or decrease the rate and severity of corrosion, including the type and arrangement of materials used in the system, stray electrical currents, water flow velocity, pressure, and temperature.

Materials

The effects of the type of materials that make up the anode and cathode were discussed above, as was the influence of the relative sizes of the anode and cathode. The types of coatings applied on both the inside and outside of pipes and tanks also will influence corrosion rates. If anodic, uncoated metal is in contact with wet soil, corrosion that can significantly reduce the life of the metal can result.

Stray Current

The grounding of electrical circuits to water pipes can result in stray current corrosion. This is particularly a problem if the plumbing system in a building is isolated from the mains by a dielectric fitting, which is common practice in Alaska. Stray current corrosion from direct current (DC) sources such as phone circuits is nearly 100 times more active than from alternating current (AC) grounding.

Temperature

As temperatures rise, rates of chemical reactions including corrosion reactions usually increase. In general, a rise of 10 °C in water temperature will roughly double the rate of corrosion. However, some temperature effects may be protective, such as deposition of $CaCO_3$ film, which occurs more rapidly at higher temperatures. In the extreme case, this can result in undesirably thick scale layers.

Pressure

Corrosion rates in high-pressure systems such as in boilers and steam lines may be much higher than in moderate-pressure systems. Even in cold water lines, high pressure will increase the concentration of corrosive gases such as carbon dioxide and oxygen.

Velocity

Flow velocity has several effects on corrosion rates. Moderate flow rates generally are beneficial, whereas very high or very low flow rates generally increase the rate of corrosion. Under stagnant water flow conditions, corrosion is usually more severe, particularly in the form of pitting and tuberculation in iron pipes. If protective chemical films are being used for corrosion protection, stagnant flow rates will greatly reduce their effectiveness. With very high flow velocities, erosion corrosion can occur, particularly in copper pipes. At rates exceeding 5 feet per second (1.5 meters per second), copper tubing will erode rapidly, particularly at joints or elbows, resulting in structural damage to the pipe. This problem often becomes evident by the presence of persistent leaks in even relatively new copper tubing. Circulating hot water systems in large buildings are particularly susceptible to erosion corrosion because of high flow velocities and temperatures.

CHEMICAL FACTORS INFLUENCING CORROSION

The chemical factors that influence corrosion include alkalinity, pH, concentrations of dissolved solids and gases such as oxygen and carbon dioxide, chlorine residual, and the type and concentrations of minerals dissolved in the water.

Alkalinity

Alkalinity is a measure of a water's buffering capacity to resist a change in pH when either acid or base is added to the water. Alkalinity is contributed primarily by carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), or hydroxide (OH^-) ions. Carbon dioxide (CO_2) also is part of the system in equilibrium because HCO_3^- is involved in nearly all the acid or base reactions. Acid reactions with alkalinity include:

$$CO_3^{2-} \text{ (carbonate)} + H^+ \text{ (acid)} \leftrightarrow HCO_3^- \text{ (bicarbonate)}$$

$$HCO_3^- \text{ (bicarbonate)} + H^+ \text{ (acid)} \leftrightarrow H_2CO_3 \text{ (carbonic acid)}$$

$$H_2CO_3 \text{ (carbonic acid)} \leftrightarrow CO_2 \text{ (carbon dioxide)} + H_2O \text{ (water)}$$

$$OH^- \text{ (hydroxide)} + H^+ \text{ (acid)} \leftrightarrow H_2O \text{ (water)}$$

Base reactions are primarily with carbonic acid and bicarbonate:

$$H_2CO_3 \text{ (carbonic acid)} + OH^- \text{ (base)} \leftrightarrow HCO_3^- \text{ (bicarbonate)} + H_2O \text{ (water)}$$

$$HCO_3^- \text{ (bicarbonate)} + OH^- \text{ (base)} \leftrightarrow CO_3^{2-} \text{ (carbonate)} + H_2O \text{ (water)}$$

In either case, the acid or base is neutralized and the pH shifts only slightly. Thus, high-alkalinity water has a strong tendency to resist a change in pH and low-alkalinity water has little buffering capacity and will change pH readily with only a small addition of acid or base. A simple method of corrosion control is to raise the alkalinity of the water by adding either carbonate- or hydroxide-containing chemicals such as soda ash (Na_2CO_3) or caustic soda (NaOH).

Another important carbonate alkalinity reaction is with calcium in the water to form $CaCO_3$:

$$CO_3^{2-} \text{ (carbonate)} + Ca^{2+} \text{ (calcium)} \rightarrow CaCO_3 \text{ (calcium carbonate)}$$

If the water contains sufficient calcium, adding alkalinity can increase the deposition of $CaCO_3$ scale, forming a protective film on the inside of pipes. An excessive amount, however, results in hardness scaling.

pH

Low-pH (< 7.0) water tends to be corrosive to pipe materials. As noted above, the pH of the water is influenced by the amount of alkalinity present. Certain pH ranges offer less protection than would otherwise be assumed. For example, water with a pH value between 8.1 and 8.3, the transition point between carbonate and bicarbonate, has a weak buffering system and may not resist corrosion as well as water with slightly lower pH values.[1]

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[1] For a detailed discussion of relations between alkalinity, pH, and CO_2, see *Chemistry for Environmental Engineers*, 1978, by C.N. Sawyer and P.L. McCarty.

Dissolved Oxygen

Dissolved oxygen (DO) is one of the most corrosive components in water, having an important role at both the anode and cathode. At the cathode, hydrogen gas (H_2) is formed in a process called **polarization**. DO then reacts with the hydrogen gas, forming water in a process called **depolarization**. Once the hydrogen gas has been removed, the corrosion reaction accelerates again.

At the anode, DO reacts with iron as it dissolves into the water to form ferric hydroxide (rust). This process of iron oxidation produces tubercules and red water. As the rust coating forms, the rate of corrosion slows until high flows remove the rust, exposing the anode to more dissolved oxygen.

Dissolved Solids

Dissolved solids, as free ions, increase the electrical conductivity of the water, which in turn increases the corrosion potential. All scale-forming components such as iron oxide (rust) and $CaCO_3$ (limestone) are present first as dissolved solids in the water before they deposit on the surface of pipes and fixtures.

Hardness

Hardness consists primarily of calcium and magnesium ions, which, at high enough concentrations, can form scale on the inside of pipes or fixtures at elevated pH levels and temperatures. As noted above, deposition of a protective $CaCO_3$ film is a common measure used to control corrosion in water systems.

Chloride and Sulfate

Chloride (Cl^-) and sulfate (SO_4^{2-}) ions in water may produce soft, non-protective calcium chloride and calcium sulfate scales rather than tough, protective $CaCO_3$ scale. To minimize this, the alkalinity should be five times higher than the total combined concentration of chloride and sulfate.

Phosphate and Silicate

Phosphate and silicate can form protective films in water systems under the right chemical conditions. When they are intentionally added to water for this purpose, they are referred to as **corrosion inhibitors**.

Heavy Metals

Metals of significance in corrosion control include copper, iron, lead, and zinc. When present at high concentrations in the distribution system, they usually indicate corrosion. Copper and lead are particularly toxic and are specifically limited under a set of regulations known as the **Lead and Copper Rule**, which requires utilities that exceed certain action levels to begin corrosion control treatment. Iron and zinc may be involved in the formation of protective films, limiting the rate of corrosion. Zinc is another common corrosion control additive, often combined with phosphates.

BIOLOGICAL FACTORS INFLUENCING CORROSION

Two types of bacteria that can influence corrosion in water systems are iron bacteria and sulfate-reducing bacteria. These bacteria can increase the rate of corrosion and the formation of undesirable corrosion by-products. Iron bacteria use dissolved iron and sulfate-reducing bacteria use sulfate as an energy source. Both types of bacteria can grow in dense masses that resist disinfection by chlorine.

Iron Bacteria

Iron bacteria are typically present in a filamentous (string-like) form, resulting in slimy reddish or brown-colored masses. These may form on well screens, inside pipes or storage tanks, and on the inside of fixtures. Some of the filamentous iron bacteria common in water systems include *Crenothrix*, *Sphaerotilus*, and *Gallionella*.

Iron bacteria convert ferrous (dissolved) iron into a ferric-hydroxide precipitate. The precipitate is deposited as rust particles in the slime sheaths surrounding the bacterial cells and can be released during periods of high flow velocity, contributing to red water conditions. Moreover, iron bacteria can cause an unpleasant musty odor. Corrosion can be accelerated under deposits of iron bacteria on pipes and tanks, resulting in pitting and tuberculation.

Sulfate-Reducing Bacteria

Sulfate-reducing bacteria can readily be distinguished by the characteristic rotten-egg odor of hydrogen sulfide (H_2S) that they produce as a by-product. H_2S can form sulfuric acid (H_2SO_4), which is extremely corrosive and may react with metals to produce black metal-sulfide deposits on the inside of pipes.

CORROSION MONITORING

Regardless of whether or not a utility is in compliance with the Lead and Copper Rule, corrosion will likely be a concern that should be monitored. Depending on the severity of the problem, a corrosion monitoring program can include the following:

- documenting the location and frequency of consumer complaints about discolored water and metallic tastes
- monitoring the presence of leaks in the distribution system
- examination of materials, such as pipe sections and fittings removed from the system when repairs are being made, particularly where leaks have occurred
- direct measurement with corrosion coupons (strips of test metal inserted into water lines) or electronic corrosion test instruments[1]
- monitoring elevated concentrations of trace metals in the water[2]
- monitoring other relevant water quality parameters such as the Langelier Index

Langelier Index

Several corrosion indices help determine whether or not water from a distribution system is corrosive to, or protective of, the metals in the system. In general, the corrosion indices determine the level of $CaCO_3$ saturation in the water because that is the compound that usually forms the protective film. The indices also use the same basic water quality data, but calculate and interpret it somewhat differently.

---

[1] Test coupons will help to establish the rate of corrosion in mils per year (thousandths of inches per year) and will show the type of corrosion such as pitting, general metal loss, or erosion corrosion, also known as "etching."

[2] Lead and copper monitoring is required under the Lead and Copper Rule, but monitoring for other metals may be helpful to understand the nature and severity of corrosion. Samples can be collected as first draw as in the Lead and Copper Rule, or as flushed samples after the sample tap has been flushed out first. Parameters can include cadmium, chromium, iron, manganese, and zinc.

The Langelier Index requires alkalinity, total dissolved solids (TDS), calcium, pH, and temperature measurements to determine the tendency for $CaCO_3$ to deposit or dissolve. The mathematical result of the Langelier Index can be interpreted as follows:

Index Result	Interpretation
Negative (<0)	$CaCO_3$ scale will dissolve, and the water is corrosive
Neutral (0)	$CaCO_3$ scale is at saturation and won't dissolve or deposit
Positive (>0)	$CaCO_3$ scale will deposit and form a protective coating

The Langelier Index can be determined by using equation 1:

$$\text{Langelier Index} = pH - pH_s \tag{1}$$

Where
pH = the actual pH of the water
pH_s = the pH at which $CaCO_3$ is saturated

To calculate the pH_s value, equation 2 can be used:

$$pH_s = A + B - \log(Ca^{2+}) - \log(\text{Alkalinity}) \tag{2}$$

Where
A = temperature factor from "Table A":

TABLE A			
Temperature, °C	A	Temperature, °C	A
0	2.34	30	1.91
5	2.27	40	1.76
10	2.20	50	1.62
15	2.12	60	1.47
20	2.05	80	1.18
25	1.98	100	0.88

B = TDS factor from "Table B":

TABLE B	
TDS, mg/L	B
0	9.63
50	9.72
100	9.75
200	9.80
400	9.86
800	9.94
1,000	10.04

Ca^{2+} = calcium hardness in $CaCO_3$ equivalents
Alkalinity = alkalinity in $CaCO_3$ equivalents
log = logarithm function (LOG or Log10 on most calculators)

In the following example of a groundwater supply, the alkalinity, calcium, and TDS were measured in a laboratory, and the pH and temperature were measured as the sample was collected to provide the most accurate data:

Known:
Alkalinity = 175 mg/L as $CaCO_3$
Calcium = 120 mg/L as $CaCO_3$
pH = 7.9 pH units
TDS = 250 mg/L
Temperature = 4.5 °C

Find:
pH_s and Langelier Index
To determine pH_s, use equation (2):
From TABLE A for a water temperature of 4.5 °C, A = approximately 2.28
From TABLE B for a TDS of 250 mg/L, B = approximately 9.81
Log_{10} of an alkalinity of 175 mg/L as $CaCO_3$ = 2.24
Log_{10} of a calcium hardness of 120 mg/L as $CaCO_3$ = 2.08
Thus, $pH_s = A + B - \log(\text{Calcium}) - \log(\text{Alkalinity}) = 2.28 + 9.82 - 2.24 - 2.08 = 7.78$
and Langelier Index = $pH - pH_s = 7.9 - 7.78 = 0.12$

Result:
A positive Langelier Index (pH greater than pHs) indicates this water is over-saturated with $CaCO_3$, and will tend to deposit scale.

The Langelier Index calculation is available on a computerized spreadsheet called the Rothberg, Tamburini & Winsor (RTW) Model, available from the American Water Works Association (AWWA). This spreadsheet, which can run on Microsoft® Excel, calculates the Langelier Index and several other common indices from the water quality data as it is entered into the spaces provided on the form. The spreadsheet is faster and more accurate than estimating the factors from the tables. The RTW Model calculated a Langelier Index value of 0.18 using the above data.

CORROSION CONTROL

Once the extent and nature of corrosion has been determined from a corrosion monitoring program, the water utility can make a decision on whether to implement a corrosion control program. As discussed previously, if the action levels in the Lead and Copper Rule are exceeded, a specific procedure exists for implementing a corrosion treatment program. Otherwise, the utility may choose a corrosion control program to solve other problems, such as red water and leaks, even if it is in compliance with the lead and copper action levels.

Several mechanical and chemical corrosion control techniques are available, depending on the type, location, and extent of the corrosion problem. Any modification to a public water system, including corrosion treatment, must be submitted to the Alaska Department of Environmental Conservation (ADEC) for plan review and approval before implementation.

Mechanical Corrosion Control Techniques

Mechanical methods of corrosion control are those that alter the corrosion circuit, or otherwise decrease corrosion effects by physical changes in the water treatment and distribution system.

Dielectric Fittings

Corrosion can only occur if the galvanic cell electric circuit is complete. One simple mechanical method that can be used to open the circuit is to install a dielectric fitting with a section of ceramic or other nonconducting material. For example, when fitted between copper pipe and a steel water storage tank, the dielectric union opens the circuit and reduces the severity of corrosion at that location.

Tank and Pipe Coatings

Tank liners and coatings are commonly used as a barrier between the water (electrolyte) and the metal. Only coatings that have been approved for potable water applications can be used, and it is critical to completely coat the surface of the metal to be protected. Imperfections in the liner could result in accelerated pitting because of the full potential of the corrosion circuit being directed to a relatively small anode.

Coating and lining techniques also are used in pipes. External surfaces of buried metal pipelines and tanks may be coated with a protective sealer to isolate them from soil moisture, and cement lining in ductile iron pipe may be used as an interior coating.

Noncorrosive Materials

For applications such as desalination plants with high levels of pressure, temperature, and TDS, relatively noncorrosive materials such as stainless steel, plastic, or fiberglass can be used to prevent corrosion. Although the capital costs may be high, an extended, low-maintenance life span for that equipment can be easily justified.

Temperature

High temperatures accelerate chemical corrosion reactions. The potential for corrosion in circulating hot water systems has been reduced by lowering the operating temperature from 160 °F to 120 °F in apartment complexes and hotels in Alaska.

Velocity

High water velocities can greatly accelerate erosion corrosion. This problem has resulted in erosion of heat exchangers in circulating distribution systems in rural Alaska, ultimately causing propylene glycol leaks in the tap water. Conversely, if corrosion inhibitors are being added, a minimum water velocity is needed to maintain protective films.

Anodic Protection

Sacrificial anodes made of metals from the active end of the galvanic series, such as zinc and magnesium, can be attached to the metal to be protected. The sacrificial anode becomes the point of metal loss, protecting the steel or other metal of the tank or pipeline. These are commonly used to protect the exterior surfaces of buried pipelines and the interiors of water storage tanks, hot water heaters, and swimming pools. Sacrificial anodes often are used in conjunction with coatings.

Cathodic Protection

Engineered impressed current cathodic protection systems apply a direct current to the metal of a tank or other structure being protected at precisely the corrosion voltage potential. This effectively blocks the corrosion cell from operating and protects the metal. Although relatively expensive, when properly installed and calibrated this type of system adjusts its potential automatically as the corrosion potential changes.

Chemical Corrosion Control Techniques

The primary methods of chemical treatment include increasing the pH and alkalinity, adjustment of $CaCO_3$, and application of corrosion inhibitors. Increasing pH and alkalinity is the easiest of these techniques, and usually is done by adjusting the pH to a range in which copper or lead solubility is minimal. Application is typically to the final treated water before storage and distribution. This technique may be only partially effective in solving red water problems caused by oxidative corrosion inside tanks and pipes. The other two procedures can be effective against a variety of corrosion problems in addition to lead and copper.

Calcium Carbonate Deposition

Deposition of a protective $CaCO_3$ film is used successfully by the larger utilities in Anchorage and Fairbanks. AWWA lists the following water quality conditions for optimal $CaCO_3$ film formation[1]:

- The water should be over-saturated with $CaCO_3$. The over-saturation should be in the range of 4 to 10 mg/L as $CaCO_3$ – that is, the theoretical $CaCO_3$ precipitation potential should be 4 to 10 mg/L as $CaCO_3$.
- Calcium and alkalinity values each should be at least 40 mg/L as $CaCO_3$ – more than that if economically feasible. They should be present in approximately equal concentrations.

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[1] *Corrosion Control by Deposition of $CaCO_3$ Films: A Handbook of Practical Application and Instruction*, American Water Works Association, 1978.

- The ratio of alkalinity to ($Cl^- + SO_4^{2-}$) should be at least 5:1, in which all concentrations are expressed in milligrams per liter as $CaCO_3$.
- pH should be between 6.8 and 7.3. Excessive pH values should be avoided if possible, particularly within the pH range of 8.0 to 8.5.
- The water velocity should exceed 2 feet per second (0.6 meters per second).

If not all of these conditions can be met, AWWA recommends that the first three conditions be considered the most important and should be preserved at the expense of the other two. A variety of chemicals that can be used to adjust the $CaCO_3$ content of the water are available.

Selection of a chemical to achieve $CaCO_3$ saturation will depend on the water quality characteristics and the cost of the chemicals. The following table compares chemicals commonly used to adjust $CaCO_3$ saturation in potable water, and lists their relative strength in terms of alkalinity added per part per million (ppm) of chemical dosed.

CHARACTERISTICS OF CHEMICALS USED TO ADJUST PH IN WATER			
Chemical	Formula	Alkalinity added, per ppm	Feed equipment
Quicklime	CaO	1.79	Lime slaker
Hydrated lime	$Ca(OH)_2$	1.35	Slurry or dry feeder
Caustic soda (50%)	$NaOH$	1.25	Chemical feed pump
Soda ash	Na_2CO_3	0.94	Solution feed system
Sodium bicarbonate	$NaHCO_3$	0.59	Solution feed system

Golden Heart Utilities in Fairbanks uses quicklime to adjust the pH of their groundwater to 9.4 to remove excess hardness; the pH is reduced to between 8.3 and 8.4 after filtration removes the precipitates. The Anchorage Water and Wastewater Utility uses soda ash to adjust the pH of its surface water supplies before fluoridating the finished water. In both cases the finished water meets the recommended AWWA specifications and is protective of the metal piping in their respective distribution systems.

Safety considerations for each of these chemicals should be reviewed before use. Alkaline chemicals tend to release heat upon mixing with water and should be handled with appropriate care to prevent splattering, burns, and spills.

Several excellent references are available to help determine the correct dosage of these additives. One method is presented in *Corrosion Control by Deposition of* $CaCO_3$ *Films, A Handbook of Practical Application and Instruction*, by the AWWA (1978). A system of charts, called Caldwell-Lawrence Diagrams, are used to determine whether or not the $CaCO_3$ is at a condition of under- or over-saturation. These charts also can be used to estimate the amount of chemicals that should be added to bring the $CaCO_3$ to the desired condition of slight over-saturation.

As noted previously, the same information is also available in a computerized spreadsheet also available from AWWA. The RTW Model allows the operator to input the water chemistry into a form, which rapidly calculates all of the primary corrosion indices including the Langelier Index. Then, various concentration of additive chemicals can be entered into the form and the corrected indices are shown. The dosages and combination of chemicals can be adjusted until the optimum water quality is determined.

Calcium Carbonate Contactors

Another method for adding $CaCO_3$ to water is with a $CaCO_3$ contactor, a tank containing crushed limestone (marble chips) through which the water flows. The water dissolves the limestone at a rate proportional to the corrosivity of the water, approaching $CaCO_3$ saturation conditions (neutral Langelier Index). This type of feeder is particularly effective in water with very low alkalinity and calcium content.

Corrosion Inhibitors

Corrosion inhibitors for potable water systems are phosphate or silicate compounds that form protective films on the inside of tanks and pipes. The protective film consists of the inhibitor, some of the by-products of corrosion such as iron, and some of the components of the water chemistry such as calcium and carbonate. The film blocks further dissolution of metal into the water.

Chemical corrosion inhibitors include:

- sodium silicate ("water glass")
- polyphosphate (usually sodium hexametaphosphate)
- zinc polyphosphate (sodium zinc phosphate, a compound of zinc and phosphates)
- orthophosphate
- zinc orthophosphate
- blends of silicate and phosphate compounds
- "polymerized" phosphates and orthophosphate/polyphosphate blends

Many inhibitors are available in liquid form, although polyphosphates including zinc polyphosphates and some silicate/phosphate blends are prepared in powder form that must be made up into stock solutions. The solutions are fed with a chemical injection pump.

Selecting inhibitors can be a bewildering process of evaluating manufacturer's claims and comparing data from the scientific literature. Consulting other water system managers and operators on their experiences can be very helpful when choosing inhibitors. Some utilities have successfully tested inhibitors on a small portion of their distribution system before full-scale implementation. The following are some general guidelines that can help to narrow down the choices available when selecting inhibitors:

- For water with very low alkalinity or hardness such as surface water supplies recharged primarily with snowmelt and rain water, zinc orthophosphate has proven to be effective. Another option for low hardness water is sodium silicate, when the pH is less than 8.4. Silicates should not be used if silica scaling in boilers is of concern.
- For water with moderate to high levels of alkalinity and hardness such as Interior Alaskan groundwater, polyphosphates, zinc polyphosphates, and orthophosphate/polyphosphate blends have been effective.
- For very small systems with moderate to high hardness levels, automatic feeders containing crystallized polyphosphates or phosphate/silicate blends are available.
- For very high alkalinity and hardness, polyphosphates and orthophosphate/polyphosphate blends have been used to sequester calcium and magnesium, preventing the deposition of undesirable scale while affording corrosion protection. This technique has also been used to sequester iron and manganese while providing corrosion protection (see Chapter 11, "Iron and Manganese Treatment").

An effective monitoring program to track the performance of the inhibitor is essential to verifying that the correct dosage is being used. Corrosion coupons, electronic corrosion instrument tests and trace metals samples are useful for such monitoring along with daily tests for residual inhibitor concentration. This data can be compared to the tests taken during a baseline monitoring program to evaluate the effectiveness of the inhibitor.

THE LEAD AND COPPER RULE

As part of the Safe Drinking Water Act Amendments of 1986, the U.S. Congress required that the Environmental Protection Agency develop a regulation regarding monitoring and control of lead and copper in drinking water. To meet this mandate, the U.S. Environmental Protection Agency (EPA) developed the Lead and Copper Rule, which was adopted in 1991. The requirements of the Lead and Copper Rule have since been incorporated into the Alaska Department of Environmental Conservation (ADEC) Drinking Water Regulations that were discussed in Chapter 2 of this manual. The Lead and Copper Rule includes the following provisions:

- maximum contaminant level goals (MCLGs), or “nonenforceable health-based targets,” and action levels for lead and copper
- monitoring requirements for lead, copper, and other corrosion analysis constituents, analytical methods and laboratory certification requirements
- treatment techniques for lead and copper, required if action levels are exceeded during monitoring, including optimal corrosion control treatment, source water treatment, and lead service line replacement
- public notification and public education program requirements
- utility system record-keeping and reporting requirements
- variances and exceptions to the regulations and compliance schedules, depending on the size of the population served by the utility system

Maximum Contaminant Level Goals

The 1977 Interim National Primary Drinking Water Regulations established a maximum contaminant level for lead, and in 1979, the National Secondary Drinking Water Regulations established a secondary maximum contaminant level for copper. The 1991 Lead and Copper Rule replaced those with MCLGs, and with treatment technique requirements when “action levels” are exceeded during system monitoring. The 1991 MCLGs and action levels for lead and copper, and the original interim limits are shown in the table on the next page.

Metal	Interim limits	1991 MCLG	1991 Action level
Lead	0.05 mg/L	Zero	0.015 mg/L
Copper	1 mg/L	1.3 mg/L	1.3 mg/L

mg/L, milligrams per liter

Monitoring Requirements

The Lead and Copper Rule requires monitoring samples to be collected at consumers' taps rather than at the water treatment plant or in the distribution system. The sample locations are to be selected by the utility as "high-risk," including residences with lead-soldered copper installed after 1982 (three years before the ban on the use of lead solder in potable water systems), or residences with lead pipes or lead service lines.

The number of samples to be collected ranges from 5 to 50, depending on the size of the distribution system. The initial sampling frequency is every 6 months for the first year, once a year for the next two years, then once every three years after that if the action levels are met. The samples are to be collected as "first draw" samples from a cold water tap used for drinking that has been flushed, then shut off for at least 6 hours and no more than 12 hours. Homeowners may collect these samples if proper sample collection instructions have been provided by the utility.

Action levels are defined as the value measured in the 90th percentile of the samples from consumer taps arranged from lowest to highest value in a list. Refer to Chapter 2 and the ADEC regulations for a detailed description of the sampling requirements and 90th percentile calculation.

Corrosion Treatment

Water systems that fail the action levels for copper or lead are required to implement corrosion treatment. Upon failure to meet the action levels, additional water quality parameter samples must be collected from the source and distribution system. Using these data, the utility then recommends a treatment technique to ADEC for acceptance or modification. Smaller utilities can use a procedure called a "desk-top study" to compare the following treatment techniques using data from other utilities and research:

- pH and alkalinity adjustment (to reduce acidity)
- calcium adjustment (to form protective $CaCO_3$ films inside plumbing)
- phosphate or silicate corrosion inhibitor addition (to form protective films inside plumbing)

Water systems are required to implement corrosion treatment within 24 months after ADEC approval and to restart the collection of first draw samples within one year of completion of installation. If the water supply is determined to be the source of the lead or copper, then treatment of the source water is required. Also, if lead service lines are present a replacement program must be implemented to correct this situation. Neither the source water contamination or lead service line situation have yet been encountered in Alaska.

Public Education

If a utility fails to meet the lead action level, a public education program must be initiated. The scope of the public education program varies based on the size of the system, but can include informational posters placed in public locations, mail out notices in utility bills, announcements in local newspapers, distribution of pamphlets to schools, health care and day care facilities, and submittal of public service announcements to radio and television stations in the area. This must be repeated every 12 months as long as the lead action level is exceeded.

The public education programs should provide the consumer with information on how to minimize their exposure to lead in the water through such activities as:

- flushing the taps before use
- cooking with cold rather than hot tap water
- checking new plumbing for lead solder
- testing their water for lead

Reporting and Record-Keeping Requirements

Special report forms are to be filed by the utility for tap water monitoring programs, source water monitoring, corrosion control treatment, source water treatment, lead service line replacement activities and public education programs. Utilities are required to keep complete, original records of sampling data, test results, reports, surveys, letters, evaluations, schedules, state determinations, and any other information required to comply with the Lead and Copper Rule for at least 12 years.

REVIEW QUESTIONS

1. What are some of the detrimental effects of corrosion in water systems:
   a. ______________________________
   b. ______________________________
   c. ______________________________
   d. ______________________________
   e. ______________________________

2. What are three main components of a galvanic cell?
   a. ______________________________
   b. ______________________________
   c. ______________________________

3. In a galvanic series of metals, which of the following would be the anode?
   a. Lead or copper ________________
   b. Steel or copper ________________
   c. Steel or zinc ________________

4. The type of materials and coatings used can affect corrosion. List four other physical factors that increase the rate of corrosion when they increase:
   a. ________________ b. ________________
   c. ________________ d. ________________

5. Of the following chemical factors that influence corrosion, indicate whether the corrosion rate tends to increase or decrease as the indicated factor increases:
   a. Alkalinity: ________________
   b. pH: ________________
   c. Dissolved Oxygen: ________________
   d. Dissolved Solids: ________________
   e. Hardness: ________________
   f. Chloride & Sulfate: ________________
   g. Phosphate: ________________

6. What general types of bacteria tend to increase corrosion in water systems?
   a. ________________________
   b. ________________________

7. A Langelier Index of -2.5 indicates $CaCO_3$ will ________________________, and a Langelier Index of 1.5 indicates $CaCO_3$ will ________________________.

8. Calculate the Langelier Index of a water sample from the following data:
   Temperature = 5 °C
   TDS = 200 mg/L
   Alkalinity = 150 mg/L as $CaCO_3$
   Calcium = 95 mg/L as $CaCO_3$
   pH = 7.65

9. Dielectric fittings have what electrical characteristic?
   ____

10. High water velocity produces what type of corrosion?
    __________________________ corrosion.

11. What metals are commonly used in anodic protection?
    __________________________ and __________________________

12. List five water quality conditions that are considered ideal for optimal $CaCO_3$ deposition in treated water:
    a. ____
    b. ____
    c. ____
    d. ____
    e. ____

13. Which of the following will add the least amount of alkalinity to water per ppm of dosage?
    a. caustic soda
    b. quicklime
    c. soda ash

14. What mineral is used in a $CaCO_3$ contactor? __________________________

15. Corrosion inhibitors that can be used in potable water systems are based on the chemistry of two types of compounds. They are:
    a. ____
    b. ____

16. Under the Lead and Copper Rule, __________________________________ samples must be collected from consumer taps and analyzed in a certified laboratory for lead and copper. The action levels for lead and copper are determined from the 90th percentile sample in set of test results. The action level for lead is ____________ mg/L and for copper it is ____________ mg/L. From the following list of test results, circle the 90th percentile value for lead and copper (all values are in mg/L):

    Lead: <0.005, <0.005, <0.005, <0.005, <0.005, <0.005, <0.005, 0.005, 0.005, 0.005, 0.005, 0.005, 0.007, 0.008, 0.009, 0.010, 0.010, 0.012, 0.015, 0.019

    Copper: <0.04, <0.04, 0.06, 0.10, 0.22, 0.28, 0.35, 0.37, 0.39, 0.55, 0.59, 0.67, 0.79, 0.90, 1.05, 1.25, 1.35, 1.48, 1.56, 1.90

17. In question 16, were either of the action levels exceeded, and if so, which?
    ____

18. What are three types of corrosion treatment that must be evaluated in a "desk-top study" under the Lead and Copper Rule?
    a. ____
    b. ____
    c. ____

Chapter 17

Management and Safety

Chapter 17 – Management and Safety

INTRODUCTION

The management of any utility, regardless of its size, is a complicated and challenging task. Utility managers must address a variety of demands, both internal to the facility and external community issues. Internal issues include financial management, operations and maintenance, emergency preparedness, safety, and regulatory compliance. External issues include concerns of the community about its drinking water and the necessity to meet those needs at the lowest possible cost. The utility must stay in compliance with water quality monitoring rules and other regulations that constantly change and often become more stringent. Moreover, a manager must keep abreast of advances in water treatment technology that can improve the quality of the water, improve plant efficiency, and reduce costs.

As operators advance in their certification levels, more supervisory responsibilities should be anticipated. This is particularly true of smaller utilities in which the Level 2 or 3 operator is often part of the management. Important resources for utility managers are (1) the course approved by the Alaska Department of Environmental Conservation (ADEC), "*Introduction to Utility Management*," (2) the California State University Field Study Training Program, "*Utility Management*," and (3) the text, "*Supervision: Concepts and Practices of Management*," by Raymond L. Hilgert and Theo Haimann. Funding for development of new village water systems may depend on whether personnel have completed adequate training to manage such a utility. Additional assistance is available from agencies such as the Rural Utility Business Advisor program, the Indian Health Services, and the Alaska Department of Community and Economic Development.

OPERATIONS MANAGEMENT

In small utility systems the manager often has multiple responsibilities. The manager may supervise utility operations, serve as lead operator, and delegate operations and maintenance

(O&M) tasks. The manager is responsible for creating and implementing an effective operations management program, which is necessary to manage both routine and non-routine O&M tasks.

A truly effective operations management program requires input from operators who know the condition of the system. O&M records need to be maintained and analyzed to find weak spots in the system so that preventive maintenance can be done before expensive repairs are necessary. Thus, an effective O&M program requires a significant up-front investment and continuing communications between the manager and the operators. The responsibility for the implementation and effectiveness of the O&M plan resides with both the manager and the operators.

Goals of an Operations Management Program

The goals of an effective operations management program are the following:

- preserve value of utility
- lower costs through preventive maintenance
- provide quality and cost effective service to customers
- maintain system capacity

An important component of the operations management effort is a system for managing equipment maintenance.

Maintenance Management Program

An effective maintenance management program has the following elements:

- a scheduled preventive maintenance plan
- a properly documented work order system
- an emergency plan for the utility
- a major component renewal and replacement schedule
- a water quality sampling, testing, reporting, and record-keeping plan
- an inventory system for consumables and spare parts

Each of these elements requires some forethought, organization, and communication to design and implement an effective system. The maintenance management plan will provide a framework for the manager to organize staffing responsibilities, determine appropriate staffing levels, and will help develop an annual budget for the utility.

Maintenance Categories

The three general maintenance categories are preventive, corrective, and emergency. The type of maintenance being done is critical from a management perspective.

Preventive Maintenance

Preventive maintenance is a scheduled, systematic approach to maintenance in which maintenance is done before a component or the entire system fails. A preventive maintenance schedule should be designed with input from maintenance records and discussions with operators. The scheduling of preventive maintenance can be either periodic, such as monthly, or as needed, such as inspection of utilidors in winter to prevent freezing. A preventive maintenance program should contain the following elements:

- planning to make changes in the program as the utility ages
- scheduling of preventive maintenance tasks
- record keeping
- an inventory of spare parts
- budgeting and tracking costs
- emergency repair procedures
- a training program

Examples of preventive maintenance include changing oil, lubricating bearings, replacing seals, checking system temperatures and flushing lines.

Corrective Maintenance

Corrective maintenance can be considered an extension of preventive maintenance, but involves replacing worn parts or repairing equipment before it fails. Rebuilding chemical feed pumps annually, replacing worn drive belts or severely corroded fittings are examples of corrective maintenance. These activities will help limit service disruptions that would otherwise require emergency maintenance.

Emergency Maintenance

Emergency maintenance is done to correct a problem or repair a system failure, such as a water main break due to freezing or corrosion. Often such failures can be prevented through a regularly scheduled maintenance program, such as circulation of the water to help prevent freezing, corrosion control, or cleaning the lines with pigs and flushing. Minimizing emergency maintenance reduces costs and disruptions to schedules, and improves service. Utilities that rely on emergency maintenance tend to have difficulties running the utility efficiently for the following reasons:

- scheduling difficulties
- difficulty in budgeting ahead of time
- inefficient use of time and money
- poor service to the customer

Emergency maintenance that needs to be done regularly in a particular area of the system is a signal that a problem should be addressed and covered in the O&M program. Thus, the recurring situation can be rectified before the system fails.

Benefits of a Good Maintenance Program

A well planned and properly implemented maintenance program has numerous benefits. Personnel costs and staffing levels can be more accurately predicted in the annual operating budget. Requirements for equipment, parts, and materials can also be identified and quantified in advance. These steps help to ensure adequate funding will be available to keep the utility running smoothly.

If preventive maintenance costs become excessive, capital improvement projects or replacement of equipment can be budgeted under an equipment replacement fund or capital improvement fund. In summary, preventive maintenance is an important management tool for preserving the useful life and value of the utility's assets.

COMMUNICATION IN MANAGEMENT

Managers must be effective communicators and must create an environment in which positive, constructive communication is the rule. It is also the responsibility of the operators to communicate with their supervisors on critical issues such as safety, budget, and improvements in operational efficiency and maintenance. This type of communication provides managers with the most useful information because it is the operator who works directly with the equipment and understands it best.

Oral and Written Communication

Both oral and written communications require that ideas be communicated in an organized, concise, clear manner and at a level appropriate for the audience. Good communication requires preparation.

Formal communication may take the form of a presentation to an audience, in a meeting format, or through written documentation. A well prepared presentation before an audience or in a meeting conveys the impression that the presenter has thought out the situation carefully. As a result, communication will be more effective. Written communications provide a means to carefully develop your thoughts and present them in a precise manner. Written communications also are considered legal documentation, so the supervisor must be accurate and careful about what is put in writing. This is particularly true when corresponding with regulatory agencies, for example.

Formal communications, whether presented orally or in written form should be direct and as short as possible. Generally, the best presentation format is to tell the audience what you are going to say, say it, then close by summarizing what you said. However, the longer the letter or presentation, the more likely you will lose the audience's attention. Graphics, slides, pictures, and other audiovisual materials greatly enhance both written and oral presentations. Specialized courses or self-help manuals in audience presentations and writing also can be helpful in developing these critical skills.

Communicating with the Public

Effective public relations (PR) are critical to the successful operation of a utility. PR is not just the manager's job, but is also an important part of every employee's work. One of the best and least expensive sources of public relations is a dedicated, service-minded staff. Utility operators or administrative personnel may be the only contact the public has with the utility. Ensuring that employees are well trained and knowledgeable about utility operations can prevent problems from developing into complaints, and can instill a spirit of teamwork. This attitude is infectious and when seen by the public can make a utility highly efficient and responsive.

It is the manager's responsibility to develop the objectives of the utility's PR program, with associated achievable and measurable goals, action plans, and time lines. Investing in a good

PR strategy is valuable since it can improve customers' perceptions of the utility and help to improve employee morale, as their job will be seen as important to the community. The manager needs to understand that different audiences will require different levels of communicating the same information. For example, improving customer relations may involve a written survey to be distributed to customers, holding town meetings, meeting with community leaders, visiting school classrooms or purchasing advertising in the local newspaper or radio. Each one of these presentations targets a different audience and communication medium requiring adjustment of the depth, content and presentation methodology used.

Some regulatory requirements include public communication. The annual Consumer Confidence Reports that must be compiled and mailed to all utility customers, are relatively new requirements of the Safe Drinking Water Act. Public notification of abnormal sampling results is also a public information regulatory requirement.

FINANCIAL MANAGEMENT

Good financial management provides for capital construction and replacement of equipment while maintaining routine operations and maintenance expenses at reasonable levels. Ultimately, financial management is reflected in the customers' utility service rates.

Budgeting

A budget is a detailed accounting document that predicts the revenues and expenses for the coming year. The utility manager is responsible for obtaining information from the customers, operators, prior year's budget, the long range plan and the capital improvement and replacement plan to prepare the budget for the following year. The manager should keep in mind the goals of operating the utility efficiently, preserving the value of the present equipment and evaluating the benefits of replacing equipment. These requirements must be reconciled with the projected revenue for the following year. Once the budget process is finalized, a policy-making board usually approves the budget and provides the authorization for the utility to spend money.

Budgets may be organized by departments or by operational functions within the utility. It is up to the manager to decide how the budget will be organized, but it usually is done within the framework of financial accounting standards set by the utility owner and the utility commission, which must approve customer service rates. Budgets may be updated throughout the year as situations change. The frequency and mechanism for this should be agreed to in advance by the manager and the owner or utility commission, particularly if an approval is required for this.

Funding the Future

Good budgeting practice requires that separate funds be maintained for capital improvement projects and for the equipment replacement needs of the utility. Two types of funds are designated for these purposes.

Equipment Repair and Replacement Fund

The manager should organize the budget so that a portion of the utility's revenue is allocated to an equipment repair and replacement fund. This fund is designed to pay for the replacement of major equipment such as pumps, motors and vehicles, which usually last for many years. To develop this fund, the manager should list the equipment to be included in a table and estimate the total usable life, the year of acquisition and the year of expected replacement of each item. The total needed each year to achieve the predicted replacement will define the amount needed to be allocated from the budget to this special category.

These funds should be preserved in a separate account and not be used for day to day operations. If properly managed in a savings account, the fund also earn some interest which can help to offset inflation.

Capital Improvements Fund

The capital improvements fund is similar to the repair/replacement fund in that it should be managed as a separate account. This budget, however, is to be used for expansion of the utility and for major upgrades such as a new water treatment plant. Note that it is not always necessary for the utility to have the full cost of the proposed upgrade in the fund in order to capitalize projects. Depending on the proposed source of funding, it is only necessary to have a sufficient amount to match a construction grant, or to be able to amortize the debt for the project if the funds are borrowed.

Capital project planning begins with the long-range plan, which should identify when and where commercial and residential growth is expected. In addition to growth, upgrades in technology such as a new treatment process that is needed to meet future changes in the drinking water standards should be included in capital equipment budget planning. The capital equipment plan should also include "weak spots" in the system where upgrades may have to be made, such as the addition of a new distribution trunk line to maintain fire flow capacity.

Capital improvement projects often require long term financing. This is generally done through bonding or grant writing. Bonds, essentially a form of loans, are sold through financial institutions in which the money is paid up front with the agreement that it will be paid back, with interest by utility fees over many years. Qualifying for bonding and for low interest rates depends on the financial viability of the utility.

Financial Assistance

Small utilities can often obtain funding for capital improvements via loans and grants through Federal and State agencies. The ADEC administers several of these, such as the State Revolving Loan Fund (SRLF), which is funded by the Federal government under annual appropriations for the Safe Drinking Water Act. The SRLF program provides low interest loans for either water or wastewater projects. Special provisions for rural sanitation projects in Alaska were written into the 1996 Safe Drinking Water Act Amendments. Funded equally by the State and Federal governments, these funds have made tens of millions of dollars available for utility upgrades in rural Alaska. The ADEC or the Department of Community and Economic Development can be contacted for information on availability of funding through these sources. Other agencies that provide grant or loan programs for utilities include:

- Federal Housing and Urban Development
- Economic Development Administration
- Alaska Native Tribal Health Consortium
- Alaska Native Regional Health Corporations
- Rural Utilities Service

A new source of Federal funding for utilities is being established in Alaska through the creation of the Denali Commission.

SAFETY PROGRAM

Every utility should have a documented safety program that addresses safety of the utility's personnel and of the public when they are on the utility property. This description of managing a safety program is only an overview. Safety procedures that apply to the particular treatment processes are included in each of the previous chapters. Other resources for developing a safety program can be found in the following references:

- *Water Treatment Plant Operation*, Volume II, Chapter 20, "Safety," Ken Kerri, Project Director, published by California State University, Sacramento Foundation, 1998
- *Utility Management*, prepared by Lorene Lindsay, published by California State University, Sacramento, Office of Water Programs, 1998
- *Introduction to Utility Management*, a training course by ACR Publications, Inc., 1997

Responsibilities and Policies

The manager of the utility is responsible for the development and administration of the safety program. The program should address new employee training as well as continuing training and safety meetings for current staff. The first component of an effective safety program is the Safety Policy Statement. This statement outlines the goals and objectives of the safety program, identifies who is responsible for implementing the program, affirms the intent to enforce the rules and describes disciplinary actions that may be taken within the safety program. A copy of the safety policy statement should be provided to every employee.

Each level of the utility staff has a role in the safety program. The manager is responsible for writing the safety policy, providing a safe workplace, setting safety goals that are achievable, providing training and delegating the authority to ensure that the program is implemented correctly. The supervisor is responsible for ensuring that the training program is implemented, that the staff uses proper safety practices and that all equipment and tools are maintained to the safety standards. The supervisor also has the responsibility to investigate accidents, to determine their cause and to implement corrective actions to prevent recurrence.

Finally, the operators also have an important level of responsibility. They should follow the safety procedures fully, report hazards or accidents immediately, including minor accidents or near misses, and use personal protective equipment when specified. An important role of the operators is to monitor the work of their peers and to advise them of potentially unsafe conditions.

Hazard Communication

As technology continues to develop at an ever increasing rate, the number of possible hazardous and toxic chemicals that personnel may be exposed to increases, and knowledge of their impact on human health becomes more defined. Federal and State laws have been implemented that prescribe methods for the handling and use of hazardous materials. These laws are commonly known as worker Right-To-Know laws (RTK) and are incorporated in the Occupational Safety and Health Act of 1970. The goal of RTK laws are to ensure that workers can safely conduct their tasks without risk of acute or chronic health problems. Acute health problems include injuries and immediate health concerns regarding exposure to a chemical. Chronic health problems are those which are often not seen for many years or even decades. The primary components of a hazardous communication program are:

- identification of hazardous materials
- provide information about hazardous chemicals (with Material Safety Data Sheets)
- appropriate labeling of hazardous materials
- safety training

The manager is responsible for ensuring that an effective hazard communication program is in place and is being practiced in their utility.

Confined Space Entry

Utility operators are frequently exposed to the risk of confined spaces, which are defined as follows:

- the space is large enough for a person to enter
- it has limited entry and exit
- it is not intended for continuous occupancy

The next level of a confined space is called a "permit-required confined space." When entering a permit-required confined space the workers must abide by OSHA regulations which are designed to ensure their safety. Permit-required confined spaces exist when any of the following criteria is met:

- the space contains or has the potential to contain a hazardous atmosphere
- it has the potential for engulfment
- it is designed such that the worker could be trapped or stuck
- it contains any other recognized serious safety or health hazard

The OSHA regulations outline what is involved in setting up an approved confined space entry program. It is the manager's responsibility to ensure that an effective program is in place that complies with the regulations, and that the rules of the program are properly implemented and followed by all workers.

Reporting

Reporting accidents and injuries is a critical part of an effective safety program. It is the responsibility of the operator to report all accidents to the supervisor. The supervisor must see that an accident or injury report is properly filled out and given to the utility management. The management must then review the incident and take appropriate action to prevent the accident from occurring again.

The main reason for reporting accidents is to prevent their recurrence in the future. Immediate and accurate reporting helps to ensure that the situation that caused the accident can be corrected, and a safe work environment established.

RECORD KEEPING

Record keeping is a specific requirement of many regulatory programs. In addition, good record keeping can help a utility improve its performance. Many operators rely on intuition and memory to evaluate problems. Good records provide a documented trail of information that can eliminate this subjective uncertainty, and help prevent problems from recurring. This requires diligence on the part of the operators to keep good records when inspecting or repairing equipment, collecting samples or even noting any unusual conditions in the system.

Types of Records

Equipment and Maintenance

For all large pieces of equipment, it is important to keep information such as date of start-up, make and model number, manufacturer contact information and address and phone number for obtaining spare parts or replaceable items. A card file is a good way to organize this information. Alternatively, a computer log can be used to manage these records.

All maintenance performed on each piece of equipment should be documented in sufficient detail that the work done is easily understood. The date, time and name of the operator or mechanic who performed the repairs should be included in the file. This includes both preventive maintenance and corrective repairs. Good records help identify persistent problems, allowing corrective actions to be implemented.

Log Sheets

Log sheets can be used for many different purposes such as water quality testing, operational inspections, or preventive maintenance. Log sheets should be formatted so that the important information is easy to record and to use. Well designed and properly filled out log sheets are valuable tools in plant operations. Furthermore, operations logs are usually required by the regulatory agencies, and are as such, considered legal documentation that the treatment works is being properly operated.

It should be noted that log entries must be accurate and factual. Current Federal and State regulations for water systems specifically address the issue of fraudulent data entry, which is considered to be a criminal act. Operators who have falsified their data or operations logs have been subjected to dismissal, legal action, revocation of operations licenses, or even fines and jail terms. Managers who fail to ensure that record keeping is accurate also expose themselves to the liability of falsification of data.

Parts and Materials Inventory and Ordering

To ensure that sufficient parts and materials are available to conduct preventive maintenance and emergency repairs, sufficient inventory and a mechanism to track and order the equipment must exist. The manager must ensure an adequate supply of routine parts and materials and that needed items are ordered well ahead of time. Some routine items should be stocked in large quantities. Other items may be rarely used but essential in the event of an emergency. Careful inventory management is a key element in utility management, since it has a significant budget impact. Over-stocking of inventory ties up the financial resources of the utility, whereas under-stocking can result in equipment down time, and excessive freight forwarding costs to obtain spare parts quickly.

The equipment card or computer files discussed above are useful tools in the management of spare parts. Exploded diagrams of pumps, motors, and other heavy equipment with number parts lists, lists of commonly used replacement items, and vendor contact information should all be maintained in these files.

Personnel

Personnel records are an important part of the documentation of any business or agency. These records are also required by law, and should contain a complete copy of all personnel actions including hiring information, performance reviews, salary adjustments, disciplinary actions, safety records, and training records. These records frequently become the basis for resolving complaints or for completing personnel evaluations as required by the employee policies.

REGULATORY COMPLIANCE AND NEW TECHNOLOGIES

The regulatory requirements of water treatment operations are discussed in Chapter 2 of this manual. Further information on regulations pertaining to particular unit processes is included in the chapters pertaining to each of the treatment processes. Regular water quality sampling and reporting are keys to regulatory compliance of the facility. In addition, annual Consumer Confidence Reports are required by law to be provided to each water utility customer.

The utility manager is responsible for being aware of changes in regulations and advances in water treatment technologies. Staying informed may require involvement in professional organizations, subscriptions to trade publications, and following legislative actions relating to drinking water regulations. Attending professional conferences whenever possible is an excellent way to stay up-to-speed on new developments and to exchange information with other water professionals. In addition to mailing lists and subscriptions, a wealth of information is available on the internet, at the ADEC and EPA websites. At the higher operational levels it becomes the individual's responsibility to be aware of new developments in the water industry.

REVIEW QUESTIONS

1. List four objectives of an effective operations management program:
   a. ____
   b. ____
   c. ____
   d. ____

2. List six elements in an effective maintenance management program:
   a. ____
   b. ____
   c. ____
   d. ____
   e. ____
   f. ____

3. List three categories of maintenance:
   a. ____
   b. ____
   c. ____

4. For each of the following activities, indicate what category of maintenance is involved:
   a. thawing a frozen water line: __________________
   b. starting up water circulation pumps for freeze protection: _______________
   c. lubricating the circulation pumps: __________________
   d. replacing a defective temperature probe on the circulation line:___________

5. Public relations is the responsibility of
   a. manager
   b. supervisor
   c. operator
   d. all of the above

6. An annual budget for a water treatment plant shows the following:

Chemicals and consumable parts	$175,000
Utililties	30,000
Labor	245,000
Sampling and testing	15,000
Travel, training, and publications	10,000
Vehicles: fuel and maintenance	12,500
Miscellaneous	15,000
Total	$502,000

A) What percent of the budget is attributed to labor? ________________

B) How might the chemical and spare parts expenses be reduced?

____

____

____

____

C) If 35 percent of the annual budget has been spent by the end of the fourth month of the fiscal year, how much money is left? $________________

7. Two "capital" funds for major equipment and system upgrades and expansions are:
   a. ____
   b. ____

8. Who is responsible for the development and administration of a utility safety program? ____

APPENDIX A
GLOSSARY

Appendix A – Glossary

2-log reduction – (or 2-log removal) the reduction by 99% of targeted microorganisms or other contaminant parameter

3-log reduction – (or 3-log removal) the reduction by 99.9% of targeted microorganisms or other contaminant parameter

4-log reduction – (or 4-log removal) the reduction by 99.99% of targeted microorganisms or other contaminant parameter

Activated carbon – particles of carbon that have been specially processed to create numerous pore spaces within the particles and on particle surfaces, used as an adsorbent in water treatment

ADEC – Alaska Department of Environmental Conservation

Adsorbent – a substance to which particles will adhere, used as the medium in the adsorption process

Adsorption – a water treatment process mostly used to remove organic substances from water. Adsorption involves the adhesion of contaminants to the surface of an adsorptive medium such as activated carbon.

Aeration – the process by which air is mixed with water to remove dissolved gases and some volatile organic compounds, and to oxidize reduced metals

Aerator – a water treatment device designed to bring air and water into contact to remove or modify substances in the water. Aerators come in a variety of designs and capacities, from basins containing air diffusers to cascade-type units in which water mixes with air by falling from one level through successively lower levels.

Air binding – the buildup of trapped bubbles of air or other gases in filters that may cause shortened filter runs and destratification of media

Algae – single-celled photosynthetic plants that live in water, existing as individual cells or as colonies that can form thick floating mats on the water surface

Alkalinity – the measure of the buffering capacity of a water to resist changes in pH. Alkalinity in water is most commonly contributed by carbonate or hydroxide chemistry.

Alum – aluminum sulfate, a commonly used chemical coagulant; it has actually been used for centuries to clarify water by helping to settle suspended particles

Anaerobic – having no air or free oxygen

Anionic – having a negative ionic charge

Anode – the positive electrode in an electrolytic cell

Anthracite coal – a type of coal that is coarsely graded for use as a filter medium

Aquatic plants – plants that live in the water

Aquifer – a subsurface source of groundwater that is bounded at its base by bedrock or other strata, and may be bounded laterally and at its upper surface

Bag filter – a water filtration device consisting of a fabric bag mounted inside a housing. Bag filters are available in different porosities, ranging from < 1 micron to > 100 microns.

Bed expansion – the expansion of filter media during backwashing that should result in an increase in the depth of filter media of 15 to 20 percent to ensure the filter media are being adequately cleaned

Body feed – the continuous addition of diatomaceous earth after the preliminary precoat formation during the diatomaceous earth filtration process

Boundary layer – a layer of high dissolved-ion concentration at the surface of a membrane

Breakpoint – the point in the reactions involved in chlorination after which the demand has been satisfied and the increase in chlorine residual is equal to the amount of chlorine added

Carbon dioxide – (CO_2) an atmospheric gas that readily dissolves in water, especially at low temperatures; CO_2 forms carbonic acid in equilibrium, reducing the pH of water

Cartridge filter – a type of filter used in smaller treatment plants, as membrane system prefilters, and in home water treatment installations, consisting of a housing for a cylindrical filter cartridge containing cellulose, charcoal, or another filter medium. Cartridge filters are available in a wide range of pore sizes.

Catchment – a small water collection and diversion structure designed to gather surface runoff

Cathode – the negative electrode in an electrolytic cell

CCR – Consumer Confidence Report

Charge destabilization – reduction of the repellent forces (zeta potential) between molecules such as negatively charged colloids, usually during coagulation by the addition of a highly charged cationic coagulant

Chloramination – disinfection with chloramines, which are not as strong as free chlorine residual, but which have a very stable residual and do not readily form disinfection by-products

Chlorination – disinfection with gas, liquid, or powdered chlorine

Cholera – a potentially fatal disease caused by the bacterium *Vibrio cholerae*

Clarification – a water treatment process involving settling or flotation of particles to remove them from the liquid

Clarifier – the tank in which clarification takes place; clarifiers can be circular or rectangular and are available in numerous designs

Clearwell – a storage unit for finished water that is being held until needed in the distribution system

Coagulant – a chemical additive that is used to initiate the coagulation process by charge destabilization of colloidal particles, causing the colloids to clump together into larger particle aggregates. Coagulants are usually cationic (positively charged).

Coagulant aid – a chemical or substance that is added during coagulation to improve the coagulation process

Coagulation – a chemical reaction between a coagulant (usually cationic) and colloidal (usually anionic) particles to form small settleable particles called microfloc

Coefficient of uniformity – (d_{60}/d_{10}) the ratio of the filter-media grain diameters that make up 60 percent and10 percent by weight of the media

Colloid – a particle in water less than 1 micron in diameter that settles very slowly. Colloids include silt, clay, bacteria, and color particles.

Color – the hue or tint of water usually caused by organic molecules such as those produced by decaying vegetation

Combined chlorine residual – the total of all chloramines and chloroorganics formed from reactions between hypochlorous acid and ammonia and organic chemicals in the water during the chlorination process

Consumer Confidence Reports – reports that must be prepared each year by water utilities for their customers. The reports list any contaminants that exceeded standards during the previous year, any other violations that may have occurred, and the measures taken to correct the violations.

Contact time – the detention time of a disinfectant in water; the destruction or inactivation of organisms is directly proportional to the product of disinfectant concentration and contact time

Conventional filtration – water treatment that includes coagulation, flocculation, clarification, and filtration

Corrosion – the damage and deterioration of water system piping and other appurtenances caused by electrochemical reactions in water

Corrosion control – specialized treatment processes to mitigate damage to water system components caused by corrosion; treatment may include pH and alkalinity adjustment, the addition of corrosion inhibitors, or precipitation of calcium carbonate films on the inside of pipes

Corrosion inhibitors – chemicals added for corrosion control treatment through the formation of protective films inside pipes and appurtenances

Corrosive – the property of being able to dissolve metal or scale inside water systems

Corrosivity – the degree to which something is corrosive

Crenoforms – iron and manganese bacteria

Crenothrix – a common iron bacteria in Alaskan groundwater supplies, it forms an orange slime layer on the interior surfaces of tanks and piping that can increase corrosion of metals by releasing acids

Cross-connection – a connection between a potable and a nonpotable water supply

***Cryptosporidium parvum* –** the flagellated protozoan that causes cryptosporidiosis, a debilitating gastrointestinal disease that can sometimes prove fatal in persons with weakened immune systems

CT – the product of residual disinfectant concentration and disinfectant contact time, a parameter used in the chlorine-disinfection process; the destruction or inactivation of organisms is directly proportional to the product of disinfectant concentration and contact time, and minimum CT values are specified in the Surface Water Treatment Rule

D/DBP – disinfectants and disinfection by-products

DBP – disinfection by-product

Degasification – the removal of dissolved gases from water

Demand – the amount of chlorine required to react with microorganisms, reduced metals, organic compounds, ammonia, and other constituents in the water before a free chlorine residual will form

Density current – a current of water that has a different density, either because of temperature or solids content, than the surrounding water in a basin, tank, or other body of water. Upon entering warmer or less dense water a density current will sink to flow along the bottom of the container, possibly causing stratification or short-circuiting of flow.

Depolarization – the reaction of dissolved oxygen with hydrogen ions to form water during the corrosion process

Detention time – the average length of time a unit of water spends in a tank or chamber, determined mathematically by the volume of the tank divided by the flow of water through the tank

Diatomaceous earth – a filter medium made up of the fossil remains of siliceous aquatic plants called diatoms

Diatoms – single-celled microscopic aquatic plants, with an internal structure dominantly made up of silica

Diffuser – a device through which compressed air is transferred into water during aeration; good diffuser designs produce small bubbles without clogging

Direct filtration – filtration after coagulation and flocculation but without sedimentation or clarification

Disinfectants and Disinfection By-Products Rule – a new rule included in the 1996 Amendments to the Safe Drinking Water Act that establishes maximum contaminant limits for chlorine disinfectants and expands the list of regulated chemical compounds that may form from the reaction of disinfectants and naturally occurring organic matter in water

Disinfection – the removal or inactivation of disease-causing organisms from drinking water

Disinfection by-product – a compound formed from the reaction of disinfectants with organic matter or other substances in water

Dissolved gases – gases such as oxygen or carbon dioxide that are dissolved in water

Dissolved metals – metal ions in their soluble valence state that are in solution in water, for example: ferrous iron (Fe^{2+})

Dissolved oxygen – (DO) oxygen dissolved in water; the oxygen concentration in water increases as temperature decreases

Divalent – an ionic charge configuration consisting of two unbalanced charges, either positive or negative, on the outer surface of an atom

Divalent metal cations – atoms of dissolved metals that have two unbalanced positive ionic charges on their surfaces

DNA – deoxyribonucleic acid, the compound that contains the genetic code of living organisms

Drawdown cylinder – valved, graduated cylinder attached to the suction side of a chemical feed pump, used to calibrate the output of the pump

EBCT – empty bed contact time

Effective size – (d_{10}) the diameter of the particles in a sample of filter media for which 10 percent of the total grains are smaller and 90 percent larger, by weight

Electrolyte – a substance that conducts electricity when in a solution

Empty bed contact time – the length of time water is in contact with granular activated carbon as the water passes through a filter bed, determined by the volume of the filter bed divided by the flow rate through the filter

Enmeshment – coagulation mechanism in which colloidal particles are enveloped by "sweep floc" formed from coagulant-hydroxide complexes

EPA – United States Environmental Protection Agency

Epilimnion – the upper layer of water in a thermally stratified reservoir or natural body of water

Equilibrium – the state at which the products and reactants in a chemical reaction have reached the concentrations at which the reaction is discontinued; in addition to the concentrations of chemicals involved, equilibrium also may be affected by temperature, pressure, pH, alkalinity, and other factors

***Escherichia coli* (*E. coli*) –** the original bacterium of the coliform group isolated in 1884 by Theodore Escherich. *E. coli* is associated with fecal contamination from warm-blooded mammals, and is thus a primary indicator of sewage pollution.

Exothermic – a chemical reaction that gives off heat

Filter cracking – the formation of cracks in filter media, caused by over-compaction and drying out of the filter media due to infrequent backwashing

Filter ripening – the process of accumulation of solids in a filter after backwashing until a sufficient number of voids in the media are filled to reduce the effluent turbidity to acceptable levels

Filtering to waste – the process of channeling filter effluent to waste after backwashing until the turbidity in the effluent is reduced to an acceptable level

Filtration – the process of passing water through granular, porous media to remove suspended particles of floc and turbidity

Filtration avoidance – a waiver of regulatory filtration requirements under the Surface Water Treatment Rule that is allowed some water systems with extremely high-quality source water

First draw – a sample consisting of the first 1 liter of cold water from a tap that has been flushed and then isolated for six hours before sample collection, used in Lead and Copper Rule sampling

Fit tested – a term applied to the practice of ensuring SCBA respirators properly fit an individual's face

Flash mix – rapid mixing of chemicals into water using vigorous agitation (or mixing)

Floc – aggregates of suspended particulate matter in water formed in the coagulation and flocculation processes

Flocculant – chemical coagulant aids that help to form larger and heavier pieces of floc

Flocculation – the physical process that follows coagulation to increase the size of floc so it will be more easily settled or filtered from the water

Flocculation basin – see **flocculator**

Flocculator – the basin or tank in which flocculation takes place, also known as a flocculation basin or tank

Fluidization – the hydraulic lifting and agitation of the media in a filter during backwashing

Fluoridation – the addition of fluoride to drinking water to reduce the incidence of cavities in children's teeth

Flux – the flow of water through a particular surface area, expressed in gallons per minute per square foot, used as a membrane treatment specification

Free chlorine residual – the residual chlorine formed after all chlorine demand in a system has been satisfied; this chlorine consists of only hypochlorous acid and hypochlorite ion and is not combined with ammonia or other substances

GAC – granular activated carbon

Galvanic cell – an electrochemical system much like a battery with an anode, cathode, and electrolyte, which can be used to describe the corrosion of metals

Galvanic series – a scale developed to describe the tendency of a given metal to be anodic or cathodic (base or noble metal, respectively)

Garnet – a type of base metal (calcium, magnesium, iron, and manganese) silicate that can be ground into sand for use as a filter medium; garnet has a higher hardness and specific gravity than regular filter sand

***Giardia lamblia* –** a flagellated protozoan that causes giardiasis, a debilitating illness with symptoms of stomach cramps, nausea, and diarrhea

Grain – or grains per gallon, a measure of concentration in which1 grain per gallon equals 17.1 mg/L

Granitic pluton – an intrusive (underground) body of crystalline silica-rich volcanic rock. Plutons do not break the ground surface until exposed by erosion. Granite is made up of larger mineral crystals than extrusive (above ground) volcanic rocks because it cools more slowly.

Granular activated carbon – specially processed high-porosity carbon filter media in granular form

Gravity filter – a filter in which water passes through the filter media under the force of gravity (downward) rather than under induced pressure

Greensand – a specially processed filter medium consisting of grains of the mineral glauconite that are coated with manganese dioxide and regenerated with potassium permanganate to enhance oxidation and removal of iron and manganese

Groundwater – water that exists in an aquifer under the ground surface, that may or may not be affected by surface water runoff

Groundwater Treatment Rule – a new rule being developed under the 1996 Amendments to the Safe Drinking Water Act that requires some groundwater supplies to be disinfected to prevent transmission of enteric viruses

Groundwater under the direct influence of surface water – groundwater sources that undergo significant changes in water quality due to contact with surface water or surface water runoff. Such systems may be classified and regulated as surface water systems, with requirements for filtration and disinfection.

GWUDISW – groundwater under the direct influence of surface water

HAA – haloacetic acids

Haloacetic acids – a class of disinfection by-products formed from the reaction of natural organic matter and disinfectants. These compounds are regulated by the Safe Drinking Water Act's Disinfectants and Disinfection By-Products Rule, with a maximum contaminant limit of 0.060 mg/L.

Halogens – a group of chemical oxidants with similar properties that include chlorine, bromine, and iodine

Hardness – a subjective measure of the concentration of divalent scale-forming cations in water, primarily calcium and magnesium

Head loss – the head or pressure differential between the top of a water column above the media in a filter and the filter outlet on the bottom, caused by friction losses due to material accumulating in and on the filter media

Hydraulic loading rate – the plant flow rate, in gallons per minute or gallons per day

Hydrochloric acid – a strong acid (HCl) that is one of the products of the reaction between chlorine and water

Hydrogen sulfide – (H_2S) a corrosive gas that may be found in groundwater and some anaerobic surface water supplies. H_2S imparts a rotten-egg odor to water and a bad taste to beverages and foods prepared with it, and can stain fixtures and silverware black. H_2S is poisonous if allowed to concentrate in an unventilated area.

Hypochlorination – the process of adding solutions of sodium or calcium hypochlorite to water for disinfection

Hypochlorite – a chemical compound containing free available chlorine (OCl^-) that is used in the disinfection of water supplies; calcium and sodium hypochlorites are the most common

Hypochlorous acid – a product of the reaction between chlorine and water (HOCl) and the strongest disinfectant of the chlorine species involved in the chlorination process

Hypolimnion – the lower layer of water in a thermally stratified reservoir or natural body of water

Infiltration gallery – a perforated pipe, well, or caisson dug or bored into the porous gravel of a river or stream to collect water

Inlet zone – the zone in a sedimentation basin in which the inflowing water is slowed and distributed uniformly across the basin

Interparticle bridging – coagulation mechanism in which molecules of chemical coagulant serve as bridges between colloids that have charges opposite to the charges on the surfaces of the coagulant molecules

Ion exchange – a treatment process in which one type of ion is traded for another of similar charge, such as an ion exchange softener in which sodium (Na^+) is exchanged for calcium (Ca^{2+}) or magnesium (Mg^{2+}) in water

Iron and manganese treatment – specialized treatment processes designed to remove iron and manganese from water. Techniques include aeration, coagulation, chemical oxidation, and filtration through a specialized greensand filter medium.

Iron tuberculation – the formation of rust scale (iron oxide or hydroxide), usually in round nodules in iron pipe and tanks

Jar test – a laboratory procedure that allows the operator to simulate the conventional treatment process on a small scale, used to estimate optimal coagulant or other chemical dosage required to achieve certain water quality goals

Langelier Index – the difference between the actual measured pH of a water and the theoretical pH at which the water is saturated with calcium carbonate (pH_S)

($\text{Langelier Index} = pH_S - pH$)

Langelier saturation index – see **Langelier Index**

Launder – discharge channels in clarifiers (or sedimentation basins) and filters consisting of weirs (in clarifiers) and conveying troughs

Lead and Copper Rule – one of the 1986 Amendments to the Safe Drinking Water Act that requires corrosion control monitoring of potable water supplies and sets 90th percentile "action limits" on the allowable concentrations of lead and copper in water supplies, of 0.015 mg/L and 1.3 mg/L, respectively

Lime softening – a softening process incorporating the precipitation of hardness-causing substances from water by reaction with lime (calcium hydroxide, $Ca[OH]_2$)

Lumen – fine fibers with tiny axial pores that are bundled to form microfilter and hollow fiber membranes

Macrofloc – larger, heavier pieces of floc formed during the flocculation process with gentle mixing; these floc particles have a snowflake-like appearance

Maximum contaminant level – the maximum allowable concentration of a substance in water that is considered safe for human consumption, established by the U.S. Environmental Protection Agency

MCL – Maximum contaminant level

Membrane separation – a water treatment process in which water is treated by passing through a semipermeable membrane barrier that allows the water to pass but excludes particles, molecules, or dissolved ions

Methane – a volatile gas formed by the decay of organic matter; methane can pose an explosion hazard if allowed to concentrate in an unventilated area

Methyl tertiary butyl ether – an oxygenated fuel additive intended to reduce air pollution but that is now a widespread contaminant in water supplies in urban areas of the United States

Microfilter – a membrane filter in the pore size range of 0.1 to 2 microns, commonly manufactured as bundles of porous tubes called lumen

Microfiltration – filtration with microfilters

Microfloc – the first small aggregates of colloidal particles formed during the coagulation process, also known as pin floc

Microscopic particulate analysis – a test run to help determine treatment requirements of a new water source, and to determine whether groundwater is under the influence of surface water. MPA samples consist of 100 to 1,000 gallons of raw water filtered through a sterile 1-micron filter. The material collected on the filter is removed, concentrated, and examined under a microscope.

Microstraining – fine mesh screening to remove algae and fine debris from raw water during pretreatment

Mixed-oxidant process – a disinfection treatment method in which a mixture of chlorine and oxygen species is produced by electrolysis of a salt brine solution

Molecular weight cutoff – the upper size limit of particles that can be rejected by a particular type of membrane

Monovalent – an ionic charge configuration with one unbalanced charge, either positive or negative, on the surface of an atom

MPA – microscopic particulate analysis

MTBE – methyl tertiary butyl ether

Mudballs – masses of floc, bacteria, turbidity, and filter media that can build up inside filter media when backwash flow rates are too low; mudball formation may be aggravated by overdosing coagulants

Nanofilter – a membrane filter in the pore size range of 0.001 to 0.02 microns, effective in the removal of NOM and hardness

Nanofiltration – filtration with nanofilters

Natural organic matter – substances composed of tannins, lignins, humic, fulvic, and other organic acids that form from decaying vegetation

Naturally occurring organic matter – see **natural organic matter**

Nephelometric turbidity unit – standard unit of turbidity measurement that is based on light reflected or scattered from a reference solution of the polymer Formazin when viewed at a 90° angle in a nephelometer

Nitrate – (NO_3^-) a highly oxidized form of soluble, inorganic nitrogen that can cause "blue baby" syndrome (methemoglobinemia) in infants

NOM – natural organic matter

Nonsettleable solids – particles suspended in water that are too small to settle out in a reasonable period, generally of the size range known as colloids

NTU – nephelometric turbidity unit

Osmotic pressure – the pressure exerted by the concentration differential of a salt solution versus a solution of lower concentration

Outlet zone – the transitional zone in a sedimentation basin that provides a buffer between the settling zone and the effluent flow area, to help prevent solids from being stirred up and carried over the weirs with the clarified effluent

Overflow rate – see **surface loading rate**

Pathogen – a pathogenic or disease-causing organism

Pathogenic – disease causing

Permeate – the product, or filtrate, of membrane filtration

Personal protective equipment – also referred to as PPE, the clothing and other equipment, including goggles, gloves, respirators, and ear plugs, worn by workers handling hazardous materials, entering confined spaces, or performing other hazardous duties

pH – a measure of the acidity (<7) or basicity (>7) of a water, expressed in pH units. The pH unit is the logarithm of the reciprocal of the concentration of hydrogen ions in an aqueous solution.

Pilot filter – a small cylinder filled with the same filter media as the full-scale filters, used to model the filters in a treatment plant. A pilot filter can be used to continuously monitor turbidity in flocculated plant water passing through it, or it can be used to help design a new filtration system.

Pilot test – a test of a water treatment process using a scale model plant, typically equipped with pilot filters, often used in pre-design studies

Pin floc – see **microfloc**

Pitting – the development of pits and abrasions in a metal surface, due to anodic corrosion

Point of entry – the point at which water enters a distribution system, a building, or other facility

Point of use – a single tap from which potable water is drawn

Polarization – the formation of hydrogen gas at the cathode of a galvanic cell during the corrosion process

Polyelectrolyte – a high molecular-weight, synthetic organic compound that forms ions when dissolved in water, commonly used as a coagulant or coagulant aid, also called a polymer

Polymer – see **polyelectrolyte**

Potability – a term used to describe whether or not water is safe to drink, from a microbiological, chemical, and physical standpoint

Powdered activated carbon – activated carbon ground into a fine powder, usually fed to water as a slurry

Prechlorination – the addition of chlorine to water at the headworks of a treatment plant upstream of other treatment processes to control tastes, odors, and aquatic growths; prechlorination also may be used to aid the coagulation process

Precipitation – the chemical transformation of soluble constituents in water to insoluble solids that will drop out of the water

Precoat – the thin coat of diatomaceous earth applied to the filter element in a diatomaceous earth filter during the initial step in the DE filtration process; the precoat provides an initial layer of media for the water to pass through

Precursors – humic and fulvic acids, and other constituents of natural organic matter, that can react with disinfectants to form disinfection by-products

Preliminary treatment – initial treatment for raw water, including coarse screening, presedimentation, microstraining, and other processes

Presedimentation – the settling out of debris and suspended matter in water before it undergoes treatment. Presedimentation may take place in a basin, a sand trap, or in mechanical grit or sand removal equipment.

Pressure filter – a sealed filter vessel that can be pressurized by pumping water through it

Pretreatment – see **preliminary treatment**

Radon – a radioactive gas that is formed from the decay of radioactive minerals in subsurface rock formations; a new radon standard is being developed under the Safe Drinking Water Act

Rapid mix – see **flash mix**

Recarbonation – the process of adding carbon dioxide to water after lime softening to stabilize the pH and react with excess lime

Reservoir – a stored supply of water, which may be either a natural basin, such as a lake, or artificially constructed basin or tank

Resin – the medium used in the ion exchange process that will exchange a hardness-causing ion in the water for an ion that does not cause hardness, most commonly sodium

Reverse osmosis – high-pressure membrane separation process used to desalinate seawater

Risk management plan – an emergency response plan required for water treatment or other facilities that store large quantities of certain types of hazardous chemicals on site. A risk management plan is required for utilities that store more than 2,500 pounds of chlorine gas on site.

RNA – ribonucleic acid, a component of the genetic code of living organisms; RNA is important in protein synthesis

Safe Drinking Water Act – The U.S. Federal legislation for potable water

Salinity – a measure of the concentration of salt in water

Schmutzdecke – a mat of microorganisms and organic and inorganic matter that forms on the surface of a slow sand filter and becomes part of the filtration medium

Screening – filtering of water through various pore or mesh sizes of fabric or metal screen, most commonly in pretreatment

Scrubber – a safety component in a chlorine gas facility consisting of a container of sodium hydroxide with ventilation floor ducts leading to it. The scrubber will neutralize a chlorine spill by mixing the chlorine gas with water and sodium hydroxide to form sodium chloride and water (salt water).

SDWA – Safe Drinking Water Act

Secondary contaminant – a contaminant regulated under the Safe Drinking Water Act that is primarily associated with the aesthetic properties of potable water

Secondary maximum contaminant level – the limit set by the EPA for contaminants that are not hazardous to human health but that affect the aesthetic properties of drinking water

Sedimentation – the separation of suspended solids from water by allowing them to settle to the bottom of a sedimentation basin or by shallow sedimentation with the aid of tube settlers or inclined-plate settlers

Sedimentation basin – the tank in which sedimentation takes place

Separation efficiency – a membrane separation term that describes the percentage rejection of salt through a membrane

Sequestration – the process of binding metal ions with other chemicals to prevent precipitation. Phosphates are used to sequester ferrous iron and manganous manganese.

Settling zone – the quiescent zone in a sedimentation basin in which the floc settles to the bottom

Short circuiting – a non-linear hydraulic path of flow through a settling tank, filter, or other liquid process in which part of the basin is bypassed, reducing treatment efficiency

Slaked lime – also known as hydrated lime, $Ca(OH)_2$, slaked lime is produced by mixing powdered or crystalline quicklime with water before adding it to water during lime softening

Slow sand filtration – a filtration method that uses a fine filter sand and operates at a filtration rate 50 to 100 times slower than conventional rapid sand filtration. An important component of slow sand filtration is the biologically active layer on the surface, called schmutzdecke.

Sludge – chemical floc and other solids that settle out in a sedimentation tank or that accumulates on a filter during treatment

Sludge blanket – a layer of sludge or floc in a clarifier that acts as a trap for particles in the water flowing upward through it

Sludge zone – the accumulation area in a sedimentation basin where suspended particles settle out of the water

SMCL – secondary maximum contaminant level

SOC – synthetic organic compound

Softening – removal of hardness from water, by lime softening, ion exchange, or coagulation in conventional treatment

Solids-contact basin – a type of clarifier in which a sludge or floc blanket is suspended in the tank to serve as a trap for suspended particles

Superchlorination – short-term chlorination with very high concentrations to disinfect new or recently repaired tanks, wells, and water mains. Dechlorination of the high-concentration disinfectant is usually required.

Supernatant – the liquid layer above a sludge blanket or settled precipitate

Surface loading rate – the ratio between the influent flow rate and the surface area of a clarifier or sedimentation basin, expressed in gallons per day per square foot; the surface loading rate is one of the guidelines for clarifier design

Surface wash – a device used to direct a strong stream of water or air through nozzles onto the surface of the filter bed in the early stage of backwashing to help clean the surface of the media

Surface water – water that is open to the atmosphere and subject to surface runoff

Surface Water Treatment Rule – a Safe Drinking Water Act regulation requiring surface water sources to be filtered and disinfected

Sweep floc – see **enmeshment**

SWTR – Surface Water Treatment Rule

Synthetic organic compound – carbon-containing chemical compounds manufactured for industrial or agricultural use; examples include polychlorinated biphenyls (PCBs), herbicides, pesticides, and fertilizers

Taste and odor – two of the aesthetic parameters that affect the palatability of drinking water; tastes and odors may be caused by a variety of contaminants such as organic matter, dissolved gases, dissolved metals, and volatile organic compounds

THM – trihalomethanes

TOC – total organic carbon

Total chlorine residual – the total of the combined and free chlorine residuals formed during the chlorination process

Total coliform bacteria – all members of the coliform group of bacteria that are aerobic and facultative anaerobic, gram-negative, non-spore-forming, rod-shaped, and that ferment lactose with gas formation in 48 hours at 35 °C

Total organic carbon – a measure of the amount of organic carbon in water

Trihalomethanes – disinfection by-products formed from the reaction of natural organic matter and disinfectants. These compounds are regulated by the Safe Drinking Water Act, with a current maximum contaminant limit of 0.100 mg/L and a proposed limit of 0.080 mg/L under the new Disinfectants and Disinfection By-Products Rule.

Trivalent – an ionic charge configuration with three unbalanced charges, either positive or negative, on the surface of an atom

Tube settlers – small-diameter inclined tubes that may be square, chevron-shaped, hexagonal, or other design, that are installed in a sedimentation basin or clarifier to enhance and speed up the settling process through shallow-depth sedimentation

Tubercule – a multi-layered deposit of oxidized iron (rust)

Turbidity – the property of cloudiness in water caused by the scattering and/or absorption of light by colloidal particles

Turbidity breakthrough – the appearance of unacceptable levels of turbidity in the filter effluent, indicating it is time for backwashing

Ultrafiltration – membrane separation in the range of 0.002 to 0.1 microns, used to remove larger organic molecules and microbes

Ultraviolet radiation – radiation in the ultraviolet spectrum of light, with a wavelength of 254 nanometers

Unconfined aquifer – a groundwater aquifer that is bounded by impermeable rock or sediment only at its base

Upflow clarifier – a type of clarifier in which the water flows upward, possibly through an installation of tube settlers or a floating sludge blanket

Van der Waals force – the attractive force between colloidal particles in a solution

VOC – volatile organic compound

Volatile – easily vaporized; a volatile substance can usually be removed from water by aeration

Volatile organic compound – a class of organic compounds that includes fuels and solvents. Currently 21 VOCs are regulated under the Safe Drinking Water Act, all of which can be tested in a single test method (EPA 524.2 or 502.2).

Water table aquifer – see **unconfined aquifer**

Weir – plates attached to the sides of effluent launders that serve as baffles for water flowing out of a clarifier; weirs may have sawtooth notches in them

Weir loading rate – the amount of water that flows over the weirs of a clarifier in a day, expressed in gallons per day per foot; the weir loading rate is a factor in the design of clarifiers and sedimentation basins

Well point – shallow well driven into an unconfined aquifer

Yoke – the connecting device that attaches to a chlorine gas cylinder

Zeolite – long, chain-like silicate minerals now available in synthetic form, used as an ion exchange resin

Zeta potential – a measurement (in millivolts) of the particle charge strength on the surface of colloidal particles, and the repellent force between particles

APPENDIX B
REFERENCES AND SOURCES OF INFORMATION

Appendix B – References and Sources of Information

REFERENCES AND SUGGESTIONS FOR FURTHER READING

Training Courses and Manuals

- *Filters and Filtration, a Rural and Small Water Systems Training Guide*, A. Steed, J. Shands, B. Carroll, National Rural Water Association, 1992.
- *Introduction to Alaska Small Water Systems*, Skeet Arasmith, ACR Publications and the Alaska Department of Environmental Conservation, 1996
- *Introduction to Utility Management*, Skeet Arasmith, ACR Publications and the Alaska Department of Environmental Conservation
- *O&M of Small Water Systems*, series, published by ADEC
- *Operator Certification Study Guide*, American Water Works Association
- *Utility Management, A Field Study Program*, Lorene Lindsay, California State University, Sacramento, 1998
- *Water Treatment Plant Operation, a Field Study Training Program*, K.D. Kerri, California State University, Sacramento, Volume I, 1996; Volume II, 1998

Professional Texts

- *Chemistry for Environmental Engineering*, C.N. Sawyer and P.L. McCarty, Third Edition, McGraw-Hill Publishing Company, New York, 1978.
- *Chemistry for Sanitary Engineers*, C.N. Sawyer, McGraw-Hill Publishing Company, New York, 1960.
- *Corrosion Control by Deposition of $CaCO_3$ Films: A Handbook of Practical Application and Instruction*, American Water Works Association, 1978.
- *Handbook of Chlorination and Alternative Disinfectants*, Geo. Clifford White, Consulting Engineer, Fourth Edition, John Wiley & Sons, Inc., New York,1999.
- *Principles and Practices of Water Supply Operations Series*, Harry Von Huben, Series Editor, The American Water Works Association:
  Water Sources, Second Edition, 1995
  Water Treatment, Second Edition, 1995
  Water Transmission and Distribution, Second Edition, 1996
  Water Quality, Second Edition, 1995
  Basic Science Concepts and Applications, 1995
- "Optimizing Your Plant's Filter Performance," Nick Pizzi, *Opflow*, American Water Works Association, Volume 22, No. 5, May 1996.

- *Quality of Rivers in the United States, 1975 Water Year*, J.C. Briggs and J.F. Ficke, U.S. Geological Survey Open-File Report 78-200, Reston, Virginia, 1977.
- *Standard Methods for the Examination of Water and Wastewater*, edited by Andrew D. Eaton, Lenore S. Clesceri and Arnold E. Greenberg, 19th Edition, published jointly by the American Public Health Association, the American Water Works Association, and the Water Environment Federation, Washington DC, 1995.
- *Technologies for Upgrading Existing or Designing New Drinking Water Treatment Facilities*, U.S. Environmental Protection Agency, with the Office of Drinking Water and the Center for Environmental Research Information, Cincinnati, Ohio, EPA/625/4-89/023, 1990.
- *The Nalco Water Handbook*, F.N. Kemmer, ed., Second Edition, Nalco Chemical Company, McGraw-Hill Book Company, New York, 1988
- *Supervision: Concepts and Practices of Management*, R.L. Hilgert and Theo Haimann, Fifth Edition, South-Western Publishing Co., Cincinnati, Ohio, 1991
- *Water and Wastewater Examination Manual*, V.D. Adams, Lewis Publishers, 1990
- *Water Treatment Plant Design*, American Society of Civil Engineers and the American Water Works Association, Second Edition, McGraw-Hill Publishing Company, New York, 1990.
- *Water Treatment Plant Design for the Practicing Engineer*, R.L. Sanks, Ann Arbor Science Publishers, Inc., 1980.

Handbooks

- OSHA Safety Handbook
- USA Bluebook, Operator's Companion

Drinking Water Regulations

- State of Alaska, Department of Environmental Conservation, Drinking Water Regulations, Title 18 of the Alaska Administrative Code, Chapter 80
- U.S. Environmental Protection Agency, Environmental Regulations, Title 40 of the Code of Federal Regulations
- *Alaska Drinking Water Procedures Manual*, Alaska Department of Environmental Conservation, 1993
- A Plain English Guide to the Alaska Drinking Water Regulations, available from the Alaska Department of Environmental Conservation

INFORMATION SOURCES

- The Alaska Water Wastewater Management Association
- The American Water Works Association
- The Chlorine Institute (www.cl2.com)

- Nalco Chemical Company
- The State of Alaska Department of Environmental Conservation
- The United States Environmental Protection Agency (www.epa.gov)
- The Water Environment Federation