WATER

FILTRATION PRACTICES

Including Slow Sand Filters and Precoat Filtration

Gary S. Logsdon, PE

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Water Filtration Practices

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First Edition

American Water Works
Association

Printed in the United States of America.

Project Manager/Senior Technical Editor: Melissa Valentine
Production: Glacier Publishing Services, Inc.

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Library of Congress Cataloging-in-Publication Data
Logsdon, Gary S.
Water filtration practices : including slow sand filters and precoat filtration / by Gary Logsdon. -- 1st ed.
p. cm.
ISBN 978-1-58321-595-1
1. Water--Purification--Filtration. 2. Water--Purification--Slow sand filtration. I. Title.

TD441.L64 2008
628.1'64--dc22

2008029708

ISBN 978-1-58321-595-1

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Contents

Figures

Tables

Preface

This book recognizes the need for a publication appropriate for experienced water-works staff. It presents information at a level more advanced than the books in the *Principles and Practices of Water Supply Operations* series but less complex and detailed than *Water Quality & Treatment*. Having been in numerous water filtration plants in a career that began in 1963, I have met many dedicated treatment plant operators and other staff members who have devoted their careers to providing safe drinking water to their friends and neighbors in the community and to the public in general. After producing the *Filter Maintenance and Operations Guidance Manual* for the Awwa Research Foundation with the team of Alan Hess, Michael Chipps, and Anthony Rachwal, I undertook the task of condensing that large document, updating it, and supplementing it with other information on slow sand filters and precoat filtration with the goal of providing an easily read and understood book that could provide practical assistance to water treatment plant staff. My wish is that this book will be a useful and helpful guide for those who are striving to operate water filtration plants in a way that consistently provides the best quality of drinking water for their consumers.

Acknowledgments

The author is grateful for the assistance, guidance, and mentoring of many people throughout a long career of pursuing an education and practicing engineering. He especially thanks his parents, who encouraged him to develop his talents to the fullest, and his wife, who has supported and encouraged his career. The author is also grateful to the educators at Madison Grade School and Canal Winchester High School in Ohio; to the professors who taught sanitary engineering at Ohio University and the University of Missouri and environmental engineering at Washington University; to Gordon Robeck and James Symons at the US Environmental Protection Agency; and to colleagues at Black & Veatch, especially Bruce Long, George Budd, and Mark Waer, who have provided constructive and helpful mentoring and guidance. The peer reviewers of this book, Professor James Edzwald, Mr. Stephen Tanner, Mr. Alan Wirsig, and Mr. William Lauer, provided a truly beneficial service by patiently reviewing the extensive text and making many helpful suggestions on ways to improve the final product.

1

Introduction

BACKGROUND INFORMATION

Treatment of municipal drinking water supplies in the United States varied in the 1800s, depending on community size and availability of sources. Some communities in New England and New York, such as Boston and New York City, were able to obtain water from upland reservoirs located in relatively unpolluted watersheds. Communities west of the Appalachian Mountains, located on the Great Lakes or on major rivers, tended to use those sources for drinking water. By the middle 1800s, persons responsible for public water supply in cities, such as Cincinnati and St. Louis, began efforts to improve the public drinking water. Sedimentation was sometimes used to aid in clarification of river waters, but results were not always satisfactory.

St. Louis sent their waterworks engineer, James P. Kirkwood, to Europe after the Civil War to document European water treatment practices. Kirkwood returned and reported on the use of slow sand filters and infiltration galleries along river banks as ways to improve the quality of drinking water. His book, *Report on the Filtration of River Waters, for the Supply of Cities, as Practiced in Europe*, was published by D. Van Nostrand in New York in 1869. Kirkwood played a role in the implementation of slow sand filtration in Poughkeepsie, New York. This was the first slow sand filter built in the United States. His book also introduced the concept of infiltration galleries to engineers in the United States and several were built following its publication.

Slow sand filters proved inadequate for treatment of turbid source waters, and by the late 1800s, engineers were attempting to coagulate and filter river water at rates considerably greater than those for use in slow sand filtration. Early attempts at this approach met with some failures as a result of the absence of any clarification process before filters. In the 1890s, George Fuller and a team of engineers and scientists evaluated filtration of the Ohio River in Louisville, Ky. They demonstrated that they could successfully treat turbid river water by using chemical coagulant, followed by sedimentation and rapid sand filtration at 5 m/hr (2 gpm/ft^2 or 125 million gallons per acre per day [mgad]). This was about 40 times greater than the typical slow sand filtration rate of 3 mgad (0.05 gpm/ft^2 or 0.12 m/hr).

Following Fuller's work in Louisville, rapid sand filtration plants were built by numerous communities to treat surface water, and the adoption of filtration, together with the introduction of chlorination, resulted in a dramatic decrease in the disease and death rates caused by typhoid fever. Prior to effective water treatment, typhoid fever had ravaged many American cities, whereas presently it is almost nonexistent in the United States.

For more information on the history of water filtration, a *Journal AWWA* paper, "Filtration Processes—A Distinguished History and a Promising Future," (Logsdon et al. 2006) reviews filtration in the United States from its early development in the latter 1800s to the end of the 20th century.

THE SEARCH FOR MORE EFFECTIVE WATER TREATMENT TECHNIQUES

Numerous refinements and advancements have been made in water treatment since Fuller's work in Louisville was performed. Water utility employees, university and federal agency researchers, and consulting engineers have sought more effective approaches or modifications to treatment. Some of these are discussed to provide examples and inspiration to those who are responsible for effective water treatment, so that they might diligently and carefully explore their ideas on how to treat water more effectively.

Early rapid sand filter design failed to provide for effective backwashing, and this led to problems with mudballs in the filters. John Baylis investigated backwashing and developed surface wash as a way to reduce or prevent mudball formation. This was a major departure from the early practice of using rotating rakes to agitate sand during backwashing in round wooden tub rapid sand filters.

For several decades after Fuller's filtration studies at Louisville, the 2 gpm/ft^2 (5 m/hr) filtration rate through sand filters was typical. Faced with the need to filter very large quantities of water to cool nuclear reactors at Hanford, Wash., engineers designed dual-media filters with coarser coal over a layer of filter sand. Walter Conley departed from typical filtration practice of the time by using polymer to help condition floc and by continuously monitoring filter effluent turbidity using a modified light-scattering microphotometer (Conley and Pitman 1960). Conley also reverted to prior water filtration practice by not using a sedimentation process for filtering low-turbidity source water. This, of course, was contrary to decades of established practice, but the work at Hanford demonstrated that clear source waters did not necessarily require sedimentation.

Conley, Herbert Hudson, and Gordon Robeck promoted the production of filtered water having very low turbidity. Conley did that for reasons related to the nuclear reactors through which the filtered water passed. Hudson was correctly convinced that attaining very low turbidity in filtered water improved the barrier to transmission of waterborne disease. Prior to Robeck's work on removal of poliovirus by water filtration, the focus of water treatment for preventing disease outbreaks had been on preventing passage of pathogenic bacteria that cause typhoid fever and other gastroenteric diseases into drinking water. Viruses were a new and different challenge, as they were so small that they could be observed only through an electron microscope. Nevertheless, Robeck's work demonstrated that properly coagulating and filtering water to produce very low filter effluent turbidity would remove viruses from drinking water. An extension of that work a decade later was the US Environmental Protection Agency (USEPA) investigation of water filtration for removal of asbestos fibers from source water. Again, the key to effective treatment was to attain very low filtered water turbidity.

New technology is not the only answer to a water treatment challenge. In the 1970s, frequent outbreaks of waterborne giardiasis occurred in watersheds mistakenly thought to provide source water so pristine that filtration was not necessary. Some of the affected communities were small and not as capable as larger communities of hiring well-trained operators who could manage coagulation and filtration. This situation led the USEPA to consider the history of water treatment in England and Europe in the latter 1800s, when slow sand filters came into use. These filters provided a barrier to waterborne disease. Operation of slow sand filters was not complicated, and if they would remove *Giardia* cysts, they could be applied by small communities using high quality source waters. The filters were proven to work as expected, and based on successful research conducted at Colorado State University (CSU), one was built in a Colorado community that had experienced a giardiasis outbreak, shortly after the CSU research findings were published.

The ability of diatomaceous earth (DE) filters to remove cysts of *E. histolytica* as proven by the US Army during WW II led to USEPA's research on DE filtration as another treatment approach for small- or medium-sized communities that needed to filter high-quality surface water for removal of *Giardia* cysts. Appropriate new applications can be found for older technologies, as was demonstrated in these two examples for slow sand filtration and DE filtration.

Numerous improvements in pretreatment and filtration have been developed by the ingenuity of water utility workers. A water utility employee invented the rotary sweep for surface wash, which was a less complex approach to surface wash than the pipe grid system developed by Baylis. In the era before use of electronic instruments for measuring turbidity, the Baylis turbidimeter was used to measure filtered water turbidity in rapid sand filtration plants. This device used artificial light to illuminate a tube containing the water sample and another tube of known turbidity, against which the sample was compared.

Filtration plant staff, motivated to produce better quality water, have departed from typical practice to attain that goal. After considering the effects of adding coagulant to raw water to improve its filterability, some have "salted" a filter with alum to counteract the challenges of high filter influent turbidity or higher effluent turbidity. Others added alum or a cationic polymer to filter influent when the filter box was refilled after backwashing and found that this practice could lower the magnitude of the initial turbidity spike when a filter was returned to service.

Recognizing that water treatment is presently technologically oriented, some utility managers have provided extra training for the staff. Their goal is to attain more efficient and effective plant operations and to develop a higher level of staff capability for addressing situations that are not ordinarily encountered. Papers demonstrating the value of this extra effort for staff preparedness can be found in *Journal AWWA*, October, 1998, which describe actions of plant staff to effectively address very high turbidity during flood events at plants in Oregon (Wise 1998) and Nevada (Norton et al. 1998).

The advances in water treatment practice previously described are discussed to encourage filtration plant workers and others to think of ways to improve water treatment. Asking how a task could be better performed or how a process could be improved is the first step to accomplishing that improvement. In a number of the previous examples, the individuals considered past practices to determine how an improvement might be made. In other instances, a break was made with past practice, and a new or different approach was evaluated. Most importantly, those who made advances were not bound by tradition.

However, it must be considered that in a full-scale plant, the water produced will be consumed by the public, so if new concepts are tried, they need to have a sound basis for working successfully. Furthermore, major changes in treatment may need to be discussed with a drinking water regulatory agency before they are implemented. With these precautions in mind, water treatment plant operators are encouraged to discuss well thought-out ideas and consider implementing them, as others have in past decades.

An important goal of this book is to provide information that will help water filtration plant operators and managers as they continue their efforts to provide safe drinking water to the public. A second objective for this book is to serve as a source of information for engineers who design water filtration plants or who assess plans for such plants or perform onsite plant evaluations and reviews. A key factor that can contribute to successful filtration plant operation and effective public health protection is *flexibility*. Flexibility in design gives plant operators options for management of treatment processes, and flexibility in water quality and plant performance monitoring provides operators with multiple sources of information with which to compare actual performance in the plant with performance goals. The concept of flexibility will be discussed throughout this handbook, and its importance to attaining successful treatment is difficult to overemphasize. Practices that work well at one filtration plant may not work as well at another. Multiple approaches to numerous water treatment challenges have been used, with some working very well in certain places but perhaps not very well in others. All feasible alternatives ought to be considered, at least in the operator's mind or on paper, even though not every alternative approach for a given situation will be tried.

The main topic of this handbook is chemical pretreatment followed by rapid rate granular media filtration. Chapters 2 through 10 are devoted to this topic. In these chapters, the word *filtration* means *rapid rate granular media filtration*. Chapter 11 deals with slow sand filtration, and chapter 12 covers DE filtration. The filtration concepts and operating procedures of these two processes are sufficiently different from rapid rate granular media filtration that separate chapters are appropriate.

Treatment of drinking water to provide safe and affordable water to the public has been a goal of water utilities for many years. Persons responsible for operating and managing water treatment plants should be aware that they are providing public health protection for their family, friends, and neighbors who live in the community and use the public drinking water. This is a major responsibility, and it has been fulfilled very capably by many persons who work for water utilities. Those who seek to learn more about drinking water and the industry throughout their careers will be the best equipped to address challenges that appear in the future and thus to continue to provide safe drinking water to the public.

A theme throughout this handbook is that obtaining a greater variety of information about treatment plant performance is valuable. As operators and other treatment plant staff understand more about how the plant operates, they are empowered to decide what chemical conditions are appropriate for pretreatment, to assess how pretreatment is functioning, to evaluate filtration performance, and to make decisions on managing filters and overall plant operations. Staff who are better informed can produce safe water for their customers.

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2

Pretreatment: Management and Monitoring of Chemical Coagulation and Lime Softening

INTRODUCTION

Effective chemical pretreatment is essential for the successful performance of rapid rate granular media filters, both for filtration plants that practice coagulation and for those that use precipitative lime softening. For either type of filtration plant, if problems exist with the chemical pretreatment, serious problems may be encountered with filtered water quality, or with physical facilities, or both. The key role of chemical pretreatment in conventional filtration, direct filtration, and in-line filtration necessitates a discussion of how to determine appropriate pretreatment chemistry and verify that pretreatment is working well. Therefore, this chapter and the following one on mixing, flocculation, and clarification are included in this handbook and are presented prior to chapters on filtration. Treatment plant operators and managers are cautioned that the goal of pretreatment is not to provide the lowest clarified water turbidity to the filters, but to provide clarified water that can be filtered most efficiently, producing long filter runs and very low filtered water turbidity.

In addition to coagulation and lime softening, preoxidation processes are used at some treatment plants. Preoxidation can influence subsequent treatment practices, so it is considered first in this chapter, followed by information on chemical coagulation and lime softening.

PREOXIDATION

Introduction

For several decades in the 1900s, prechlorination was practiced to reduce the load of bacteria on filters, to control growth of algae in basins, and to help control biological growths on basin walls and filters. Other reasons for prechlorination included color removal, control of some taste and odor (T&O) problems, and longer filter run times. In the mid-1970s, it was discovered that chlorination can cause formation of trihalomethanes (THMs) in drinking water. Some utilities modified or ceased their prechlorination practice to lower the concentration of THMs in their distribution systems.

Current reasons for preoxidation include control of zebra mussel growth at intakes and in raw water transmission lines; control of tastes and odors; control of algae in the treatment plant; disinfection; conditioning of particulate matter for improved filterability; lowering oxidant demand prior to use of ozone; and oxidation of iron, manganese, and arsenic. Oxidants used include chlorine, chlorine dioxide, potassium permanganate, and ozone. This handbook focuses on the use of oxidants as related to coagulation and filtration. Oxidants used for preoxidation are briefly reviewed, and their use for removal of iron, manganese, and arsenic, and the benefits to filtration performance that may result from preoxidation, are discussed.

Oxidants

Atmospheric Oxygen

The least expensive oxidant available to water utilities is oxygen in the atmosphere, although the process equipment needed to quickly transfer oxygen into water can be expensive if aeration towers are constructed. Aeration has been used to control some tastes and odors, and it can be effective for oxidizing iron in groundwater prior to filtration. When both arsenic and iron are present and aeration is employed for oxidation, however, iron is oxidized much more quickly than arsenic, and this may affect arsenic removal adversely.

Free Chlorine

The oxidant used most commonly in the United States is chlorine, which became widely used in the first half of the 20th century. Following the discovery of THMs in drinking water and their mechanism of formation, use of free chlorine as a preoxidant has been subject to greater scrutiny. Some source waters have very low concentrations of natural organic matter (NOM) and can be treated by prechlorination without creating disinfection by-product (DBP) problems. However, in other situations, reduction of the concentration of NOM is advisable before chlorine is applied.

Prechlorination can be useful for oxidizing iron, manganese, and arsenic in groundwaters, which often have very low concentrations of NOM. Chlorine reacts with these constituents much more rapidly than oxygen, and this can be advantageous, depending on the reaction time available before sedimentation or filtration. When both arsenic and iron are present in groundwater, removal of arsenic will be more effective if both iron (Fe^{+2}) and arsenic (As^{+3}) are oxidized simultaneously by a strong oxidant such as free chlorine because As^{+5} is not adsorbed well by preformed iron floc (Ghurye and Clifford 2004; Ghurye et al. 2004). Thus, groundwater containing both iron and arsenic should not be aerated or exposed to the atmosphere for extended periods before a strong oxidant is applied. Following oxidation, iron floc with adsorbed arsenic can be removed from water by granular media filtration.

The potential for prechlorination to improve filter performance in some waters was recognized several decades ago (Babbitt and Doland 1955) and continues at some locations in pilot-plant filtration studies or at treatment plants. Filtration testing of Lake Mead, Nev., water demonstrated the benefit of prechlorination for producing lower filtered water particle counts. During an interruption of chlorine feed, filtered water particle counts increased rapidly, rising from 6/mL to 200/mL between 2.5 μm–150 μm (Carollo, Black & Veatch 1996). If chlorination is used as a preoxidant to improve filter performance, the gains in filter performance may need to be weighed against possible loss in water quality in the context of DBP formation.

Free chlorine can be used to react with a portion of the oxidant-demanding constituents in raw water to reduce the ozone demand before ozone is applied. This procedure can reduce treatment costs, and applying a lower ozone dosage to water containing bromide may also decrease the extent to which bromate forms.

Ozone

The most powerful oxidant and chemical disinfectant used in water treatment is ozone, which must be generated onsite. Ozone can inactivate *Cryptosporidium* oocysts, although it is less effective in cold water. It is effective for controlling many kinds of T&O problems. Ozone can be used to oxidize manganese, but the presence of NOM interferes with this. The use of ozone for oxidation of manganese must be managed carefully, as an excessive ozone dosage can oxidize manganese to its permanganate form and cause pink water. Ozone oxidizes and breaks down NOM so that it is more readily used, or assimilated, by microorganisms. For this reason, ozone is able to enhance the level of microbial activity in biologically active filters. Ozone followed by filtration through biologically active granular activated carbon (GAC) has been shown to control T&O problems caused by 2-methylisoborneol (MIB) and geosmin (Nerenberg et al. 2000).

Using ozone also can improve coagulation and filtration. Before the Los Angeles Aqueduct Filtration Plant was designed and built, direct filtration testing indicated that using ozone as a preoxidant resulted in improved turbidity removal during filtration while at the same time facilitating the use of lower coagulant dosages than were needed to yield the same quality of filter effluent without preozonation. In addition, the filtered water turbidity resulting from preozonation was slightly less than half that of filter effluent when prechlorination was practiced and when the same coagulant chemical dosage was fed with each preoxidant (McBride and Stolarik 1987). These observations may help explain why some plants have longer filter runs when preozonation is practiced.

At plants using ozone in pretreatment, the loss of ozone can cause filtration performance to worsen. During pilot-plant testing of the direct filtration process at Lake Mead, within about four weeks, nine filter runs employing preozonation produced filtered water having particle counts ranging from 0.6 to 2.0 particles/mL (2.5 to 150 μm). In two other filter runs in which ozone feed was interrupted during the run, particle counts rose to 20 particles/mL and 45 particles/mL in the absence of ozone preoxidation (Carollo, Black & Veatch 1996). At any plant where ozone is used prior to filtration, operators need to be particularly alert if ozone feed is lost. This would be extremely serious if ozone is used for disinfection, but loss of ozone also could cause filtered water quality to deteriorate, creating another undesirable outcome.

One drawback to the use of ozone is the formation of bromate in waters that contain bromide. If ozone is used for disinfection, attempting to attain higher ozone Ct (residual concentration C, mg/L × contact time t, minutes) values in waters containing bromide can create higher concentrations of bromate, with the possibility of exceeding the 10 µg/L maximum contaminant level (MCL). Source waters containing bromide and also NOM that is not readily removed by coagulation present a challenging situation for use of ozone as a disinfectant for *Cryptosporidium*.

The use of free chlorine to react with some of the oxidant demand in Lake Mead water, followed by the addition of a carefully controlled dosage of ammonia to eliminate free chlorine, was shown to be an effective means of lowering the concentration of bromate formed when ozone was used to attain Ct values appropriate for inactivation of *Cryptosporidium*. A pilot-plant investigation undertaken by the Southern Nevada Water Authority (SNWA) demonstrated that using a small dosage of chlorine oxidized some of the organic matter and thus reduced the ozone demand of the water. Ammonia was added after the chlorine had reacted with bromide to form HOBr and OBr^- (hypobromous acid and hypobromite ion). The overall result was lower concentrations of bromate in the disinfected and filtered water. Details of the reactions involved and of the results have been published by Wert et al. (2007). A full-scale evaluation of the process at two SNWA plants using Lake Mead as the water source showed that the plant using no bromate control could attain a Ct of 3.0 mg-min/L and meet the bromate MCL, whereas the plant using the chlorine–ammonia pretreatment attained a Ct of 8.6 mg-min/L while meeting the MCL for bromate. A U.S. Patent, No. 6,602,426 B2 entitled "Water Treatment Having a Reduced Likelihood of Bromate Formation From Bromides Formed in Water," has been issued and is in the public domain so that water utilities will be able to use the process without paying royalties.

Ozone is both more versatile and more expensive than other oxidants and disinfectants. The multiple purposes that can be served by ozone at a water treatment plant may justify its use at some plants, whereas at others the costs of using ozone might outweigh the benefits. At a plant where ozone is not being used, the most reliable means of learning if using ozone would improve filtration performance is to undertake a pilot-plant study.

Chlorine Dioxide

Chlorine dioxide is an oxidant and disinfectant that is used by some water utilities to minimize formation of chlorinated DBPs during disinfection. Pure chlorine dioxide does not chlorinate NOM, so it does not produce THMs, and the concentration of halogenated DBPs resulting from its use is minimal (Gates 1998). Note that this can be attained only if the chlorine dioxide is not contaminated with free chlorine. Whereas very low production of halogenated DBPs is an advantage for chlorine dioxide, a disadvantage is the degradation of chlorine dioxide to chlorite and chlorate after chlorine dioxide has been added to water. The USEPA's MCL for chlorite in drinking water is 1.0 mg/L (as chlorite). The maximum residual disinfectant level for chlorine dioxide is 0.8 mg/L, so an upper boundary exists on the dosage that can be applied while maintaining regulatory compliance. Like ozone, this oxidant must be produced onsite.

Chlorine dioxide can be effective for controlling some tastes and odors, color, and for zebra mussels at raw water intakes and transmission lines. It can oxidize iron and manganese and can help to control growth of algae in basins at treatment plants.

Potassium Permanganate

Control of zebra mussels at water intakes, control of tastes and odors, and oxidation of iron and manganese are uses for potassium permanganate. A positive attribute of this oxidant is that it does not form chlorinated DBPs. This makes potassium permanganate useful for zebra mussel control, for which it is added at water intakes and exposed to the NOM in the raw water. When potassium permanganate is used for oxidation of iron and manganese, careful dosing and monitoring of treated water are important factors in avoiding overdoses of this chemical. Pink water can result if some of the added permanganate does not react with constituents in the water, oxidizing them, and becoming reduced to other forms of manganese. Calibration of permanganate feeders and quality control checks to verify feed rates are helpful in avoidance of pink water problems.

CHEMICAL PRETREATMENT CONCEPTS

Necessity for Effective Coagulation

At filtration plants treating surface water or groundwater under the influence of surface water, chemical coagulation has been required since 1993, when the USEPA's Surface Water Treatment Rule (SWTR) became effective. The importance of chemical coagulation had been noted at least nine decades earlier, in water treatment studies performed at Louisville, Ky., under the direction of George Fuller (Baker 1981), and in testing carried out at Pittsburgh, Pa., by Allen Hazen around the same time and described later in his book on water filtration (Hazen 1913).

A key to successful treatment of the Ohio River at Louisville was use of sedimentation and coagulation in a manner that reduced the amount of suspended matter reaching the sand filters (Baker 1981). Prior to Louisville and Fuller's work, rapid sand filtration had tended to employ addition of coagulant chemical followed immediately by filtration, and that was a process train that could not cope with high-turbidity source water.

In the filtration testing for the city of Pittsburgh, Hazen's team measured plate count bacteria in raw water and filtered water. His book summarized results of bacteria removal according to alum dosages and demonstrated that filter performance was related to alum dosage. One filter run with zero alum yielded 64 percent removal, another with an alum dosage of about 4.5 mg/L gave 86 percent removal. Filter runs in which alum dosages were 18 mg/L to about 30 mg/L typically resulted in 98 to 99 percent removal of bacteria (Hazen 1913).

Journal AWWA contains numerous articles that discuss coagulation and the treatment of drinking water. One that is particularly significant is "Integration of the Clarification Process," published by Walter Conley, Jr. in October, 1965. In this paper, Conley wrote, "No water plant can achieve good results, regardless of the excellent design of flocculators, settling basins, and filters, unless the coagulation is correctly done." Conley's experience included operation of water filtration plants at the Atomic Energy Commission's Hanford facility in Washington. In this instance, Columbia River water was treated with the goal of attaining very low filtered water turbidity. In the years following World War II, Conley worked with dual-media filters that were operated at rates as high as 8 gpm/ft^2 (20 m/hr). When the turbidity of the river was very low, the filters could successfully treat water that was flocculated but not clarified. Water treatment practice at Hanford was far ahead of what was being done elsewhere in that era. Failure to coagulate water properly would have caused filtration failure under the operating conditions at Hanford, so Conley knew well the importance of effective coagulation.

This and other published papers emphasizing the importance of coagulation influenced water treatment practice at many, but not all, water utilities. In the 1970s and early 1980s, some communities in the Rocky Mountain states experienced waterborne giardiasis outbreaks. In that era, chemical coagulation was not practiced at some rapid rate filtration plants during winter, when source waters were exceedingly clear, with turbidity less than 1 nephelometric turbidity unit (ntu). Filtration without a chemical coagulant was ineffective, and if chlorination was not adequate to inactivate *Giardia* cysts in cold water, outbreaks happened. This background of disease outbreaks related to absence of adequate coagulation was influential in development of the SWTR's requirement that coagulation must be practiced at rapid rate filtration plants.

In a 1989 Awwa Research Foundation (AwwaRF) report (Cleasby et al. 1989), the authors wrote, "Chemical pretreatment prior to filtration is more critical to success than the physical facilities in the plant." The authors' strong emphasis on the importance of chemical pretreatment was based on detailed observations at 21 water filtration plants, and it dispels the notion that if source water appears to be clear and unpolluted, coagulation is of minimal importance to successful plant operation and production of safe drinking water.

Particles in Water

Many types of particles can be found in surface waters. These include inorganic particles such as clay, finely ground rock (glacial flour); particles of soil resulting from runoff in tilled fields and bare ground; decaying organic particles including fragments of rotted vegetation and animal manure; microorganisms such as viruses, bacteria, and protozoan cysts and oocysts; and algae and plankton. Particles in the size range of approximately 1 μm to 0.001 μm are referred to as *colloidal particles*. Their settling velocities are so low that unless they are agglomerated into much larger particles, colloids will settle only slightly in water treatment plant basins. Effective coagulation, clarification, and filtration can remove not only colloids but also larger particles of the types previously described.

At ambient pH, most of the naturally occurring particles found in surface waters have an apparent surface charge (zeta potential) that is electronegative, whether the turbidity is less than 1 ntu or over 1,000 ntu. Zeta potential of a particle is calculated on the basis of its electrophoretic mobility, which is the ability of the particle to migrate in a fluid when an electrical potential is imposed. Another concept, *streaming current*, is also related to electrophoretic mobility and will be discussed later in this chapter. For a specified voltage potential, the velocity with which a particle moves in water is proportional to its zeta potential. Particles with low zeta potential move very slowly, whereas those with high zeta potential move much more rapidly when observed with a zeta potential instrument.

A very thin layer of water surrounds a particle in water and moves with the particle as it travels through the water. Thus, there is no measurement of the charge on the surface of the solid particle. Rather, the apparent surface charge, or zeta potential, is measured. Examples of particles with negative zeta potential include clays, algae, bacteria, *Giardia* cysts, *Cryptosporidium* oocysts, and viruses. Colloids and particles in the size range of bacteria and protozoan cysts or oocysts with negative zeta potentials are not likely to adhere to grains of filter media unless the zeta potential of the colloids and particles is changed by coagulation, because sand and anthracite media grains also have a negative charge. Changing their zeta potential so it is less negative increases the probability that particles will adhere to grains of media in the filter bed when collisions occur. Positively charged metal coagulants and positively charged polymers are used in pretreatment to counteract the negative zeta potential and coagulate particles found in water. The coagulated particles can join together and form flocs and then be removed by clarification and filtration, or they can be removed in the filter bed if direct filtration is practiced. One of the challenges faced by filtration plant operators is determining the appropriate chemical conditions for coagulation.

Source Water Influence on Coagulation Chemistry

Several aspects of source water quality can influence coagulation chemistry. These are reviewed individually in the following sections. In some situations, multiple factors will affect coagulation chemistry, especially when a filtration plant must meet multiple water quality goals, such as low turbidity and a decreased concentration of NOM as measured by total organic carbon (TOC), as well as a low residual coagulant concentration.

Turbidity

Turbidity gives water a cloudy appearance. Using the nephelometric turbidity method, turbidity is measured by a turbidimeter as light scattered by small particles at an angle of 90° from the light source. Turbid water was not appealing to water utility customers as a source of drinking water; therefore, removal of turbidity, i.e., clarification of water, was an early goal of water filtration. To some extent, higher turbidity may require higher coagulant dosage, but the relationship is generally not a 1-to-1 ratio.

Microbiological Contaminants

Removal of pathogenic microorganisms is a very important function of coagulation and filtration. Because of the time needed to test water for microbiological contaminants, the extent of contamination by pathogenic viruses, bacteria, and protozoa is hardly ever known when water is being treated. If it were known, the numbers of those pathogens typically would be very small compared to the number of other particles in source water. Nevertheless, removal of microbiological contaminants does indirectly affect coagulation practice, because attaining very low filtered water turbidity is necessary for minimizing the number of pathogenic microbes in filtered water. The goal of attaining very low filtered water turbidity, which does influence coagulation practice, is related to controlling microbes in filtered water.

Natural Organic Matter

NOM in source water has a strong influence on coagulation practice. NOM can be measured as dissolved organic carbon (DOC). A surrogate measure for NOM is ultraviolet (UV) absorbance at 254 nanometers (UV_{254}), as described by Edzwald et al. (1985). Both DOC and UV_{254} analyses are performed on water filtered through 0.45 μm membrane filters. Another measure related to NOM is the specific ultraviolet light absorbance (SUVA), which is an indicator of the molecular weight distribution of the NOM in the water (Edzwald 1993). UV absorbance is expressed in units of m^{-1}, where m is the length of the absorbance light path in meters. DOC is expressed in units of mg/L. SUVA is UV_{254}/DOC, and the units are $[m^{-1}]/[mg\ C/L]$ or $L/mg\ C \cdot m^{-1}$.

For water with SUVA greater than 2.5 to 3 $L/mg\ C \cdot m^{-1}$, a chemical proportionality exists between the concentration of DOC and the dosage of coagulant needed for effective coagulation (Edzwald 1993). Coagulant demand exerted by DOC must be satisfied for coagulation to be effective; therefore, in waters with high SUVA values, the DOC is a much more important factor in determining coagulant dosage than turbidity. For water in which this is the case, measuring absorption of UV radiation as UV_{254} may be both faster and less expensive than measuring DOC. The standard procedure for measuring UV_{254} must be used.

A word of caution is needed, however. If ozone is used in the process train, the nature of the organic molecules can be changed so that UV absorbance decreases, even though no reduction in the concentration of DOC takes place. Generally, ozone changes but does not remove organic matter from water; therefore, UV absorption results after application of ozone need to be interpreted with this in mind.

DETERMINING APPROPRIATE COAGULATION CHEMISTRY AND EVALUATING THE RESULTS

As water treatment practice has evolved, techniques for determining proper coagulation conditions have been developed. These techniques were rather rudimentary in the early days of water treatment. Over time, more sophisticated and useful procedures have been discovered or adapted for water treatment. They are discussed in this section. AWWA Manual M37, *Operational Control of Coagulation and Filtration Processes* (2000), provides more detailed information on jar tests, streaming current instruments, zeta potential, particle counting, and pilot filters.

Visual Observations

Visual observations of the condition of flocculated water may have been one of the earliest approaches for judging whether coagulation chemistry was appropriate, in the era when sedimentation basins providing several hours of theoretical retention time were used for clarification. Visual observation was mentioned in a 1915 text on water treatment, in which the author suggested that if the water looked clear or smoky with no visible floc, a larger alum dosage was needed; whereas if flocs were large and feathery, the alum dosage might be too high.

Although much more refined approaches for selecting coagulant chemical dosage currently exist, visual observation of floc, determination of the level of the floc blanket in the sludge blanket processes, and observation of the quality of water passing over weirs in sedimentation basins can be helpful to operators. Visual observation of floc would not be useful at direct filtration or dissolved air flotation (DAF) plants, where particle destabilization is performed and very small pin-flocs form. Failure of floc to form at coagulant dosages that typically form large flocs indicates a problem with coagulation chemistry, just as it would have a century ago. Large floc particles carried over the weirs in sedimentation basins in greater quantities than usual can indicate that the floc density is not much greater than the density of water in the basin. Compact flocs having a density greater than water are able to settle better than low-density, fluffy flocs.

The denser floc formed in lime softening can settle much more rapidly than coagulation floc. Figure 2-1 shows the transition from the flocculation basin through the baffles into the clarifier at a softening plant. The floc settled rapidly and the turbidity of the water declined markedly after flocculated water entered the clarifier.

Operators at plants where floc blanket processes are used have found that having adequate lighting at sedimentation basins, provided either by underwater lights or overhead lights, is helpful for observing basin performance at night. Many treatment plants operate 24 hours per day; therefore, observing conditions occurring during the night is just as important as observing conditions during daylight hours. Tools are available

Courtesy of Black & Veatch Corporation.

Figure 2-1 Dramatic improvement in clarity at lime softening plant as water enters sedimentation basin

for determining blanket depth and condition in blanket clarifiers. Samplers exist for withdrawing suspended sludge from the clarifier, and a device similar to a Secchi disk mounted on the end of a graduated rod or pole could be used to determine the depth at which the blanket obscures the view of the disk.

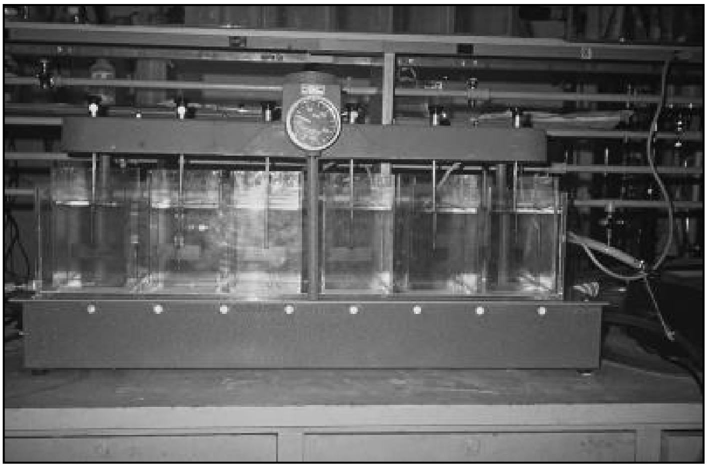
Historical Chemical Dosing Charts

The use of historical information to estimate the appropriate chemical dosage for a specific raw water quality is several decades old, as it was a practice discussed in a water supply text published in the 1950s (Babbitt and Doland 1955). A logical approach to estimating the proper chemical dosage was to consider what dosage worked effectively in a similar, prior situation. Most likely, this is how chemical dosage charts developed.

Chemical dosage charts typically consist of a graph or data table showing a raw water quality, such as turbidity, and an appropriate coagulant chemical dosage for use to treat that level of turbidity. A graph used to indicate the appropriate chemical dosage for various levels of raw water turbidity would be two-dimensional, with turbidity plotted as the independent variable and coagulant dosage plotted as the dependent variable. Such a graph provides for only one water quality condition; therefore, if both the source water turbidity and TOC concentration vary substantially, multiple graphs are needed. Data tables or charts also can be used, but the advantage of having a graph is that each time a certain water quality condition is encountered and treated successfully, another data point can be added to the graph. As more and more data are collected, if the data fall close to a line through all data points, operators can have an increased level of confidence in the value of the chart for predicting appropriate chemical dosage. If, however, the data are scattered, use of a chemical dosage chart may be limited to defining a range of coagulant dosages appropriate for use in jar tests that can more precisely identify the proper dosage.

Operators who plan to use or who are already using coagulant dosage charts or graphs to estimate appropriate chemical dosages need to be aware of some limitations to this approach. They are

- The data developed for a particular chemical are specific to that chemical and may be specific to the chemical as received from the supplier. At one water utility using liquid alum, a change of chemical supplier resulted in a dosing regime slightly different from the one that had been used for the same chemical from a different supplier. With liquid chemicals and with polymers, testing the chemical that will be supplied to verify its strength should be performed before making the purchase.
- Data used to develop a chemical dosage chart must NOT include any dosages that did not give a successful treatment. Furthermore, successful treatment must be defined as treatment that met the present-day water quality standard or the utility's internal quality goal. With the decrease in the filtered water turbidity performance requirement in the SWTR and the regulatory updates that have followed, data on chemical dosages developed in the 1980s and perhaps in the 1990s might not be appropriate for meeting treatment standards in the 21st century.
- The range of water quality conditions covered by a single chemical dosage chart must not be too broad.
  - In a source water with variable turbidity and variable TOC concentration, multiple graphs or charts should be used, each covering a wide range of turbidity but a narrow range of TOC concentration.
  - For cold water, charts or graphs should be used with a temperature range of about 10°F or 5°C, such as 32° to 40°F and 41° to 50°F (0° to 5°C and 6° to 10°C). The efficacy of alum coagulation is especially sensitive to cold temperatures. Above 50°F or 10°C, using charts covering a temperature range of about 20°F or 10°C may be satisfactory.
  - The pH for minimum solubility of alum is lower at warm water temperatures than at temperatures near freezing, so for cold water, both pH and alum dosage may need to be different from those used for warm water.
- For a source water that typically has low turbidity but which is colored and has a SUVA > 2.5 to 3, consider developing a graph or chart in which the independent variable is true color or UV_{254} absorbance.



Courtesy of David Hendricks, CSU, USEPA Cooperative Agreement.

Figure 2-2 Jar test apparatus in water bath for cold temperature testing

- If historic data are to be used for a reservoir source subject to a fall turnover condition that results in elevated concentrations of iron and manganese or in other water quality problems, source water quality problems following the turnover might become so complex that the dosing chart or graph will not be useful.

Operators who use historic data as a guide to chemical dosing should focus on the actual results produced by pretreatment and filtration, and if the chemical dosing indicated by the chart or graph does not give satisfactory results, changes in pretreatment may be needed.

Jar Tests

For many decades, jar tests have been used at water treatment plants to provide guidance on appropriate pretreatment chemistry. Performing jar tests can be time-consuming; as a result, some treatment plants do not use this procedure. The information gained from properly performed jar tests can be quite useful, so this procedure ought to be evaluated and adapted for use at plants where the equipment is available. Figure 2-2 shows a jar test apparatus. It should be noted that the plastic jars are set in a clear plastic water bath for temperature control.

Calibration of Jar Test to Treatment Plant

The manner in which water is treated in jar tests differs in some important ways from how it is treated in a full-scale plant. Typically in a jar test, the chemicals are dosed onto the water surface rather than into the water close to the mixing impeller; therefore, the chemicals are not mixed into the raw water as quickly and thoroughly as they would be in rapid mixers designed to accomplish instantaneous dispersion and mixing of coagulant chemical. Also, the rapid mixing period is usually longer in a jar test than in the plant. Flocculation in a jar test is performed as a batch process, with a carefully controlled residence time; whereas in a full-scale plant, flocculation is a continuous process that involves some degree of short-circuiting of flow and thus a range of flocculation times. Furthermore, a variety of impellers or stirring devices are used in full-scale plants, and very few, if any, are shaped like the paddles in a jar test apparatus. In spite of these differences, jar tests that are performed properly can be useful predictors of pretreatment chemistry requirements in the plant.

The key to obtaining useful jar test results for physical–chemical processes of coagulation, flocculation, and sedimentation is to perform calibration testing with jar tests in which a variety of rapid mixing times and energy inputs, flocculation times and energy inputs, and settling times are evaluated to determine what bench-scale procedures are best able to yield the treatment plant results. For plants that employ tapered flocculation, with decreased energy input in the latter stages of flocculation, simulating tapered flocculation can be done by employing two or more periods of flocculation, with lower energy input in the later flocculation time interval(s). When the rpm of stirrers is an important aspect of a jar test, verification that the tachometer of the jar test equipment is giving correct readings is an important quality control measure. In AWWA Manual M37, a calibration curve is available for relating the rpm of the standard stirrer paddle to velocity gradient (G) values for the standard design square jars.

The goal of exploring the influence of variations in the jar test procedure is to develop a plant-specific jar test procedure that most closely produces test results that are like those attained in the plant. Performing such an evaluation could require testing over a period of days; therefore, this task should be performed during a time of stable source water quality. Jar tests can be used with confidence after a procedure has been developed that accurately predicts full-scale results.

Uses for Jar Tests

At treatment plants employing sedimentation (but not sedimentation with sand-weighted floc), a common purpose for jar tests is the identification of pretreatment chemistry that will result in formation of floc that settles well. Behavior of floc in a filter bed is difficult to predict with jar tests because the quantities of water produced are quite limited in the context of filtration testing. Jar tests are very useful in identifying which chemical coagulant dosage works well, the appropriate pH for coagulation, and perhaps the dosage of flocculant aid polymer if this is added in rapid mix or at the entry to the flocculation basin in the plant. Jar tests can provide guidance on whether to add caustic for pH adjustment before or after adding a metal coagulant.

Jar tests can be very useful for predicting treatment results when chemical reactions with contaminants are being evaluated. Examples of this include removal of arsenic by oxidation, coagulation with ferric coagulants, sedimentation and filtration; and the removal of hardness (calcium and magnesium), radium, and barium by lime softening at varying pH values. Jar tests also can identify the dosages of metal coagulant needed for removal of true color and TOC. The versatility of this treatment evaluation procedure is one of its primary assets and is a reason that, with the possible exception of iron and manganese removal plants, any plant using chemical pretreatment and granular media filtration ought to have a jar test apparatus available and use it for exploring pretreatment chemistry options.

Good Practices to Follow Using Jar Tests

The following practices are recommended:

- Document carefully the preparation of all treatment chemicals used, and mark each container with the date prepared and an expiration date.
- Solutions of inorganic coagulant having a concentration of 10 mg/mL should be prepared on the day the jar tests are performed. Polyaluminum chloride and other inorganic polymeric coagulants are subject to rapid degradation; therefore, they should not be diluted.
- When polymers are used, stock solutions having a strength of 0.2 mg/mL should be prepared on the day of use.
- When more than one chemical is added in a jar test (e.g., alum and caustic), measure and add each chemical separately. Combining chemicals before adding them to jars allows concentrated chemicals to interact, and this may have undesirable results if floc forms before chemicals are added to the jars.
- Premeasuring chemicals to the correct dosage for each jar makes it easier to add all chemicals at once and thus apply the same rapid mixing time for each jar. Approaches for this are
  - Dosing chemicals in a series of test tubes or small plastic beakers mounted on a rack so they can be tipped simultaneously to dump the chemicals into the jars.
  - Using small syringes to measure the correct volume for each jar and using a device that can inject all chemicals simultaneously, as presented in *Opflow* (Mical 1997, 1998).
- Test raw water samples that are representative of water treated in the plant. Keep cold water cold during testing, and do not allow highly turbid water to settle before testing it.
- For jar tests performed for guidance related to water clarification, the settling time in the test jars needs to be related to the overflow rate for the basins in the plant. For a sedimentation basin with an overflow rate of 1 gpm/ft^2 (2.4 m/hr or 4 cm/min), the sampling time for a 10-cm depth in a test jar is 2.5 min. Table 2-1 presents sedimentation basin overflow rates and corresponding settling times in test jars.

Table 2-1 Jar testing settling times for clarifier overflow rates

Overflow Rate, gpm/ft^2	Overflow Rate, m/hr	Overflow Rate, cm/min	Minutes to Settle 10 cm in Test Jar
0.4	1.0	1.7	6.0
0.6	1.5	2.5	4.0
0.8	2.0	3.3	3.0
1.0	2.4	4.0	2.5
1.5	3.7	6.0	1.7
2.0	4.9	8.2	1.2

- For jar tests undertaken to evaluate both turbidity removal and the effect of preoxidation on DBP formation in sedimentation basins, the residence time in the jar should be based on the overflow rate of the sedimentation basin for turbidity removal but based on the actual residence time of water in flocculation and sedimentation for evaluating DBP formation in full-scale treatment.
- For direct filtration plants, do not settle water in the test jars, but remove samples at the conclusion of flocculation and filter through Whatman #40 filter paper (Wagner and Hudson 1982, AWWA 2000). The test results can provide guidance on turbidity that may be attained by full-scale filters, but nothing can be learned about chemical dosing effects on filter head loss by this procedure.
- Quality control checks on jar test procedures are advisable.
  - Periodically perform a test in which four to six jars are dosed identically and subjected to identical stirring times and energies, as well as identical settling times, to check on reproducibility of the procedure.
  - When source water quality is in a steady state, perform jar tests using chemical dosages identical to those used in the plant to verify that the test procedures are giving a good prediction of plant performance.

Data to Record

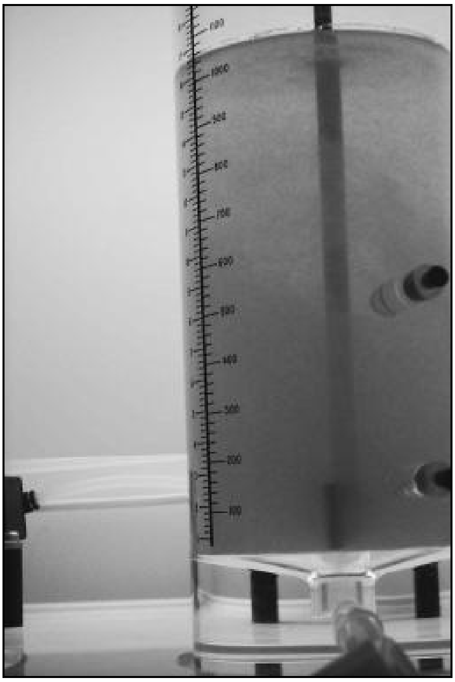
Careful record-keeping is important for jar test studies, as data may be useful both for the immediate and long-term purposes. The following data are needed:

- Raw water, before any chemicals added
  - Temperature
  - Turbidity
  - pH
  - Alkalinity

  - Any preoxidant residual concentration and preoxidant dosage, if added prior to sample collection
  - TOC concentration if testing is related to TOC goals, DOC concentration if that controls coagulant dosage, or UV_{254} as a surrogate for TOC
  - Concentration of other chemical or contaminant for which testing is being done, such as arsenic
- Chemical dosing data for each jar
  - Oxidant dosing and contact time before other chemical addition
  - Coagulant
  - Polymer
  - Caustic or acid, and note whether added before or after coagulant
  - Any other chemical
- Rapid mixing time and energy for each jar
- Flocculation time and energy (constant or tapered over time) for each jar
- Settled water data for each jar
  - Turbidity, with depth of sample and time when sampled
  - pH
  - Alkalinity
  - Filter the settled water and measure TOC concentration or UV_{254}
  - DBP concentration, if this was a goal of testing, along with disinfectant or oxidant contact time (DBP formation time) before sampling
  - Disinfectant dosage and residual at time of sampling
  - As an alternative to settled turbidity, filtered turbidity if direct filtration is evaluated
  - Concentration of other chemical or contaminant for which testing is done, such as arsenic (if chemical contaminant removal is a goal of treatment, extended settling might be appropriate)

Alternative Procedures

As a quick alternative to performing a jar test, some operators collect a sample of coagulated water entering the flocculator and then flocculate it in one or more jar-test jars to observe floc formation, size, and settling characteristics. This procedure provides no insights into alternative chemical dosing though, other than evaluation of adding flocculant aid polymer at the entry of the flocculation basin.



Courtesy of James K. Edzwald, Visiting Professor, Clarkson University.

Figure 2-3 Dissolved air flotation test jar; water with supersaturated air just added

Courtesy of James K. Edzwald, Visiting Professor, Clarkson University.

Figure 2-4 Dissolved air flotation test jar; floated floc on top of water

Modified jar test procedures can be employed for alternative clarification processes such as DAF and ballasted flocculation. Such procedures are likely to be used by plant operators only if the plant uses DAF or ballasted flocculation. Engineers might evaluate treatment options for a source water by these procedures before undertaking pilot-plant testing.

DAF involves addition of a clarified water recycle volume at a rate of 5 percent to 10 percent of plant flow. The recycled water is subjected to aeration under high pressure, so it is supersaturated. When the supersaturated recycle water is introduced into flocculated water, air escapes solution and forms microscopic bubbles that rise, carrying floc to the surface. Injecting a 5 percent to 10 percent volume of supersaturated water into the bottom of a test jar at the end of flocculation could simulate the DAF procedure. A DAF jar test apparatus is commercially available. DAF test jars are shown in Figure 2-3 and 2-4. The jar in Figure 2-3 has just been dosed with a premeasured volume of supersaturated water, and in the jar in Figure 2-4, the air bubbles have risen to the water surface, carrying the floc.

In the ballasted flocculation process, particles in water are coagulated first, and then measured dosages of very fine sand and polymer are added and stirred for a period of time to attach the sand to the floc that has formed. To keep the weighted floc and the sand in suspension, jar test paddles have to be located about 3 mm above the bottom of the jar. This procedure requires higher paddle rotational speeds than are employed for flocculation to prevent premature settling of the weighted floc. Guidance from process equipment manufacturers is recommended when test procedures are developed.

A device using an automated procedure for evaluation of chemical dosages (RoboJar) has been developed, and its evaluation was one task in a project sponsored by the AwwaRF to optimize filtration pretreatment by floc particle characterization (Drewes et al. 2007) The RoboJar consists of a chemical addition and mixing unit and a flocculation unit, both electronically controlled. Raw water is pumped into the device at a known flow rate, coagulation chemicals are injected by syringe pumps and then flash-mixed, and the coagulated water is transferred into a baffled flocculation reactor. Both flocculation time and mixing intensity can be varied. During floc formation, floc particles are analyzed optically. Based on digital images of floc, the average floc particle diameter is determined. When charge neutralization is the goal of coagulation, the coagulation conditions that result in maximum floc particle size (perhaps only a few tenths of 1 mm) provide effective filtration. This device is automated and can be programmed to perform up to 50 runs. Thus, a wide range of pretreatment chemistry options can be explored with only a small amount of operator labor involved.

Zeta Potential and Streaming Current Instruments

Instruments used for measuring zeta potential and streaming current utilize properties related to electrophoretic mobility but in somewhat different ways. Both types of measurements are sensitive to pH and the concentration of total dissolved solids in the water being analyzed. Multivalent ions can suppress the apparent electrical charge on particles. Therefore, if the total dissolved solids concentration is above 500 mg/L, these instruments may become less sensitive and as a result, less useful for determining or monitoring coagulant dosage. At pH values greater than 8, instrument sensitivity may also decrease, so zeta potential and streaming current instruments are not appropriate tools for monitoring chemical dosage at precipitative lime softening plants.

Zeta Potential

Instruments that measure zeta potential of particles in water typically are used in laboratory settings, therefore they would not be found at plant locations where exposure to dirt, dust, or precipitation occurs. Zeta potential instruments can be used to measure the charge on particles in water before coagulation and to measure the zeta potential resulting from various dosages of cationic polymer or inorganic coagulant. Used in this manner in the laboratory, the data can provide guidance on the dosage of coagulant or polymer needed in the plant. Another use for zeta potential measurements is to assess the coagulant dosage needed for charge neutralization at various pH values. These instruments can be used for both operational control in a plant and for exploratory studies at bench-scale.

A limitation on using these zeta potential instruments relates to the nature of floc formed in the treatment plant. Changing the zeta potential to a value close to neutral or zero enables the coagulated particles to stick together when they collide, thus forming flocs that stick to grains of filter media when making contact. Charge neutralization is useful for direct filtration and for in-line filtration (coagulation and filtration with neither flocculation nor sedimentation).

Zeta potential measurements will be less useful if a sedimentation basin is operated in a sweep floc mode, as the coagulant dosage will exceed that for charge neutralization. The same would apply for *enhanced coagulation* practice, when a treatment goal is to reduce the concentration of TOC by coagulation, clarification, and filtration. Note that for waters with SUVA greater than 2.5 to 3, using a coagulant dose that produces floc near a zeta potential of zero will give close to optimum coagulation. Typically, larger dosages of alum or ferric coagulants are used for enhanced coagulation than for coagulation and clarification.

Streaming Current

Measurement of streaming current is an online method for assessing the charge characteristics of particles in water. Whereas zeta potential is measured by observing the velocity of particles in water under an applied voltage potential, streaming current is a measure of the current that is created when a suspension of charged particles passes through a capillary space. Streaming current instruments utilize a piston that moves up and down in a cylinder containing coagulated water. Some particles temporarily attach to the piston and their motion relative to the water creates the streaming current.

Streaming current instruments are suitable for use in treatment plant settings, and an example of such an application is presented in Figure 2-5. Location of sampling points is a key factor for validity of data and for instrument maintenance. When a coagulant chemical is added to water, coagulation and charge neutralization occur very rapidly, so the coagulant should be quickly and thoroughly dispersed.

In a full-scale plant, the desired instantaneous dispersal of coagulant may not happen, and chemical reactions may continue to occur for a short time. A typical value for the time lag between application of coagulant and sampling for streaming current instrument is 2 to 5 minutes after coagulant addition. The water sample for a streaming current should be representative of the quality of all of the flow of coagulated water. The sampling point should not be close to the bottom nor near a wall of the pipe or channel conveying coagulated water to the next treatment process. Mixing along walls may be less effective, and sand or grit, which can damage the instrument's sensor, are more likely to be found in coagulated water near the bottom of a pipe or channel.

Courtesy of Doug Wise, Eugene Water & Electric Board.

Figure 2-5 Streaming current instrument installed at water treatment plant

Streaming current instruments are calibrated by using other approaches to optimize coagulation for effective filtration and then obtaining a streaming current reading. Optimized conditions may be defined by measures such as filtered water turbidity or particle counts or both, jar test results, pilot filters, or a combination of those. Other indicators of filter performance, such as run times or unit filter run volume (gallons of filtered water produced per square foot of filter area, or m^3 of water produced per m^2) also may be helpful. However, these can be influenced by factors not related to coagulant dosage, such as filter aid dosage, and so must be used with care. The streaming current value at optimum coagulation is known as the *set point*. Streaming current is then monitored, and if the reading differs from the previously determined set point, coagulation chemistry is modified until the set point value is attained. Periodic checks of streaming current readout at optimum coagulation chemistry are needed to verify that the set point identified earlier is still valid, as set point values may change on a seasonal basis. Other maintenance needed from time to time includes cleaning the instrument and the line that feeds coagulated water to the instrument. The guidance provided in the instrument manual should be followed for maintenance and calibration tasks.

Pilot Filters

The terms *pilot filter* and *pilot-plant filter* can be confusingly similar, but these are two distinct types of small-scale filters with two different purposes. Pilot-plant filters are used to explore water filtration processes and process variations. Pilot filters are actually full-time monitoring devices that can indicate whether coagulation is adequate.

Courtesy of Doug Wise, Eugene Water & Electric Board.

Figure 2-6 Pilot filters used for evaluating coagulation efficacy

Pilot filters consist of a pair of filter columns like those shown in Figure 2-6. Typically, they are 4 to 6 in. (10 to 15 cm) in diameter and are filled with the filter media having the same effective size and depth of the media layer or layers as that used in the plant. During operation of a pilot filter, particles are removed in the filter bed, which gradually clogs. When terminal head loss is reached, the filter is removed from service and the second pilot filter is placed into service. Then the clogged pilot filter is backwashed. Use of pilot filters in an alternating pattern ensures that one filter is always operating and monitoring filtration efficacy. The filtration rate for the pilot filter should be similar to that used at full scale, but varying the rate on pilot filters to keep up with filtration rate changes in the plant may not be practical.

Pilot filters are used to filter coagulated water that has been discharged from the rapid mix. A continuous stream of water is extracted from the plant at a location that provides a water sample representative of that going to the flocculator, and sometimes this sample is pumped to the pilot filter installation. Floc can be damaged when a centrifugal pump is used. Therefore, if this type of pump is used to feed water to a pilot filter, the water sample must be extracted from the plant after coagulant chemical is thoroughly dispersed but before floc forms.

Monitoring pilot filter performance is the key to predicting full-scale filter performance. Head loss and rate of flow are monitored so the operating conditions of the filter are known. The key filter performance indicator is effluent turbidity. The turbidity of filtrate from a pilot filter with the same media design as that used in full-scale filters provides plant operators with an early indication of the condition of filter effluent when the water entering the flocculation basin passes through this basin and sedimentation (if used) and is filtered in the plant. At conventional plants, the time of travel between entry to flocculation and appearing in filter effluent can be several hours, but the time between extraction of a sample of coagulated water and its appearance in pilot filter effluent would be a fraction of an hour. If for some reason coagulation suddenly is not effective, having a pilot filter online is a way for the plant operator to realize that a problem exists long before a conventional settling basin is full of water that is not going to be filtered effectively. Pilot filters also can quickly confirm that a change in coagulation practice indicated by jar test results or streaming current readings is actually going to be effective. Thus, pilot filters can verify the validity of chemical pretreatment decisions made using other approaches.

Pilot filters treat coagulated water, not clarified water, so they are not capable of predicting filter run length in the plant. However, this is not an obstacle to the use of pilot filters, because other procedures used for assessing pretreatment chemistry also fail to provide information on filter run length.

Maintenance activities for pilot filters include periodic checking of piping and valves, verification that media has not been lost from the filters during backwashing, and checking on the condition of the pump, if one is used. Quality control checks include periodic verification of the effluent turbidimeter's calibration, and verification that measurements of head loss and flow rate are accurate.

Filter Performance as an Indicator of Pretreatment Chemistry

A practical approach to assessing the adequacy of pretreatment chemistry, and the final proof of the adequacy, is evaluation of filter performance. With the use of online turbidimeters, data on filtrate turbidity are continuously available, and deterioration of filtered water quality in all filters is an indicator of problems in pretreatment. Conversely, if filtered water turbidity from most or all of the filters is excellent, this is interpreted as indicative of effective pretreatment.

Filter performance also can be a good indicator of how polymer use is managed. Filter aid polymers often are dosed after clarification, so jar tests and other approaches to assessing pretreatment chemistry are not useful for making decisions about filter aid usage. A typical approach is to apply enough filter aid to attain effective filtration but not so much filter aid that head loss increases too rapidly. Often a goal at filtration plants is to manage pretreatment and filter aid use so terminal head loss is reached just before turbidity breakthrough would begin.

Raw Water Quality as a Guide to Pretreatment Chemistry

At some treatment plants, certain aspects of raw water chemistry such as NOM, pH, and alkalinity have a strong influence on how pretreatment is managed. Sometimes these parameters, or surrogates, are monitored online to provide additional information for those making decisions on water treatment chemistry.

pH and Alkalinity

Controlling coagulation based on the pH of raw and coagulated water can be helpful at some filtration plants. When very soft waters having low alkalinity and a pH of about 7 or lower are coagulated with alum or ferric coagulants, addition of those coagulants consumes alkalinity and can lower pH of the coagulated water. In some source waters, the alkalinity is so low that the pH of coagulated water would be unacceptably low if operators attempted to operate in a sweep floc regime rather than in a charge neutralization regime with alum or ferric coagulants. If coagulation reduces the pH of coagulated water below the pH range for minimum solubility for aluminum or iron, coagulation will be less effective and residual metal will remain in solution. Monitoring of both pH and alkalinity is advisable when coagulation practice could depress pH to this extent.

Natural Organic Matter

In some raw waters, NOM, as measured by DOC concentration or UV_{254} absorbance, has a strong influence on pretreatment chemistry from a practical or a regulatory perspective, or sometimes both. As noted previously in this chapter, when raw water has a SUVA value greater than 2.5 to 3 $L/mg\ C \cdot m^{-1}$, the coagulant dosage tends to be governed by the DOC content of the water, as coagulant demand of DOC must be satisfied for coagulation to be effective. Low turbidity, colored waters are in this category, and as a less expensive and fairly rapid test for raw water quality, UV_{254} absorbance can be used as a guide to the coagulant dosage needed. As previously noted, this approach is not valid if ozone is used as a preoxidant because ozone reduces the UV_{254} absorbance without removing DOC. Also, free chlorine can reduce UV absorbance without removing TOC (Edzwald and Kaminski 2007).

For raw waters with an average SUVA exceeding 2.0 to 2.5 $L/mg\ C \cdot m^{-1}$, Edzwald and Kaminski (2007) have shown how alum dosage can be controlled by the raw water UV_{254} absorbance. They reported that several Aquarion Water Company filtration plants in Connecticut have set their alum coagulant dosage based on measurement of this indicator of water quality. A key aspect of using UV measurements when alum is the coagulant is to use the proper pH for coagulation, which is about 6.0–6.2 for water at 20°C and 6.5–6.7 at 4°C. The authors stated that good coagulation performance for

Table 2-2 Required percentage removals of TOC by enhanced coagulation in the 1998 Disinfectants and Disinfection Byproducts (DDBP) Rule

Source water TOC (mg/L)	Source Water Alkalinity (mg/L as $CaCO_3$)		
	0 to 60	>60 to 120	>120
>2.0 to 4.0	35.0%	25.0%	15.0%
>4.0 to 8.0	45.0%	35.0%	25.0%
>8.0	50.0%	40.0%	30.0%

removing TOC and UV-absorbing organics corresponds to a treated water UV_{254} absorbance of 0.03–0.035 cm^{-1}. The Easton plant, reported on by Edzwald and Kaminski and operated by monitoring UV_{254} absorbance and practicing alum coagulation at pH 6–7, routinely produces settled water turbidity less than 1 ntu and filtered water turbidity less than 0.1 ntu. The feasibility of coagulating with alum at a pH between 6–7 may depend in part on the alkalinity of the raw water, as high alkalinity water requires more coagulant or acid to drive down pH.

Another treatment challenge related to NOM is the regulatory requirement for removal of a fraction of TOC in raw water, depending on the concentrations of TOC and alkalinity in the source water, as presented in Table 2-2. The rule is complex, and Table 2-2 is given as a general guide only. Some source waters with low TOC concentrations, or treated waters with low TOC concentrations, may satisfy the rule with alternative compliance criteria instead of compliance with the TOC removal percentages stipulated in the table. Details can be found in the rule as published in the *Federal Register* (USEPA 1998b). The rule's definition of enhanced coagulation is "...the addition of sufficient coagulant for improved removal of disinfection byproduct precursors by conventional filtration treatment." Neither this definition nor the table of required TOC removal percentages specifies a pH at which coagulation is to occur, so plant operators should consider whether the pH at which coagulation is occurring is appropriate for meeting mandated TOC removal percentages. The best pH for coagulation is the value at which coagulant solubility is a minimum, which is between 6–7 for aluminum and 5–6 for ferric coagulants. However, high alkalinity in raw water may influence the feasibility of coagulating at those pH values.

Balancing the need for efficient and effective filtration plant operations with the need to achieve compliance with the regulations can be quite challenging, depending on source water quality and on the design and operation of the filtration plant. If the approach for removal of a specified percentage of TOC is based on adding increased dosages of alum or ferric coagulants, this may not be very effective in raw waters with low values of SUVA, i.e., less than 2.5 $L/mg\ C \cdot m^{-1}$. When considering both overall water treatment cost for water with a low SUVA and the treated water quality, the best coagulation practice for clarification and filtration may not be the same as the optimum for TOC removal. Therefore, comprehensive testing to identify the pretreatment conditions that will satisfy both the 1998 DDBP Rule and surface water treatment regulations may be needed. Furthermore, using higher dosages of metal coagulants will produce larger quantities of sludge in sedimentation basins, and if excessive quantities of floc carry over to the filters, shorter filter runs and more frequent backwashing may result.

Issues Related to Dilution and Overfeeding or Underfeeding Metal Coagulants and Polymers

Long-term consequences of underdosing metal coagulants and cationic polymers used to aid coagulation are likely to be poor settling and ineffective filtration. The long-term consequences of overdosing these treatment chemicals can be the formation of mudballs in filter media and excessive amounts of sludge that must be treated and managed for disposal. Another long-term consequence associated with overdosing cationic polymer at one plant was formation of blobs of polymer that resembled small jellyfish. Air-assisted backwash was not able to break up the polymer blobs, and the rise rate employed at the plant was not adequate to wash them out. This approach to polymer usage definitely disproved the adage, "If a little bit is good, a lot is better."

PRACTICAL APPLICATION OF METHODS FOR DETERMINING AND MONITORING COAGULATION CHEMISTRY

Much of the content in AwwaRF's *Filter Maintenance and Operations Guidance Manual* was based on information from 49 water filtration plants provided by three dozen water utilities in the United States and Canada, plus information on plants operated by Thames Water Utilities, Ltd. in England and elsewhere in the world. Staff at the filtration plants provided information on plant practices as well as on raw and filtered water quality and plant design. The responses provided to a question on how coagulation dosages were determined and monitored are presented in Table 2-3.

The most important concept presented in this table is that only four of the 37 plants that provided responses to this question used a single method for coagulant dosage determination, and only four used two approaches. Twenty-five plants reported using three, four, or five ways to determine coagulant dosage or to monitor the results of coagulation; and four plants used six different procedures. The advantage of using multiple techniques is that if a single approach for determining dosages or monitoring coagulation results gives erroneous information, comparing that information with information obtained by two or more other techniques should help operators determine which information is likely to be invalid. Obtaining invalid but consistent information from multiple approaches of coagulation assessment seems to be a highly unlikely event. The advantage of using multiple approaches is the higher degree of confidence provided by agreement of the various methods used.

In addition to the methods listed in Table 2-3, filtered water turbidity from each filter that is in operation, or particle counts from each filter, or both are monitored at many

Table 2-3 Methods used for determining and monitoring coagulation chemistry at 37 filtration plants

Method	Number of Plants Using Method
Jar test	29
Streaming current instrument	26
Zeta potential	4
Pilot filters	2
Historical dosage charts	32
Visual observations	25
pH and alkalinity	20
UV absorbance	5
Only one method	4
Two of above	4
Three of above	6
Four of above	8
Five of above	11
Six of above	4

Source: Logsdon et al. 2002

filtration plants as a means of assessing the adequacy of coagulation. This is after-the-fact information, as further reduction in turbidity or particle counts will not happen after the filter. Nevertheless, if problems develop with filter effluent quality, this can signal the need to reassess coagulation. Unsatisfactory turbidity or particle counts in filtered water can occur for a variety of reasons, one of which is inadequate coagulation. If degraded effluent is coming from all of the filters in the plant having the same media design, this is a strong indication of problems with pretreatment.

Using filtered water quality as a guide for adequacy of coagulation is good practice, but the water quality data should be interpreted with a good understanding of the individual filters. Sometimes filters in a plant have different media designs that result in differences in particle capture capabilities, or some filters may have physical problems whereas others are in excellent condition. When filters are not all alike, the poor performers may signal a coagulation problem even though filters that typically produce better effluent quality are operating satisfactorily. If a filter is performing poorly because of physical problems, such as upset support gravel or media loss, this problem should be corrected. When filters have different media designs that result in different particle removal capabilities for properly managed filters, the ones that do not perform as well become the critical filters for assessing filter effluent quality.

PRECIPITATIVE LIME SOFTENING

Various Approaches to Lime Softening

Hardness in water is caused mainly by the presence of calcium and magnesium in water. In the precipitative lime softening process, the concentration of these ions is reduced by adding lime to raise the pH sufficiently to precipitate them. Calcium hardness can be removed by raising pH to about 10.3. For removal of magnesium hardness, pH is raised to between 11.0 and 11.3, a value higher than the pH at which magnesium theoretically would precipitate. The higher pH resulting from using excess lime enables the magnesium precipitation to react faster than it would if the pH were raised only to the value at which the magnesium would precipitate. Addition of lime (calcium oxide or calcium hydroxide) to water converts bicarbonate ions to carbonate and increases the concentration of calcium carbonate. If sufficient lime is added to form calcium carbonate in excess of the concentration that is soluble, it will be precipitated, and the calcium concentration in the water is decreased. If insufficient bicarbonate is present, sodium carbonate or sodium bicarbonate also are needed to precipitate calcium carbonate. When magnesium is present and pH is raised sufficiently to remove it, magnesium hydroxide is the precipitate that is formed.

Calcium carbonate and magnesium hydroxide precipitates formed during lime softening are quite different. If only calcium is removed in lime softening, the calcium carbonate formed by precipitation is in the form of dense crystals that are negatively charged. In this case, using a coagulant to aid in clarification and filtration is helpful to attain effective particle removal. Ferric coagulants are effective over a wider pH range than alum and are used in some lime softening plants for this reason. On the other hand, magnesium hydroxide floc is similar to alum floc. If surface water or groundwater under the influence of surface water is softened for magnesium removal, the magnesium hydroxide formed can help remove calcium carbonate crystals and flocculate particles in the surface water. The important point to consider is that if the SWTR is applicable to the source water being treated, it must be coagulated, and precipitation of calcium carbonate crystals but not magnesium hydroxide floc during lime softening does not constitute coagulation.

At lime softening plants treating surface water or groundwater under the influence of surface water, chemical dosage determination is more complex than at plants where the goal of treatment involves only controlling turbidity. Lime softening plants often have multistage process trains with softening and sedimentation followed by coagulation and sedimentation, or coagulation and sedimentation followed by softening and sedimentation. If softening is performed first and only calcium carbonate is removed, jar tests to identify coagulant dosage and pH needed for turbidity removal could be performed by using effluent from the softening clarifier. At plants that soften first and remove both calcium carbonate and magnesium hydroxide, jar tests using process basin effluent might determine if polymer addition would give lower settled water turbidity. If coagulation and clarification are undertaken before lime softening, raw water should be used for jar tests performed to remove turbidity. Additional jar tests may be needed on softened water to provide guidance on polymer dosage for removal of lime softening precipitates.

The use of split treatment in lime softening is another instance in which the SWTR may apply. Split treatment is an excess-lime process used to soften groundwater by softening most of the raw water flow at high pH, and then lowering the pH and stabilizing the water by blending into the softened water a smaller portion of the raw water flow that had bypassed the softening process. For treatment of groundwater under the influence of surface water, the blended water must be coagulated before it is filtered to comply with the SWTR.

Determining Treatment Chemistry and Monitoring Results

Maintaining the correct treatment chemistry at a lime softening plant facilitates production of water softened sufficiently, while avoiding overdosing chemicals and encountering excessive chemical costs. After softening has been accomplished, the water must be stabilized to avoid deposition of precipitates in filters and water mains.

Assessing Treatment Chemistry

Jar tests can be useful for assessing treatment chemistry. Although jar test results are not good predictors of floc strength and filter run time, they do produce chemical results on a small scale, such as a 2 L jar, that are like those attained in full scale. One exception to this would be related to recycling of some lime sludge back to rapid mix, or treatment in sludge blanket reactors. Unless a way is found to introduce preformed sludge back into a jar test, lime dosage results from the jar test might not correctly indicate the dosages needed in the plant where some sludge is recycled.

Examples of procedures for determining dosages of lime and other chemicals are provided in Chapter 10, "Chemical Precipitation," in AWWA's *Water Quality & Treatment*, 5th ed. (Benefield and Morgan 1999) and also in *Hoover's Water Supply and Treatment*, 12th ed. (Pizzi 1995). For calculation of chemical requirements for lime softening, data on hardness, pH, alkalinity, and carbon dioxide concentration in the water are needed. Those publications provide details.

When surface water is treated by lime softening, turbidity removal will be required, so turbidity and TOC concentration in the raw water can influence the amount of coagulant chemicals needed. Multistage treatment of surface water is often practiced in lime softening plants as a way of attaining multiple treated water quality goals. Jar tests are useful for assessing turbidity removal and softening in multistage plants.

Monitoring Results of Softening

Serious problems can arise in the absence of careful monitoring and process control at lime softening plants. Where surface water or groundwater under the influence of surface water is treated, compliance with surface water treatment regulations must be maintained. Regardless of the water source, the chemistry of lime softening has to be closely monitored so problems do not develop.

At plants where surface water treatment regulations apply, the procedures available for process monitoring may be more limited if softening is practiced first, followed by coagulation and clarification for control of turbidity. Unless the high pH of the softening process is lowered to less than pH 8, streaming current and zeta potential are likely to be insensitive and not well suited for determining coagulant dosages. In this situation, the use of jar tests and historical data charts is preferred. Because of the importance of pH at softening plants, online monitoring of pH in softening basins and after pH adjustment subsequent to softening is helpful.

Potential for Problems Related to Unstable Water

For filtration to be effective over the long term, the condition of filter beds must not be allowed to deteriorate. If water applied to filter beds is oversaturated with calcium carbonate, precipitation of this compound onto filter media can occur. Usually this tends to occur slowly, so it may not be noticed for a long while. Precipitation of calcium carbonate increases the size of filter material and may cause the volume of media in the filter to increase. Particle removal in granular media filters is more effective for smaller filter media, so increased media size is not desirable. Precipitation of calcium carbonate in filter beds also can cement media grains together into a conglomerate "rock" that ceases to act as filter material. Although this might happen rapidly in some cases, cementation of media in a filter bed also can occur gradually and might not be noticed for a while. Another potential problem with calcium carbonate precipitation is coating GAC media, which would ruin its adsorptive properties.

At one lime softening plant, a likely overdosing of polymer in pretreatment resulted in formation of calcium carbonate crystals bound up with the polymer and shaped like iron filings or debris from a pencil sharpener. A portion of this calcium carbonate-polymer material agglomerated into large lumps, some of which were several inches across. High dosages of lime were being used at the same time, and after the source water quality episode that resulted in overdosing had subsided, the depth of material in the filter boxes had increased by several inches.

Passage of unstable lime-softened water into the distribution system can create other problems when calcium carbonate precipitates on water main walls and gradually decreases the inside diameter of the mains, either reducing their carrying capacity or requiring higher pressure to carry the desired flow. Costly damages to infrastructure can occur when lime-softened water is not stabilized, so this aspect of lime softening must not be ignored.

To prevent problems caused by deposition of calcium carbonate on filter media and in water mains, softened water must be chemically stabilized. This can be done before the softened water is filtered by lowering the pH to convert carbonate to bicarbonate. Typically, carbon dioxide is added in a process basin after softening but before filtration, and a detention time of about 20 minutes is provided to stabilize the water before it is filtered. As an alternative to recarbonation, sequestering chemicals such as polyphosphates can be added to prevent unwanted calcium carbonate precipitation.

Control of filter influent stability can be managed at lime softening plants using Caldwell–Lawrence diagrams, as explained by Benefield and Morgan (1999) and in greater detail by Merrill (1979). These diagrams resemble a very complex contour map, with three groups of lines for (1) equal alkalinity as $CaCO_3$, (2) equal calcium as $CaCO_3$, and (3) equal pH. For those familiar with topographic contour maps, these diagrams might be considered to be analogous to complex chemical concentration contour maps. As with topographic maps, interpolation between "contour" lines may be necessary to use the diagrams. A saturated condition exists at points where the three lines intersect. After water has been softened, if the three values for pH, alkalinity, and calcium do not intersect at a single point, an equilibrium condition has not been attained. If the measured calcium value is higher than the equilibrium calcium value found on the Caldwell–Lawrence diagram, calcium would be supersaturated and would tend to precipitate in the filter media or on pipe walls. These figures have been prepared for a range of temperatures and total dissolved solids concentrations in water.

The presence of phosphates or TOC could render the calcium carbonate saturation calculations questionable, because the equilibrium constants are for pure water, not waters with phosphates or organic matter present (Schock, personal communication).

An alternative to chemical calculations is use of the marble test to observe potential for calcium carbonate deposition. This is referred to as the Calcium Carbonate Chemical Balance or Stability Test by Pizzi (1995). As stated by Pizzi, the procedure is as follows:

1. Fill two 500 mL glass stopper bottles completely full of water to be tested. Let bottles be subjected to same temperature and time conditions.
2. Add about ½ gram of reagent grade precipitated $CaCO_3$ powder in one. Place stoppers in both bottles.
3. Mix by inverting every five minutes for ½ hour or longer, or use a magnetic type of stirrer.
4. Filter both through clean filter paper into clean beakers.
5. Determine methyl orange alkalinity on each. Results on untreated sample designated as (a) and on calcium carbonate treated sample as (b).
6. If (a) is greater than (b), the water is supersaturated with carbonate and may be scale forming.
7. If (a) is less than (b), the water is undersaturated as to carbonate and may be corrosive.
8. If (a) is equal to (b), the water is in equilibrium as to carbonate constituents.

The procedure delineated by Pizzi will not determine the extent of either supersaturation or undersaturation.

SUMMARY

Attaining proper pH and treatment chemical dosages is a key factor in successful operation of rapid rate granular media filters. Without proper chemical pretreatment, filter operation cannot be optimized, and performance may be so poor as to risk having a waterborne disease outbreak. Determining the proper pretreatment coagulation conditions and assessing the efficacy of coagulation can be done in a number of ways. Reliance on multiple assessment techniques gives operators a stronger data base for making decisions about coagulation.

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3

Chemical Feed and Mixing, Flocculation, and Clarification

INTRODUCTION

After appropriate pretreatment chemistry has been identified through one or more of the methods described in chapter 2, that treatment approach is implemented at the plant. This begins with the addition of treatment chemicals to the water at one or more locations within the plant, mixing of chemicals into the water, and usually flocculation and clarification before the pretreated water is filtered. At an in-line filtration plant, coagulated water is applied directly to filters, without flocculation and clarification. At a direct filtration plant, water is mixed and flocculated and then filtered.

All of the pretreatment processes need to be functioning properly if filtration is to be effective. As mentioned in chapter 2, the goal of these pretreatment processes at plants with clarification is not to provide the lowest clarified water turbidity to the filters, but to provide clarified water that can be filtered most efficiently, producing long filter runs and very low filtered water turbidity. At direct filtration plants, the goal is to produce floc that filters well, giving low filtered water turbidity and long filter runs.

CHEMICAL FEEDERS

Chemical feed is the first step in pretreatment. When coagulation is practiced, a uniform flow of coagulant chemical at the proper dosage gives the best results. Feed pumps have moving parts, and over time they can gradually drift out of calibration. Periodic checks of pump calibration are helpful for verifying that a pump is delivering the desired rate of flow, or on the other hand, indicating that calibration has drifted and the pump should be recalibrated.

Failure of a coagulant feed pump and interruption of chemical feed will eventually cause filtration to fail. At a conventional plant, a chemical feed failure might go unnoticed for a few hours until inadequately coagulated water reaches the filters. If a streaming current instrument has been installed at the plant, however, the loss of coagulant feed would be detected within minutes, alerting plant staff of a serious problem.

Chemical Dosage Issues Related to Feed Pumps

When aluminum or ferric coagulants are fed, potential problems exist with both liquid coagulants and dry coagulants. Liquid coagulants often are fed without being diluted, but in hard waters, iron, or aluminum precipitates can form where the metal coagulant is introduced into the source water and clog nozzles or orifices in the device used to introduce the coagulant into the raw water. If dry chemicals are used, they should not be excessively diluted to make feeding the solution easier. Overdilution can result in hydrolysis of the coagulant and formation of a precipitate in the dilute chemical solution. This occurred in a small pilot filter study. Because the chemical feed pump could not be turned down sufficiently to attain the low coagulant dosage needed, a temporary resolution of the problem was achieved by acidifying the coagulant solution and thus preventing precipitation of the metal coagulant. If a diluted solution of ferric coagulant has a pH of 2.2 or lower, it will not hydrolyze and lose strength. Likewise, if the pH of a diluted alum solution is 3.3 or lower, it will not hydrolyze.

The efficacy of polymers also can decrease if they are diluted excessively, which might occur in a small plant attempting to feed very low dosages of filter aid without a feed pump that could be turned down to a very low feed rate. As noted in chapter 2, the shelf life of very dilute polymer solutions is short.

Location of Chemical Addition Points

The effectiveness of pretreatment can, in some cases, be influenced by the location of chemical addition points. Some chemicals may not be as effective when added with other chemicals as they would be if added sequentially, allowing for mixing and chemical reaction between the addition of the two chemicals. For example, if caustic is added too close to the point where alum or ferric coagulants are added, concentrated metal coagulant and caustic might interact and form preformed floc before some of the particles in the raw water are destabilized. Another example of chemical interference is adding fluoride with or ahead of alum, which can cause aluminum to complex with fluoride, resulting in the need to use a higher dosage of alum than would seem to be required based on performing jar tests with raw water to which no fluoride had been added. If chemical feed piping has been arranged in this manner, it should be changed so fluoride can be added after filtration.

When caustic is added during coagulation, the order of addition of caustic and metal coagulant sometimes can influence how well coagulation works. Adding caustic before the coagulant versus after the coagulant can be explored in a program of jar testing. If the order of addition does make a difference in jar test results, verifying this effect in the full-scale plant using temporary chemical feed lines or a temporary setup for one of the chemical feed systems could prove worthwhile.

Location of polymer feed also can have an effect on the results obtained. Vigorous mixing is needed to rapidly disperse metal coagulants into water; however; if polymers are subjected to the mixing energies used for alum and ferric coagulants, the long-chain

Potential for Treatment Problems Related to Chemical Feed Pumps

Pulsed Flow From Diaphragm Pumps

Particle destabilization happens very quickly when coagulants are introduced to raw water. Often in pilot plants and in smaller water filtration plants, diaphragm pumps are used to feed chemicals. Diaphragm pumps operate in a pulsing mode, pumping and then taking more chemical into the pump's chamber and pumping it out. If coagulant is delivered to flowing water in a pipe ahead of an in-line mixer, this results in overdosing the water passing the point of chemical addition when coagulant is flowing but underdosing (zero dosage) coagulant when the pump is not forcing chemical into the feed line. Because particle destabilization takes place so rapidly, pulsed feeding of coagulant chemical is highly undesirable if destabilization is the goal of coagulation. One way to avoid the pulsed delivery of coagulant is to place a tee and a capped vertical pipe about 1 to 2 ft (0.3 to 0.6 m) in length in the feed line downstream of the diaphragm pump. Such a device is known as an *accumulator* and may be available commercially.

The capped vertical pipe contains air, and when the diaphragm pump forces chemical into the feed line, some chemical goes up into the vertical pipe, compressing the air inside. When the diaphragm pump is resting, the compressed air in the vertical pipe forces chemical out and along the feed line, and this produces a more steady flow of chemical. Over time, the air in the vertical pipe can dissolve into the water. If a metallic air valve that functions like an automobile tire valve is placed at the top of the capped pipe, this will facilitate adding more air to the vertical pipe.

Chemical Feed Difficulties at Low Water Flow and Low Chemical Dosage

A chemical feed problem that may be encountered in new filtration plants is the difficulty of turning down chemical feeders sufficiently to feed low dosages of chemicals at low flows. Designers should provide the capability to feed the maximum dosage of chemical needed for effective treatment at a high rate of flow; however, in new plants that have been designed with future water demand increases in mind, present-day low flows may be only a small fraction of the future maximum flow for which the plant was designed. If a chemical feed pump cannot be turned down sufficiently to deliver the low dosage of coagulant chemical needed with desired precision and accuracy, dilution of the chemical might provide temporary relief. However, this approach should be used with great care so operators know the strength of chemical being fed and could adjust the pump accordingly. A longer term solution would be the installation of a smaller chemical feed pump that could function well in the range of coagulant feed rates needed at low flows and low dosages.

polymeric molecules can be broken up, decreasing their efficacy. For this reason, flocculant aid polymers are added after vigorous rapid mixing, either in a more gentle mixer or in a conduit downstream of rapid mixing, ahead of the flocculator. If filter aid is used, its efficacy may be improved by adding it far enough ahead of filters to allow the filter aid to disperse throughout the water going to all filters. Generally, mixing is not applied to clarified water, but if filter aid is dosed ahead of bends in pipes or channels, some hydraulic mixing could aid in dispersion of the chemical.

Physical Checks of Chemical Feed

Records of chemical dosage are useful for keeping track of chemical inventory as well as for developing historical data charts. For chemicals fed as liquids, the fundamental means of determining flow rates, as taught in hydraulics laboratory classes in engineering schools, is to measure volume of liquid transferred over time. A properly calibrated day tank can be useful for this, if the single day's depth change in the tank can be read to ±5 percent. Measuring to ±2 percent is better, as the precision of chemical usage calculations cannot be better than the precision of the volume and time measurements. Another approach to measuring chemical feed for flows in the range of less than 1 gpm (4 L/m) to about 10 gpm (about 40 L/m) is to use a plastic nutating-disk water meter. If the meter is resistant to corrosion and operated within its specified flow range, it can be expected to deliver accurate measurement for flow of chemical solutions.

An efficient method for determining chemical feed rates is to set up piping, valves, and a large graduated cylinder so a chemical feed pump can feed from the day tank or alternatively, can feed from the graduated cylinder. The cylinder should be sized so at maximum pumping rate, the change in chemical volume can be determined to within ±5 percent or preferably ±2 percent. After the cylinder is filled to the full mark, a stopwatch is used to measure time, and the volume of liquid pumped from the cylinder in the specified time period can be used to calculate the rate of flow. A photograph of such a system of pipes and valves is shown in Figure 9-3 in chapter 9.

By keeping records of pump settings and actual flow delivered, operators will be able to verify that the pump calibration curve is still valid. Pumps can wear with usage; therefore, checking present performance against the calibration curve for the pump when it was new is advisable. If the performance has changed, development of a new calibration curve is recommended. Having records of pump performance is also helpful when making decisions about pump repair or replacement.

Inspecting and Maintaining Feed Pumps

Long-term dependable performance of chemical feed pumps will be enhanced by periodic inspection and maintenance. Keeping spare parts on hand is advisable, especially those parts that are known to be subject to wear and thus needing periodic replacement. Extra parts or spare pumps should be available to ensure that failure of a part or a pump will not prevent the feeding of chemicals needed for effective treatment. Inability to

Feeding Lime Slurry

Transporting lime slurry can be difficult on any scale from pilot plants to very large treatment facilities. From the author's experience, the least amount of difficulties were encountered at pilot-plant scale when a container of stirred lime slurry was positioned higher than the water being treated and a peristaltic pump was used to pump the slurry downhill in tubing at a velocity of about 0.5 ft/s (0.2 m/s). When lime slurry can settle in a pipe or tube, clogging can result and cause inadequate lime feed. In full-scale plants, the use of open troughs or troughs with removable covers facilitates the needed maintenance of lime slurry conveyance facilities. If pipes are used to carry lime slurry, periodic pigging of the pipes may be needed to clean clogged areas in the pipes. This was done at an older plant with a very long lime slurry feed pipe. Providing for easy access to the pipes carrying lime slurry would facilitate the periodic pigging operations at plants where this is a necessary maintenance task.

feed a coagulant chemical could result in a plant shutdown, as rapid rate granular media filtration plants are required by regulations to practice coagulation when treating surface waters or groundwater under the influence of surface water. Again, records of inspections and repairs will be valuable in making decisions about pump replacement.

Chemical Handling and Feed at Lime Softening Plants

Feeding and handling lime generally is more challenging than feeding and handling metal coagulants. Whether quicklime (CaO) or hydrated lime ($Ca(OH)_2$) is used, these dry chemicals can cause dust problems. Hydrated lime is more expensive than quicklime, but the latter must be slaked, and this operation can be messy if not carefully maintained. Lime is fed as a dry chemical at softening plants. Operators should not breathe lime dust, therefore, dust control equipment must be used. A good maintenance program and careful handling of lime are important if the softening plant is properly maintained.

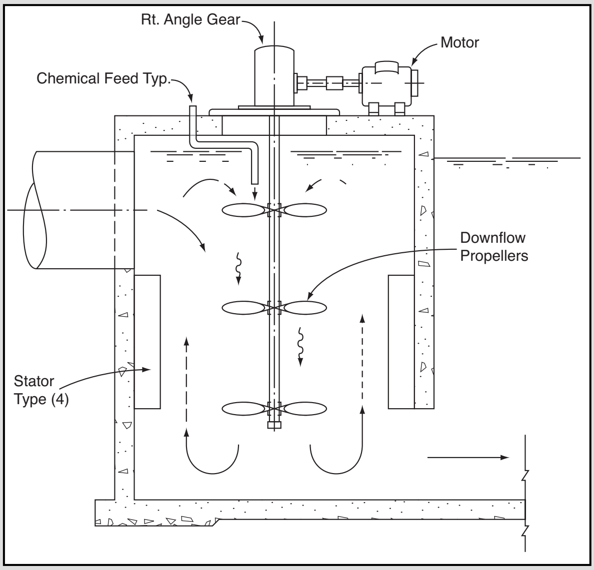
MIXING

After chemicals are added to water in a treatment plant, they must be dispersed thoroughly throughout the water. Generally, plant designers place more emphasis on effective mixing of coagulant chemicals than on mixing of chemicals such as chlorine, potassium permanganate, or powdered activated carbon (PAC). However, effective mixing contributes to efficient use of any added chemicals. The efficacy of mixing tends to be a factor determined by design engineers rather than operators, but plant staff should ensure that mixers are working as they are intended. At some plants operators have observed little difference in plant performance when the rapid mixer is turned off. This may indicate the rapid mixing design is not very effective rather than rapid mixing is not needed.

Chemical Mixing

Mixing for Coagulation

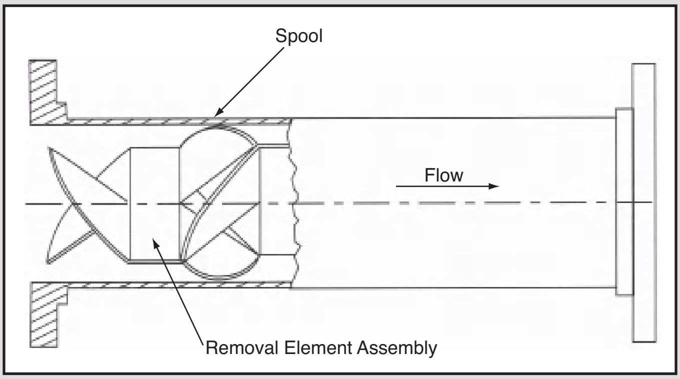
Rapid mixing concepts include a propeller mixer stirring a tank (back-mix reactor, shown in Figure 3-1), hydraulic jump, static in-line mixers (Figure 3-2), motorized in-line mixers (Figure 3-3), high-shear chemical induction mixers (Figure 3-4), and injecting chemical into the eye of a centrifugal pump impeller. Mechanical, or motorized, mixers have a fixed energy input based on the power of the mixer motor. In static mixers and hydraulic jump mixers, the energy input is related to the head loss incurred during mixing; therefore, energy input will be lower for low flows and higher for high flows. During the early days of conventional treatment, much less attention was given to effective rapid mixing than designers devote today. Old plants may not have rapid mixing that is as effective as that provided in modern plants.



Source: Water Treatment Plant Design, 2nd ed.

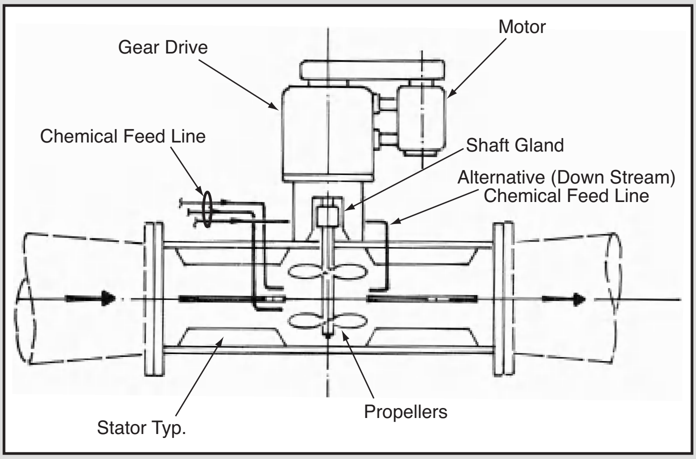
Figure 3-1 Backmix reactor and motorized mixer

Chemical Mixing (continued)



Source: Water Quality & Treatment.

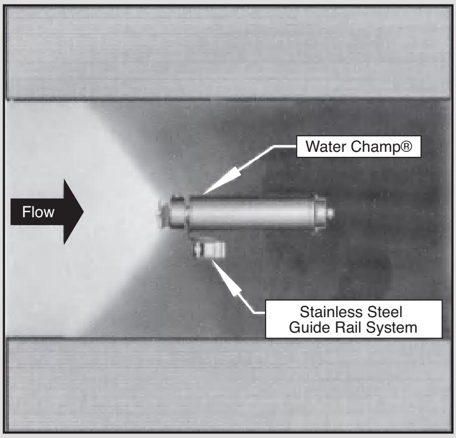
Figure 3-2 Static mixer



Source: Water Treatment Plant Design, 2nd ed.

Figure 3-3 In-line motorized mixer

Chemical Mixing (continued)



Courtesy of Siemens Water Technologies Corportation.

Figure 3-4 Water Champ® chemical induction system

When inorganic coagulants are added to water, the chemical reactions occur quickly except for the case of alum in very cold water, so mixing should disperse coagulant chemical very quickly throughout all of the water as uniformly as possible. When the less complex hydrolysis products of aluminum (e.g., $Al(OH)_2^+$) or iron coagulants contact particles in water, the positively charged coagulant chemicals destabilize the particles so they can form flocs or adhere to media grains in filter beds. Sweep floc coagulation generally is employed to form large flocs as an aid to sedimentation, and higher dosages of coagulant than those needed for particle destabilization are used. This also is generally the case at plants that use enhanced coagulation to attain greater removal of TOC.

If sweep floc formation is not needed, for example in a direct filtration plant or a plant using DAF clarification, using a rapid mix technique that attains very rapid dispersion of coagulant may be a way to decrease the coagulant dosage needed for effective treatment. Mixers that disperse coagulant chemical very rapidly include pump-injected mixers, motorized and static in-line mixers, a hydraulic jump (if chemical is dosed into the water uniformly across the entire width of the jump), and a centrifugal pump impeller. Backmix reactors do not provide the instantaneous dispersion of coagulant into all of the water in the reactor, and these reactors have wide variation in the residence times of water in the reactor. For coagulation, the water and chemical should come in contact very quickly, and the coagulated water should go on to the next treatment process.

Chemical Mixing (continued)

Mixing for Lime Softening

The approach for mixing at lime softening plants is much different than that for coagulation because of the different nature of chemical reactions in the two kinds of plants. Adding lime to hard water causes precipitation of calcium carbonate crystals. The presence of calcium carbonate crystals promotes rapid precipitation of more calcium carbonate. In this situation, the quick introduction of chemical and then movement of water to the next treatment process is not the more effective approach. For lime softening plants, rapid mixing does not need to be as intense as for coagulation plants, and the lingering of some calcium carbonate crystals in a backmix reactor would be beneficial for calcium carbonate precipitation. In some plants, a portion of the lime sludge from the sedimentation basin is recycled to the rapid mix to help promote formation of calcium carbonate. Use of sludge blanket reactors in which sludge circulates back to the mixing zone is also an approach used for lime softening.

Problems Related to Mixing

Inadequate mixing, or failure of mixing to attain uniform chemical concentrations before water leaves the mixing chamber, has the potential to create problems downstream in the process train.

An example of minimal mixing is the addition of chlorine about midway in a sedimentation basin at a treatment plant. Here, the chlorine did not mix thoroughly into the water until it had passed over the weirs and into the channel leading to the filters. Quiescent water promotes sedimentation, whereas turbulent water promotes mixing. At this same plant, PAC was added ahead of flocculation but mixing was ineffective and grey water containing PAC flowed down the side of a flume away from the entry points into the multiple flocculation basins. The chances of obtaining similar dosing of PAC in all basins were not good because the PAC was not uniformly mixed into the water that entered the flume.

At another treatment plant, one rapid mix unit fed two trains of flocculators and sedimentation basins that had unequal performance. The rapid mix chamber was square, with one stirrer providing turbulence, but two discharge lines led from the mixer to the separate treatment trains. The rotary motion imparted by the mixer to the water may have caused unequal distribution of chemical by the time the water exited the mixing chamber and thus caused the unequal performance observed in the two clarification trains.

Inspecting and Maintaining Rapid Mixers

Mixers with moving parts, such as motors, bearings, and gear drives, require periodic inspections to check for wear. When highly concentrated metal coagulants are introduced to water, depending on the mineral content of the raw water, precipitates may form. For this reason, inspection of coagulant discharge piping for accumulation of precipitates is advisable, as is checking for precipitates on mixing impellers and shafts. In-line mixers also can be susceptible to build-up of precipitates. Formation of scale and precipitates on shafts or impellers has the potential to alter the balance of rotating equipment and cause vibration, just as the loss of a wheel weight on an automobile wheel can cause the wheel and tire to vibrate when rotating. Excessive deposits on chemical delivery piping could block flow from one or more orifices, interfering with optimum usage of coagulant chemical. Clogging of some orifices in piping designed to deliver a chemical solution across the width of a weir or channel could cause temporary overdosing where chemicals can flow, and underdosing could occur in the region of the blocked orifices. Periodic inspections of mixers and chemical delivery piping are advisable, and as the propensity for development of precipitates is determined, the time interval for the inspections can be modified accordingly.

FLOCCULATION

Formation of floc is encouraged in most water filtration plants, with the possible exception of in-line filtration plants that employ only rapid mixing and filtration. However, in these plants, some flocculation is thought to occur as coagulated particles pass through the pores in the filter bed. Process equipment and facilities used for flocculation include baffled channels, paddle wheels, turbines, roughing filters, and reciprocating paddles. In wastewater treatment, flocculation of biological organisms is induced by the gentle turbulence caused by aeration in the activated sludge process. The principle behind all of these methods is use of gentle stirring that causes coagulated or sticky particles to collide and form larger particles.

Concepts

After water is coagulated, the destabilized particles are still very small, often colloidal in size. These destabilized particles have very, very slow sedimentation velocities and would not be removed readily in sedimentation basins, even though they could attach to grains of filter media and be removed in filters. To produce particles large enough to settle in the time available in sedimentation basins, coagulated water is gently stirred in the flocculation process. Production of settleable floc in the hundreds of microns is the goal of flocculation in many conventional filtration plants, and often some visible floc in millimeters is visible in basins. Large, settleable floc is neither needed nor desired at direct filtration plants or at plants using DAF as the clarification process. At these facilities, smaller, pinpoint floc in the tens of microns is more appropriate, and this can be attained by a shorter period of flocculation than that needed at conventional plants.

Flocculation facilities are designed to impart energy to water so the turbulence increases the rate of particle-to-particle collisions and results in faster formation of floc particles. The energy input in flocculation is expressed as Gt, where G is the velocity gradient and t is the retention time in the flocculator, in seconds. The velocity gradient is expressed in ft/sec per foot, or ft × sec^{-1} × ft^{-1} (m × sec^{-1} × m^{-1}). Thus, the units for velocity gradient are sec^{-1}. Time is expressed in seconds, therefore the Gt product is a dimensionless number.

Water treatment literature suggests that for plants employing conventional sedimentation (i.e., not ballasted flocs) Gt values in flocculation ought to be between 10,000 to 100,000. For a G value of 17 sec^{-1} and a 10-min flocculation time, the Gt product is 10,200. To attain a Gt product of 100,000 in 40 min of flocculation, the G value would be approximately 42 sec^{-1}, so 10,000 to 100,000 covers flocculation conditions for the range of flocculation approaches used in water treatment.

Initially in a flocculation basin or channel in a plant employing sedimentation, a higher level of energy input is needed as many small particles need to be brought together to form flocs. As floc sizes grow during flocculation, the floc can become more susceptible to breakage in the turbulence created by flocculation, therefore the energy input, or G value, is decreased. This can be accomplished by reducing the rotation speed of paddles or hydrofoils in the basin, or by reducing the area of paddles or hydrofoils in later stages of flocculation. Figure 3-5 shows a long, baffled flocculation basin in which water flows down the axis of the paddle drive shaft. All paddles rotate at the same speed, but the second and third flocculation zones have progressively smaller paddle area as compared to the first zone. In a hydraulic flocculator, spacing the baffles farther apart would decrease the energy input in the latter stage of flocculation.

The rate of floc formation decreases when water temperature is low. At treatment plants where water is cold on a seasonal basis, operators might consider increasing flocculation energy input. This process modification is used at some plants that experience cold water.

Types of Flocculation

Modern water treatment plants typically use mechanical flocculation, whereas historically baffled flocculation was used in early filtration plants, such as the Chain of Rocks plant in St. Louis, Mo. Each approach for flocculation can work effectively if properly designed.

In hydraulic flocculation, the energy input (head loss) decreases as flow squared (velocity squared) decreases, but residence time (which increases) is inversely proportional to the flow (which decreases). Lower flow rates have the overall effect of lowering the Gt energy input. This can be a disadvantage for hydraulic flocculation if a wide range of flow rates is encountered in a plant. An advantage for hydraulic flocculation is having fewer mechanical devices to maintain. A design that permits controlling energy input with flow rate at plants using hydraulic flocculation is the use of movable baffles that can be repositioned by operators to induce the desired head loss and energy input.

In process basins using mechanical flocculators, energy input to turbine impellers or to paddle wheels is independent of plant flow, and some process equipment is built so operators can change the energy input by changing the rotational speed of the impellers or paddle wheels. This gives operators more control over the *G* factor in *Gt* than typically can be attained with hydraulic flocculation.

Source: Logsdon.

Figure 3-5 Paddle wheel flocculator, with three stages of energy input achieved by decreasing paddle area for each stage

How Flocculator Type Relates to Overall Process Train

In a review of 21 filtration plants successfully operating at filtration rates of 4 gpm/ft^2 (10 m/hr) and higher, Cleasby and co-authors (1989) noted that different types of mechanical flocculators were appropriate for different treatment processes. For direct filtration plants operating with low coagulant dosages (particle destabilization), vertical shaft, multispeed hydrofoil type flocculators worked well. Paddle wheel flocculators worked well at conventional plants where settleable flocs were needed. Flocculation equipment that could produce small flocs was desirable in DAF plants.

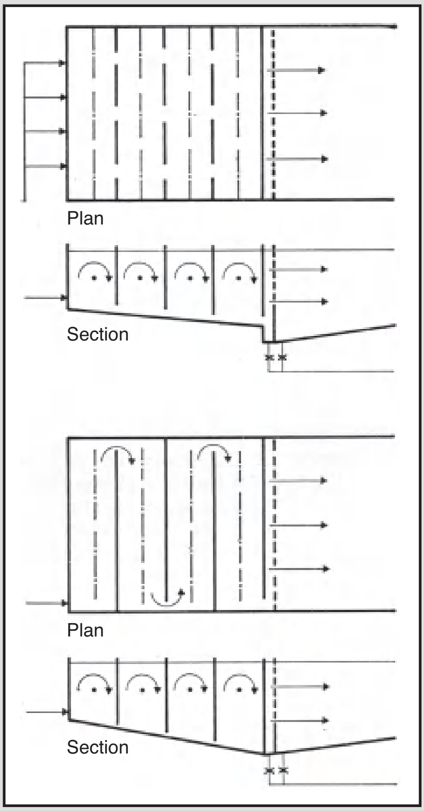
Importance of Baffling in Basins With Mechanical Flocculators

When mechanical flocculation is used, the flocculation process is designed to provide a specified energy input, or a range of energy inputs if tapered flocculation is used. Energy input, *G*, is one of the two factors related to flocculation. The other factor, flocculation residence time *t*, depends on the rate of flow through the flocculation basin, and this varies with plant flow. At some plants where a wide range exists between minimum and maximum flow on a seasonal basis, some process trains are shut down at low flow to keep the flocculation residence time within a desired range. This is a way to avoid having an excessively long flocculation time.

Even if a plant were base-loaded with the same flow every day, residence time would not be identical for all particles passing through flocculation basins. These basins are stirred, and a potential exists for short circuiting. The extreme example would be a flocculation basin stirred by only one paddle or vertical shaft pitched blade. This would be the equivalent of a backmix reactor in which residence times range from the shortest time for travel through the basin, perhaps substantially less than 10 percent of the theoretical residence time, to a retention time several times the theoretical residence time. This is a highly undesirable situation, as floc particles grow with energy input and time. When energy input is constant over the short term, as in mechanical flocculators, the variable determining floc size is the residence time. When tube or plate settlers are employed for high-rate clarification, floc particles settle better if they are all of a similar size, so ideally the flocculation basin would exhibit plug flow and the residence time would be identical for all floc particles. This is practically impossible to attain, but a closer approximation of plug flow can be attained as the flocculation process is subdivided into multiple chambers in series. In addition, long, narrow chambers with the inlet at one end of the chamber and the outlet at the other are better able to approximate plug flow than basins that are rectangular but with a width similar to the length. The effect of producing floc particles in a range of sizes is compensated for in blanket reactors where small flocs are enmeshed in the blanket, and to some extent in conventional sedimentation basins, where large flocs settle faster than small ones and can carry along the small ones when they collide.

Figure 3-6 shows diagrams of cross-flow and serpentine baffling patterns of flow in flocculation basins. Serpentine flow is more effective in approximating plug flow, and this flow pattern has been used at wastewater treatment plants to reduce the amount of short-circuiting in basins that disinfect treated wastewater before it is discharged to a receiving water. At a plant treating water from the Rocky Mountains, a flocculation basin with a cross-flow flow pattern was successfully changed to a serpentine flow pattern, which improved the effectiveness of plate settlers receiving the flocculated water (Bryant et al. 1990).

Importance of Baffling in Basins With Mechanical Flocculators (continued)



Source: Water Treatment Plant Design.

Figure 3-6 Plan view and section view of cross-flow baffle pattern and serpentine baffle pattern in flocculation basins

Monitoring Flocculation

Traditionally, flocculation has been much more difficult to monitor than coagulation. Both pilot filters and streaming current instruments offer the opportunity to obtain real-time assessments of the efficacy of coagulation. Until recently, no instrumentation offered the hope of real-time assessment of floc condition, so operators relied on visual observations. This has changed somewhat with development of the FlocMonitor (Drewes et al. 2007), a device that can perform in-situ sampling and analysis of the size of flocs in a flocculation basin or in the water discharged from such a basin. This device is in an early stage of development and use, therefore, until more experience is gained using it, the appropriate applications may be for direct filtration and DAF, where small floc rather than large sweep floc, is desired.

A procedure commonly used at plants is to visually check the size of floc produced as it exits the flocculation basin or enters the sedimentation basin. Also, if producing a settleable floc is a goal of treatment, substantial changes in the appearance of the water in the flocculation basin will occur between the entry and exit of the basin. Water entering a flocculation basin has a cloudy or turbid appearance, but when exiting the basin, it ought to look fairly clear, and if sedimentation follows flocculation, visible settleable flocs should be present.

Inspection and Maintenance of Equipment and Basins

Mechanical flocculation equipment requires periodic inspections and maintenance. Paddle-wheel flocculators are designed so that a single paddle wheel can cover the entire width of a floc basin; thus, a basin with three chambers for flocculation would have only three paddle wheels with associated chain drives, supports, and bearings. Underwater moving parts and bearings are vulnerable to wear and are not as easy to inspect as equipment that is above water, so this aspect of paddle-wheel flocculator maintenance is challenging. On the other hand, all but a portion of the vertical shaft and the impeller are above water when vertical turbine flocculators are used. A drawback of these units is that they generally are designed to treat water in a zone where the length and width are similar. Thus, for a long narrow portion of a floc basin where one paddle wheel might suffice, two, three, or four turbine units would be needed. This means more motors, gear drives, and bearings will need to be checked and properly maintained, although all of this equipment is above water and more easily accessed.

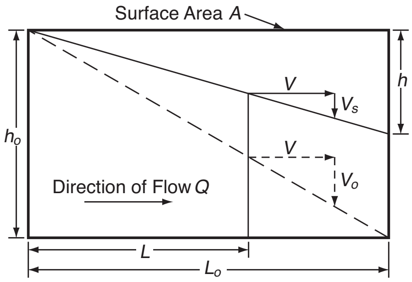
Lubrication of the moving parts in flocculation equipment must be maintained to minimize wear. Maintenance workers should be careful to avoid spilling lubricating grease or oil into the water being treated in flocculation basins. Also, checking for leaks and drips of lubricants from drive units into the water is a good idea.

Periodic inspection of flocculation basins is important, and timing this with drawdown and inspection of sedimentation or DAF facilities in the same treatment train can minimize time in which the train is out of service. If wood baffles are used in flocculation basins, checking on the condition of the wood is advised. When a flocculation basin is drained for inspection, the location of excessive deposits of floc may indicate the presence of dead zones where little flow occurs.

CLARIFICATION

Concepts of Sedimentation and Flotation

Sedimentation basins were used in the latter part of the 1800s in an attempt to clarify river water used for public water supplies. At some facilities, coagulant chemicals were added. After George Fuller's work at Louisville demonstrated that coagulation, sedimentation, and filtration could dependably treat Ohio River water, numerous water utilities



Source: Hansen and Culp 1967.

Figure 3-7 Ideal settling. Particles with settling velocity equal to or greater than V_o will settle to bottom of basin. Only a fraction of particles with settling velocity less than V_o, such as V_s, will settle to bottom of basin.

built filtration plants employing a conventional treatment train in the United States by the 1940s.

Particles settle in water because their density is greater than the density of water. The greater the difference in the density of the particle versus that of water, the more rapidly that particle can settle. Thus, floc formed in a lime softening process settles more rapidly than floc of the same size formed at a plant treating low-turbidity water with large dosages of metal coagulant for removal of color and NOM. Settling velocity also is related to the viscosity of water, so as viscosity increases with colder temperature, settling velocity decreases if particle size and density are held constant. As discussed previously, larger particles settle faster than smaller ones of the same density.

A concept of settling proposed by Alan Hazen about a century ago is still used to explain sedimentation of particles in basins, as illustrated in Figure 3-7. As particles pass through the settling basin, particles that start at the top of the water in the quiescent zone and settle at a velocity sufficient to reach the bottom of the basin or the sludge that has settled in the basin before leaving the quiescent zone (the particles with a settling velocity $\geq V_o$) will be removed from the water. Particles with a settling velocity less than V_o can be removed if they enter the quiescent zone at a depth sufficient to enable them to settle to the bottom before leaving the quiescent zone. However, those entering at a higher level in the basin will not settle to a depth that results in particle removal, as illustrated by the trajectory of the particle with settling velocity V_s. An outcome of this concept for sedimentation is that a shorter residence time would result from a shallow basin. A very shallow basin could carry a large flow only if it was very wide, but such basins are not hydraulically stable, so the idea of using very shallow basins did not become practical until tube settlers and plate settlers were developed (Hansen and Culp 1967).

The simplifying assumptions of Hazen's concept are that water flows horizontally across the quiescent zone under plug flow conditions, each particle in the water is discrete, and no flocculation occurs during settling. These simplifications are not likely to

Effect of High Wind on Large Sedimentation Basins

At large water filtration plants, the large size of conventional sedimentation basins can make them susceptible to process upsets by high winds. If sustained high winds are expected in a location where such large basins are to be built, designers should consider whether the high winds might set up a flow pattern in water at and near the top of the basin. This could result in water moving toward the basin wall and then diving to the bottom of the basin. Wind-induced circulation might result in short-circuiting and poor basin performance in extreme cases. Basins with a length to width ratio of 3:1 to 5:1, with the narrow dimension (width) parallel to the direction of the prevailing wind, would be less susceptible to flow upsets by wind than basins with the length parallel to the direction of the wind.

be totally applicable in a real sedimentation basin. If flocculation does occur as particles settle and if the larger flocs have the same density as the smaller flocs before aggregation occurred, the larger flocs should settle faster than smaller ones. Thus, in a deep sedimentation basin, in contrast to a jar-test jar, sedimentation velocity has the possibility of increasing with depth. Samples are extracted after only a short travel distance in the jar test procedure, so additional flocculation is much less likely in the test jar as compared to the full-scale basin. This may be offset, though, by nonhorizontal flow in a full-scale basin, whereas if the jar-test jar is manipulated carefully, vertical currents can be minimized.

Summarized very briefly, the concept for flotation is similar to that for sedimentation. If particles can rise to the water surface or to the accumulated floc resting on the water surface and protruding slightly into the water before the water flows out of a flotation process basin, those particles will be retained in the basin to be removed later when the floated floc is removed.

Conventional Sedimentation Basins

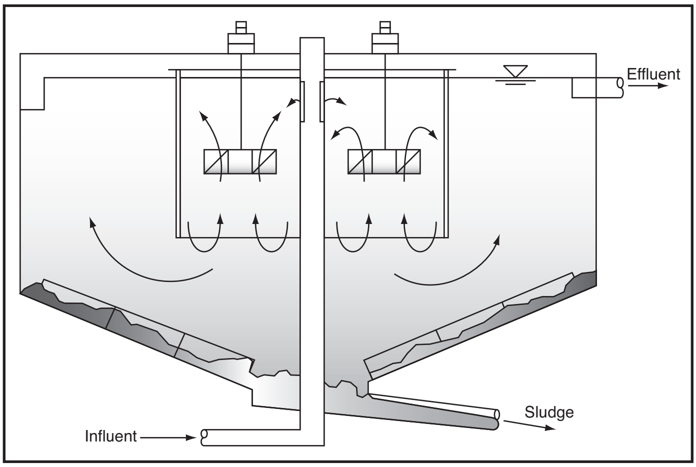
Conventional sedimentation basins that provide several hours of detention time for clarification are not commonly used in new plant designs, but many older plants have these basins. Some older conventional sedimentation basins at plants using coagulation may not have sludge removal equipment, so they are removed from service and cleaned manually on a periodic basis. If sludge removal is performed manually, scheduling basin cleaning and maintenance during times when water demand is below average is advisable. Sedimentation basins at lime softening plants are more likely to have sludge removal equipment because of the larger amount of sludge produced at these plants.

High Rate Sedimentation Processes

Conventional sedimentation basins with overflow rates of approximately 0.2–0.5 gpm/ft^2 (0.5–1.2 m/hr) and detention times of around 4 hours that were commonly used in large treatment plants in the 1940s occupied a considerable footprint, with commensurate capital cost. Therefore, processes to hasten sedimentation were sought throughout a considerable portion of the 20th century. Several of these processes are described in this section.

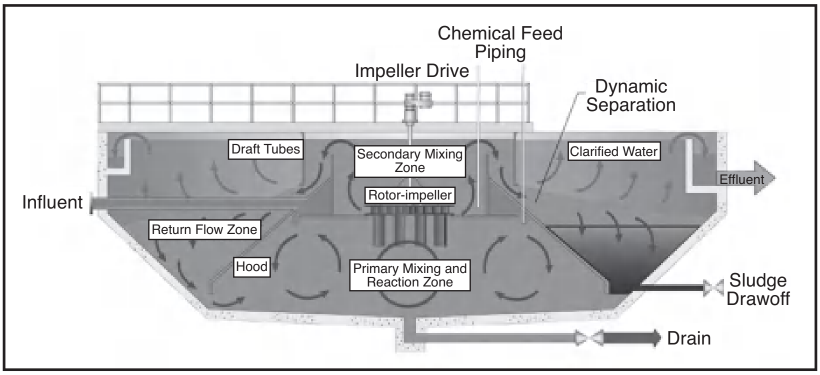
Solids Contact Clarifiers and Sludge Blanket Clarifiers

An early approach to eliminating large sedimentation basins and long detention times was to use flocculation clarifiers (Figure 3-8) and solids contact clarifiers (Figure 3-9). These types of process equipment combine a central mixing zone, flocculation, and an outer sedimentation zone in one basin. In some process equipment, the mixing and flocculating zones are separated from the sedimentation zone by a baffle wall. Recirculation



Courtesy of WesTech Engineering Inc.

Figure 3-8 Flocculator / clarifier



Courtesy of Degremont Technologies.

Figure 3-9 Blanket clarifier

of water within the mixing zone, mixed with incoming water and sludge drawn from the bottom of the basin, promotes chemical reactions and floc formation. The units can achieve high solids in the mixing zone and may be operated with a sludge blanket in the settling zone. In sludge blanket clarifiers, the upward flow of water through the sedimentation zone causes floc to rise and form a sludge blanket. Some sludge blanket and solids contact clarifiers are designed so the cross-section of the sedimentation zone increases as water moves upward toward the weirs or launders. This causes the rise rate to decrease and is helpful in preventing the blanket from washing out of the sedimentation zone.

These process units have been operated at overflow rates of about 1.8 gpm/ft^2 (4.4 m/hr) for softening and about 1.0 gpm/ft^2 (2.4 m/hr) for chemical coagulation applications. Pulsed sludge blanket clarifiers were also developed, with later designs utilizing plate settlers to improve performance, and these units have been operated with loading rates of 2.5 gpm/ft^2 (6.1 m/hr) and higher.

Blanket clarifiers and reactor clarifiers are intended to operate on a continuous basis, 24 hours per day, and if used at coagulation plants, are most effective if they can be used in a base-loaded mode. When this process equipment is operated at a constant rate of flow, the blanket level within the sedimentation zone should not rise or drop substantially. If the rate of flow decreases, the rise rate decreases, causing the blanket level to drop. If the flow increases, the higher rise rate will cause the top of the blanket to move closer to the effluent weirs or launders. Daily increases and decreases in flow in a blanket clarifier, and worse, on-and-off operation of such process equipment, can cause serious problems.

Unsteady operation of this kind of clarification equipment has been observed at two plants where waterborne disease outbreaks took place. A giardiasis outbreak involving a

Floc Density and Operation of Solids Contact Clarifiers and Sludge Blanket Clarifiers

When floc formed in pretreatment has a density only slightly greater than the density of water, it settles slowly. Examples are the floc formed by coagulation of low-turbidity water and floc formed by coagulating water with color but little turbidity. In process basins employing upflow clarification, the low-density floc in a floc blanket can be disrupted and washed out of the clarifier when the flow is increased in the clarifier, resulting in a rise rate that exceeds the settling velocity of the floc. When chemical pretreatment produces low-density floc, these clarifiers are more suitable for application at plants that can be operated at fairly constant flow rates rather than at plants that are subjected to frequent rate increases. On the other hand, floc formed in the lime softening process tends to be considerably denser than water, so solids contact clarifiers and sludge blanket clarifiers are less susceptible to poor performance caused by flow increases at lime softening plants.

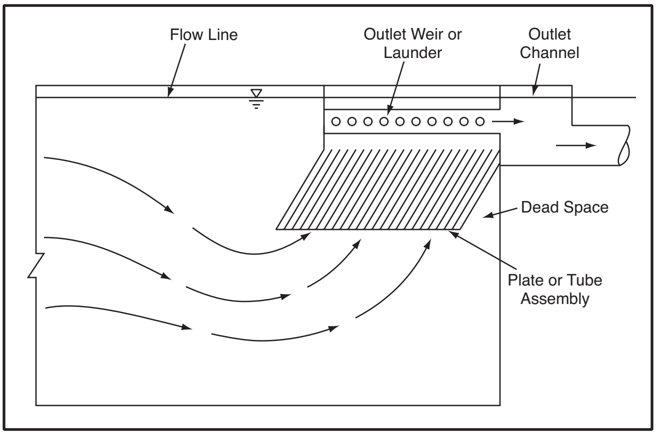
new water filtration plant with a blanket clarifier in New England was thought to have been partially related to the attempt of plant staff to pace water production in the plant to system demand. This operating mode tended to wash out floc each morning when the flow rate through the plant was increased and inhibited development of a good sludge blanket needed to improve clarification (Lippy 1978). An outbreak in western Canada was in part related to the on–off operation of a solids contact clarifier. In that instance, about a month's time was required to re-establish an effective blanket after the clarifier was returned to service following maintenance work (Hrudey and Hrudey 2004). Both of the outbreaks associated with variable rate operation of the clarifiers occurred at plants using coagulation.

If on–off operation of a blanket clarifier were practiced at a lime softening plant, stopping operation of sludge removal equipment and restarting it after the lime sludge had settled could prove difficult. At lime softening plants with multiple units, taking one or more out of service during extended times of low flow may be a better approach than operating all units at a rate of flow that is so low that formation of an effective sludge blanket does not occur.

Blanket clarifiers, particularly those at coagulation plants treating low-turbidity surface water, can be upset by rapid temperature changes that cause density differences in water in the clarifier. The density differences can cause short-circuiting and impaired settling. In a worst-case situation, the sludge blanket can be lost. One possible remedy for an upset blanket clarifier or solids contact unit is a temporary reduction in flow through the plant to reduce floc carry-over to the filters.

Tube Settlers and Plate Settlers

Inclined tube settlers were developed in the 1960s as a practical approach to the problem of providing short distances for sedimentation while also providing for narrow sedimentation basins that had lateral hydraulic stability (Hansen and Culp 1967). They resolved the question of how to apply Hazen's sedimentation theory and increase the settling surface area to achieve settling in a short time. The tube settler concept involved placing a bundle of inclined tubes in a settling basin, positioned so that flocculated water passed upward through the tubes. The vertical distance from the *ceiling* to the *floor* of the inclined tube was measured in inches (centimeters) instead of feet (meters). For example, a common angle of inclination for a tube is 60°, and for such a tube with an internal distance of 2 in. (5 cm) from wall to wall, the vertical distance from the top of the inclined tube's wall to the bottom of the tube's wall is 4 in. (10 cm). A bundle of tubes provides many *false floors* onto which floc particles can settle, agglomerate, and slough down to the bottom end of the tube, to be discharged and settle to the bottom of the settling basin. Figure 3-10 illustrates how tube settler bundles are used in a sedimentation basin, and Figure 3-11 shows the clarity of settled water at a plant using tube settlers.



Courtesy of Kerry E. Dissinger, Brentwood Industries, Inc.

Figure 3-10 Tube settler installed in sedimentation basin

Source: Logsdon.

Figure 3-11 Tube settlers in settling basin producing very clear effluent

Tube settlers were initially employed in small, pre-engineered package plants with the objective of maximizing treatment capacity in a small volume. They have also been used to uprate conventional sedimentation basins as well as for new sedimentation basins specifically designed for the shorter detention time appropriate for basins with tube settlers. Gross overflow rates range from 1 to 3 gpm/ft^2 (2.4 to 7.3 m/hr), depending on the settling characteristics of the floc that is formed in pretreatment.

Tube settlers in small package or pre-engineered plants tend to be placed at shallow angles of inclination. They are cleaned by backflushing water through the tube settlers. Periodic flushing of the steeply inclined tube settlers may be needed if floc tenaciously adheres to the tubes and does not slough out.

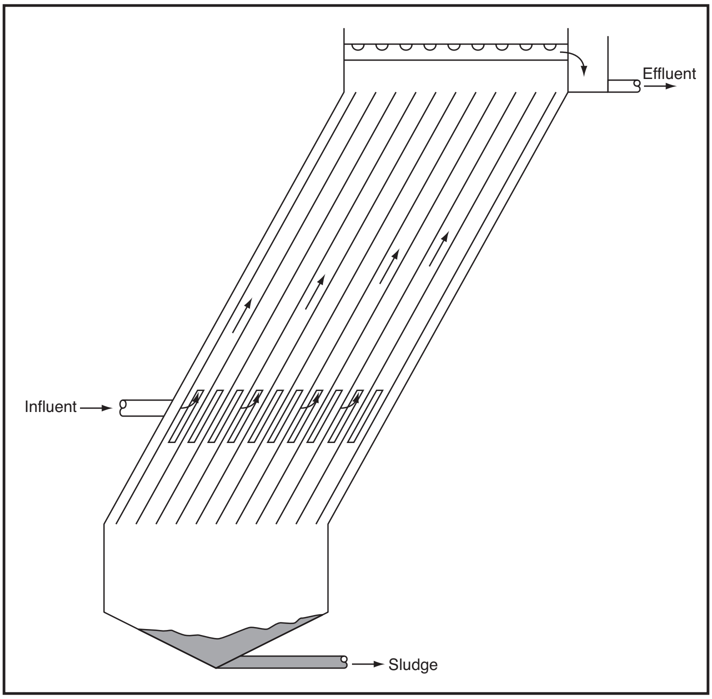
Often tube settlers are fabricated from light-weight, noncorroding material such as plastic. This eliminates corrosion problems and decreases the weight of the tube bundles that are supported near the upper level of the basin. If tube settler modules are made of plastic, which can be flammable, repair work that generates intense heat (e.g., welding) has the potential to deform tube settlers or cause them to burn.

Somewhat analogous to the inclined tube settlers is the European concept of inclined plate settlers that operate with gross overflow rates in the range of 2 to 4 gpm/ft^2 (5 to 10 m/hr). Treatment is enhanced by the formation of uniform-sized floc. Plate settlers have been used in large plants as well as in some package plants. These are not as easy to retrofit into existing sedimentation basins as they often require basins that are deeper than some conventional basins. A schematic diagram of plate settlers is presented in Figure 3-12.

Contact Clarifiers

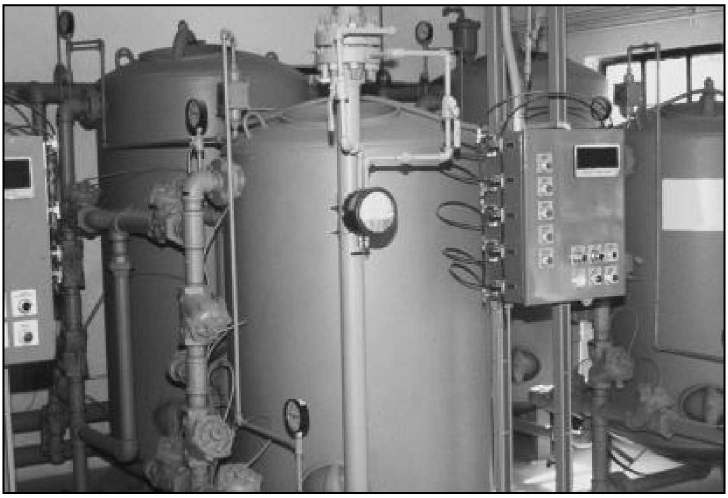
Contact adsorption clarifiers (CAC), or roughing filters, have been used in some package plants, with a multimedia filter placed in series after the CAC unit. These are produced for operation in both pressure filtration (Figure 3-13) and gravity filtration modes (Figure 3-14). The CAC consists of a bed of coarse filter material through which coagulated water passes, making many twists and turns. This aids in flocculation and removal of floc, preparing the water for filtration in a dual- or mixed-media bed. Large CACs can serve as stand-alone pretreatment facilities ahead of conventionally constructed filters. Overflow (or filtration) rates for CACs and roughing filters can be as high as 10 gpm/ft^2 (24 m/hr), with application generally limited to low-turbidity sources with low coagulant demands.

When used in smaller, pre-engineered package plants, a CAC process unit is placed ahead of a multimedia filter, and the two processes are operated in series. Unlike other clarifier processes in which floc is removed continuously as water passes through the unit, a CAC performs a filtration function, so a CAC requires periodic flow interruption to clean out accumulated floc. If head loss builds up faster in a CAC unit than in the granular media filter following the CAC, filtration must be stopped while the CAC is cleaned, if the two pieces of process equipment are piped in series. For a small system



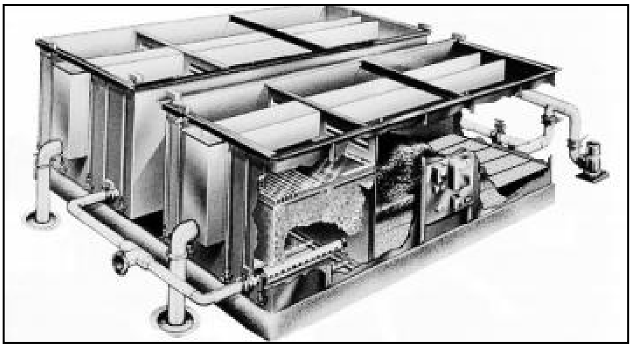
Source: Edzwald et al. 1998.

Figure 3-12 Plate settler



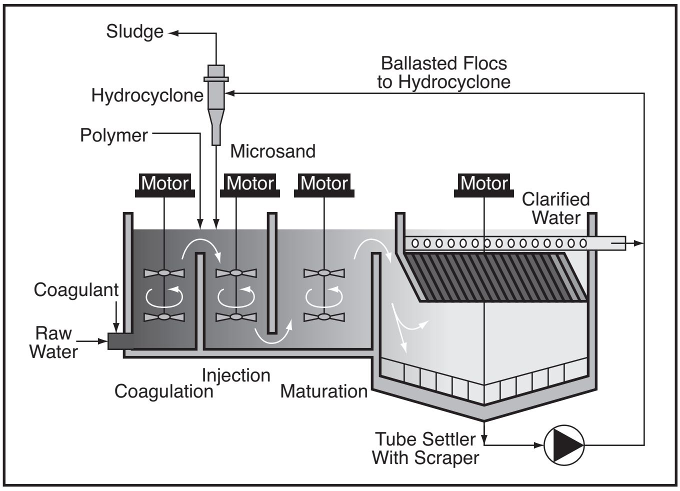
Source: Logsdon.

Figure 3-13 Contact adsorption clarifier and pressure filtration in series at small water system



Courtesy of Siemens Water Technologies Corporation.

Figure 3-14 Contact adsorption clarifier and multimedia gravity filter in series



Courtesy of I. Krüger, Inc.—A Veolia Water Solutions & Technologies Company.

Figure 3-15 Ballasted flocculation process diagram

operating a single CAC unit and filter, if the filter is not backwashed each time the CAC unit is taken out of service and cleaned, operators should be very careful restarting the filter when treatment resumes. Chapter 4 presents a discussion of the risks of restarting filters that have not been backwashed, along with suggestions for procedures to follow if filters absolutely must be restarted without a backwash.

Ballasted Flocculation Clarifiers

A clarification technology developed in Europe is the ballasted flocculation clarifier, which can attain overflow rates of 16 gpm/ft^2 (39 m/hr) or higher. A schematic diagram of the process is shown in Figure 3-15. Ballasted flocculation involves coagulation of raw water and the addition of fine sand (60 to 100 μm), followed by polymer addition and

Contact Adsorption Clarifiers

When multiple CAC units are used at a plant, combining CAC effluent into a common flume and then providing filter influent to multiple filters from that flume is a much better approach than having multiple sets of independent CAC units with each followed by its own filter and no interconnection capability. The ability to share clarified water among multiple filters eliminates the temptation to stop a dirty filter and restart it without backwashing because the filter had not reached terminal head loss when the CAC unit ahead of it had to be taken out of service for cleaning. Providing for interconnection of multiple CAC units and filters also enables operators to remove a single unit process from service for maintenance instead of taking an entire treatment train out of service.

Design of Sand Recirculation Equipment

Silica sand that is pure quartz has a Moh hardness value of 7, whereas the Moh hardness of steel can range from 5 to 8.5. The microsand used in ballasted flocculation has the potential to be abrasive when it is pumped back to the cyclone separator to be separated from the floc and reused. The potentially abrasive nature of the sand should be considered when pumps, valves, and piping for sand recirculation are designed. Use of abrasion-resistant piping and pumps, and gentle bends in pipe rather than abrupt, 90° bends should be considered.

mixing to cause the coagulated particles to stick to the sand. After a period of stirring (the maturation process) to form the floc, a short detention time is provided to attain effective sedimentation of the relatively dense floc that has been weighted by the very fine sand. The weighted floc that settles out is continuously pumped through a cyclone separator where sand and floc are separated so the sand can be reused.

Management of ballasted flocculation clarifiers can be more complex than management of other clarifiers involving sedimentation because of the necessity to feed both a coagulant and a polymer, to manage the cyclone separator, and to add a small amount of make-up sand because of sand losses in the cyclone.

Some potential treatment difficulties can be encountered with this process. If coagulation is not effective, coagulated particles will not exist to bind to the fine sand when it and polymer are added, and filtered water turbidity will be high. If coagulation is effective but polymer is underdosed, attachment of floc to fine sand will be less effective than desired. The result is passage of unweighted floc to the clarifier, where it is not sufficiently dense to settle at the high overflow rate, so excessive quantities of floc will appear in filter influent. Overdosing the polymer can cause an excessive rate of head loss increase in filters and premature ending of filter runs. Floc also can carry over if the quantity of sand circulating in the process is insufficient to attach to the floc and increase its density, so periodic checking of the quantity of sand in circulation is needed to keep the appropriate concentration of fine sand in the system.

Advantages of ballasted flocculation clarification include the ability to start up or stop in a short time, depending on water demand in the system and flow through the plant. In addition, a wide range of source water quality can be treated using this clarification process. When managed carefully to ensure correct coagulant and polymer dosages, ballasted flocculation can be highly effective.

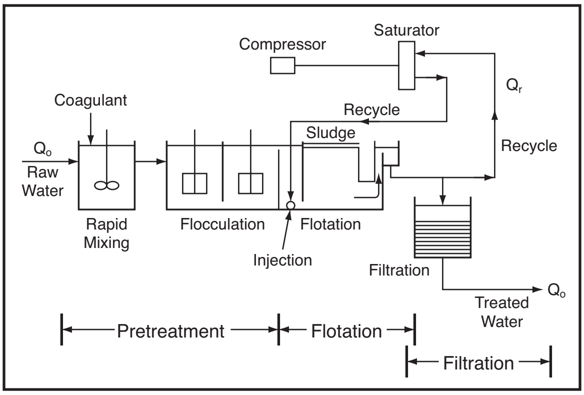
Management and Maintenance of Clarifiers

Conventional basins, and to some extent, higher rate sedimentation processes, are susceptible to some problems, perhaps the most serious of which is short-circuiting. When water travels through a basin in a time shorter than the theoretical retention time, to some extent short-circuiting occurs. Attaining perfect plug flow in clarifier basins is not possible, but serious deviations from plug flow decrease the time during which particles in the water can settle out, resulting in higher settled water turbidity.

Causes of short-circuiting include poor inlet and outlet design, wind-induced currents in the basin, and density currents. Density differences can result from rapid changes in source water temperature or from sudden, large increases in raw water turbidity. Warm water is less dense than cold water; therefore, if temperature changes quickly, warmer water will float over the colder water in a basin, whereas colder water entering a basin will sink to the bottom of the basin under the warm water. In each case, water can reach the basin effluent prematurely because the entire cross-section of the basin is not utilized as a result of the short-circuiting. Other short-circuiting effects can be induced by a strong and sustained crosswind at sedimentation basins.

Performance of sedimentation facilities can be degraded if sludge or algae growths build up on weirs and disrupt the intended flow pattern. Basin performance also may decline if sludge builds up excessively in the basin, either because the time between manual cleanings is too long or because mechanized sludge removal equipment fails to perform adequately. Excess sludge reduces the effective volume of the basin, reducing the basin's retention time. The degradation of organic matter in sludge and development of anaerobic conditions in the sludge at the bottom of a basin presents another potential clarifier basin problem. Under anaerobic conditions, oxidized iron and manganese precipitates can be reduced to their soluble oxidation states and released into the water. T&O problems also might occur if substantial quantities of biodegradable matter are captured in the floc, settle to the bottom of the basin, and then decay.

Sedimentation basins that have sludge removal equipment need periodic inspections. Sometimes basins must be drained so maintenance can be performed on equipment that operates underwater. Chain drives, shafts, seals, and bearings require attention. Annual inspections should be conducted during times of low water demand.



Courtesy of James Edzwald, Visiting Professor, Clarkson University.

Figure 3-16 DAF process train diagram

Dissolved Air Flotation Clarifiers

For treatment of colored or low turbidity waters and those containing algae, European practice has differed from the U.S. practice of coagulation, flocculation, and sedimentation. Scandinavian countries and the United Kingdom use DAF for treatment of such waters. Effectiveness with respect to turbidity removal varies somewhat depending on the nature of particles; the presence of heavier particles tends to reduce efficacy of DAF.

In the DAF process, as depicted in Figure 3-16, a clarified-water side stream of about 6 percent to 10 percent of the raw water flow is pumped at high pressure (60 to 80 psi or 420 to 560 kPa) into a saturator. At this point, water supersaturated with air can be returned to the DAF clarifier where coagulated and flocculated water is introduced into the DAF clarifier. When the supersaturated water returns to atmospheric pressure in the clarifier unit, many microscopic bubbles are released, rising to the top of the water and carrying floc. This was shown in jar test equipment in Figures 2-3 and 2-4. In a properly operated unit, the water containing the microscopic bubbles looks milky, as shown in the pitcher of water in Figure 3-17. Large bubbles and turbulent, frothy water are indicative of failure to form the microscopic bubbles that carry floc to the water surface and are a symptom of serious process problems likely related to re-entry of recycled flow into the clarifier. DAF clarifiers can be operated at overflow rates of 4–6 gpm/ft^2 (10–15 m/hr) and higher, so this process is a high-rate clarification process.

Although the United States has lagged behind European countries in the use of DAF clarification, about 100 plants are presently operating in the United States. The largest to date is the 75 mgd (280 ML/d) plant in Greenville, S.C., but at the time of publication of this handbook, a 290 mgd (1,100 ML/d) plant was under construction to treat New York City's Croton supply.

Courtesy of James Edzwald, Visiting Professor, Clarkson University.

Figure 3-17 Pitcher of water with water supersaturated with air, showing bubble cloud rising toward water surface

Unlike blanket clarifiers, DAF clarifiers do not require steady-state operation. However, if flow through the process is changed, the recycle rate of flow probably needs to change as well to maintain the same percentage of recycle. Another operating parameter that affects process performance is saturator pressure. A sufficient volume of dissolved air should be provided to form air bubbles capable of lifting the suspended solids in the flocculated water to ensure successful operation of the clarifier. This is attained by a combination of the percentage of recycle flow through the saturator and the air pressure maintained in the saturator. Higher concentrations of suspended solids, such as algae or turbidity in the raw water, will need a greater volume of dissolved air for effective removal.

Correct management of pretreatment chemistry is a must for effective operation of a DAF clarifier, and as discussed in chapter 2, chemical dosages can be determined by jar tests. In a pilot-plant evaluation of both direct filtration and DAF followed by filtration, the pretreatment chemistry that was working well for direct filtration was used when the DAF clarifier was brought online for testing, and very effective treatment was attained in the DAF unit. In fact, within a half hour of startup, the clarified turbidity produced by the DAF process was less than 0.5 ntu. This demonstrated

Engineering Considerations for DAF

DAF clarifiers can be designed as an independent process ahead of filtration or DAF, and filtration can be combined in a single process basin in which floc floats to the top of the water over the filter while clarified water flows down and through the filter media. Coupling the two processes may provide capital cost savings, but it does limit the clarifier rate to the filtration rate and may decrease the operational flexibility of the treatment plant.

DAF clarifiers generally are covered to prevent high wind or intense rain from disrupting the floated floc and causing it to sink. Also, DAF clarifiers need to be housed at locations where water cannot freeze in cold weather, because the water surface where floc accumulates must not freeze.

A serious limitation for DAF is the tendency of floc containing large amounts of clay and other soil particles to sink instead of float. Therefore, DAF is not an appropriate clarification process for turbid waters and is generally applied to waters having turbidity of 20 ntu or lower. The process is capable of treating water with occasional excursions to values as high as 50 to 100 ntu (Edzwald et al. 1998). The limit on the treatability of high-turbidity water would to some extent depend on the density of the particles causing the turbidity. Very fine but dense particles would result in the formation of floc with higher density than floc consisting of algae and precipitated coagulant chemical.

In contrast to sedimentation sludges having solids concentrations of less than 1 percent, the floated solids removed from a DAF clarifier can have a solids content ranging from 1 percent to 3 percent. This is especially true if the float is scraped off mechanically rather than washed out by raising the water level in the clarifier so the floated floc washes out. DAF sludge may not flow as readily as the wetter sludges produced in sedimentation basins, but the higher solids content is advantageous if the sludge has to be dewatered to prepare it for disposal.

the ability of this process to be brought online quickly and achieve effective treatment, if correct pretreatment chemistry has been identified.

Specialized DAF jar test devices have been manufactured and can be used to determine coagulant dosages. Less elegant but workable devices to saturate water with air under pressure and then discharge a measured volume of the water into the bottom of a single jar-test jar probably can be produced by water utility staff with skills in plumbing and plastics fabrication.

As a DAF clarifier is operated, floc is carried to the top of the water by the air bubbles, where the floc accumulates. A layer of scum forms on the water surface and gradually grows thicker as the operation continues. At some point in time, the accumulated floc, called *float*, becomes so thick that it must be removed from the water surface before it begins to break apart and sink back down into the clarified water. As time passes, the float next to the clarifier wall may begin to adhere to the wall. If this happens, spraying water on the clarifier wall for a short time before the float is removed and in the early stage of removal can help alleviate this condition.

Maintenance tasks at a DAF plant involve recycle pumps, air compressors that maintain pressure in the saturator, the condition of the saturator, and the nozzles that deliver supersaturated water into the clarifier. Periodic inspection of the saturator packing to verify that there is no the build-up of precipitates and slimes should be performed.

DAF clarifiers have multiple discharge ports or nozzles through which supersaturated water is introduced into the clarifier. If each port has an adjustable valve that is used to balance flow across the clarifier, checking and adjustment of valves is performed to keep flow in balance and to ensure that very small bubbles are produced. Bubbles that are too large have a greater tendency to disturb floated floc and prevent floc from rising to the top of the water.

Monitoring Clarifier Performance

Particles are removed in clarifiers by four different approaches:

1. Sedimentation, sometimes aided by enmeshment in a floc or sludge blanket
2. Sedimentation aided by using fine sand to increase floc density and settling velocity
3. Filtration in contact clarifiers
4. Flotation in DAF clarifiers

As a result of the different processes used for clarifying water before filtration, monitoring of clarifier performance tends to differ from process to process. The common monitoring approach is clarified water turbidity, which is the goal regardless of the process used. Also if a visual check of clarifier effluent reveals cloudy water, clarification problems and possibly pretreatment chemistry problems exist. Other monitoring techniques are somewhat more process-specific.

Observation of uncovered sedimentation basins from a high elevation helps detect problems with inlet flow patterns (Hudson 1981). A localized cloud of floc may indicate an inlet flow distribution problem. If a serious problem with flow in a clarifier is suspected, this may be checked by either going to the highest location near the sedimentation basin, or by flying over and photographing a sedimentation basin at low altitude. Much more can be seen by observing the water from high above than by looking at water from several feet above the water surface, standing beside the basin. At basin level, a good sign is clear water with perhaps a limited amount of floc flowing over the launders. Cloudy water indicates a problem.

Blanket clarifiers that are working well will have clear effluent with a visible floc blanket at an appropriate distance below the launders, as determined by experience.

If the floc blanket resembles a bank of low-lying clouds but has one or more zones where floc is rising higher like thunderclouds, investigation should be made as to why flow patterns seem to be lifting floc in localized areas.

Monitoring contact clarifiers is somewhat akin to monitoring filters. Knowing the head loss across a contact clarifier is a way to estimate the extent of clogging in the coarse filtration media. With this information, cleaning of the clarifier by washing out the accumulated floc can be scheduled.

The ballasted flocculation process involves operation of more equipment, so more monitoring is needed. The rate of withdrawal of the weighted floc from the sedimentation basin (the recirculation rate) should be tracked. Checking the quantity of sand in the maturation process tank on a daily basis ensures that adequate sand is present to bind with the floc that forms. Monitoring the status of the mixer in the maturation tank can verify that this equipment is working properly. Checking the torque on the scraper in the settling tank is done to determine whether solids are building up so rapidly that removal might be beyond the capacity of the sludge scraper.

Like ballasted flocculation, DAF has a recycle flow external to the clarifier and equipment associated with that recycle flow. Rates of flow for recycle pumps and the pressure in the saturator should be monitored. The condition of the floated floc should be checked periodically, so the float can be removed from the clarifier before it starts to break up. A visual inspection of the area where flocculated water and recycled water enter the clarifier is valuable for identifying flow distribution problems and observing the condition of the air bubbles formed as recycled water is introduced into the flocculated water. Appearance of large bubbles above the entry zone indicates a failure to form microscopic bubbles needed for effective flotation and the need for adjustments to recycle pressure or to valves and nozzles.

Energy Requirements for Ballasted Flocculation and DAF Clarification Processes

Both ballasted flocculation and DAF clarifiers require recycle of a liquid stream. The former process recycles sludge (floc and microsand) to a cyclone clarifier where floc and microsand are separated. DAF recycles 6 percent to 10 percent of the raw water flow at high pressure to attain supersaturated water that is returned to the clarifier. In addition, an air compressor maintains air pressure in the saturator. These clarification processes have higher energy requirements than some other clarification processes, and this may need to be weighed against the benefits offered by ballasted flocculation and DAF clarifiers when a clarification process is selected.

The extra energy required to operate DAF as compared to a number of the sedimentation processes can be a disadvantage in some situations, but this needs to be evaluated in the context of the benefits attainable with the process.

SUMMARY

Several types of clarification processes are used in pretreatment. For any clarification process to be truly effective, however, prior stages of pretreatment must be performed properly, including chemical dosing, mixing, and flocculation. Furthermore, operators should remember that the goal of clarification pretreatment is not the production of the absolute lowest turbidity attainable, but the production of water that can be filtered to produce very low turbidity meeting goals for filtered water, while at the same time producing filterable floc yielding long runs.

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4

Granular Media Filtration Concepts, Operation, and Management

INTRODUCTION

This chapter presents information on properties of granular media filter materials and concepts of how rapid rate filters remove particles in a filter bed. Following a brief discussion of the filter cycle from the start of a run through backwashing, the focus of this chapter will be on operating filters from the end of the initial improvement or ripening period to the backwash procedure. Other chapters discuss filter washing and restarting filters after backwash.

MEDIA PROPERTIES AND FILTRATION CONCEPTS

Filter materials used in rapid rate granular media filters include silica sand, anthracite coal, GAC, high-density sand, and specially manufactured granular media. The portion of this chapter dealing with filtration concepts explains how filter material properties influence particle removal in granular media filters.

Filter Media Properties and Characteristics

Filter materials have a number of characteristics that are relevant to their use in granular media filters. Some of these characteristics are included in AWWA standards. AWWA Standard B100-01, *Filtering Material* describes sand, anthracite, and high density materials such as garnet, ilmenite, hematite, and magnetite. AWWA Standard B604-05, *Granular Activated Carbon* describes GAC. Using filter materials that are suited for their intended purpose will help to attain optimum filter performance. Several material properties influence that performance.

Size and Uniformity

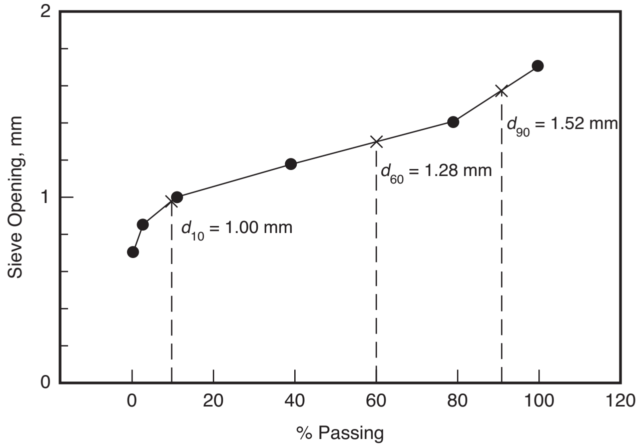
Size of filter media affects particle removal, head loss development, and the behavior of media during backwashing. The filter materials used in water works filters are not unisized, i.e., particles of only a single size. Producing such materials might be possible for manufactured media, but most natural mineral filter media are produced by mining materials, then in some cases, crushing the material, and sieving the material to obtain the desired size distribution. Producing media of a single size could be done by rejecting all media grains not meeting the specified size during sieving, but that would result in exceedingly expensive filter media because of the amount of wasted material during sieving. As a result, filter materials are supplied in a size range rather than as monosized material.

Sieve analysis. AWWA B100-01 includes text on performing sieve analysis. This is a somewhat complicated procedure that requires specialized equipment. Large water systems may purchase and use this equipment according to the standard procedure, but for other systems, sieve analysis performed by a commercial laboratory can be a more cost-effective approach.

The procedure involves first obtaining a representative filter material sample, which is also discussed in AWWA B100-01. The dried, weighed sample is placed in the top sieve of a nest of sieves, positioned so the sieve with the largest size opening is on top, with each size below being successively smaller. The smallest sieve is immediately above the collector pan. A lid is placed over the top sieve after the sample is placed in that sieve. Typically, 100 to 200 g of media are used for the analysis. After a specified period of shaking in a mechanical apparatus, the mass of filter material retained on each sieve is determined by weighing on a laboratory balance.

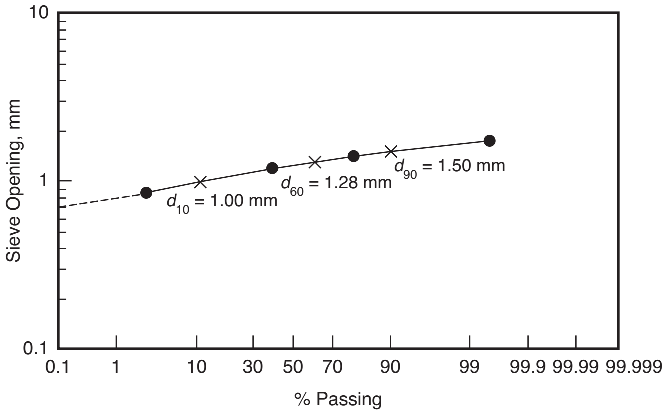
From the data obtained by weighing the material retained on each sieve, the cumulative mass of media retained by a specified sieve and all those above it can be calculated. Subtracting that cumulative value from the original mass of filter material tested yields the mass of material that passed the sieve in question. This calculation is done for each of the sieves in the nest of sieves. Then, the mass passing through each sieve is divided by the mass of the filter material used for the test and multiplied by 100 to give the percentage of media passing each sieve (percent passing). The percentage passing can be plotted on a graph in which the percentage passing is plotted on the X-axis on arithmetic grid graph paper against the sieve opening size on the Y-axis as shown in Figure 4-1. This plot generally yields a sigmoidal or S-shaped curve, which can be difficult to interpret. If graph paper having a logarithmic Y-axis for sieve opening size and a probability-scaled X-axis for percentage passing is used, a line drawn through the sieve analysis data points will approach a straight line (as in Figure 4-2) when the size distribution of the media approximates a statistical normal distribution. From this line, the apparent sieve size for 10 percent passing and for 60 percent passing can be determined. The apparent sieve size for 90 percent passing also could be determined.

If the data points on the log-probability plot do not approximate a straight line, the size distribution has been distorted in some manner. An example of this is a sample that is supposed to be either sand or anthracite taken from an existing dual-media filter in which the two kinds of filter material were intermixed to some extent and not separated before the sieve analysis was performed. The effect of media intermixing can be quite apparent when sieve analysis data are plotted on log-probability graph paper.



Source: Logsdon et al. 2002.

Figure 4-1 Filter media sieve analysis plotted on arithmetic grid paper



Source: Logsdon et al. 2002.

Figure 4-2 Filter media sieve analysis plotted on log-probability paper

Effective size (ES) and uniformity coefficient (UC). The sieve size opening that will pass just 10 percent of the media sample (by dry weight) of the filter material is defined as the effective size (ES), or the d_{10} size.

A second media property related to size and sieve analysis is the uniformity coefficient, (UC). The size of sieve opening that would pass 60 percent of the media sample (by dry weight) is the d_{60} size. The UC is the ratio of the d_{60} size to the d_{10} size, or d_{60}/d_{10}. As the UC increases, the range of sizes from the smallest to largest size in the batch of media increases. For filters that are backwashed, high UCs are undesirable, as will be explained in following sections. Current practice typically involves specifying a UC of 1.4 to 1.5, although for some media, a UC of 1.3 may be specified.

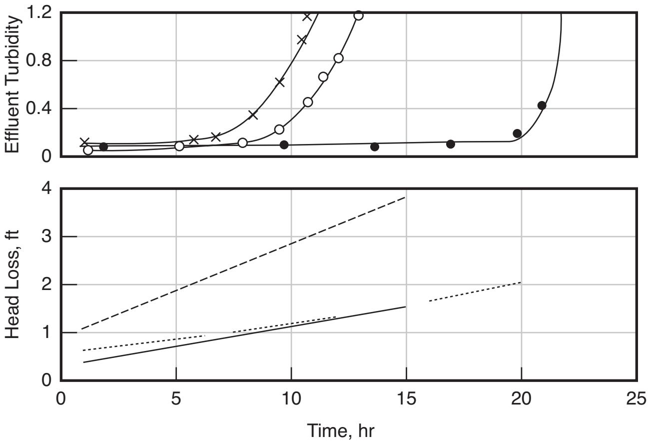
Influence of media size on filter performance. The size of filter media relates to filter performance in three ways. Smaller filter grains are more effective for capturing particles that are passing through a filter bed and thus are more effective for turbidity removal than large filter grains.

However, small filter grains have smaller pore spaces between the grains resulting in higher clean-bed head loss for a given filtration rate. Rapid sand filters designed in the early 1900s used sand with an effective size of about 0.4 mm to 0.5 mm. When these filters were operated at a rate of 2 gpm/ft^2 (5 m/hr), the clean-bed head loss (loss through a clean, backwashed filter) was not excessively high. As higher filtration rates were used, the clean-bed head loss in rapid sand filters of this design became undesirably high, and as a result, other filter bed designs were developed. Operators at rapid sand filtration plants with sand approximately 0.5 mm should not expect to operate filters at rates much higher than 3 gpm/ft^2 (7 m/hr).

Figure 4-3 illustrates filtration results obtained by Robeck et al. (1964) when settled water was filtered at 2 gpm/ft^2 (5 m/hr) through filters with sand monomedium, anthracite monomedium, and anthracite/sand dual media. This experiment involved alum coagulation but no effort was made to strengthen the floc, and turbidity breakthrough eventually occurred in each filter. The anthracite filter exhibited turbidity breakthrough first, followed by the sand filter. The dual-media filter had the longest period of operation before breakthrough occurred. When activated silica was used to strengthen the alum floc, filtered water turbidity was low and breakthrough did not occur, but terminal head loss was reached first by the sand filter, then by the anthracite filter, and finally by the dual-media filter, as shown in Figure 4-4.

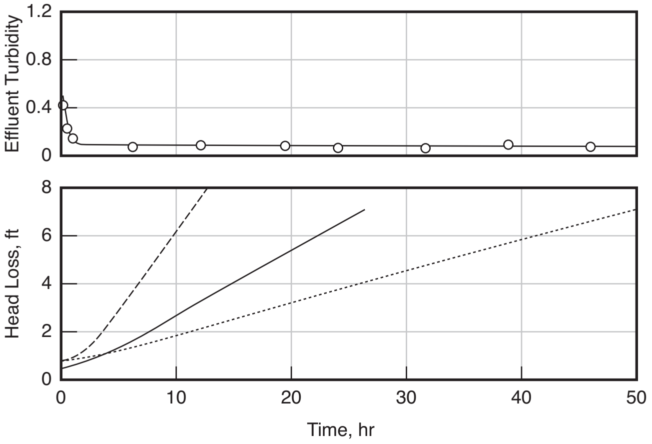
A third factor in managing filters in which media size is important is backwashing. For media having a constant specific gravity (SG), smaller sizes are fluidized at lower backwash rise rates, while larger sizes require higher rise rates. If the uniformity coefficient is excessively high, small media might be washed out in an effort to increase the rise rate sufficiently to fluidize the large media. As discussed in chapter 6, care must be used in backwashing to avoid loss of small filter media. However, it is acceptable when filter materials are placed in a filter box and then the filter is backwashed extensively to wash out the media fines that are excessively small and would increase the clean-bed head loss if allowed to remain in the filter bed.

Typical effective sizes of filter materials are about 0.2 to 0.3 mm for garnet and ilmenite, 0.45 to 0.7 mm for sand, and 0.9 to 1.7 mm for anthracite. Sand and anthracite in the larger size ranges for those materials generally would be used in filters having a depth of 3 ft (0.9 m) or greater, as particle removal in shallower beds probably would not be satisfactory on a consistent, long-term basis.



Source: Robeck et al. 1964.

Figure 4-3 Effect of filter media on length of run with weak floc. In the upper graph, x points are data for anthracite medium, open circles are for sand medium, and solid circles are for dual media. In lower graph, dashed curve is for sand medium, dotted curve is for dual media, and solid line is for anthracite medium.



Source: Robeck et al. 1964.

Figure 4-4 Effect of filter media on length of run with strong floc. In top figure, all media types gave same results for turbidity. In lower figure, dashed curve is for sand medium, solid line is for anthracite medium, and dotted line is for dual media.

Shape and Porosity

Media grain shape affects filter bed porosity, clean-bed head loss, backwash rise rate required for fluidization of media, and particle removal in the filter bed. The term *sphericity* is used to describe grain shape in terms of its relationship to a sphere and is defined as the ratio of the surface area of a sphere having the same volume as the media grain to the surface area of the actual media grain. For example, the sphericity of a sphere is 1.0, and the sphericity of a cube is 0.81. Sphericity values for silica sand typically range from 0.7 to 0.8 because it is not spherical in shape, whereas for anthracite coal values are in the range of 0.46 to 0.60.

Filter sand from some media suppliers is quarried from natural deposits of sand and gravel, and then sized by sieving without being crushed. Such sands are likely to have higher values of sphericity than crushed sand. Anthracite coal is mined and crushed, which would account for its lower sphericity. The crushed materials are more angular and have more surface area in proportion to their volume. This is an aid in particle attachment within the filter bed.

The shape of new filter materials is related to the type of material selected by the designer. Over time, though, the shape of filter grains can change. If anthracite is not sufficiently abrasion resistant, the angular shape can be lost to some extent as edges become rounded. Filter material shape also can change if deposits build up on the media grains. Again, angular media would become less angular and more rounded if coated with calcium carbonate or deposits of iron or manganese precipitates. If samples of filter material are saved when new material is placed in filters, the condition of media after years of use can be compared to the original material, and this may help in evaluating whether replacement of filter media is needed.

Porosity is defined as the ratio of the volume of voids in a filter bed divided by the total volume of the filter bed. A granular filter bed consisting of one filter material and having higher fixed bed porosity has lower clean-bed head loss and a greater capacity to hold floc during the filter run than a similar bed with lower porosity. During the operation of a filter, as floc is trapped in the pores of the filter bed, the volume of pores decreases, thus decreasing the porosity. For a filter operating at a constant rate of flow, velocity in the pore spaces increases with accumulation of floc, increasing head loss.

Porosity in a multimedia (dual media or mixed media) filter can be influenced by the degree of intermixing of the different filter materials. For multimedia filters having low values of the UC and appropriately selected effective sizes for the different filter materials, the intermixing of coal and sand, or of sand and garnet or ilmenite after backwashing will be less than for filters having high UCs or improperly sized media. Another factor that can cause intermixing of filter materials is abruptly terminating backwash, rather than gradually decreasing the rise rate at the end of filter washing. Gradually reducing the rise rate decreases the amount of intermixing of anthracite and sand in dual-media filters.

When media grains of different sizes intermix, small grains sometimes lodge in the pores between large grains. This effectively reduces the porosity of the filter bed and would cause higher clean-bed head loss. Values of porosity range from about 0.42 to 0.47 for silica sand and 0.56 to 0.60 for anthracite coal. The lower porosity values for sand probably represent values for quarried natural sand rather than for crushed sand.

Density

Filter material density influences the rise rate needed to fluidize a filter bed for backwashing. When different filter materials are used in a filter bed, each material must be fluidized for backwashing to be effective, and ideally each material in the bed would fluidize at approximately the same rise rate. This issue is further complicated by the fact that small grains of a given density fluidize before larger grains having the same density. For this reason a low UC is desirable. Even though all of the grains of media in a filter bed will not have the same fluidization velocity, in a properly designed filter, a fluidization velocity will exist at which all of the media can fluidize without undue loss of filter material.

Porosity of Pilot Filter Beds

Porosity of filter beds in full-scale plants is a function of the type of filter material used, whereas in small pilot-plant filters, the filter bed porosity can be a function of how the filter is managed at the termination of backwashing. In pilot-plant filter columns, the media tends to settle somewhat on termination of backwash, but it can be compacted further by gently tapping the filter column with a rubber mallet. Compacting the media decreases the porosity and increases clean-bed head loss.

One procedure that has been used to attain uniform porosity for pilot filter runs is to allow the media to naturally settle and when the media is at rest, the position of the top of the media is marked on the side of the filter column. Then, using a rubber mallet, gently tap the filter column until the media will no longer settle when the column is tapped. This location is marked, which will be lower on the filter column. Finally, a location is marked on the column at the midpoint between the high and low marks, which represents a compaction midway between the minimal compaction caused by natural settling and maximum compaction attained by tapping the column. This results in a reproducible fixed bed porosity as long as media loss does not occur.

An inadvertent example of media compaction and porosity decrease took place during pilot-plant testing at a site where a mobile pilot plant was operated at a gravel quarry. An equipment operator drove a heavy machine close to the mobile pilot plant, shaking the ground and the pilot plant. The filters reacted, exhibiting higher head loss as the media settled slightly as a result of the shaking that had occurred.

When dual- or mixed-media filters are used, the smaller effective size of the denser filter materials results in a filter bed that can be fluidized and retain both the denser and the less dense filter materials during backwash. The smaller but denser filter material will settle at the bottom of the bed after the backwash is terminated and the bed comes to rest.

The materials of highest density used in filters are garnet (3.9–4.2 g/cm^3) and ilmenite (4.2–4.6 g/cm^3). These are used in the smallest sizes at the bottom layer of mixed-media filters. Silica sand has a density of 2.65 g/cm^3 and is used beneath anthracite in dual-media filters. The density of anthracite coal ranges from 1.4 g/cm^3 to 1.7 g/cm^3 depending on the source. Thus, anthracite is appropriate for the top layer in a multimedia filter.

GAC is used in some filters for controlling tastes and odors or for removal of some NOM in addition to being used for removal of particles. GAC density ranges from 1.3 g/cm^3 to 1.5 g/cm^3. The lower density filter materials sometimes are more likely to be washed out of the filter box during backwashing, therefore careful management of backwash is needed when these materials are used.

Density of filter material depends on the type of material specified for use in a granular media filter and should not change if the media remains clean. With the passage of time at lime softening plants, however, the density of anthracite filter material could increase if it is covered with a thick coating of calcium carbonate, which is similar in specific gravity to silica sand. Over time, the behavior of calcium carbonate-coated anthracite during backwashing could change as both grain size and density increase because of precipitation of calcium carbonate on the filter material. For this reason, periodic inspections of filter media condition should be performed at lime softening plants, as recommended in chapter 10.

Hardness and Durability

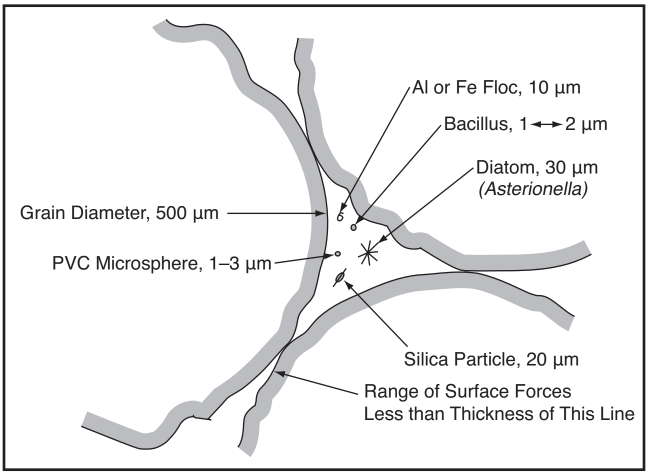
Although hardness and durability do not directly influence filter performance in a new granular media filter, the ability of filter material to resist abrasion and breakage during filter backwashing can affect its performance over the long term. Breakage and abrasion can form small media particles that are washed out during backwash so that both the volume of material in the bed and the effective size of the media gradually decrease over time. In the absence of a better means of predicting filter material durability, AWWA Standard B100-01 has specified Moh hardness values for anthracite coal and high-density filter materials. Silica sand is durable and has a Moh hardness of 7, so it breaks down more gradually than anthracite or GAC. Anthracite hardness should be 2.7 or higher, and hardness of garnet and ilmenite should exceed 5. GAC is a less durable filter material than anthracite, so special care should be used in backwashing filters in which GAC is used.

Particle Removal in Granular Media Beds

Particle Removal Mechanisms

As explained in chapter 2, removal of particles in granular media filters is highly dependent on proper chemical conditioning of the particles during pretreatment. Particle removal in rapid rate filters can occur by attachment of particles to filter material grains or by physical straining, which occurs when the particles are too large to pass through pores in the filter bed. In a hypothetical filter having spherical media with a size of 0.5 mm (500 µm), a sphere smaller than about 75 µm could pass through the pore space between media grains that are touching.

In a real filter, of course, media are not perfect spheres, so some pore spaces would be larger and some would be smaller. However, microbiological contaminants as large as protozoa with sizes of 7 to 12 µm (*Giardia*) or 3 to 6 µm (*Cryptosporidium*) could readily pass through the pores of a rapid sand filter and would even more readily pass through a bed of anthracite in the size range of 1 mm or 1.5 mm effective size. See Figure 4-5, from Edzwald et al. (1998), which illustrates relative sizes of filter media, pore spaces between media grains, and some particles that can be found in water. Although some removal of microbiological contaminants might take place in a rapid rate filter operated without proper coagulation, such removal will be erratic, undependable, and certainly far less than could be attained with proper coagulation, in the context of the USEPA's 2-log removal requirement for *Cryptosporidium*.



Source: Edzwald et al. 1998.

Figure 4-5 Relative sizes of pore space between 0.5 mm filter material grain and several kinds of particulate contaminants

Removal of particles by attachment in a granular media filter is known as *depth filtration*. This term implies that particles are removed into the depth of the filter rather than just at the surface. When raw water is coagulated properly, the fine particles in the water, such as clay, bacteria, protozoa, algae, and others can attach to the grains of filter media as they pass down through the bed. Particles also can attach to other previously attached particles that are held in the filter bed. This is somewhat analogous to flocculation, in which very small destabilized particles attach and form larger particles.

Influence of Bed Depth and Media Size on Particle Removal

As a particle in coagulated water passes into a filter bed, it may flow past grains of filter media at the top of the filter and continue down deeper into the bed, passing more grains of filter media. Filtration theory suggests three ways for a particle to collide with a grain of filter material.

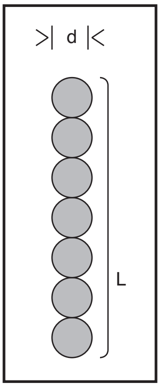
1. The particle follows the streamline of laminar flow down through the filter bed, but because of the particle's large size, the streamline in which the particle is traveling is close enough to a media grain for the particle to touch the grain of filter material.
2. The streamline of laminar flow departs from a vertical path as water flows around the particle, and the density of the particle causes it to settle slightly, putting the particle on a collision path with the grain of filter material.
3. The particle is very small, under 1 µm, so it moves in a random manner (Brownian movement) as it flows down through the filter bed; ultimately, this random movement causes the particle to collide with the grain of filter material.

The particle might strike a grain of media as previously discussed but not stick to the media. If a particle passes to the bottom of the filter bed without attaching to a media grain, then it will exit the filter in the effluent. If the particle collides with a grain of filter material and sticks to it, the particle is removed from the water. To decrease the possibility that a particle will pass through and out of a filter, the number of filter media grains should be increased.

The concept of the number of grains that must be avoided during passage through a filter is expressed as the ratio of the depth of the filter bed, L in mm, divided by the effective size of the media, d in mm. The L/d ratio is essentially the number of spherical grains of filter media that would be stacked one on top of another to create a column of grains as tall as the depth of the filter. An example of this is presented in Figure 4-6. In this figure, the stack has only 7 grains, so the L/d ratio is 7. Higher values of L/d indicate that particles passing through the granular media bed must pass by more grains of filter media. Lower values of L/d indicate that fewer grains of media are present to capture particles flowing toward the filter effluent. The L/d ratio is not an absolute concept, as changes in coagulant chemistry and polymer usage can influence capture of particles in a

L/*d* Ratio and Filter Bed Design

Considering the *L/d* ratio, increasing the *L* term (bed depth) increases the ratio, whereas increasing media ES (*d*) decreases the ratio. Using smaller diameter media has an adverse effect on clean-bed head loss. Therefore, for filters designed to operate at rates of 5 to 10 gpm/ft^2 (12 to 24 m/hr), the trend in design has been to provide deeper filter beds with larger sized media. The Los Angeles Aqueduct Filtration Plant has beds of anthracite with a depth of 6 ft (1.8 m) and an ES of 1.5 mm (McBride and Stolarik 1987). For these filter beds, the *L/d* ratio is 1,800 mm/1.5 mm, or 1,200. A filtration plant designed by Black & Veatch and Stantec Consulting, Inc. and under construction in Vancouver, B.C. in 2007 will have dual-media filters with 1.7 m of 1.4 mm ES anthracite over 0.30 m of 0.7 mm ES sand, for an *L/d* ratio of slightly over 1,600. Both of these plants were designed for operation in a direct filtration mode in which all particle removal occurs in the filter bed.



Source: Logsdon.

Figure 4-6 ***L*/*d* ratio represents the number of collector grains in a filter bed of depth *L* with grain size *d***

filter bed. Nevertheless, *L/d* does give a relative comparison of the “tightness” or “looseness” of a filter with respect to its ability to capture and hold particles in the bed.

MANAGING FILTER OPERATION

The Filter Cycle

Pretreatment processes, such as chemical feed and mixing, flocculation, and sedimentation, in basins equipped with mechanized sludge removal devices can operate continuously for months without interruption, after which they may be taken out of service for routine maintenance. Filters, however, can not be operated continuously for such long times but are operated for periods of time measured in hours or days before being taken out of service.

The filter cycle begins when a clean filter is placed into service. Head loss through the filter gradually increases as particles and floc are removed in the filter bed. If particles are removed effectively throughout the filter run, eventually terminal head loss will be reached, and the filter will be removed from service for backwashing. If the filter fails to remove particles effectively, it will be removed from service and be backwashed before terminal head loss is reached. In other instances, a filter performs well up to the limit the utility places on the number of hours a filter is allowed to operate without backwashing and is then taken out of service, or a decrease in water demand in the system results in the need to take one or more filters out of service. After a filter is taken out of service, backwashing removes accumulated floc from the filter so the clean-bed head loss is restored, and the filter can be returned to service.

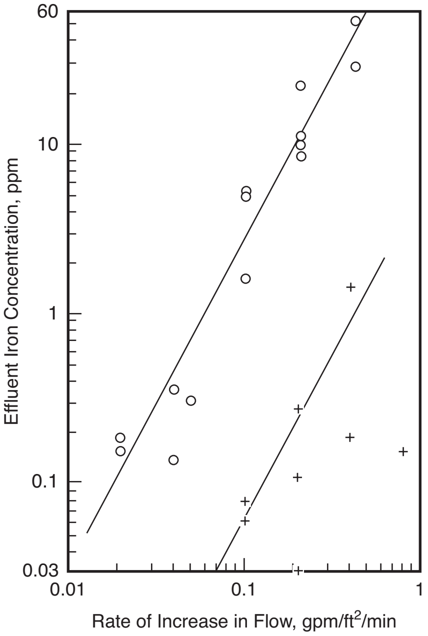
The filter cycle involves multiple steps in which the filter is manipulated in a variety of ways, and in this regard, it is more complex than the continuous processes that do not require as much active management. Separate chapters in this handbook are devoted to filter backwashing and returning a filter to service after backwash. The focus of the remaining portion of this chapter is on managing a filter during the portion of the run after filter ripening, when water production is under way and may continue for hours or days before the run is terminated.

Effect of Filtration Rate Increases on Filter Effluent Quality

Particles are removed by attachment and held in a bed of granular filter media, but they also can be detached from the filter bed and re-enter the water flowing through the filter. Discharge of such particles into filter effluent is a cause of turbidity breakthrough. Detachment of particles in a filter bed is caused by shear forces acting on attached particles as water flows through the filter. As a filter bed removes floc particles, pore spaces become increasingly clogged so velocity in the pore spaces increases. This causes increased shear forces on floc and eventually can result in turbidity breakthrough.

An increased rate of flow through a filter (filtration rate increase) also causes greater shear forces, and potentially can cause previously removed particles to exit the filter. For this reason, operating filters at a constant rate from the start of a run to the end, or operating in a declining rate filtration mode (with no rate increases) are ideal approaches to filter rate management. Realistically, the ideal concept of filtering without rate increases is impractical if not unattainable.

Imposing rate increases on filters from time to time is a necessity in filtration plants; therefore, when this must be done, it should be done carefully. Failure to manage filtration rate increases properly can cause turbidity breakthrough and impaired filtered water quality. If increases in filtration rate and shear forces cause detachment of particles previously held in the filter bed, the detached particles might pass through the filter and into the effluent, as demonstrated by experimental evidence.



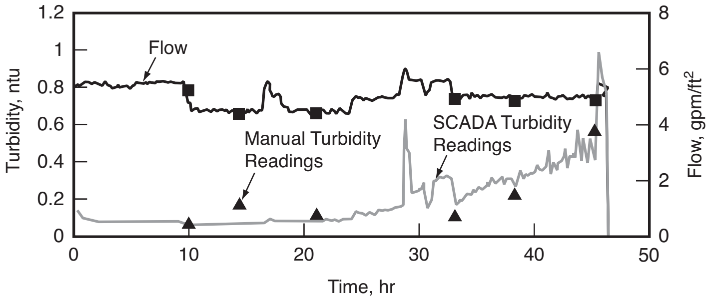
Source: Cleasby et al. 1963.

Figure 4-7 Effect of filtration rate increase on passage of particles through granular media filter. Upper line shows greater increase in effluent iron concentration when floc was weak, versus lower increase in effluent iron in lower line, when floc was strong.

Research on the effect of filtration rate increases on filtrate quality by Cleasby et al. (1963) showed the potential for creating filtered water quality problems by improper management of rate increases. Turbidity does not directly relate to the mass of particles in water; therefore, in addition to using turbidity as an indicator of filtrate quality, the research team applied a filter influent containing preformed iron floc at a concentration of 10 mg/L and measured the iron content of the filtered water using the colorimetric bipyridine method. This method for iron analysis provided quantified results, so chemical analysis of filter effluent provided a more elegant research approach. Some of those results are reproduced in Figure 4-7.

The research showed that when filtration rates are increased gradually, the increase in iron concentration in filter effluent was less than when an abrupt rate increase was applied. For example, the peak concentration of iron floc was about 30 times greater for an instantaneous 25-percent rate increase than for a 25 percent increase that was gradually applied over a 10-minute time period. Also, a lower percentage of rate increase resulted in a lower increase in iron concentration in the effluent. A 100-percent rate increase discharged 22.5 times more iron than a 25-percent rate increase.

Filters with a considerable amount of floc lodged in the filter bed, as indicated by high head loss, are likely to be more vulnerable to turbidity breakthrough as a result of



Source: Harms and Horsley 2001.

Figure 4-8 Filtered water turbidity and rate of flow for filter run about four days long

rate increases than filters in which head loss is low. In an AWWA *Opflow* article, Harms and Horsley (2001) presented a figure reproduced herein as Figure 4-8 showing rate of flow and filtered water turbidity. Note that during the first increase of filtration rate from about 4.5 to about 5.5 gpm/ft^2 (11 to 13 m/hr) at about 17 hours into the run, the turbidity barely increased and returned to its previous value, whereas after the filter had been operated about 28 hours, a rate increase from slightly below 5 gpm/ft^2 (12 m/hr) to slightly below 6 gpm/ft^2 (15 m/hr) caused turbidity to increase from less than 0.2 ntu up to about 0.6 ntu. Previously, at a run time of about 24 hours, a rate increase of about 0.5 gpm/ft^2 (1 m/hr) appeared to initiate a slight turbidity increase followed by a gradual rise in turbidity.

The second turbidity increase in Figure 4-8 occurred when head loss on the filter was higher, and the consequences for filtered turbidity were more severe. This is consistent with observations made at a filtration plant on Lake Superior, where asbestos fiber counts in filtered water generally were low during normal operation but spiked during a rate increase applied at high head loss (see Table 4-1).

USEPA research on coagulation and filtration for removal of *Giardia* cysts indicated that strong floc was more able to resist turbidity breakthrough during a rate increase than weaker floc (Logsdon et al. 1981). In two experiments in which rate increases were imposed on a filter operating at 4 gpm/ft^2 (10 m/hr), the test using a nonionic polymer to strengthen alum floc showed only a slight increase in filtrate turbidity as a result of a 100-percent rate increase, whereas using alum alone resulted in a weaker floc that displayed turbidity breakthrough following a 170-percent rate increase. Both filters had been operated between 6 and 7 hours when the rate increases were imposed. Although a 170 percent increase is a larger percentage than would be applied at an operating filter plant, the results of the two tests did indicate the value of polymer-conditioned floc for resisting breakthrough during a rate increase.

The importance of floc strength also can be discerned from Figure 4-7. In the studies of Cleasby et al. (1963), preformed iron floc was prepared using two different

Table 4-1 Comparison of water quality from dual-media filter after filtration rate increase from 3.25 to 4.33 gpm/ft^2 (7.9 to 10.6 m/hr) versus equilibrium values during normal operation at Duluth filtration plant

Plant Operating Mode	HL at Rate Increase, ft (m)	Normal ntu	Normal MFL	Peak ntu at Rate Increase	Peak MFL* at Rate Increase
In-line	2 (0.61)	0.09	0.07	0.16	0.38
In-line	2 (0.61)	0.06	0.06	0.07	0.38
Conventional	2 (0.61)	0.04	0.04	0.05	0.3
In-line	7.2 (2.2)	0.1	0.06	0.44	12.8
Conventional	7.5 (2.3)	0.04	0.04	0.08	0.06

Source: Logsdon 1979.

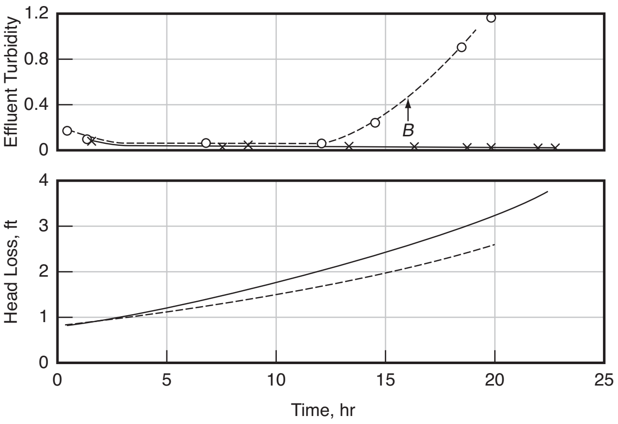
This plant capable of operating in three modes: In-line with rapid mix filtration; direct filtration with rapid mix, flocculation, filtration; and conventional treatment.

*MFL = million fibers/L.

methods. Two distinct groups of data can be seen in this figure, which shows the relationship between the rate increase imposed on the test filter and the concentration of iron in the effluent resulting from the rate increase. The upper data group on the graph result from rate increases that took place with the weaker floc in the filter. Iron precipitates in this data group were formed in the presence of copper (Cleasby et al. 1963), whereas no copper was present when the stronger iron floc was formed. It is important to note also that in the work of Cleasby et al., the influent iron concentration was 10 mg/L in all filter runs, but some effluent iron concentrations ranged from about 20 mg/L to over 50 mg/L.

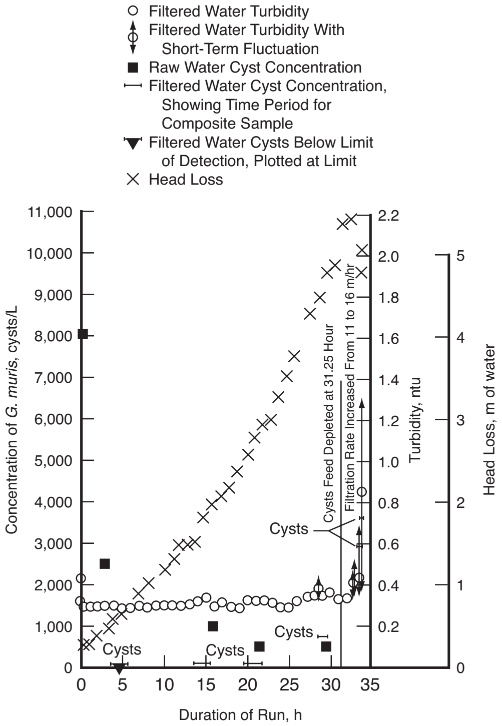
The influence of floc strength for preventing turbidity breakthrough and the role of polyelectrolytes (polymers) in this was demonstrated by Robeck et al. (1964). Their results are shown in Figure 4-9, in which a polymer dosage of 0.08 mg/L resulted in production of low filtered water turbidity for over 22 hours, with only a modest penalty for increased head loss, whereas the filter operated without polymer began to display turbidity breakthrough after 12 to 13 hours of operation.

The risk associated with filtration rate increases at high head loss was also demonstrated in a pilot filter operated for *Giardia* cyst removal in direct filtration mode (no sedimentation) with approximately 30 minutes of flocculation time attained in three separate flocculation basins with a 10 minute theoretical retention time in each basin. Figure 4-10 shows results of a USEPA pilot filter run (Logsdon et al. 1981) in which *Giardia* cysts were continuously added to raw water before coagulation for over 31 hours, until the supply of cysts was gone. The filter continued to operate, and a filtration rate increase from 10 m/hr to 16 m/hr was imposed 2 hours (4 theoretical retention times in the flocculation basins) after the cyst supply was exhausted. Head loss was high on the filter after it had operated for over 33 hours, and a massive turbidity breakthrough took place. Also, a very large number of *Giardia* cysts were detected in the effluent, despite the



Source: Robeck et al. 1964.

Figure 4-9 Comparison of filter performance with and without filter aid polymer. In both upper and lower graphs, dashed line is data for floc with no polymer, solid line is for 0.08 mg/L polymer added.



Source: Logsdon et al. 1981.

Figure 4-10 Filtration for *Giardia* cyst and turbidity removal. Horizontal bar for *Giardia* cyst data shows time of sample collection.

fact that few or none should have been in the filter influent after four theoretical retention times through the flocculators, during which time no cysts were added to the raw water. The source of the cysts in the effluent was cysts stored in the filter bed during the stable portion of the run. Because the floc was not strong enough to resist being sheared off the media grains and consequently washed out of the filter, cysts were discharged into the filter effluent. This kind of filter performance can occur in full-scale plants as well as in pilot filters.

Minimizing Effects of Rate Increases

The goal of filtration should be to produce filtered water turbidity that is 0.1 ntu or lower, if practical. This is lower than the filtrate turbidity requirements in the USEPA's rules for filtration, but this is good practice for two reasons. First, when filtered water turbidity is 0.1 ntu or lower, removal of particles is more effective; and second, by maintaining filtrate turbidity well under the USEPA requirements, operators have a greater opportunity for corrective action before incurring a turbidity violation, if turbidity in filter effluent rises. In general, maintaining very low filtered turbidity is a function of chemical pretreatment and clarification. Thus, if filtered water turbidity is too high throughout a filter run in all filters at a plant, pretreatment needs corrective action. If, however, a filter is performing well but the turbidity increases rapidly one or more times in a filter run, this may be related to rate increases, as shown in Figures 4-7, 4-8, and 4-10. Several factors come into play with regard to minimizing the potentially deleterious effects of filtration rate increases. Among those are

- Extent of flexibility for raw water pumping rates
- Available storage for finished water
- Design of collector weirs for sedimentation basins
- Filtration plant capacity versus water demand in system and number of filters in service
- Mode of filter rate control
- Management of filtration rate
- Floc strength

These factors are discussed in this section. Many of them are determined by plant designers rather than by operating staff, so a detailed discussion is provided in the sidebar for engineers. The factors that concern treatment plant staff are filtration plant capacity versus the number of filters in service when a rate increase is needed, management of filtration rate, and floc strength. The mode of rate control is determined by the plant designer, but operators should understand how this influences filter operation. This aspect of filter design is discussed in this section for operators.

Factors That Can Help to Mitigate Adverse Water Quality Effects of Filtration Rate Increases

Pumping Flexibility and Water Storage Capacity

Flexibility in filtration plant operation is highly desirable, and it is helpful when dealing with rate increases. For day-to-day plant operations, water production should keep pace with demand in the system. This does not mean, however, that production must match water demand on an hourly basis. When abundant finished water storage is available at the treatment plant site or in the distribution system, a portion of that storage can be used for flow equalization so that changing the rate of flow through the filtration plant on a frequent basis is not necessary.

Flexibility in raw water pumping rates also is beneficial. If raw water flow can be increased in modest rather than in very large increments, this may enable operators to apply filtration rate increases of a smaller magnitude. On the other hand, if raw water pumping can be brought on only in large increments, then the filters have to accept large rate increases if no filters are being held out of service when the increase is applied.

In the mid-1980s, a discussion of filter operation at a USEPA conference on small water systems illustrated these points very well. Following a presentation on granular media filtration by Dr. John Cleasby, an operator from a small system asked about stopping and starting filters. This operator said he worked at a system with pressure filtration and a pneumatic tank for filtered water storage. The use of water in the system lowered the level in the pneumatic tank, eventually causing the raw water pump to start and pump water through the pressure filter system into the storage tank. The tank was not large, and sometimes filtration would be stopped and started once per hour, or maybe more often than that. Dr. Cleasby explained that filters work best when they are operated from the beginning of the filter cycle to the end, without stopping and restarting. The dilemma of the operator at this small system was that pumping lacked sufficient flexibility to permit treating water at about the same rate as demand in the system, and the small size of the pneumatic tank provided for almost no storage that could be used for equalization between rate of production and rate of use of water in the system.

Operators who face situations where little flexibility exists for raw water pumping and where finished water storage is inadequate to provide equalization capacity may have to impose rate increases that are larger than desirable. In the short term, changing the situation may not be possible, but the important contribution of raw water pumping flexibility and adequate finished water storage should be kept in mind when water system master plans and facility expansions or equipment replacement concerns are addressed.

Factors That Can Help to Mitigate Adverse Water Quality Effects of Filtration Rate Increases (continued)

Sedimentation Basin Design

Some sedimentation basins, particularly conventional basins and those designed for tube settlers, may be sufficiently large that they could act as equalization basins in the short term, when a filter is removed from service or when a modest increase in raw water pumping is initiated. When basins are used for equalization, inflow exceeds outflow from the basin, and water rises within the basin. Eventually, this higher rate of flow has to be accommodated by the filters; however, if the increase in filtration rate is gradual, effects on filtered water quality can be reduced or eliminated.

Large, conventional sedimentation basins have the greatest capability to act as equalization basins, as they have the greatest surface area per unit of depth increase, as compared to basins used for high-rate sedimentation processes. It should be noted, however, that the design of the settled water collection system is important. Many sedimentation basins have collection troughs with numerous V-notch weirs. When such troughs are level and not submerged, flow into the troughs occurs only at the V-notch weirs. This controls the location of the discharge of settled water from the basin, an important factor in attaining good settling. If the weirs are submerged, control of discharge along the weirs is much less effective. An alternative design for collection and discharge of settled water is the use of troughs with submerged orifices. The orifices are always submerged, and water can rise on the side of the troughs, increasing the rate of flow into the troughs. This design facilitates use of a sedimentation basin for equalization purposes.

Number of Filters in the Plant

The number of filters in a plant affects the construction cost of the plant, as more filters require more valves, valve operators, piping, and auxiliary scour equipment. On the other hand, larger filters require larger backwash pumps, if elevated storage is not used for backwashing. As the number of filters at a plant increases, greater operational flexibility is provided, and taking a single filter out of service imposes a smaller overall rate increase on filters still in service. All of these factors should be weighed when a filtration plant is designed. For very small plants, the design may be strongly influenced by regulatory agency requirements for the minimum number of filters allowed in a plant.

Filtration Plant Capacity Versus Water Demand in System and Number of Filters in Service

The production capacity of a filtration plant in relation to the water demand in the system can influence the extent to which filtration rate increases are needed, and the number of filters in the plant can influence the magnitude of rate increases. Water utilities in regions that have not experienced growth, or that have lost industries or population, may have excess production capacity in the context of the current system usage.

If a plant has more filters than are needed, either on a seasonal basis or year-round, one approach to managing filtration rate increases is to use only the number of filters needed to produce enough water to meet system needs on a daily basis, and keep the other filters off-line. If this can be done without operating filters at the maximum allowed rate, operational flexibility is greater because the options of placing more filters into service and increasing rates on operating filters are both available.

If at least one filter is out of service but available for use, when a filter is removed from service for backwashing, another filter can be placed online with no decrease in overall production. If carefully done, this can eliminate the need for a rate increase caused by filter backwashing. In a similar manner, if raw water pumping can be increased in manageable increments, and if a sufficient number of filters are held off-line, increasing water production without increasing filtration rates again may be feasible.

It should be noted that when filters are held off-line for long periods of time, biological growth can and does occur in granular media filters. Even filters to which a free chlorine residual is applied do not have sterile filter media. If a filter remains off-line too long, microbiological growth within the bed may exhaust the dissolved oxygen (DO) that was present in the filter influent. Anaerobic conditions in the filter bed can lead to dissolution of iron or manganese if those previously had been oxidized and sorbed onto the filter media. Anaerobic conditions in a filter bed could also cause T&O problems if the filter was not backwashed before being returned to service. Finally, growth of coliform bacteria might occur in a filter held off-line too long. These problems are more likely to occur when water in the filter bed is relatively warm because bacterial growth rates are higher in the warmer water. If exhaustion of the DO in a filter is suspected, a water sample could be taken from within the filter and analyzed for DO. A less complicated approach would be to simply backwash the filter to ensure that when it is placed into service, no water containing excess iron, manganese, T&O substances, or bacteria will be discharged to the clearwell.

When a plant does not have the production capacity to leave a filter off-line for return to service after backwashing, the number of filters at the plant has a direct effect on the magnitude of the filtration rate increase that will occur when a filter is backwashed, unless a change is made in the rate of raw water pumping. A very small plant with a minimum of two filters would experience a 100-percent rate increase when one filter was removed from service for backwashing. A plant with four filters would experience a 33-percent rate increase in a similar situation. And a plant with 10 filters would experience an 11 percent increase. The greater the number of filters, the smaller the magnitude of the rate increase when all are in service and one is removed from service for backwash. Therefore, this issue is more important at small- and medium-sized plants than at large plants with many filters.

Mode of Rate Control

The type of rate control provided by the design engineer influences the nature of rate increases. Filter rate control can be divided into two broad categories: constant rate and declining rate. Understanding how the rate control system functions enables operators to manage filters more effectively.

Declining rate control involves providing water to a bank of filters in which influent water in a common channel enters each filter **below** the water surface. Filtered water is discharged to the clearwell by passing over a weir at an elevation above the top of the filter media or by passing through a valve set to control the maximum flow rate when the filter is clean. On the influent side, the filters operate in parallel hydraulically, so the amount of flow through a given filter is governed by the extent of clogging in the filter bed. This is analogous to the flow of direct current through a group of resistors in parallel or to the flow of water in pipes connected in parallel. The cleanest filter has the least amount of floc deposited in the bed and operates at the highest rate of filtration. The filter that is clogged to the greatest extent produces the lowest flow of water.

When the filter with the lowest rate of flow is taken out of service for backwashing, water level in the influent channel and over the filter media gradually rises, and the flow through the other filters gradually increases. This mode of rate control imposes rate increases gently, except when a filter is returned to service after backwashing. Then, depending on how quickly the effluent valve is opened, the filter will begin operation at its peak production rate gradually or rapidly. This situation is discussed in chapter 6.

Constant rate filtration is the approach to rate control that has the greater potential for imposition of severe rate increases on filters, so the focus of this chapter is on managing filters with this approach to rate control. Constant rate filtration is not a technically accurate term because filters actually cannot operate at a constant rate for an entire filter run in most situations because of the need to backwash filters or change rates of production at a filtration plant. The term *equal rate* filtration was used in *Water Quality & Treatment*, 5th ed. in the chapter on filtration (Cleasby and Logsdon 1999). However, plant operators may choose to operate some filters at higher rates than others at a constant rate or equal rate plant, depending on the mode of rate control and the quality of filter effluent that is produced by various filters. In this handbook, the more common term *constant rate* will be used.

Two influent flow-splitting approaches for filter rate control do involve operating all filters at equal rates. In each, the influent flow split occurs hydraulically over control surfaces such as weirs or upturned pipes, each having the same elevation. One equal rate mode uses an effluent weir or upturned pipe **above** the surface of the filter media to control the minimum level of water over the filter media. The water is discharged over the influent control structure at an elevation greater than the maximum depth to which the water is allowed to rise during the run, so the influent water is always above the water surface in the filters. The filter with the greatest head loss has the highest depth of water over the media. This is how an operator determines which filter to wash next.

A second equal filtration rate approach uses a water level sensor for each filter and an effluent rate of flow control valve to maintain a predetermined depth of water over the filter media, while the influent flow is governed by the means previously described in which water flows over a control surface higher than the level of water in the filters. Water surface elevations in these filters would fluctuate within a narrow range, so plant operators need head loss instrumentation to determine when a filter should be backwashed because it has reached terminal head loss.

With either approach to equal rate filtration, if the water level in a filter box rises above the influent control structure, that filter then changes from an equal rate mode to a declining rate mode. Problems in pretreatment and clarification that cause excessive amounts of floc to carry over to filters result in very short filter runs. If too many filters are out of service for backwashing, the water level of those remaining in service might rise above the level of the influent control structure because of the need for more head to drive water through the filters at a high rate.

The most common approach to constant rate control is to maintain the water level in the influent channel in a predetermined depth range and use a control valve on the effluent to maintain the desired rate of flow through each filter. Instrumentation is necessary to measure rate of flow and head loss through each filter, so operators know how the filters are performing. With this approach for rate control, operators can select flow rates appropriate for different filters. Those with a history of producing lower turbidity effluent could be operated at a higher rate than one or more filters that are not capable of performing as well.

Management of Filtration Rate

Filters equipped with effluent rate control can be managed to mitigate some of the effects of rate increases, but the extent to which this can be done depends in part on aspects of the plant and water system that have been discussed previously in this section. The ability to apply gradual rate increases when a filter is removed from service for backwashing will be related to both the number of filters at the plant and the capability of the sedimentation basin to serve as an equalization basin on a short-term basis. Using flow equalization to achieve a gradual rate increase during backwash may be practical for a plant with six filters and a 20-percent rate increase caused by backwashing one filter, but not feasible for a plant with only two filters and a 100-percent rate increase during backwash. Also, the magnitude of a production increase will influence the extent to which flow equalization can mitigate the effects of the filtration rate increase.

As discussed previously, in 1963, Cleasby and co-workers demonstrated that gradual filtration rate increases disrupt filtered water quality less than abrupt rate increases. Their paper did not give suggestions for appropriate rates of increase, but more recently the AwwaRF *Filter Maintenance and Operations Guidance Manual* did suggest that for floc of typical strength, a rate increase should not exceed 3 percent per minute, whereas for strong floc the rate increase might reach as high as 5 percent per minute. To increase filtration rates when the floc is weak, it may be appropriate to hold the increase to 1 percent per minute. To express these recommendations in the context of filter operation, for a plant with six filters and all operating, after removal of one for backwashing, attaining the 20-percent rate increase for the five filters remaining in operation would require 7 minutes for floc of average strength, only 4 minutes for strong floc, but 20 minutes for weak floc.

Floc Strength

As discussed in chapter 2 and in the previous paragraph, floc strength, or its ability to resist shear forces within the filter bed, plays an important role in whether previously captured floc will be retained within the bed when the filtration rate is increased. Floc strength can be inferred from filter behavior, but no direct method of measuring floc strength has been developed. One indicator of floc strength is the rate at which head loss through a filter increases, but head loss gain also is related to the rate of filtration and to water temperature. Water viscosity, which increases at lower temperatures, influences head loss, so both the viscosity and rate of flow through the filter need to be considered as well.

If the geometry of a filter and the pipe gallery are suitable, it may be possible to use one or more piezometers within a filter bed to assess the extent of head loss development at specific locations in the filter. Two or three piezometers might be used with one at the interface of coal and sand in a dual-media filter, and one 6 to 9 in. (15 to 23 cm) below the surface of the media. Excessively strong floc tends to be removed in the upper portion of the filter, so the extent of head loss development at the uppermost piezometer location would be a valuable indicator of floc strength. For such a monitoring system to work, the sample pipes into the filter bed would need to be screened to prevent any filter media from entering the piezometer, and the top of the piezometer tubes ought to be 1 ft (0.3 m) above the highest expected water level in the filter, and high enough that water could not flow out the top of the tube during backwashing.

Other Factors Generally Determined by Design Engineer

Even though some aspects of a water treatment plant are determined by the plant designer, operating staff who understand how those aspects of the plant influence management of flows and filtration rates are better equipped to manage the plant.

Flexibility in raw water pumping rates is helpful because increased flexibility can enable operators to avoid making large changes in flow to a plant when smaller increases would suffice to meet demand. Examples of low flexibility in raw water pumping are a plant that could operate at either 4 mgd or 8 mgd (15 or 30 ML/d) and another that could operate only at 20 or 30 mgd (76 or 114 ML/d). When water demand was less than the minimum raw water pumping rate and storage reservoirs were full, a short-term shutdown of the plants was needed.

Availability of storage for finished water is a key factor in provision of flexibility for plant operation. Generally, water use varies considerably over a day's time, and if little finished water storage is available, operators are constrained to operate the plant at a production rate closer to the hourly demand rate. This, of course, would result in more frequent filtration rate changes than are desirable.

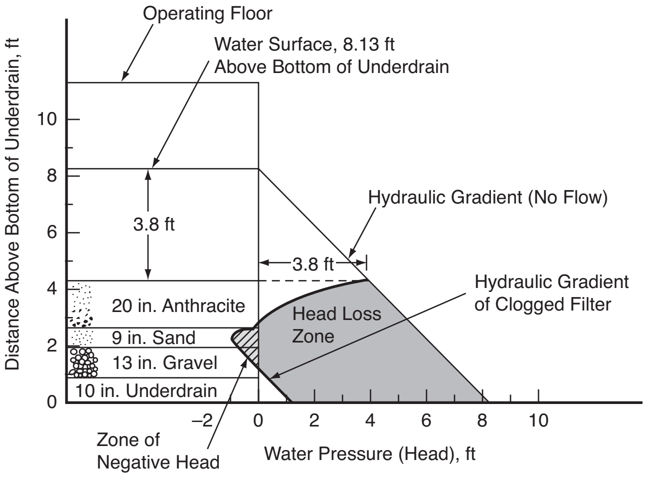
Design of settled water collection troughs for a large conventional sedimentation basin can influence how filtration rates are managed. If troughs with V-notch weirs are provided, these must not be submerged, as this would result in loss of control over the locations for withdrawing water from the sedimentation basin, and short-circuiting could ensue. Thus, the use of V-notch weirs provides for very little flexibility in the water surface elevation in a large sedimentation basin. If troughs have submerged orifices, however, the water surface elevation can rise and fall within a range defined by the top of the troughs and the location of the orifices. Therefore, when a filter is taken out of service for backwashing, the water surface in the sedimentation basin can be allowed to slowly rise while filtration rates are gradually increased to make up for the capacity lost by taking a filter out of service. This permits greater operational flexibility in management of filtration rates as compared to basins with V-notch weirs.

The key to managing filtration rate increases effectively is to understand how all of the factors discussed in this section influence rate changes and subsequent effects of filtered water quality.

Air Binding in Filters and Methods of Correction

When filters are used to treat water that is near saturation, or perhaps supersaturated with atmospheric gases, the phenomenon called *air binding* can occur. If the head loss (pressure drop) within the filter bed results in pressure within the bed that is lower than atmospheric pressure, the dissolved gases may escape solution and form air bubbles in the bed. Figure 4-11 shows how development of high head loss in the upper portion of a filter bed can result in pressure less than 1 atmosphere lower in the bed. When air escapes solution and forms bubbles, water cannot flow through the area occupied by a bubble; therefore, the cross-sectional area available for filtration is reduced and head loss increases. The higher head loss results in still lower pressure within the bed, causing even more air to escape solution as water passes through the bed.

Air binding can be associated with cold water, as the solubility of oxygen and nitrogen is greater in cold water than in warm water. Air binding can also occur in warm water, if the DO concentration is elevated sufficiently high by algae.



Adapted from Hudson 1981.

Figure 4-11 Head loss within filter bed, illustrating how negative head can occur

The typical approach to air binding is to limit head loss in filters during times when air binding might be a problem. At the end of a run when a filter has been air-bound, the air bubbles in the filter bed are not kept in place by the downward velocity of water through the bed, so they can rise to the top of the bed and float to the water surface. If backwashing is started before the air leaves the filter bed, this can cause media to rise up with the bubbles and be lost from the bed. If air binding is suspected, the operator can allow the level of water in the filter box to drop down below the wash water trough so any bubbling action that might occur could not wash media out of the bed. If the filter backwash is begun while air remains in the filter, the upward water flow may cause a violent release of the remaining air. Delaying the initiation of the wash, and starting the backwash with a low rise rate can help to minimize the potential for disruption of an air-bound filter bed during backwash.

STOPPING AND RESTARTING FILTERS WITHOUT BACKWASHING

Stopping and restarting a filter without backwashing while the filter is out of service is considered a special case of imposing a rate increase on a dirty filter. As stated previously, best filter operation practice consists of returning a filter to service following backwash, and then operating the filter continuously with a minimum of rate increases until the filter run is terminated and the filter is again backwashed. At some filtration plants, especially those operated by small systems, this preferred mode of operation may be difficult to attain. The risk associated with starting a dirty filter is that particles trapped within the filter bed can be washed out when the filter is restarted.

Discharge of pathogens into finished water resulting from restarting filters without backwashing was a suspected factor in the occurrence of a waterborne cryptosporidiosis outbreak at a community in the southeastern United States. During the outbreak investigation, effluent turbidity from filters that had been operated continuously since being backwashed and returned to service ranged from 0.07 to 0.18 ntu, whereas turbidity from filters stopped and then restarted without backwashing ranged from 0.20 to 3.2 ntu over a period of about 3 hours following restart. Four samples from one of those filters had turbidity ranging from 1.6 to 3.2 ntu. The difference in filtered water turbidity was dramatic.

Water quality produced by filters that were restarted without backwashing was evaluated at a filtration plant on Lake Superior, where a filtration plant was built but existing low-service pumps rated at 20 mgd and 30 mgd (76 ML/d and 113 ML/d) were used to provide raw water to the plant. During extended times when water demand in the system averaged less than 20 mgd (76 ML/d) the plant had to be shut down when finished water storage reservoirs were full. Backwashing four filters on shutdown was not feasible because of a requirement to recycle treated wash water. Thus, sometimes filters were taken out of service and returned to service without being backwashed.

The data in Table 4.2 show a higher risk of large numbers of asbestos fibers (particles) breaking through on restart of a filter that had high head loss when taken out of service but was not backwashed before being returned to service. As with rate increases imposed on an operating filter, when head loss is high, the shear forces acting on the materials deposited within the filter are relatively high. The difficulty presented by the data is that filter performance on restart is not predictable. Polymer generally was used to strengthen floc for treatment of the Lake Superior water, which may explain why turbidity did not spike so badly at this plant as at the plant in the southeastern United States.

Even though best operating procedure calls for backwashing a filter before restarting, at some plants, particularly small systems, operators may find it difficult or impossible to backwash a filter every time before it is returned to service. A serious risk related to restart of a dirty filter is passage of *Cryptosporidium* oocysts into finished water. Whereas bacteria, viruses, and *Giardia* cysts can be inactivated by drinking water chlorination, even many hours of exposure to free chlorine may fail to inactivate *Cryptosporidium* sufficiently.

Clearly, it is risky to restart a filter without backwashing it, but if this is unavoidable, special precautions need to be taken. They are

- An online turbidimeter must be used to monitor the filtered water continuously from the time when effluent flow begins, and data should be recorded at intervals no longer than 60 seconds. This will provide a record of changes in turbidity at a time interval short enough to capture the shape of the turbidity spike on restart and alert the operator if a serious problem is developing. This data recording should continue until filter effluent turbidity has declined below 0.5 ntu for

Table 4-2 Comparison of filtered water quality after starting filter at 3.25 gpm/ft^2 (7.9 m/hr) without backwashing versus equilibrium values during normal operation at Duluth filtration plant

Plant Operating Mode and Media	HL at Restart, ft (m)	Normal ntu	Normal MFL	Peak ntu	Peak MFL*
Conventional; dual media	2.0 (0.61)	0.04	0.06	0.05	0.48
Conventional; dual media	2.5 (0.76)	0.05	0.02	0.05	0.19
In-line; dual media	3.5 (1.1)	0.04	0.07	0.04	0.09
In-line; dual media	9.0 (2.7)	0.07	0.03	0.71	3.7
Conventional; mixed media	2.0 (0.61)	0.07	0.05	0.05	0.11
In-line; mixed media	2.7 (0.82)	0.04	0.02	0.04	0.12
Conventional; mixed media	9.0 (2.7)	0.05	0.08	0.12	2.2
In-line; mixed media	6.9 (2.1)	0.04	0.03	0.04	0.04

Source: Logsdon 1979.

This plant capable of operating in three modes: in-line with rapid mix filtration; direct filtration with rapid mix, flocculation, filtration; and conventional treatment.

*MFL = million fibers/L.

15 minutes, at which time data collection at the frequency required by regulations must be performed. Recording filtrate turbidity at frequent intervals is an aid to public health protection, even though pathogens in filtered water would not be detected. By knowing the effluent turbidity at frequent intervals, an operator can gain insight into filter performance at this crucial time in filter operation.

- If filter-to-waste is available, it must be used until filtered water turbidity meets the regulatory requirements and also the filtered water quality goal of the water system.
- If a filter is not equipped with filter-to-waste, the filter run must be ended and the filter must be backwashed if a regulatory reporting requirement would result from continued operation. If filtered water turbidity exceeds 1.0 ntu twice in a 15 minute period, a special reporting requirement is triggered by the Interim Enhanced Surface Water Treatment Rule (IESWTR). If filtered water turbidity does not rapidly decline and go below 0.3 ntu in 15 minutes, the filter should be backwashed, even though the filtrate turbidity may not result in a regulatory

reporting requirement. This recommendation is related to the need to attain 0.3 ntu or lower in 95 percent of the combined filter effluent results obtained each month for regulatory compliance.

- Knowing the head loss before the filter was shut down is very important. A filter that has reached or exceeded 75 percent of the typical terminal head loss should be backwashed before it is returned to service because of the higher risk of serious turbidity breakthrough on restart at high head loss. If a filter has developed more than 50 percent but less than 75 percent of the typical terminal head loss, backwashing is recommended before the filter is returned to service.
- Operators need to be aware of the greater risk associated with restarting dirty filters when floc is weak. Use of a filter aid polymer can help to strengthen floc and improve the ability of the floc to resist shear forces on restart of the filter.

SUMMARY

The potential for degrading filter effluent by imposing rate increases has been known for more than four decades. Research demonstrated that small rate increases are less disruptive than large ones, and that gradually raising the filtration rate is less disruptive than abruptly increasing the filtration rate. Plant operators should be aware of these concepts as they manage filtration rate changes at their plants. Flexibility in raw water pumping can help to reduce the magnitude of filtration rate increases when the increase in production cannot be met by placing idle filters into service. When all filters are used and one is removed from service for backwash, the effect on other filters is more pronounced when the plant has very few filters to accept the increased flow rate. If conventional sedimentation basins can be operated at a variable water level, allowing the water level to increase temporarily during filter backwashing or when raw water pumping is increased is a means of applying a more gradual rate increase on filters rather than an immediate or very abrupt rate increase. Restarting a dirty filter instead of backwashing and then returning it to service is a last option for filter operations and should be avoided if at all possible. Monitoring effluent turbidity during a rate increase at time intervals shorter than the required 15 minutes for regulatory reporting provides a much better understanding of filter behavior during this critical time.

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5

Water Treatment Under Difficult Raw Water Conditions

INTRODUCTION

Some water sources have quality that is highly variable and able to change rapidly, whereas the quality of other sources typically changes little from day to day; however, occasionally major changes in quality do occur. Major storm events that result in heavy runoff can cause such changes. Runoff from intense precipitation or snowmelt has the potential to carry pathogens into source water, so water treatment plant staff should be alert and should maintain effective treatment during such events. Other water quality challenges, such as very cold temperature, are present for long periods of time in some sources.

This chapter discusses some of the challenging water quality conditions that are encountered at filtration plants. Maintaining high-quality filtered water even when challenged by difficult treatment conditions often involves management of both the chemical pretreatment and the filtration processes. Information presented in this chapter is drawn from the AwwaRF reports, *Filter Maintenance and Operations Guidance Manual* (Logsdon et al. 2002), *Design and Operation Guidelines for Optimization of the High-Rate Filtration Process: Plant Survey Results* (Cleasby et al. 1989), other literature, and the author's experience.

VARIABLE RAW WATER TURBIDITY

Pretreatment chemistry may need to be changed because of substantial changes in raw water turbidity. Many plants use jar tests to identify effective chemical dosages. At some filtration plants, historical dosage charts are relied on to provide guidance. Others use streaming current or zeta potential measurements.

As an example, at a filtration plant using a river source in the Pacific Northwest, coagulant is slightly overfed as raw water turbidity rises, and then it is slightly underfed as the raw water turbidity declines. Jar tests, a streaming current instrument, pilot filters, and continuous monitoring of filtered water turbidity are also used at this plant.

The staff at a plant in the Rocky Mountain region adjust coagulant and polymer dosages based on zeta potential testing, observation of floc size, and streaming current data. Treatment results are compared to past results using historical data charts.

Alum dosage is changed, plant production is minimized if possible, and real-time data are relied on for guidance in treating high-turbidity water at a plant on the Great Lakes. Streaming current data are also used.

Staff at an eastern water utility rely on detailed historical dosage charts for alum, coagulant aid, and potassium permanganate. Charts are set up for different temperature ranges, and one set of charts is used for rising turbidity, whereas another set is used for declining turbidity (Logsdon et al. 2003).

Flexibility in acquisition of raw water is a tool employed at some filtration plants. On reservoirs, if intakes are designed to permit withdrawal of water from different depths, changing the depth from which water is drawn may improve source water quality. Another option is to change to a source with better quality, if more than one source is supplied to the treatment plant.

VARIABLE RAW WATER pH

The control of pH when coagulation occurs is important, especially for alum, which has a more narrow range of low solubility than iron coagulants. When source water has variable pH, or very low alkalinity such that adding metal coagulants can consume most of the alkalinity and depress pH excessively, the ability to control pH during coagulation is necessary. Online monitoring of pH is recommended in these situations. If pH needs to be increased, caustic soda or lime can be fed in pretreatment. Soda ash also can be used. Carbon dioxide and acids can be used to lower pH if source water pH is too high for effective treatment. At some water utilities, both alkalinity and pH are monitored and alkalinity data are used as part of the input for making decisions on coagulation practice.

Algae blooms can raise pH in the source water, as the algae consume carbon dioxide in the water. Sunlight promotes growth; therefore, pH rises and falls on a diurnal basis as a result of algal growth during daylight hours. Such fluctuations can be quite challenging but can handled more effectively if online pH monitoring is available. If the blooms raise pH out of the zone where alum is effective as a coagulant, careful monitoring and adjustment of pH are needed to maintain optimized treatment.

HIGH COLOR AND LOW TURBIDITY

Some source water is highly colored but relatively clear, having low turbidity. In such water, the coagulant dosage needed is determined mainly by the concentration of true color and tends to be proportional to the concentration of color, UV_{254} absorbance, or TOC. When the coagulant demand of the color is satisfied, a small additional dosage of coagulant will form floc and provide clarification and filtration. Floc formed in water with high color and low turbidity has a density only slightly greater than that of water; therefore, clarification by flotation may be easier to accomplish as compared to sedimentation.

HIGH TURBIDITY AND HIGH COLOR/HIGH NOM

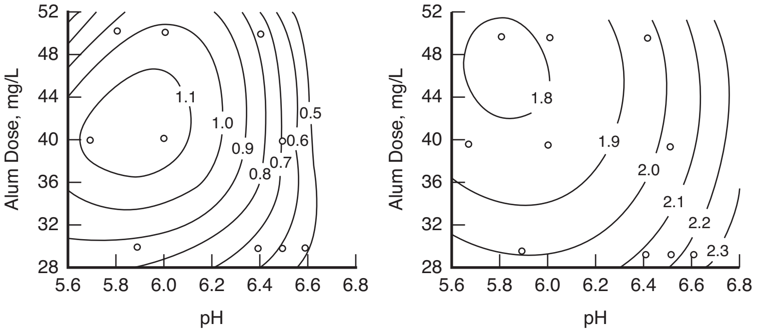
True color is one form of organic carbon found in source water. High concentrations of true color require high dosages of coagulant; therefore, monitoring true color can be used to estimate the dosages of coagulant. This monitoring can be done by analyzing grab samples for true color or by monitoring UV_{254} absorbance. When low-turbidity waters are treated for color removal by addition of metal coagulants, determination of proper coagulation conditions involves evaluation of both coagulant dosage and coagulation pH. This can be performed by jar testing.

It becomes a major challenge to identify the appropriate pH and chemical dosage for coagulation when the source water has both high color or NOM concentration and high turbidity. If the treatment is for regulatory compliance to reduce TOC concentration, that parameter should be measured. If DOC is a concern, use the analytical procedure for DOC and filter the samples before analysis. Edzwald (2007) recommends coagulating at the pH of minimum aluminum solubility to attain the most removal of particles and color or other types of NOM when alum is the coagulant. For ferric coagulants, pH of 5.5 to 6 is recommended by Edzwald. Jar tests covering a range of coagulant dosages at several pH values can be used to provide a database sufficiently complete to identify the appropriate pH and dosage that yield satisfactory results. After the tests are complete, one graph can be plotted for settled water turbidity and a second for true color, DOC, or TOC in settled water samples that have been analyzed as specified in the appropriate method.

For turbidity results, the graph should have either pH or coagulant dosage on the X-axis and the other parameter on the Y-axis on arithmetic grid paper. Each settled water turbidity result is plotted as a data point at the pH and coagulant dosage location that identifies those conditions in the jar test. The actual settled water turbidity is written beside the data point. When all of the jar test results have been plotted on two-dimensional graph paper, interpolations are made between data points to identify locations of settled water turbidity such as 0.5, 1.0., 2.0, 3,0., 4.0, and 5.0 ntu. After those locations are identified, contours for specific values of turbidity are plotted. The data results then resemble a contour map or topographic map, and on this map of treatment responses, a zone of effective coagulation for turbidity removal can be identified. Figure 5-1 (Budd et al. 2004) is an example of this type of data plot.

A similar data plotting exercise is performed for true color, DOC, or TOC concentration in treated water, or for percentage removal of TOC. If the treatment plant has to meet TOC reduction percentages stipulated in the 1998 DDBP Rule, plotting data in terms of percentage removal of TOC provides directly usable results.

When the contour map for coagulant concentration and coagulation pH and concentration of true color or DOC, or the TOC removal percentage has been developed,



Source: Budd et al. 2004.

Figure 5-1 Jar test results for effect of alum dose and pH on settled water turbidity (ntu) in left diagram and on settled water DOC concentration (mg/L) in right diagram

the region for best color or NOM treatment results should be compared with the region for low turbidity, and a zone of overlap should be identified. Although more often the trends for removal of turbidty and DOC follow one another, in Figure 5-1 this did not occur. The region bounded by pH 6.0–6.2 and alum doses of 40 and 44 mg/L appears to represent a compromise for lower TOC concentration and a reasonable settled water turbidity. The challenge in this case is meeting dual goals of low filtered water turbidity, for which jar tests are an indicator but not an absolute guarantor of successful treatment at full-scale, and removal of color or NOM as measured by DOC or TOC, for which jar tests are a good indicator of full-scale outcome because of the chemical nature of treatment for those constituents. Final validation of the jar test results is attained when treatment is implemented and filtered water turbidity is measured, as the jar test should be a good estimator for TOC removal. Maintaining effective treatment when source water has both high turbidity and a high concentration of color or TOC can be challenging; however, it is more difficult if water quality changes rapidly and repeated jar testing is required.

Even though faced with the challenge of treating raw water with a high concentration of TOC and also high turbidity, filtration plant staff must maintain compliance with requirements for filtered water turbidity while also attaining the required removal percentage for TOC. A balanced perspective must be kept. The greater immediate threat to public health involves a waterborne disease outbreak; therefore, coagulation and filtration must be effective for particle removal. Reducing the concentration of TOC is a regulatory requirement that must be met; however, if the removal percentage falls below the required value for a few days, an immediate threat to public health is highly unlikely. Failure to meet the TOC removal requirements for even a very short time should, however, motivate plant staff to diligently explore the options available for improving TOC removal so that regulatory requirements are satisfied as soon as possible.

TASTE AND ODOR

T&O problems quickly become evident to water system customers. The water quality characteristics most obvious to customers are those that are detected by human senses: taste, odor, and visual appearance such as turbidity and color. Various species of algae and actinomycetes can produce unpleasant tastes and odors in water. These have been described by various characteristics such as earthy/musty, fishy, grassy, or having a geranium or cucumber smell, among others. Factors related to the extent of a T&O problem include the type of organism involved and the biomass and condition of the organisms. Intact cells or colonies may cause some T&O, but the problem can increase substantially if the cells degenerate and the contents inside the cells are released.

A variety of approaches are used to address the issues with T&O. Oxidants, such as ozone, potassium permanganate, free chlorine, and chlorine dioxide are often used. When chlorine is used, and if oxidation of T&O-causing substances is not complete, the compounds formed by chlorine in some instances can cause worse T&O problems.

PAC can be used for intermittent problems. However, PAC dosages needed for controlling T&O can be high because PAC is not as effective for adsorbing organics as GAC. When it is dosed into water at the treatment plant, fresh PAC encounters T&O-causing compounds at their highest concentration. After the PAC has adsorbed some of those compounds and some of its adsorption capacity has been used, the concentration of the problem compounds has decreased. With a lowered adsorption capacity and a decreased concentration of organics in water, the efficiency of the PAC for removing more organics is reduced as the water and PAC travel through the treatment plant. On the other hand, at a plant with GAC in a contactor or in a filter bed, the GAC is exposed to a higher concentration of organic contaminants at the top of the bed, where the higher concentration provides a driving force to promote adsorption, even though some of the adsorption capacity of the GAC has been used. Deeper into the bed, the less-exhausted GAC encounters lower concentrations of the compounds being removed so a driving force for adsorption still is in effect. This makes GAC more effective for adsorbing organic compounds than PAC. Even though PAC is more costly than GAC for continuous, long-term use in many applications, PAC can be used on an intermittent basis and has a much lower capital cost; therefore, it is used at many treatment plants.

Contact time is important for adsorption on PAC and GAC. GAC contact time is a function of filtration rate and GAC bed depth and is shorter than contact times for PAC. To gain a longer contact time for PAC, it is added in raw water transmission lines at some facilities. At others, PAC is dosed at the treatment plant. Depending on the point of application of PAC, some may pass through filters. PAC is black and scatters little or no light in a turbidimeter, so it does not appear as turbidity. To check filter effluent for the presence of PAC, a sample of effluent is filtered through a white membrane filter with a pore size of 0.45 μm. If the filter is white after PAC-treated water has passed through, little PAC is getting through the granular media filter. If too much PAC passes through the treatment plant into finished water, it might cause off-color laundry, especially with white clothing and bedding. As with aesthetic problems in tap water, customers may notice discolored laundry and file a complaint; therefore, preventing PAC from passing through filters into finished water is a matter of maintaining good customer relations.

ALGAE AND DIATOMS

Source waters that are rich in phosphorus and nitrogen can support very large growths of algae, called *algae blooms*. Algae in general, and especially the blooms, can cause a number of problems, including T&O, high concentrations of TOC, and filter clogging. Diatoms, a type of algae having a rigid silica cell wall with an organic coating (AWWA 2004), can create T&O problems and clog filters. The organic compounds that algae produce can be precursors for DBPs, and high concentrations of algae have caused high concentrations of DBPs. The organics produced by algae also can interfere with coagulation. Amorphous biological matter, consisting of plant or animal fragments, often in a state of decay, can also clog filters.

The problems presented by algae, diatoms, and other organisms in water can be complex. The AWWA Manual M7, *Problem Organisms in Water: Identification and Treatment*, 3rd ed. (2004) is a recommended source of additional information. Numerous color photomicrographs are presented to aid in the identification of organisms found in raw water, and the manual includes a troubleshooting guide for handling problems caused by various organisms in raw water.

Avoiding Algae and Diatom Problems

The first line of defense against problems caused by algae and diatoms is to have fewer of these organisms in the source water, either by control measures, withdrawing lake or reservoir water from a different depth, or by obtaining water from a different source. Organism control may be applied in the short-term, but using alternative sources is a long-term and perhaps expensive approach.

Copper sulfate has been used for algae control in reservoirs, as copper is toxic to algae. Its effectiveness depends on the quality of the source water. To be effective, copper must be ionized. In water with high pH and high carbonate hardness, copper precipitates as copper carbonate, losing its toxicity to algae. This can be overcome to some extent by using larger dosages of copper sulfate, but this can be expensive. However, using copper to control algae can be less expensive and more quickly implemented than other remedies, but this approach addresses the problem but not the cause. For long-term prevention of algae blooms, watershed protection measures are needed to reduce nutrient input to the source water, but implementing nutrient input controls may require cooperation and active participation of others in the watershed such as farmers, golf courses, homeowners and lawn care companies, and wastewater treatment agencies.

Another approach to algae control is to circulate reservoir water to the surface from a zone below the depth to which sunlight will penetrate. Creating a pattern of circulation down into the depth of the reservoir takes algae cells out of the photic zone where they receive sunlight needed for growth, and this can help to inhibit algae blooms. Controlling algae in this manner involves installation of equipment on the reservoir. Because this is time-consuming, it would not provide results as quickly as copper sulfate could unless the equipment has already been installed and is ready to use.

At some water utilities, reservoir intakes have been designed to acquire raw water at a variety of depths in the reservoir. This can be an effective approach to avoiding algae problems where such capability exists.

Algae and Diatom Removal by Clarification and Filtration

Numerous species of algae and diatoms can clog filters if they are present in raw water in very large numbers. Effective coagulation and clarification can ease the load on filters by removing algae and diatoms before the water is filtered. Coagulation of some algae can be more effective if pH is lowered. Bernhardt and Clasen (1994) reported that pH 6 was needed to flocculate the small blue-green alga *Synechocystis minuscule*, which has a diameter of about 6 µm, when charge neutralization with alum was used. Sweep flocculation became the dominant mechanism of flocculation at pH 7. At the high end of the range of pH used in water treatment, lime softening in solids contact units (pH not specified) was reported to attain algae removals exceeding 90 percent, as compared to 37 percent removal by alum coagulation, flocculation, and sedimentation (Speedy et al. 1969). A previous paper (Kross et al. 1968) reported results of an earlier study on the performance of the same solids contact units and indicated that they were operated in the pH range of 10 to 10.9. The density of lime softening floc is considerably greater than the density of water, whereas the density of alum floc is only slightly denser than water. The higher density of lime softening floc gives it much better settling properties when the water being treated contains algae.

After water containing algae or diatoms has been coagulated and flocculated, clarification is more effective when DAF is the clarification process, followed by filtration. When exposed to sunlight, algae and diatoms produce oxygen, which can form bubbles on the plant cells or in floc. Bubbles decrease the overall density of the floc particles to which they are attached, so sedimentation can be impaired. On the other hand, the objective of clarification by DAF is to float coagulated and flocculated particles, so DAF removes particles from water in a manner consistent with the tendency of algae to rise in water. Removal of *Aphanizomenon*, *Microcystis*, and *Chlorella* by DAF has been reported to be in the range of 90 percent to 98 percent (Zabel 1985), whereas removal by sedimentation ranged from 76 percent to 87 percent. Removal of *Stephanodiscus* by DAF was 83 percent but only 59 percent by sedimentation. Zabel also noted that sometimes the algae counts in DAF clarified water were lower than the counts in settled and filtered water, and that removal can be improved by lowering coagulation pH. A more recent discussion of DAF for treating waters containing algae is found in *Water Quality & Treatment*, 5th ed., in Chapter 7, Sedimentation and Flotation (Gregory et al. 1999).

During a bloom of algae or diatoms, clarified source water may still contain large numbers of organisms, which can result in filtration problems. The nature of the algae or diatoms influences how they are removed in filters, and the kinds of problems that may be caused. Single-celled organisms behave differently from filamentous organisms.

Single-celled algae and diatoms tend to be removed at the top of rapid sand filter beds. Backwashing filters results in stratification of filter media, with the smallest media grains of a particular kind of filtering material resting at the top of that layer of material. Thus, for a rapid sand filter, the smallest sand grains are at the top of the filter bed. A typical effective size for sand in such filters is 0.5 mm, so sand grains in the size range of 0.5 mm and smaller are found at the top of the bed. Rapid sand filters typically remove algae in the top of the filter, in the first 0.5 in. (1.3 cm) according to Palmer (1980). Removal of compressible particles at the top of a filter results in surface mat filtration, which causes head loss to increase at an accelerating rate during the filter run.

Studies of direct filtration of Great Lakes water in Canada demonstrated that by using larger coal in a dual-media filter (1.5 mm ES versus 0.92 mm ES), penetration of algae into the depth of the bed was possible and filter runs were longer (Hutchison 1976, Hutchison and Foley 1974). This allows for more storage of floc and algae in the filter bed before terminal head loss is reached. On the basis of the Canadian studies, deep bed dual-media filters having anthracite with an ES of 1.5 mm or larger, or deep monomedium filters of media with an ES of 1.5 mm or larger, are expected to be more effective for filtering single-celled algae and diatoms than the more typical dual-media filter bed with a layer of 1.0 mm ES anthracite over 0.5 mm ES sand.

When algae are found in a filamentous form, the filaments tend to be so large that penetration into a granular media filter bed is unlikely. Filamentous algae have the potential to clog filters and cause shorter filter runs as a result of filtering through a mat, just as filtering algae on a rapid sand filter causes filtration through a compressible mat and head loss gain at an accelerating pace. Furthermore, by forming a mat on the top of filter media, the filamentous algae can impede drainage of water from the filter bed when the run is terminated and the filter must be backwashed. The seriousness of this problem is increased when filter runs are shorter than normal and filters are held out of production longer to accomplish backwashing. In such a situation, procedures that are not usually used during backwashing may be necessary. If a filter will not drain well by gravity, water above the top of the wash-water trough can be drained by opening the valve that permits spent wash water to flow to waste. Once the water level drops to the top of the trough, a brief application of air scour or a short flow of wash water can be applied in an attempt to break up the mat. If a filter is equipped with filter to waste, the water above the media can then be drained to waste. If not, backwash would need to be started with the water surface at the top of the trough.

COLD WATER

Effective treatment of cold water can be challenging, especially if alum is used as the coagulant. For this discussion, cold water is considered to be between 32° and 41°F (0° and 5°C). At warm temperatures, alum coagulates particles very quickly, in fact almost instantaneously. When water temperature is near freezing, the reaction time for alum is much slower and it can be less effective as a coagulant. This phenomenon was observed during a USEPA-funded evaluation of preengineered (package plant) filtration equipment that used alum as the coagulant. The filtration treatment train consisted of three pressure filtration vessels in series. The first contained coarse filtration material to promote flocculation and some floc removal, the second contained multimedia for filtration, while the third contained GAC for T&O control. During summer, the water was warm and alum worked well. Turbidity removal by the multimedia filter was excellent. In winter, however, when the water temperature dropped to 5°C or lower, the reduction of turbidity through the multimedia filter declined to about two thirds. Most of the remaining third of the turbidity was removed in the GAC filter vessel, after a longer reaction time for the alum.

Other potential difficulties caused by cold water include higher clean-bed head loss and greater shear forces acting on attached particles in the filter bed as a result of higher water viscosity at low temperatures. If floc is weaker as a result of low temperatures, turbidity breakthrough is more likely. For this reason, rate increases on filters must be carefully applied when treating cold water.

Some operating strategies have been developed to cope with cold water conditions. At treatment plants having access to both groundwater and surface water, when the surface water temperature is lower than the groundwater temperature, increasing the proportion of groundwater in the raw water supply can moderate the cold temperature somewhat. If alum is used to coagulate both cold water and warm water, some utilities increase the pH of coagulation for cold water. For example, pH for alum coagulation was reported to be 6.8 in summer and 7.3 in winter for one plant on the Great Lakes.

At some filtration plants where the use of alum has not been as successful as desired when water is very cold, alternative coagulants have been used. Ferric chloride and ferric sulfate can be used with cold water, but the chemical handling equipment and piping must be suitable for use with these corrosive chemicals. Polyaluminum chloride (PACl) is also used. Some utilities have changed from alum to a different coagulant on a year-round basis, whereas at others, alum is used for warm water and an alternative coagulant is used part of the year for treating cold water.

Before changes in coagulant chemical are made at the plant, a careful and well-documented program of jar testing using cold water should be established for plant staff to learn how a different coagulant will behave in a variety of conditions. If a naturally occurring episode of high turbidity does not take place during the jar test program, augmenting turbidity with sediments associated with the source water could be helpful. The most severe test could be source water with spiked constituents to raise both turbidity and NOM concentration. Finding a source of DOC is challenging. In the 1970s, USEPA researchers performing in-house studies attempted to create a source of NOM by soaking fallen leaves in water for an extended period of time. Perhaps a more effective approach would be to purchase peat moss and soak it for several weeks or until the TOC of the water in which the peat is immersed has ceased to increase. Another procedure is to obtain organic materials from the watershed and soak them in the source water to obtain a high concentration of NOM with properties similar to those encountered during water quality episodes at the treatment plant.

The objective of a jar test evaluation of alternative coagulants for cold water treatment is to select one that will give a better performance over a range of raw-water quality conditions that might be encountered in the future. By learning how a different coagulant can perform in jar tests, if raw water conditions depart from what is expected, plant staff are better prepared to handle the situation. At a filtration plant where coagulant dosage charts have been relied on in the past as a guide to coagulation practice, changing coagulant chemicals removes that tool until sufficient experience is gained with the new coagulant for a new chart to be developed.

Other strategies for cold water treatment reported by water utility staff include

- increasing flocculator speed, possibly with the goal of producing a more compact floc
- using filter aid polymer, presumably because floc formed in the cold water is weaker
- increasing the dosage of alum

The importance of maintaining effective treatment through all source water conditions cannot be overemphasized. Waterborne disease outbreaks have happened in a variety of circumstances, including episodes of high turbidity and at times when source waters were very cold. When difficult treatment conditions are encountered, maintaining effective treatment is even more important than it is during routine, stable water quality situations.

IRON AND MANGANESE

The presence of iron and manganese in finished water can cause the staining of laundry and plumbing fixtures, resulting in customer complaints. Some filtration plants are operated primarily to remove iron or manganese or both.

Iron and manganese can be present in source water as a result of their natural occurrence in the environment. Both also can be present in water within the treatment plant as a result of treatment practices. Soluble iron and manganese are present in water that has little or no dissolved oxygen (DO). Groundwater generally has little or no DO, and some surface waters can have very low DO concentrations. In reservoirs that stratify in warm weather and if biodegradable substances are present at the bottom of the reservoir, bacteria surviving on those substances can in some cases exhaust the DO in the bottom layer or the hypolimnion. During warm weather, lower density warm water remains above the cool water in the hypolimnion; however, as the weather cools and water temperature drops in fall or early winter, the formerly warm water can cool to the same temperature as the hypolimnion. Then water currents can circulate throughout the entire depth of the water, and water can rise from the bottom to higher levels. This circulation pattern, called *turnover*, enables constituents that had remained in the hypolimnion to mix into all of the water and cause its quality to deteriorate. Iron and manganese then may reappear in the raw water.

Another way in which iron and manganese can be present in a treatment plant is by inadvertent recycling of iron coagulants or potassium permanganate, or recycling of manganese that was present in raw water but subsequently removed in the plant. Recycling can occur if sludge containing precipitated iron or manganese remains at the bottom of a fill-and-draw sedimentation basin or in some other basin or lagoon at the plant long enough for anaerobic conditions to develop, allowing iron or manganese to be redissolved. If that happens and supernatant liquid from such a basin passes through the plant or is recycled to the plant, dissolved iron or manganese can be reintroduced. To avoid this problem, plant operators must take care to handle sludges containing iron or manganese properly and prevent supernatant liquids containing dissolved iron or manganese from returning to the plant via recycling to the influent water.

Treatment for iron and manganese has been practiced for decades. Aeration can oxidize iron quickly enough to be effective; however, manganese is not oxidized rapidly by aeration, so chemical oxidants such as chlorine, ozone, or potassium permanganate are necessary. When iron, or manganese, or both are present as a result of reservoir turnover, the source water also might contain TOC, which could exert an oxidant demand and influence the concentration of oxidant needed to oxidize the iron or manganese. As compared to ozone and potassium permanganate, chlorine is less expensive and can be used to oxidize iron. If ozone is used as an oxidant for manganese, care is needed to prevent overdosing ozone and forming the permanganate form of manganese, which could result in pink water entering the distribution system.

Adding chlorine just prior to the filter is effective in the long term for manganese removal (Knocke et al. 1988, 1991). Soluble manganese as Mn^{+2} sorbs onto filter media that is coated with manganese dioxide. Long-term exposure to free chlorine gradually oxidizes the Mn^{+2} to manganese dioxide. This process has worked without special effort from plant operators, but if manganese removal is taking place at a filtration plant by this process, changing filter media to a material without the manganese dioxide coating can permit manganese to pass through the plant. Manganese removal capability of filter media also could be lost if the media is subjected to a chemical cleaning procedure that removes the manganese dioxide coating. This is discussed in chapter 10.

EXTREME CONDITIONS

Sometimes raw water quality changes so much that treatment is not feasible. Contaminant spills and excessively high turbidity caused by storms or high runoff events are two such circumstances. The Great Lakes and rivers large enough to support barge or ship traffic are subject to the risk of spills resulting from accidents on the water. Large spills and accidental discharges from industrial sites also are a possibility, and spills caused by railway and highway accidents near source water also occur occasionally. An accidental spill of diesel fuel that found its way into the Ohio River caused water utilities to close their intakes as the fuel passed, thus avoiding contamination of transmission mains and treatment facilities and preventing drinking water containing diesel fuel from being distributed to consumers.

When an intake has to be closed, customers should be instructed to conserve water, and as much finished water as possible should be produced and stored prior to closing the intake. This, of course, requires advance notice. The intake closure strategy formerly was used by a water utility on the Great Lakes as a means of coping with high-turbidity events caused by major storms. The source water at that time was chlorinated but unfiltered; however, the water system had sufficient water storage for three days of use, so time was available for the storm to subside and turbidity to decline before pumping resumed. During a major flood in Oregon, staff at one filtration plant closed the intake when turbidity was extremely high and performed jar tests to find an effective chemical pretreatment regime. After some hours of testing, turbidity had subsided somewhat, and treatment based on the jar test results resumed and was successful.

The ability of meteorologists to predict major storms has increased greatly with the development of satellite surveillance and enhanced computer programs, so water utility management can use forecasting information to guide operations and manage production prior to the arrival of storms. Some increase production prior to a time of heavy runoff and deteriorated source water quality when a decreased production rate might be needed to maintain filtered water quality. Precipitation forecasts also can provide guidance about near-term water demand in the system; therefore, if heavy rainfall is expected, water needed for irrigating lawns may decrease substantially, and the utility may be able to plan for a decrease in production.

As discussed in chapter 1, two water utilities in the western United States were able to handle extremely high turbidity as a result of special training provided to the staff and the extra sense of confidence and willingness of well-trained treatment plant staff to address challenges greater than those usually seen. Training, availability of information resources, and a willingness to communicate with staff at other water treatment plants where difficult water quality situations have been encountered can all combine to enable utility personnel to cope with challenging water quality that to others might seem impossible to treat.

SUMMARY

Source water quality conditions that cause treatment difficulties may happen occasionally or seldom, but for almost any source water, those conditions will be encountered from time to time. During such situations, treatment plant staff should be open-minded and maintain an investigative attitude if a new water quality condition is encountered. Prior staff training for addressing difficult water quality conditions and a good database of past water quality and treatment approaches can be very helpful when source water quality is challenging.

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6

Backwashing Filters

INTRODUCTION

This chapter discusses the complexity of washing filters and the possible damage to filters caused by improper filter washing procedures. Mechanisms by which attached particles are removed from filter media and various methods of auxiliary scour are discussed. Loss of filter media is a common problem, so this is also covered. The availability of backwash water and the capability of a plant to handle spent wash water are important considerations related to scheduling filter backwashes. For declining rate plants, knowing the clogging condition (rate of flow through the filter) and effluent turbidity status of all filters is key to managing backwash in a group of filters. For constant rate filters, key data are head loss across each filter and turbidity status. Time in service is important for all filters when runs become exceptionally long.

BACKWASHING FUNDAMENTALS

In the operating cycle of a rapid rate granular media filter, the filter is placed into service, operated for a period of time, and ultimately the filter run is ended and the filter is backwashed. Filter runs may be terminated on the basis of total hours of filter operation, because terminal head loss has been attained, because of turbidity breakthrough, or for other reasons such as the need to decrease production at the plant. Backwashing removes the accumulated floc and particles trapped in the filter bed during the run, thus preparing the filter for another run. For dual-media or multimedia filter beds, backwashing is managed to restratify the media at the end of the backwash, so the larger, less dense filter material rests at the top of the bed and the smaller, denser material is at the bottom of the filter bed.

Filter backwashing is the most complex phase of filter operation, as it involves manipulation of valves, monitoring and controlling the flow of wash water, managing auxiliary scour using surface wash or air scour, and completing the backwash. All of these activities must be done carefully, as the potential for physical damage to the filter bed or underdrain is greatest during backwashing. The rates of flow used for backwashing are considerably greater than the filtration rates in most plants. Furthermore, backwash involves upflow through the bed, with the potential to damage the filter if it is not performed properly.

If it is excessive or started rapidly at a high rate, the upward flow of water also has the potential to lift a filter bottom or to burst underdrain tiles. Gradually increasing the wash-water flow rate during the beginning of the backwash is a safer procedure than suddenly applying a high rate of upward flow. Presence of air in the underdrain or in the pipes supplying wash water to the filter can cause damage if air is not supposed to be used in backwashing.

Observing Filter Backwash

Carefully looking at a filter before, during, and after backwashing offers plant operators the opportunity to look for irregularities or symptoms of problems that develop in the filter. This activity is performed during filter inspections, but frequent observations of backwash can help operators detect problems before they become serious and expensive to fix.

Implicit in this discussion of filter observation is that the filter is an open, gravity filter. Observing backwashing of pressure filters on a routine basis is very difficult or perhaps not possible, depending on the design of the filter; therefore, filters of this type must be taken out of service, opened for access to the interior of the pressure vessel, and then carefully inspected on a periodic basis.

Before backwash begins, if the level of water in the filter box is allowed to slowly drain to the top of the media from time to time, any hills and valleys in the media surface can be detected. Also, cracks in the filter bed, shown in Figure 6-1, or areas where the media has pulled away from the filter wall can be detected at this time. Mudballs also can be observed if they have formed and remain on the surface of the filter bed, as seen in Figure 6-2. Presence of algae mats and release of entrapped air caused by air binding can be detected when the water level is drawn down before washing. The froth on the water surface in Figure 6-3 is the result of air binding.

When the water is drawn down to the media surface, if surface wash is employed, the absence of a water jet coming from a clogged surface sweep nozzle can be seen as the sweep rotates. This is noticeable while the water surface is slightly below or at the level of the sweep because functioning nozzles leave a trail of bubbles when the sweeps rotate, as shown in Figure 6-4. After water has risen above the sweep, the absence of the water jet is difficult or impossible to detect. Other potential problems to watch for include vibration of the arms, unbalanced sweeps or nonuniform rotation, and leakage at the point of rotation. Rotary sweeps work well in the circular area within which they rotate, but attaining effective scouring action in corners of a filter box can be difficult. These areas need special observation and attention. The most effective action by surface wash takes place when the bed is expanded and the jets of water scour the media grains and scrub off floc and dirt that has attached to the media and accumulated in the filter bed.

Source: Thames Water Utilities, *Filter Maintenance & Operations Guidance Manual.*

Figure 6-1 Cracks in filter bed

Courtesy of Filter Plant Programs Section, Pennsylvania DEP.

Figure 6-2 Mudballs on top of filter bed

Courtesy of Seattle Water Department, USEPA Cooperative Agreement.

Figure 6-3 Air bubbles rising to top of water after end of filter run. (Source water supersaturated with air, and operator used garden rake to agitate media in small, pre-engineered water treatment plant to remove air before backwash.)

Source: AWWA Filter Surveillance Techniques Video.

Figure 6-4 Rotary surface wash sweeps in action, with clogged nozzles leaving no bubble trails

It is best to observe air scour when a filter bed has not been disturbed by any inspection procedures. Uniform air scour, illustrated in Figure 6-5, is the desired effect. An irregular pattern of air bubbles with excessive bubbling and turbulence or a minimal amount of agitation in an area of the filter bed (Figure 6-6) is an indication of uneven distribution of air during air scour. Nonuniform distribution of air scour is an indication of the need for more extensive investigation.

When a filter is backwashed, the upflow of water should be uniform across the filter bed (see Figure 6-7) during the water-only portion of the procedure, with no dead or quiet zones and no areas of excessive rise rate. Damage to the underdrain or support media that allows an excessive upflow or jet of water in a small area of the bed can be

Courtesy of Siemens Water Technologies Corp.

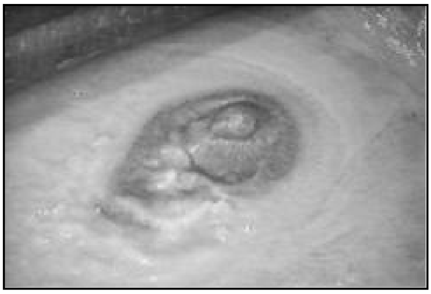
Figure 6-5 Filter backwash with uniform air scour

Source: Logsdon.

Figure 6-6 Filter backwash with nonuniform air scour

Courtesy of Black & Veatch Corporation.

Figure 6-7 Filter backwash with uniform rise rate for wash water

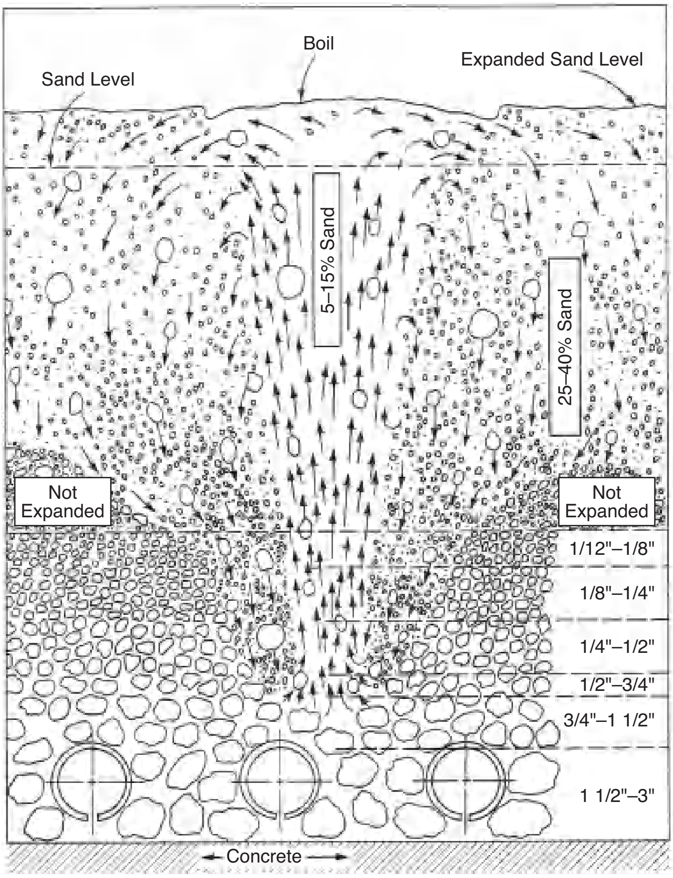


Source: AWWA Filter Surveillance Techniques Video.

Figure 6-8 Filter backwash with filter boil visible

observed as a filter "boil," as seen in the picture in Figure 6-8. Figure 6-9 is an illustration of a filter boil in a filter with graded gravel support materials. Boils occur when water flows up in the filter bed at an excessively high rate in one location. Figure 6-9 depicts a filter with a pipe lateral underdrain, but other underdrain types could fail in a way that causes filter boil. For example, loss of a nozzle in a filter floor, or a break in a single clay underdrain tile could result in a hole of sufficient size to result in a localized high water flow.

When a filter boil is discovered, a detailed filter inspection is needed, with excavation of media in the area of the boil to assess the condition of support gravel, if used, and the condition of the underdrain. Excavation of media to inspect the support gravel or underdrain is discussed in chapter 10. As shown in Figure 6-9, the boil can seriously disrupt the support materials; if not corrected, a hole large enough to allow a high water flow has the potential to permit support materials and filter media to be lost into the underdrain system during continued operation of the filter. Figure 6-10 shows a cone of depression where filter media loss took place after a nozzle in the filter floor was lost.



Source: Water Quality & Treatment, 3rd ed.

Figure 6-9 Filter boil showing displacement of media and support gravel

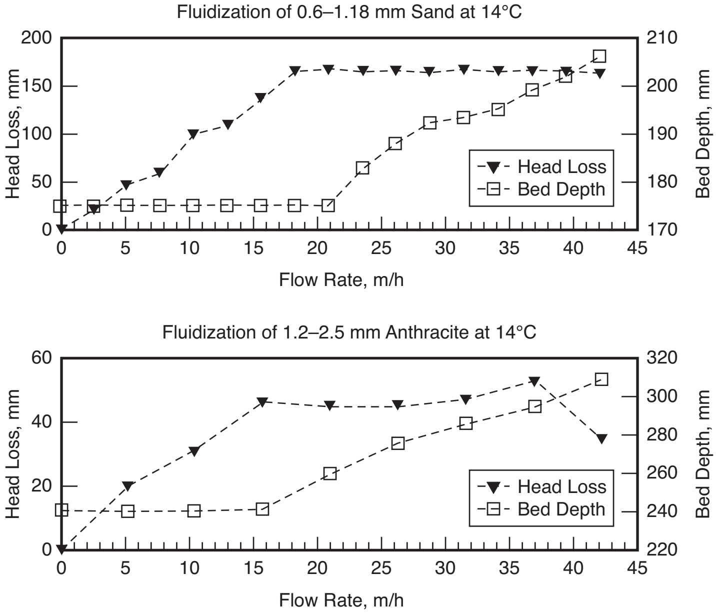
After the backwash is finished, the surface of the filter bed should be level, with no mudballs or foreign debris on the surface if the backwash was thorough and auxiliary scour was effective. Corrective action may be possible before the filter bed or underdrain become severely damaged if a developing problem is detected before it becomes acute.

Filter Bed Expansion, Media Size and Density, and Temperature Effects

When wash water is applied to a filter, the upward flow of water in the filter bed causes head loss. As the rise rate increases, head loss through the filter bed increases until the upward velocity is sufficient to lift particles of filter material and fluidize the bed. At this point, the head loss cause by flow through the porous bed ceases to increase. This is illustrated in Figure 6-11, which shows the behavior of an anthracite filter bed and a sand filter bed as the rise rate was increased in steps over time. As the head loss ceases to

Source: John L. Cleasby, *Filter Maintenance & Operations Guidance Manual.*

Figure 6-10 Cone of depression in filter media resulting from loss of nozzle in filter bottom



Fluidization of 0.6–1.18 mm Sand at 14°C

Fluidization of 1.2–2.5 mm Anthracite at 14°C

Source: Thames Water Utilities, *Filter Maintenance & Operations Guidance Manual.*

Figure 6-11 Filter bed depth and head loss during backwash at increasing rise rates

increase with a higher rise rate, the filter bed begins to expand, as indicated on the graph by the data for bed depth.

Fluidization velocity can be determined experimentally in test filters large enough that they allow the media to fluidize naturally as the rise rate is increased. Before attempting to determine fluidization velocity in a pilot filter column, backwash the filter and observe the behavior of the media when the rise rate is started at a low value and gradually increased. Any filter column in which media rises like a piston in an internal combustion engine, with water below the "piston" of media at the start of backwash, is too small for use in determining fluidization velocities. If the media fluidizes naturally without the "piston" behavior, the pilot filter can be used to evaluate fluidization velocity. Another experimental approach to evaluating fluidization velocity is for an operator to place a long pole about 1 in. or 3 cm in diameter into the filter box on the top of the filter media at rest. Then a backwash should be initiated at a very low rate and the rise rate gradually increased in small steps. When the pole sinks into the media, fluidization has begun.

Grains of filter material rise in the filter bed because of the drag forces created by the rising water. The forces causing media to fluidize during backwash are related to the density and size of media, rise rate, and viscosity of the water. Table 6-1 lists values of 1.1× minimum fluidization velocity for a range of mean sizes of anthracite, sand, and garnet filtering materials. The values listed in Table 6-1 are comparable to the rise rates used for backwashing typical filter media in many existing plants with dual-media or mixed-media filter beds. Because it is necessary to fluidize not only the small (d_{10})-sized media grains but also the large (d_{90})-sized media for effective filter backwashing, the mean grain sizes and fluidization velocities in Table 6-1 are related to the d_{90} media. The d_{90} value can be calculated if the d_{10} size and the UC (d_{60}/d_{10}) are known using the formula:

$$d_{90} = d_{10}(10^{1.67\log \mathrm{UC}})$$

Table 6-2 presents d_{90} sizes for filter materials having an effective size (d_{10}) of 1.0 mm for UC values ranging from 1.3 to 2.0. As the UC increases, the d_{90} size increases at an even greater rate, as shown in Table 6-2. Low UC are preferred because of the narrower range of media sizes, which results in the ability to use a rise rate that is capable of fluidizing the d_{90}-sized media but not excessively high for small media such as the d_{10}-sized media.

Viscosity, which influences the minimum fluidization velocity, is related to water temperature. Cold water has a higher viscosity than warm water, so a rise rate just sufficient to fluidize a filter bed at 41°F (5°C) would not be adequate to fluidize the filter bed at 77°F (25°C), when a rise rate of nearly 50 percent higher would be needed. Table 6-3 lists correction factors to apply to fluidization velocities for water temperatures other than 77°F (25°C). The correction factors in Table 6-3 indicate why using the same rise rate over a wide range of temperatures could result in washing media out of the filter or

Table 6-1 Calculated values of 1.1× minimum fluidization velocity (V_{mf}), gpm/ft^2 and m/hr at 25°C, calculated with Wen & Yu equation for mean sizes ranging from 0.27 mm to 2.59 mm

Mean Size, mm	Anthracite, SG = 1.7		Sand, SG = 2.65		Garnet, SG = 4.3	
	gpm/ft^2	m/hr	gpm/ft^2	m/hr	gpm/ft^2	m/hr
2.59	28.7	70.0				
2.18	23.5	57.3				
1.84	18.8	45.9	35.9	87.6		
1.54	14.5	35.4	28.8	70.3		
1.30	11.1	27.1	23.0	56.1	39.3	95.9
1.09	8.3	20.2	17.6	42.9	31.2	76.1
0.92	6.1	14.9	13.3	32.4	24.4	59.5
0.78	4.4	10.7	10.0	24.4	18.8	45.9
0.65	3.1	7.6	7.2	17.6	13.8	33.7
0.55			5.2	12.7	10.1	24.6
0.46			3.7	9.0	7.3	17.8
0.38			2.5	6.1	5.1	12.4
0.27					2.5	6.1

Source: Cleasby 2001.

Table 6-2 Values of d_{90} for d_{10} = 1.0 mm, for UC ranging from 1.3 to 2.0

d_{10} = 1.0 mm			$d_{90} = d_{10}(10^{1.67\,\log UC})$
UC	log UC	1.67 log UC	$10^{1.67\,\log UC}$
1.3	0.1139	0.1903	1.55
1.4	0.1461	0.2440	1.75
1.5	0.1761	0.2941	1.97
1.6	0.2041	0.3409	2.19
1.7	0.2304	0.3848	2.42
1.8	0.2553	0.4263	2.67
1.9	0.2787	0.4655	2.92
2.0	0.3010	0.5027	3.18

Table 6-3 Temperature correction factors to be applied for temperatures other than 25°C for typical sand and anthracite d_{90} sizes. Multiply the 25°C value by the most appropriate factor below.

Water Temp., °C	Anthracite, d_{90} = 2.0 mm	Anthracite, d_{90} = 1.0 mm	Sand, d_{90} = 1.0 mm	Sand, d_{90} = 0.5 mm
30	1.06	1.10	1.09	1.13
25	1.00	1.00	1.00	1.00
20	0.93	0.91	0.91	0.90
15	0.86	0.80	0.83	0.79
10	0.79	0.70	0.73	0.69
5	0.71	0.61	0.64	0.61

Source: Cleasby 2001.

Note that the factors have more effect for smaller and/or lighter media because viscous effects are larger for smaller and lighter media.

the failure to adequately fluidize the bed, depending on whether the rise rate is appropriate for cold water or warm water.

BACKWASHING METHODS

Four approaches have been used for filter washing, with the variations involving the nature of the auxiliary scour intended to enhance the effectiveness of the backwash. They are: water wash only, water wash with surface wash, air scour followed by water wash, and combined air and water for scrubbing action followed by water wash.

The original approach to filter washing involved water only, with mechanical rakes intended to agitate the media and assist washing. This was cumbersome and was abandoned early in the application of rapid rate filtration. Using water in an upflow mode with no auxiliary scour was the least effective means of filter washing and led to formation of mudballs in numerous plants before improved backwash procedures were developed.

When grains of filter media are not cleaned thoroughly, deposits of floc and dirt can accumulate on the media and grow over time. The accumulated floc and dirt can grow to include filter media, growing larger and forming mudballs. Excessive dosages of metal coagulants or of polymers can promote mudball formation. With the passage of time, mudballs can increase in size, and they may become more compact, increasing in density. If they are not broken up, mudballs can sink into the media and work their way to the bottom of the filter. They interfere with effective filtration and, if present in excessive amounts, can necessitate removal and cleaning or replacement of filter media.

When the weakness of backwashing by rising water without some scouring action was realized, surface wash was developed as a means of providing extra scrubbing action to clean the filter media. Originally, this was accomplished by using a grid of fixed nozzles, but rotary surface sweeps were developed and supplanted the fixed nozzle grids in most plants. Surface wash creates additional turbulence and scouring action in the vicinity of the water jets. This form of auxiliary scour has helped to control formation of mudballs in filters; however, at some plants, mudball problems are still encountered even though surface wash is used.

Another variation of backwashing involves use of air scour for 1 to 2 minutes with no water flow, followed by water rinse after the air scour concludes. Rising air bubbles tend to create paths in the media, and subsequent air bubbles follow the paths of least resistance. Near the bottom of the filter, media grains near the orifices where air is delivered are scoured, but away from the sources of air, media may be agitated only slightly, with little scouring action. This approach to filter washing and the use of surface wash plus water wash are about equally effective for cleaning media.

The most effective approach to filter washing is combined air and water wash. This procedure uses air scour alone for 1 or 2 minutes, followed by air scour plus water wash at a rate of about half of the minimum fluidization velocity. Air is shut off when the water in the filter box rises to about 6 in. (15 cm) below the top of the wash-water trough. When the air bubbles have dissipated, the full rise rate is applied to rinse the bed.

Typical rates of flow for air and water for filters that use air scour and water wash are presented in Table 6-4.

Table 6-4 Typical water and air-scour flow rates for backwash systems employing air scour

Filter Medium	Backwash Sequence	Air Rate, scfm/ft^2 (m/hr)	Water Rate*, gpm/ft^2 (m/hr)
Fine sand 0.5 mm ES	Air first Water second	2–3 (37–55)	15 (37)
Fine dual and triple media with 1.0 mm ES anthracite	Air first Water second	3–4 (55–73)	15–20 (37–49)
Coarse dual media with 1.5 mm ES anthracite	Air first Air + water on rising level Water third	4–5 (73–91)	10 (24) 25 (61)
Coarse sand 1.0 mm ES	Air + water first Water second	3–4 (55–73)	6–7 (15–17) Same or double rate
Coarse sand 2 mm ES	Air + water first Water second	6–8 (110–146)	10–12 (24–29) Same or double rate
Coarse anthracite 1.5 mm ES	Air + water first Water second	3–5 (55–91)	8–10 (20–24) Same or double rate

Source: Cleasby and Logsdon 1999.

*Water rates for dual and triple media vary with water temperature and should fluidize the bed to achieve restratification of the media.

MANAGING AND MONITORING BACKWASH

Filter washing is monitored and managed for a variety of purposes. With respect to washing the filter, these include attaining effective washing to control mudballs and clean the bed, minimizing loss of filter media during backwash, and avoiding any damage to the filter bed or underdrain system. For the filter plant and the water system, backwashing is managed for several purposes:

- Have sufficient filters available for service when needed,
- Spread the workload for plant operators more uniformly over time,
- Avoid overloading a backwash residuals management facility (if one exists at the plant) by the volume of wash water produced in a given time period,
- Avoid an adverse affect on plant production by performing a number of backwashes in quick succession, and
- Avoid exhausting the wash-water supply before all filter washes are completed.

All of this requires careful planning and execution.

Managing and Monitoring Backwash of a Single Filter

Cleaning the Media Effectively and Restratifying the Filter Bed

The principal reason for filter washing is to clean the filter bed and prepare it for another filter run. A second important aspect of backwashing is to return multimedia beds to their original configuration of coarser media in the upper part of the bed and finer media in the lower portion of the bed at the end of the backwash. Restratification is not necessary for monomedium filters.

When filters are equipped with surface wash, typical practice is to turn on surface wash and operate this for 1 or 2 min before initiating backwash. Surface wash continues during fluidization to scour the filter materials as they circulate within the filter box during fluidization. For the commonly used rotary-sweep surface wash, the typical flow range is 0.5 to 1 gpm/ft^2 (1.2 to 2.4 m/hr). Surface wash can be turned off 2 to 3 min before the backwash ends and must be off when the backwash rise rate is decreased to allow the filter media to restratify. After the bed has been cleaned, the extended subfluidization wash procedure described by Amburgey et al. (2003) can be used. This procedure, which focuses on minimizing the turbidity spike when a filter is returned to service after backwashing, is described in chapter 7.

When air scour is employed during backwash, typical rates of flow for water and air are provided in Table 6-4. Air is applied for 1 to 2 min without any water flow. If air is not applied along with water, air is shut off and water is applied. If air and water are used together, the timing for application of air depends on the time needed for water to rise to within 6 in. (15 cm) of the top of the wash-water troughs. Again, if the extended subfluidization wash is used as the final stage of backwashing, this is applied after the bed has been cleaned.

Effective backwashing calls for use of enough water to clean the filter without using excessive amounts of wash water. A filter bed must be washed effectively to remove floc and prevent build-up of gummy deposits on media grains and growth of mudballs in the bed. Washing a filter for an excessively long time is wasteful of water that has already been treated, and it holds a filter out of service longer than necessary, which is an important consideration when peak water production is needed. To avoid wasting wash water, monitor spent wash-water turbidity and cease washing when that turbidity reaches about 10 ntu. If the extended subfluidization wash is used, this is when that procedure should be initiated, as it is a procedure that is managed on the basis of operating time rather than on the basis of spent wash-water turbidity.

Techniques for evaluating the extent to which backwashing is effectively cleaning filter materials are presented in chapter 10.

Controlling Media Loss and Disruption During and After Backwash and Avoiding Physical Damage to Filters

Although the primary purpose of backwashing is to clean the filter bed and prepare it for return to service, this must be carried out in a way that minimizes loss of filter media during backwashing and must avoid causing physical damage to the filter bed and underdrain system. This aspect of performing a filter backwash can begin when the filter is taken out of service rather than when backwash is initiated. If air binding is thought to have happened during a filter run, resting a filter for several minutes after ending the run can give air bubbles the opportunity to rise out of the filter bed and to the top of the water. Drawing the water in the filter box down to within about 6 in. (15 cm) of the media surface reduces the head on air bubbles and dissolved air within the filter and can hasten removal of air. Initiating backwash before air has left the filter bed carries a risk of media loss if air bubbles are still rising to the water surface when wash water overflows the troughs. This has happened during the operation of a pre-engineered water filtration plant, so it is not merely a theoretical concept. Also, air bubbles have the potential to carry media to the water surface and over the troughs if air scour is not turned off in time for the air to leave the wash water before it flows over the troughs.

Initiating the backwash gradually over a period of at least 30 sec instead of turning on the full flow of wash water abruptly also avoids media loss. This also is necessary to avoid damaging the underdrain or upsetting support gravel, if it is present. An example of the effect of improper management of filter wash occurred when a new filtration plant operator being trained to operate filters manually in event of a power loss opened the wash valve to 100 percent immediately on initiating backwash. The surge of water into the filter disrupted the anthracite layer in the dual media, causing the loss of about 2 yd^3 or 2 m^3 of media. Surges of wash water also have the potential to lift filter bottoms or disrupt tile underdrains.

During backwash, rise rates that are too low may not clean the filter bed adequately, but if rise rates are too high, some media can be washed out of the filter. Filter media consists of grains of material in a range of sizes, as described by the effective size and UC. As shown in Table 6-3, this size range is narrower when the UC is low, around 1.4 or 1.5 rather than from 1.7 to 2.0. When the UC is low, the upflow velocity, or rise rate, needed to fluidize large d_{90} filter material is not so large that it presents a high risk of washing out the small d_{10} filter material. Having filter media with a low UC favors being able to effectively clean media during backwash with a minimum of media loss.

Monitoring the rate of flow of backwash water must be done to control backwash properly. Usually this is done by checking the rate of flow as indicated by a flowmeter. Periodically, during a filter inspection the flowmeter can be checked for accuracy by observing the time for water in the filter box to rise to a predetermined distance and hence a predetermined volume. This is further described in chapter 10, Filter Inspection and Maintenance. At plants equipped with surface wash, this flow rate also must be monitored.

When air scour is employed, performance of the air system also needs to be monitored. Data on air pressure and rate of flow can be used to calculate the rate of air delivery to the filter during air scour, and such data can be useful for assessing air compressor performance.

Underdrain failures caused by uplift or rupture have happened at filtration plants equipped with porous plate underdrains and tile underdrains. In recent years, failures have also happened at plants equipped with tile underdrains equipped with porous plate caps. Surging could rupture clay tile underdrains, thus the need for carefully controlling backwash flow rates. When underdrains are equipped with porous plate caps, floc that penetrates through the media has the potential to stick in the porous plate cap. If these caps are used in lime softening plants, the potential for calcium carbonate to precipitate in the caps also exists.

Monitoring backpressure on underdrain systems can give an indication of whether water is flowing freely, as it should, or whether some sort of blockage has developed. Excessive backpressure can result in underdrain failure. Additional knowledge of what is happening in underdrains can be gained by monitoring head loss across underdrains, such as porous plates, porous caps on tile underdrains, and nozzle underdrains. If this practice begins when the underdrain system is new, baseline data on the head loss through the underdrain can be gathered. If head loss at a fixed rate of flow and temperature (or adjusted for a specified rate of flow and temperature) increases substantially, this could signal the existence of clogging in the underdrain and need for filter inspection and possibly chemical cleaning of the underdrain system. Cleaning filter underdrains is described in chapter 10.

Filter bed expansion is another aspect of backwash that needs to be confirmed periodically. Various approaches to this task, including using a device similar to a Secchi disk and a filter bed expansion tool, are described in chapter 10. When the rise rate is too high and bed expansion is excessive, media can be washed out. However, a rise rate that is insufficient to fluidize a filter bed can result in backwash that is not as effective as desired.

At a filtration plant that employed a cluster of four self-backwashing filters, water produced by three filters was the source of wash water for the one being backwashed. This plant had been downrated because of difficulties with pretreatment, however, so when filters were operated at only 2 gpm/ft^2 (5 m/hr), the rise rate was only 6 gpm/ft^2 (15 m/hr) and only a subfluidized wash was achieved.

Wash-water trough design and the relative position of the bottom of the troughs and the top of the media when the bed is expanded are factors that influence media loss during backwashing. Above the bottom of the wash-water troughs, the cross-section of the filter box available for upflow of water is reduced by the area occupied by the troughs, so the rise rate increases. If filter media has risen higher than the bottom of the troughs, the higher rise rate has the potential to carry it over the troughs and out of the filter box. Plant staff are constrained to operate with the existing trough design, at least until physical changes can be made, but some flexibility may be available with regard to the amount of bed expansion practiced on a routine basis. Although a 50-percent bed expansion

Designing Filters to Avoid Media Disruption and Media Loss

Trough design influences media loss to some extent. Troughs made of metal, for example, are much thinner than cast concrete troughs. Thus, a metal trough would not extend down from its top so deep into the filter box as would a concrete trough with the same inside depth and width. The smaller cross-sectional area of the metal trough also would result in a somewhat lower rise rate in the zone where the troughs are located. If media loss is a serious concern, such as when GAC is used as the filter media, use of baffled wash-water troughs, such as those shown in Figure 6-12, can reduce media loss and expensive media replacement costs. Even though they can be very helpful for cutting down on media loss, the baffles do occupy some of the area of the filter box that is not occupied by conventional troughs. This can to some extent hinder access to filters when inspection and maintenance procedures are performed. If baffled troughs are installed, the possibility of attaching the baffles to troughs in a way that permits removal of the baffles for filter bed inspection merits consideration.

Filling the filter box after backwash is complete has the potential for media disruption. Excessive entry velocities then and during filter operation can cause water to flow to the filter box wall opposite the point of entry for filter influent, with the potential for water to have a high velocity current along the filter box wall and down into the media. Erosion or washing away of some filter media next to the filter wall would provide a path of lower resistance for water to flow through the filter, and thus a higher filtration rate in this area of the filter. The potential result is passage of excessive turbidity and perhaps pathogens into finished water. Figure 6-13 shows baffles that were installed to dissipate energy and keep a high velocity

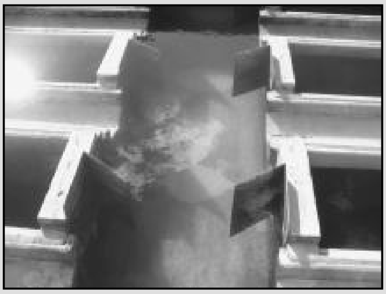
Designing Filters to Avoid Media Disruption and Media Loss (continued)

jet of water from reaching the filter box wall opposite the point of entry. The baffles were angled toward the filter influent entry point to cause the energy dissipation.

Another potential for disruption of filter media early in a filter run is the situation in which water falls several feet from a weir into a filter at an influent flow splitting plant. A possible remedy for filter bed disruption in this kind of plant is to provide a large splash plate on which the water can fall early in the filter run when the depth of water over the filter bed is relatively shallow. The overall objective is to minimize disturbance of the filter bed by influent water, regardless of the type of flow control utilized in the plant.

Courtesy of Black & Veatch Corporation, Taylor Mill Water Treatment Plant, Northern Kentucky Water District.

Figure 6-12 Baffled wash-water troughs



Courtesy of Doug Wise, Eugene Water & Electric Board.

Figure 6-13 Baffles installed in filter to reduce influent water velocity

may be considered when filters are designed, generally this extent of bed expansion is not used in practice. Bed expansion of 15 percent to 30 percent is more commonly used, and if expansion as low as 15 percent provides adequate cleaning, there is a greater distance from the top of the expanded bed to the bottom of the wash-water troughs.

Managing and Scheduling Backwash in the Context of Plant and Water System Operations

Scheduling filter washing has consequences for the overall operation of the filtration plant, for supplying water to the system, and for the capacity of residuals holding and treatment facilities, if these exist at the plant. Filter washing also has to be managed in accordance with the supply of wash water available.

Influence of Filter Washing on Other Filters

The ideal approach to filter washing is to space out backwash events rather uniformly over the hours when operators are present. At a plant where a filter is not held off-line to be placed into service when another filter is taken out of service for backwashing, a rate increase is imposed on filters remaining in service unless plant inflow is decreased. This rate increase can be moderated if equalization storage is available in sedimentation basins ahead of the filters. When filters remaining in service have to take all of the increased flow caused by backwashing a filter, the increase in filtration rate causes an increase in head loss for each filter in service. In a plant with only four filters, the rate increase would be 33 percent, and this has the potential to cause a substantial increase in head loss. If more than one filter is close to terminal head loss when a filter is backwashed, the filter that has high head loss and remains in service might quickly reach or exceed terminal head loss, thus requiring another filter to be removed from service for washing. This situation has the potential to affect filters in constant rate plants. This could also happen in automatic backwashing plants where head loss triggers backwash.

If too many filters approach terminal head loss in a short time frame, a chain reaction of filter washings can occur. One remedy for this is to carefully observe the head loss on each filter and the rate of gain of head loss. If too many filter washings are projected for a future time, starting to wash one or more filters at less than the usual terminal head loss may avert having too many backwashes clustered in a short time frame. This sort of approach to filter washing might also be necessary if filters are abruptly clogging at a faster-than-normal rate as a result of air binding or filter clogging algae.

Another circumstance that could cause an increase in head loss on all filters is operating a filtration plant at a production rate somewhat similar to the diurnal system demand while keeping all filters in service, so if a large increase in production is initiated when demand increases, head loss also would increase. In this case, a better operating strategy is to hold one or more filters out of service and place them into service when greater production is needed, thus avoiding a filtration rate increase or at least reducing its magnitude.

Effect of Filter Washing on Wash-Water Supply

At some filtration plants the supply of wash water is limited by the volume of a dedicated elevated storage tank and the rate at which it can be filled, or by the extent to which a clearwell can be drawn down while still satisfying other operational requirements at the plant. If a "chain reaction" of filter backwashing happens at a plant, washing too many filters in too short a time can exhaust the supply of wash water. To avoid this dilemma, the head loss status of each filter should be observed, and filters should be backwashed on a staggered basis, with backwash spread out over time, as previously discussed. Failure to backwash filters in a timely manner can have serious consequences. The inability to backwash filters at one water treatment plant because of excessive demand in the distribution system was a contributing factor to a giardiasis outbreak.

Effect of Filter Washing on Residuals Holding and Treatment Facilities

An increasing number of water treatment plants are treating residuals, including sedimentation basin sludge and spent wash water, either for purposes of water pollution control or for water conservation. When water is scarce, failing to reuse spent wash water is not good conservation practice. Plants that treat residuals need facilities for storage and flow equalization, and for treatment. Without flow equalization, residuals treatment would need to be sized for the maximum rate of flow expected.

When multiple filters are washed in a short time frame and the rate of flow of spent wash water into the storage and equalization facility exceeds conditions for which it was designed, the residuals treatment facility can become overloaded. The quality of the water from the residuals treatment facility can become degraded to the extent that performance of the water treatment plant is affected adversely by the return of poorly treated residuals flow to the headworks of the plant. This is another very compelling reason for managing filter backwashing carefully and spacing backwash events uniformly over time to the extent feasible.

Influence of Filter Washing on Plant Production

Washing filters, even though absolutely necessary, does decrease the net water production at the plant. This occurs both because filtered or finished water is used to wash filters and because filters are not producing water when they are out of service for backwashing. In addition, if filter-to-waste is employed when filters are placed back into service, this

Avoiding Adverse Effect of Residuals on Drinking Water Quality

At filtration plants where residuals are treated and the liquid stream is recycled to influent raw water prior to coagulation for purposes of water conservation or pollution control, an alternative flow path should be provided for the liquid stream in case of a process failure in the residuals treatment train. This would ensure that if residuals treatment became ineffective, recycle of inadequately treated residuals to the influent water would not be mandatory. The recycling of residuals that have received inadequate treatment can cause influent water quality to deteriorate and can disrupt chemical coagulation, thereby causing problems in the treatment of the drinking water. Difficulties in treating raw water can lead to the use of greater dosages of coagulant, carry-over of floc from clarifiers, shorter filter runs, more frequent backwash, production of more residuals, greater difficulties with the residuals treatment train performance, and even to problems with the filtered water quality. A residuals disposal option is needed to get inadequately treated residuals “out of the loop” if such an event should occur. Treatment plant staff should not have to recycle residuals to the plant influent in situations when doing so is likely to cause excessive deterioration of drinking water quality.

also results in a decrease in net water produced and sent to the distribution system. As filter runs become shorter, an increased percentage of a day's time is devoted to operations in which filters are not producing water that will be sent to the distribution system. This has the effect of reducing the maximum production available for use in the system, and if an episode such as an algae bloom and filter clogging happens during a time of high demand, the plant, the system, and the operations staff can become stressed. In this situation, both careful planning and system-wide water conservation efforts may be needed to cope with difficult circumstances.

SUMMARY

Backwashing filters is an essential procedure for keeping filters fully functional. Failure to clean filters adequately can result in higher clean bed head loss and formation of mudballs over the long term. Because water flows involved in backwashing are much greater than the flows during filtration, and because the flow of water is upward rather than downward, backwashing has the potential to cause loss of filter media and damage to filter beds and underdrains. Therefore, extra care must be taken for this part of filter operation. Rise rates must be measured accurately, and introduction of backwash water into the filter in a gradual manner rather than abruptly is good practice. If filters are not equipped for air scour, the presence of air in a filter during backwash is undesirable, and an investigation to determine the cause is appropriate. Because of the importance of backwashing filters properly, visual observation of this procedure is recommended periodically for every filter, if each backwash cannot be observed.

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7

Returning Filters to Service After Backwashing

INTRODUCTION

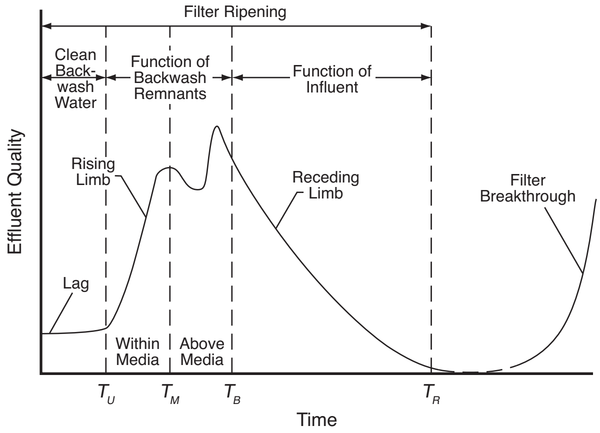
Returning a filter to service following backwash is an operation that now has greater potential for regulatory consequences as a result of the IESWTR's stipulations on filtered water turbidity in §141.175 (b)(1) and (2) (USEPA 1998). If an individual filter produces filtered water turbidity exceeding 1.0 ntu in two consecutive measurements taken 15 min apart, the result must be reported by the water utility to the agency with regulatory enforcement responsibility and certain other actions must be taken as prescribed in (b) (1). The tendency of filters to produce an initial turbidity spike was implicitly recognized in the rule, as another provision, (b) (2). This requires the same response from the utility as that stated in (b) (1) if an individual filter produces filtered water turbidity exceeding 0.5 ntu in two consecutive measurements taken 15 min apart after the filter has been operating for 4 hours. Thus, after 4 hours of operation, the performance goal is more stringent.

An important objective in the Partnership for Safe Water program is to produce filtered water having low turbidity when a filter is returned to service. The Partnership goals related to the turbidity upon starting a filter are:

- The initial turbidity spike should not exceed 0.3 ntu.
- Filtered water turbidity should be <0.1 ntu within 15 min after the filter is returned to service.
- If filter-to-waste is employed, turbidity should be <0.1 ntu when filter-to-waste is ended and filtered water is discharged to the clearwell.

These operational goals reflect the need for careful management of filters when they are returned to service.

This chapter discusses the techniques for attaining low filtrate turbidity when a filter is returned to service. Several procedures have been shown to reduce the initial turbidity peak in some filtration plants. These have not been universally effective; however, one or more of the several approaches to controlling the initial turbidity peak and reducing the



Source: Amirtharajah and Wetstein 1980.

Figure 7-1 Effluent turbidity during filter run, illustrating changes in turbidity and sources of particles causing the turbidity. (Note that the time scale is variable, with filter ripening occuring for perhaps less than an hour, whereas the time from end of filter ripening [beyond T_R on the X-axis] to beginning of filter breakthrough might last for 24 to 48 hours or more.)

time needed to produce filtered water turbidity lower than that required by regulations have the potential for improving filter performance on startup at a given plant. If none of the procedures is used at a plant, a series of in-plant trials can be performed to identify the most effective way to control the initial turbidity spike.

FILTER RIPENING, THE INITIAL IMPROVEMENT PERIOD

Filtered water turbidity often is higher at the start of a filter run, and then it improves. The sources of particles that cause turbidity when a filter is returned to service after backwashing are explained (Amirtharajah and Wetstein 1980) and illustrated in a diagram presented as Figure 7-1. The first filter effluent water after backwashing is actually water that had been used for backwashing but never reached the filter bed or support materials. Then wash water from within the filter bed passes out of the filter. This is followed by wash water that was between the top of the media and the wash-water trough when backwash ended. When a filter box is refilled, pretreated water mixes into the water between the top of the media and the top of the wash-water trough, diluting to some extent the spent wash water that was not removed at the end of backwashing. Then, as more pretreated water enters the filter box, the remaining wash water is further diluted and it passes through the filter, so finally, all of the water being filtered is the filter influent.

During backwashing, floc that was caught in the filter bed during the run is detached from grains of filter media and most washes out of the bed. Some floc particles may be very strongly attached to the media and can remain on the media grains during backwash. Some of the detached particles, referred to as *backwash remnant particles*, are not

Backwash Water Source and Quality

Edzwald (2007) has suggested that an increase in electronegativity of the remnant particles could be caused by backwashing a filter with finished water that has a higher pH than the filter influent water. This could occur if the pH of water used for backwashing has been increased after filtration as a means of controlling corrosion in the distribution system. An alternative that avoids washing filters with higher pH water is to take water for backwashing before the pH is raised.

washed out, but just circulate in the rising wash water. When backwash terminates, the particles either settle into the media as it comes to rest, or they remain in the water above the filter media, either suspended or slowly settling.

Filter ripening occurs as some of the remnant particles attach to filter media and themselves become collectors to which other particles attach. Capture of particles present in the influent water also promotes ripening. The filter ripening process, as indicated by filter effluent turbidity or particle counts, may be completed before all of the spent wash water has passed through the filter bed, or ripening may continue for a long time after the filter is treating only pretreated influent water. Several ways to hasten filter ripening are discussed in the following section.

Research by Amburgey et al. (2003) has demonstrated that during filter backwashing, the zeta potential on backwash remnant particles gradually becomes more electronegative. The increased negativity of those particles causes them to be less likely to reattach to filter media grains again if contact is made in the subsequent filter run. The remnant particles that pass through the filter into the effluent contribute to the initial turbidity spike.

PROCEDURES FOR MINIMIZING HIGH FILTRATE TURBIDITY WHEN STARTING FILTERS

Various techniques that can help to control the initial turbidity spike and hasten filter ripening involve modifications to backwashing procedures, holding a backwashed filter out of service for an extended period of time before returning it to service, and modifications to filter starting procedures.

Concluding Backwash With Subfluidization Rise Rate

The rise-rate management approach advocated by Amburgey et al. (2003) has been demonstrated to be effective for reducing the initial turbidity spike. They suggested that the subfluidization washing step could be added at the end of a backwash procedure in which the bed was fluidized. The recommended time for the subfluidization wash is based on the rise rate used and the time needed for wash water to pass through the pore volume of the filter bed at rest plus the time needed to rise from the top of the media to the top of the wash-water trough. The equivalent distance for the pore space in the filter bed is equal to the depth of the bed multiplied by the porosity. For example, in a monomedium anthracite bed with a porosity of 0.60 and a depth of 6 ft (1.8 m), the equivalent pore volume would be 0.60 × 6 ft or 3.6 ft (0.60 × 1.8 m or 1.1 m). As an aid to estimation of appropriate minimum fluidization velocities (V_{mf}) for the subfluidization wash, a modification of Table 2 in the paper by Amburgey et al. (2003) is presented as Table 7-1. In this handbook, minimum fluidization velocities have been rounded to two significant figures, whereas the original table in most instances presented V_{mf} to three significant figures.

A good estimate of the rise rate that fluidizes the filter bed can be obtained by placing a hollow, light weight pole about 1 to 2 in. (3 to 5 cm) in diameter, with a solid end, on the filter bed when it is at rest. The solid end keeps the pole from penetrating the filter bed until it is fluidized. By gradually increasing the rise rate, the rise rate at which the pole penetrates into the bed can be determined. This rate is the rise rate that fluidized the bed.

An advantage of using a subfluidization rise rate to conclude backwash is that this procedure requires no special equipment or facilities other than the ability to control

Table 7-1 Calculated minimum fluidization velocities for filter materials at cold, medium, and warm temperatures

Media Type	Sand	Anthracite	Anthracite
Effective size, d_{10}, mm	0.5	1.0	1.5
UC	1.5	1.3	1.3
d_{60}, mm	0.75	1.3	1.95
d_{90}, mm	0.98	1.55	2.32
Media density, g/cm^3	2.65	1.6	1.6
Fluidization velocities for d_{90}-sized filter material: gpm/ft^2 (m/hr)			
V_{mf} at 5°C	8.7 (21)	7.7 (19)	15 (37)
V_{mf} at 15°C	11 (27)	10 (24)	18 (44)
V_{mf} at 25°C	14 (33)	12 (29)	21 (51)
Fluidization velocities for d_{60}-sized filter material: gpm/ft^2 (m/hr)			
V_{mf} at 5°C	5.2 (13)	5.6 (14)	11 (28)
V_{mf} at 15°C	6.8 (17)	7.2 (18)	14 (34)
V_{mf} at 25°C	8.5 (21)	8.9 (22)	16 (40)
Fluidization velocities for d_{10}-sized filter material: gpm/ft^2 (m/hr)			
V_{mf} at 5°C	2.4 (5.9)	3.4 (8.3)	7.2 (18)
V_{mf} at 15°C	3.1 (7.6)	4.4 (11)	9.2 (22)
V_{mf} at 25°C	4.0 (9.8)	5.6 (14)	11 (27)

Adapted from Amburgey et al. 2003 with fluidization velocities rounded to two significant figures.

the rise rate during backwash. Therefore, this procedure is applicable at any plant where the staff can modify backwash procedures.

Addition of Extra Coagulant or Polymer

The research by Amburgey et al. (2003) provides a scientific explanation for the beneficial effects of adding positively charged chemicals to backwash water near the end of the filter backwash or adding such chemicals to influent water as the filter box refills following backwash. Backwash remnant particles that have become more electronegative during the washing process can be rendered less electronegative by the addition of positively charged coagulant or polymer. This is deduced from the beneficial effect of adding such chemicals when a filter is returned to service, rather than on the basis of experimental evidence, such as zeta potential of backwash remnant particles before and after chemical addition to modify their surface charge.

Procedures for determining the appropriate dosage of coagulant chemical or polymer were not described in studies that reported that this practice was beneficial, so a trial-and-error evaluation may be the most straightforward way to ascertain what dosage of chemical will be effective. A possible laboratory procedure for estimating the dosage of metal coagulant or cationic polymer is to: first, collect a large sample of wash water remaining in the filter box at the end of backwash; second, place it in jar-test jars and mix in a range of dosages of coagulant or polymer, including a control jar with zero added chemical; and third, measure the zeta potential of the backwash remnant particles after charge modification by the added chemicals. This technique would reveal the change in surface charge but would not necessarily predict the extent to which remnant particles would be removed during filtration. It has the potential to provide a starting point for full-scale chemical addition trials at filtration plants with instruments that can measure zeta potential.

Addition of Chemical to Backwash Water Near the End of Backwash

The addition of coagulant chemical or polymer to backwash water has been used to help improve the filter ripening process for over three decades. An initial report of this practice (Harris 1970) described the use of nonionic polymer, which would toughen floc and promote bridging of floc particles but would not decrease the electronegative surface charge of backwash remnant particles. Results of studies published in the 1980s and 1990s have supported the original report of improved filter ripening when metal coagulant or polymer is added into wash water.

Adding coagulant chemical or polymer to backwash water is done to condition the backwash remnant particles that are not washed out of the filter box, but adding excessive chemical might result in some coagulant or polymer remaining in the water and passing through the filter into finished water. Also, the water used for filter washing passes up through the underdrain before reaching the filter media. At a plant where filter-to-waste is not employed, if coagulant or polymer is added to backwash water until the end of backwash, water in the underdrain and piping below the filter will contain that chemical and will be discharged to the clearwell when the filter is returned to service. This situation can be avoided by ending the addition of chemical to backwash water at a predetermined time before the backwash is terminated based on the rate of flow of wash water and the volume of the piping and underdrain associated with the filter.

Where this procedure is used, chemical storage vessels may be needed, along with piping, valves, a pump, and controls to deliver the coagulant or polymer. Adding chemical to backwash water requires some investment of funds.

Addition of Chemical to Filter Influent as Filter Box Refills at End of Backwash

A second approach to adding supplemental chemical to improve filter ripening involves the addition of metal coagulant or cationic polymer to pretreated water as it flows into the filter box and refills it after backwashing is completed. This technique was identified during the AwwaRF study of filter maintenance and operation and was described by Logsdon et al. (2002). It differs from adding chemicals to the backwash water because no expensive equipment is needed for adding chemical to the filter influent. Filtration plant operators can simply take a premeasured quantity of coagulant or polymer to the filter being refilled and pour it into the influent water as the filter box is refilled.

At filtration plants treating water from Lake Michigan, both cationic polymer and alum have been effective for improving filter performance upon startup. An explanation for the effectiveness of this procedure again can be found in the work of Amburgey et al. (2003), as adding a metal coagulant or cationic polymer is expected to cause the surface charges on backwash remnants to be less electronegative and thus more likely to stick to media grains during filtration.

Adding coagulant chemical as the filter box refills at the conclusion of backwashing was evaluated by the Greenville Water System (GWS) in South Carolina at its Adkins Plant, a 30-mgd (114 ML/day) conventional filtration plant that treats water from Lake Keowee, using alum as the coagulant chemical. The source water turbidity ranges from 1 to 2 ntu, and alkalinity is low. Filter media consisted of 18 in. (46 cm) of anthracite over 12 in. (30 cm) of sand.

GWS undertook a study of the effect of starting a filter with alum added to the influent settled water as compared to starting a filter without adding alum when settled water fills the filter box. Filtration rates used during the evaluation of filter starting techniques ranged from 2.5 to 4 gpm/ft^2 (6 to 10 m/hr). The water temperature range for the testing was 72° to 82°F (22° to 28°C). During the study period, two filters were operated alternately with alum added and without the addition of alum; therefore, the comparison of plant performance would not be influenced by changes in source water quality during the evaluation period. When alum was added, about 1.2 L of liquid alum was poured into the influent water over approximately 45 sec during the time when the filter box was being refilled after backwash. During the trials, the alum feed in the raw water was 8 to 9 mg/L, and the effective feed rate for alum added to the influent settled

Table 7-2 Comparisons of turbidity peaks during filter starts with and without added alum at GWS's Adkins Plant

	Peak Turbidity During Starts Without Added Alum	Peak Turbidity During Starts With Added Alum
Number of starts	28	29
Minimum peak	0.07 ntu	0.07 ntu
Lower quartile	0.14 ntu	0.09 ntu
Median	0.20 ntu	0.11 ntu
Upper quartile	0.27 ntu	0.14 ntu
Maximum peak	0.64 ntu	0.32 ntu

Source: Filter Maintenance and Operations Guidance Manual (Logsdon et al. 2002).

water was about 3.2 mg/L based on the quantity of alum added and the volume of water in the filter box, from the top of the media to the water surface.

Results for 28 runs without added alum were compared with 29 runs in which alum was added to influent settled water, and adding alum to the incoming settled water did lower the initial turbidity spike when filters were placed into operation. The minimum, maximum, median, and lower and upper quartile turbidity peaks are summarized in Table 7-2. Average turbidity peak was 0.23 ntu for runs without added alum, and 0.12 ntu for runs with added alum. The difference was statistically significant at the 0.05 level. Minimum turbidity peaks were the same with and without added alum, but all others were substantially lower when alum was added before the filters were started.

The average time for turbidity to return to 0.10 ntu after filter startup was greatly improved by addition of alum to filter influent The minimum, maximum, median, and lower and upper quartile times to reach 0.10 ntu after filter runs started are presented in Table 7-3. The reduction in time to 0.10 ntu from 16.5 min to 1 min for the median time is a valuable improvement in performance, as this would have substantially decreased the time needed to filter-to-waste, if that procedure had been used until filtrate turbidity dropped to 0.10 ntu.

Delayed Start After Backwash Completed

At some filtration plants, filters are not returned to service immediately after the conclusion of backwashing but are held out of service for a period of time. Staff at some plants do this to ensure that a clean filter will be available the next time a filter should be backwashed, whereas others use this practice as a means of attaining better filter performance upon the start of a new run.

Delayed filter starts have been evaluated at full scale with mixed results. At some plants, the procedure resulted in improved filtered water quality during the initial improvement period, whereas at other plants no improvement was noted. Pizzi (1996) evaluated the procedure at a filtration plant in Ohio and reported that the filter that

Table 7-3 Comparisons of time for filtered water turbidity to decrease to 0.10 ntu during filter starts with and without added alum at GWS's Adkins Plant

	Time to Reach 0.10 ntu During Starts Without Added Alum	Time to Reach 0.10 ntu During Starts With Added Alum
Number of starts	28	29
Shortest time	0 min	0 min
Lower quartile	7.5 min	0 min
Median time	16.5 min	1 min
Upper quartile	27.5 min	7 min
Longest time	45 min	26 min

Source: Filter Maintenance and Operations Guidance Manual (Logsdon et al. 2002).

was started immediately had a turbidity peak about twice the magnitude of the peak for a filter that was rested for 4 hours before being returned to service. At this plant, a second benefit was that the ripening period was 45 percent shorter for the filter that had been rested. On the other hand, at two water utilities that provided data for the *Filter Maintenance and Operations Guidance Manual*, no improvement in initial filtered turbidity was seen when the delayed start procedure was used.

Amburgey et al. (2004) evaluated delayed starts in a study of backwashing and reported that the presence of polyphosphates in wash water inhibited attachment of filter backwash remnant particles to filter media at the start of a new run by increasing the negative zeta potential of the remnant particles. Among the conclusions in their article was one stating that the surface charge, concentration, and size distribution of backwash remnant particles at the end of backwashing have an important influence on the height of the turbidity peak and the duration of the ripening period when the filter is returned to service. In their article, they noted that aspects of wash-water quality such as pH, chlorine concentration, and concentration of polyphosphates can influence formation and behavior of backwash remnant particles. Thus, the chemical content of backwash water can contribute to good or poor turbidity removal performance when a filter is restarted. This suggests a potential benefit to be obtained by backwashing filters with filtered water that has not been modified by chlorination or by adding chemicals for pH adjustment or corrosion control.

Because of the inconsistent results attained when using the delayed start procedure, its efficacy at a given plant can not be assured. Nevertheless, it has proven effective in some plants and is one possible procedure to consider when trying to attain better filtered water quality when filters are returned to service.

Whether filters are held off-line to improve initial filtrate quality or for other reasons, if a filter is held out of service for a long time (perhaps one or two days, depending on water temperature), the potential for water quality problems on restart is increased.

Bacteriological growth can occur if a filter is held out of service for an excessively long time, particularly when the water is warm. This could cause anaerobic conditions in the filter, with dissolution of iron or manganese coated on the filter media. Growth of bacteria could result in higher heterotrophic plate counts or perhaps the presence of coliform bacteria in filtered water. Even if a filter was backwashed just after being taken out of service, if it has been held out of service too long, it is advisable to backwash it again before returning the filter to service.

The delayed start procedure does not require extra equipment such as filter-to-waste piping or chemical feeders, storage tanks, and piping. However, the procedure is not applicable when all filters in a filtration plant must be used to meet water production goals. As this generally does not happen all of the time at filtration plants, holding a filter off-line for a delayed start until another filter is backwashed is a procedure that could be used at most plants, during much of the year.

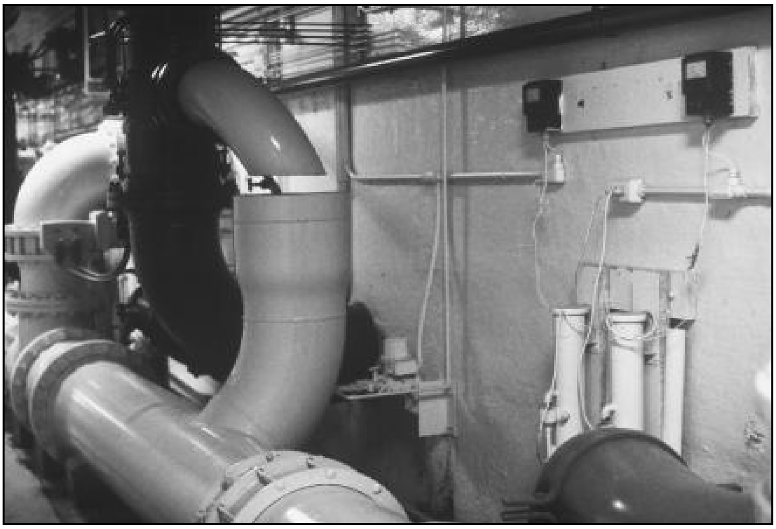
Filter-to-Waste at Start of Run

The filter-to-waste procedure involves wasting filtered water at the beginning of a filter run rather than discharging it to the clearwell. The time for filtrate turbidity to improve varies from run to run and from plant to plant; therefore, no set time for performing filter-to-waste can be recommended. Instead, monitoring the turbidity of the wasted filtered water is the cost-effective approach, as plant operators can end the filter-to-waste as soon as the plant's initial filtered-water turbidity goal is met. In this way, filter-to-waste can be done as long as necessary for water quality purposes, but no longer than needed. At plants where filter operation and filtered water quality monitoring depend on particle counting for meeting internal water quality goals, counting particles in filtrate being wasted would be appropriate.

Some plants have filter-to-waste piping that is not adequate to carry the flow that filters can produce when operated at their maximum filtration rate. In this situation, filter-to-waste at a reduced filtration rate can be performed, followed by gradually increasing the filtration rate after filter-to-waste has ended. When this is done, care must be exercised when raising the filtration rate.

The transition from filter-to-waste to filtering to produce water for the community presents another potential filtration rate change. Closing the valve for filter-to-waste and opening the valve to allow filtrate to flow to the clearwell has the potential to cause abrupt rate changes and turbidity spikes if not managed carefully. It is highly preferable to open the filter outlet valve and close the filter-to-waste valve smoothly and with no overall filtration rate change.

Of all the approaches to avoid or minimize the initial turbidity spike and produce low-turbidity water when a filter is placed in service, filter-to-waste is the one that is most certain to meet initial filtrate quality goals if it is properly managed. This procedure is not one that is easily retrofitted into many plants though, because of the additional valves and piping that are needed (see Figure 7-2). Adding filter-to-waste at an existing plant



Source: Logsdon.

Figure 7-2 Piping for filter-to-waste

What To Do With Water Produced During Filter-to-Waste

When filter-to-waste is practiced, large quantities of water are produced with quality that may be much better than the quality of raw water, while falling short of the goal for filtered water quality. If possible, segregate this water from other plant residuals streams, such as backwash water or sludge from sedimentation basins. This is consistent with engineering practice for managing industrial wastes, which calls for segregation of large, weak waste flows from smaller, concentrated waste flows. Combining two such flow streams can result in a large volume of waste that is more difficult to treat. At a water filtration plant, combining the filter-to-waste flow with sludge from clarifiers would result in the need for a considerably larger treatment facility for the combined waste stream, with consequently higher treatment costs. If water from filter-to-waste can be recycled to the raw water entering the plant without its quality being impaired by any other residual waste flow, this practice often would improve the quality of the influent water. Filter-to-waste is an intermittent procedure, however, so diverting this water to an equalization basin from which it could be recycled to the head of the plant will avoid imposing frequent increases and decreases on the flow through the plant, and this procedure is recommended.

is more costly than adding facilities to feed coagulant or polymer into backwash water, and some of the other procedures described in this chapter require no investment in additional facilities.

Starting at Low Filtration Rate With Gradual Increase to Full Rate

Another approach for managing the initial turbidity spike is to start filters at a low rate and then gradually increase the filtration rate, either very slowly and steadily or in small increments at short time intervals. This procedure is appropriate for use with filters designed for effluent rate control. It has been effective when used in some plants but not as successful at others.

An example of the gradual rate increase procedure that has been used successfully at a filtration plant in California is to start filters at 2 gpm/ft^2 (5 m/hr) and increase that rate by 0.2 gpm/ft^2 (0.5 m/hr) at 2-min intervals. Step increases are continued until the desired filtration rate is attained. At this plant, the filtration rate attained using the gradual start procedure can be as high as 4.9 to 5.7 gpm/ft^2 (12 to 14 m/hr), with the total time for the multistepped rate increase ranging up to about 30 or 40 min.

At plants using effluent rate of flow control, managing the filtration rate to attain periodic small incremental increases would not require additional equipment or facilities.

USING MULTIPLE PROCEDURES TO CONTROL THE INITIAL TURBIDITY SPIKE

When information was sought on procedures employed to aid in controlling the initial turbidity spike during the development of the *Filter Maintenance and Operations Guidance Manual* (Logsdon et al. 2002) for AwwaRF, 37 water filtration plants participating in the project reported that they generally were able to limit the initial turbidity spike to 0.3 ntu or lower. Seven reported that they did not consistently control the initial filtrate turbidity to 0.3 ntu or lower.

At filtration plants that were successful in controlling the turbidity spike, use of multiple approaches for this purpose was common. A summary of results reported during the AwwaRF project is provided in Table 7-4. Eighteen used combinations of two methods, while eight used combinations of three methods. Nine plants used one method, and two plants used no special approach to minimize initial filtrate turbidity. Thus, 26 of 37 plants used multiple techniques that helped attain better water quality when filters were returned to service. Of the seven plants not successful in controlling the initial spike to 0.3 ntu or lower, four used no special approach, two used one method, and one used a combination of two approaches. Using more than one method for controlling the turbidity spike is recommended for general use at filtration plants as a result of the findings published in the AwwaRF report.

Table 7-4 Techniques used at surface water treatment plants to control turbidity in filter effluent at start of filter run

	Nearly Always Control Initial Turbidity to 0.3 ntu or Less	Not Consistently Controlling Initial Turbidity to 0.3 ntu or Less
Number of filtration plants reporting information	37	7
Number of plants using coagulation	35	4
Number of plants using lime softening	2	3
Filter-to-waste (FTW) only	3	0
Rest filter (delayed start) + FTW	4	0
FTW + gradual rate increase (gradual start)	3	0
Delayed start + FTW + gradual start	6	0
Chemical in backwash + FTW + gradual start	1	0
Chemical in backwash + delayed start + FTW	1	0
Rest filter (delayed start) only	4	2
Gradual rate increase only	2	1 reported trying this with no success
Delayed start + gradual start	6	1
Chemical in influent water + rest filter	1	0
Chemical in influent water + gradual start	2	0
Chemical in backwash + rest filter	1	0
Chemical in backwash + gradual start	1	0
Nothing	2	4
Number of plants using only 1 method	9	2
Number of plants using combination of 2 methods	18	1
Number of plants using combination of 3 methods	8	0

Source: Filter Maintenance and Operations Guidance Manual (Logsdon et al. 2002).

SUMMARY

Flexibility in plant operations is again a key recommendation. Procedures that help control the initial turbidity spike at the start of a filter run may be successful at one plant and not so effective at another. Trial-and-error testing at the plant generally is the approach to use to identify workable procedures for producing better filtered water quality when filters are returned to service.

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8

Monitoring Filter Performance

INTRODUCTION

Filtration is a dynamic process where conditions within the filter and quality of water produced by the filter can change from hour to hour, so monitoring filter behavior is crucial to successful management of filters. A filter run is initiated, managed, and eventually terminated. During a filter run, which might be as short as a few hours or as long as a few days, conditions change within the filter, and filtered water quality also can change. Without appropriate monitoring, plant operators will not be aware of the performance of rapid rate filters, and because changes can occur quickly, continuous or online monitoring is highly desirable. For turbidity, continuous monitoring is a practical requirement for regulatory compliance. As with monitoring of the coagulation process, it is quite useful to have several kinds of filter behavior data available when deciding how to manage filter runs.

Information that can help operators understand the condition of a filter and what is occurring includes

- Total head loss through a filter
- Head loss in selected increments of filter depth
- Standardized clean bed head loss
- Rate of head loss gain, and rate of head loss gain/filtration rate
- Filtration rate
- Volume of water produced during the run, gal per 1 ft^2 or m^3 per 1 m^2 of filter area
- Filter effluent turbidity
- Magnitude and duration of high turbidity when a filter is placed in service
- Filter effluent particle counts
- Turbidity of water withdrawn from a specified depth within the filter bed
- Other measures of filtered water quality

Some of this data, such as filtered water turbidity, are measured at every rapid rate filtration plant. Others, such as rate of head loss gain normalized in terms of filtration rate, may be used at only a few filtration plants. Measures of filter performance are discussed in this chapter.

PHYSICAL PERFORMANCE OF FILTERS

Physical performance of filters is evaluated mainly in terms of head loss and water production.

Head Loss During the Filter Run

Total Head Loss

For any condition of filter clogging, the head loss incurred as water flows through the filter is related to the rate of flow, or filtration rate. For filtration rates up to about 5 gpm/ft^2 (12 m/hr), laminar flow exists in the filter bed containing media up to about 1.0 mm ES In such filters, doubling of the rate of flow doubles the head loss through the filter bed. Head loss in a filter is also related to water viscosity, which is temperature-dependent. Knowing the head loss through the filter is very important, as reaching terminal head loss is one reason for ending a filter run. Total head loss generally is monitored continuously, so operators know what it is at all times. As discussed in chapter 4, both media size and bed depth affect head loss.

Head Loss at Depths Within the Filter Bed

Knowing the total head loss through a filter bed is useful and necessary for routine filter operation, but for assessing various filter media designs in pilot testing or for understanding the depth of floc penetration and where head loss is occurring within the filter bed, data on head loss at specific depths within the filter bed provides important information. This is seldom done for full-scale filters, but often is a feature of pilot-plant filters. In lieu of constructing a pilot plant or a pilot-scale filter for evaluating filter performance, filtration plant staff might consider the feasibility of installing head loss taps at depths of 6, 12, and 18 in. (15, 30, and 46 cm) in the filter bed (as measured from the top of the media). For reference data, one tap also is installed somewhere above the filter media but below the surface of the water when the filter is operating. All taps should be screened to prevent penetration by filter media. Measurement of head loss is accomplished by using translucent piezometer tubes and determining the difference in the water level in the tube for the sample tap above the media as compared to the water level in a tube for a sample tap within the filter bed. The design of the filters and layout of the pipe gallery may preclude installing these devices, but if it is physically possible to install within-bed head loss taps, they will enable operators to obtain valuable information on an as-needed basis.

Standardized Clean-Bed Head Loss Data

Clean-bed head loss, or starting head loss of a filter can provide useful insights into filter bed condition, if careful records are kept over time. Clean-bed head loss in a filter depends on the rate of filtration and water temperature, when other factors such as porosity of the filter bed, bed depth, and media size are constant. Over a period of several months or a year, the filtration rate at the start of a filter run and the temperature (viscosity) of the water being filtered are likely to vary. When filter material is thoroughly cleaned during backwashing, buildup of deposits on the media and the resulting increase in clean-bed head loss are less likely to happen. As explained in the *Filter Maintenance and Operations Guidance Manual* (Logsdon et al. 2002), if conditions are adjusted (or normalized) to a standard water temperature and a standard rate of filtration, the clean-bed head loss should change very little. (Theoretically, it would be unchanged.)

Long-term collection of data on conditions encountered when a filter is placed into service can help to indicate whether the filter has gradually accumulated deposits of material on the media, or whether media condition is unchanged over time. Note that this procedure would not work well for the gradual start procedure unless data were collected after the full production rate had been attained, and it would not work in declining rate filters unless rate of flow is measured. At plants where the filter is started at the full operating rate, the first four head loss measurements taken at 15 min intervals (first hour of operation) can be averaged for the calculations. The temperature and filtration rate selected as standard conditions must be used for all calculations, in a procedure used by Michael Chipps, a co-author of the *Filter Maintenance and Operations Guidance Manual*. The head loss for filtration rate should be adjusted as follows:

$$H_{std} = H_{meas}(Q_{std}/Q_{meas})$$

where:

H_{std} = clean-bed head loss adjusted to standard filtration rate
H_{meas} = average head loss measured in first hour of filter run
Q_{std} = standard filtration rate
Q_{meas} = measured filtration rate during first hour

Then the head loss value that was standardized for filtration rate should be adjusted for the effect of water temperature by adjusting for viscosity.

$$H_{adjusted} = H_{std}(\mu_{std}/\mu_{meas})$$

where:

$H_{adjusted}$ = clean-bed head loss adjusted for both filtration rate and water viscosity
H_{std} = clean-bed head loss adjusted to standard filtration rate
μ_{std} = absolute viscosity of water at the standardized temperature
μ_{meas} = absolute viscosity of water at the measured temperature when filter run was performed

Rate of Increase of Head Loss

Knowing the rate at which head loss is increasing can help in planning for future filter backwash operations. In addition, adjusting filter head loss gain-per-hour to a standardized filtration rate can be helpful if some filters are operated at higher rates than others. Operating a filter at a higher rate causes head loss to increase at a faster rate. At a plant where filters are operated at constant rates but some filters are operated at higher rates than others, dividing the rate of head loss gain-per-hour by the filtration rate gives the gain that would occur for a rate of 1 gpm/ft^2 or 1 m/hr. This kind of performance evaluation has been practiced by staff at a midwestern water filtration plant and can be used to compare filter performance when filters within a plant are operated at different filtration rates.

Filtration Rate

Knowing the filtration rate is a must for filters operated with effluent rate-of-flow control. If a flow controlling valve were to malfunction and open too far, allowing an excessively high filtration rate, this might produce high turbidity from that filter, and if filtration rates were limited by a regulatory agency, an operating violation might also occur. Some plants employ influent flow-splitting to apply the same flow of water to each filter in service, so if the flow in the plant is known and the number of filters in operation is known, the filtration rate can be calculated. In this instance, the total flow through the filters must be known to determine the filtration rate. It should be noted, however, that for a filter in which the water surface rises in the filter box as head loss increases, this mode of rate control provides constant rate filtration only when the water surface in a filter is below the hydraulic control device and influent water is spilling over it. If the water surface in a filter rises up to the level of the water on the upstream side of the hydraulic control device (a weir or upturned pipe, for example) the device ceases to act as a hydraulic control, and the flow control mode for that filter changes from constant rate to declining rate.

A filtration plant operated without knowledge of the filtration rate was observed during a giardiasis outbreak in New England involving an old pressure filtration plant having eight filters piped in parallel. The total flow through the filters was known, but because they were piped in parallel, their hydraulic behavior was like the behavior of a network of parallel pipes. Head loss through all filters was the same, but the filter that was clogged to the greatest degree had the lowest rate of flow, whereas the filter with the least clogging carried the greatest flow. As no flowmeters were provided for individual filters, operating staff had no idea of the filtration rate for any specific filter. When examined during the outbreak investigation, some filters were found to have media that was severely clogged. This could not have been determined, though, during routine operation because of the absence of flow monitoring for each filter.

Water Production by Filters

The volume of water produced per 1 ft^2 or 1 m^2 of filter area (UFRV or unit filter run volume) can be an indication of the efficacy of both pretreatment and filtration. Rather than measuring only the length of filter runs, the UFRV also takes into account filtration rate. For example, a UFRV of 4,800 gal/ft^2 (slightly more than 190 m^3/m^2) could be attained by a filter run at 5.0 gpm/ft^2 (12 m/hr) for 16 hr or by a filter run at 3.3 gpm/ft^2 (8.0 m/hr) for 24 hr. The UFRV represents gross water production by a filter but does not account for water used for backwashing.

If coagulation is not correct, filter runs may end prematurely because of turbidity breakthrough. If filter aid polymer is overdosed and floc is too strong, the filter may "blind off" when the strong floc is removed primarily in the upper reaches of the filter bed. Passage of excessive amounts of floc or filter-clogging algae can cause short filter runs if the media grains at the top of the bed are small enough to strain out large particles as they enter the bed. Air binding also can cause filtered water production to decrease substantially. As water production drops below about 5,000 gal/ft^2 or 200 m^3/m^2, larger amounts of water are consumed by filter washing, and this reduces productivity. When water production exceeds about 10,000 gal/ft^2 or 400 m^3/m^2, further increases in productivity do not result in large increases in overall efficiency as indicated by the percentage of backwash water used relative to total water filtered. Another measure of water production is the percentage of net water produced, in which water used for backwashing is subtracted from the gross production in a run, to give the value for net production. The net production percentage is calculated as:

$$\text{Net production \%} = \frac{(\text{gross production volume} - \text{backwash volume})}{\text{gross production volume}} \times 100$$

Typical net water production after adjustment for water used in backwashing ranges from 95 percent to 99 percent, with 1 percent to 5 percent used for backwashing.

FILTER PERFORMANCE AS INDICATED BY WATER QUALITY

Turbidity is the most widely used indicator of filter performance in terms of filtered water quality, and it is a measurement required by USEPA regulations. Other measures of filter performance include particle counts, microbiological assays, and the physical appearance of filters used for sampling filter effluent. Procedures for a number of the water quality measurements discussed in this section are found in *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA, and WEF 2005).

Turbidity and Filter Performance

Of all the indicators of filtered water quality, filtrate turbidity has been used most commonly as an indicator of filter performance in the last five decades. Turbidity measurement was attempted throughout the 20th century, but prior to the development of laboratory and online turbidimeters that measured scattered light at 90° using photoelectric cells (nephelometers) in the 1960s, measurement of low turbidity as produced by effective filtration was difficult. Measuring filtered water turbidity by light scattered at 90° is the basis for *Standard Method* 2130. Use of the nephelometric method to measure turbidity for regulatory compliance is required by regulations.

Even with the development of modern turbidimeters, using turbidity as a measure of filtered water quality has limitations. Turbidity is measured as scattered light, but PAC is black and does not scatter light well; therefore, a turbidimeter may not detect passage of PAC into filtered water. Customer complaints could result if PAC gets into the distribution system and onto laundered white sheets, so monitoring techniques other than turbidity measurement ought to be used if passage of PAC through filters is a concern. Scattered light is dependent on the index of refraction of the particles in the water, and biological matter having an index of refraction similar to the index of refraction of water will scatter only a small fraction of the incident (incoming) light. Scattered light does not identify the nature of the particle that caused the scatter in turbidimeters used for monitoring drinking water; therefore, the type of particles in water causing light scatter cannot be determined from a nephelometric turbidity measurement.

Turbidimeters differ from particle counters in a number of ways. Turbidity is a general physical property rather than a quantifiable measurement such as the number of particles per milliliter. Nephelometers can detect particles, such as clay, most effectively between 0.1 to 1 μm. A nephelometer can have its peak response for particles about 0.2 μm in size, whereas light blockage particle counters, which are the type typically used in water filtration plants, often have a minimum detection size of 2 to 2.5 μm. Thus, although particle counters can quantify particles in water, they would not detect some submicron particles that could scatter light and be registered as turbidity by a nephelometer. Therefore, these two kinds of instruments are complementary, with each having a sensitivity or detection capability in a different particle size range. For detection of floc particles that are dislodged from within a filter bed, the capability of responding to particles larger than 2 to 2.5 μm is an advantage possessed by particle counters.

In addition to the regulatory necessity for having an online turbidimeter for each granular media filter, this is a practical necessity. Operating rapid rate water filters without an online turbidimeter for each filter is like operating the plant blindfolded. It is an operational necessity as well as a regulatory need to know the quality of filtrate from every filter in operation, because different filters in a plant can perform in different ways. To ensure optimal filtration, it is imperative to know when turbidity breakthrough is about to occur and to prevent it from happening.

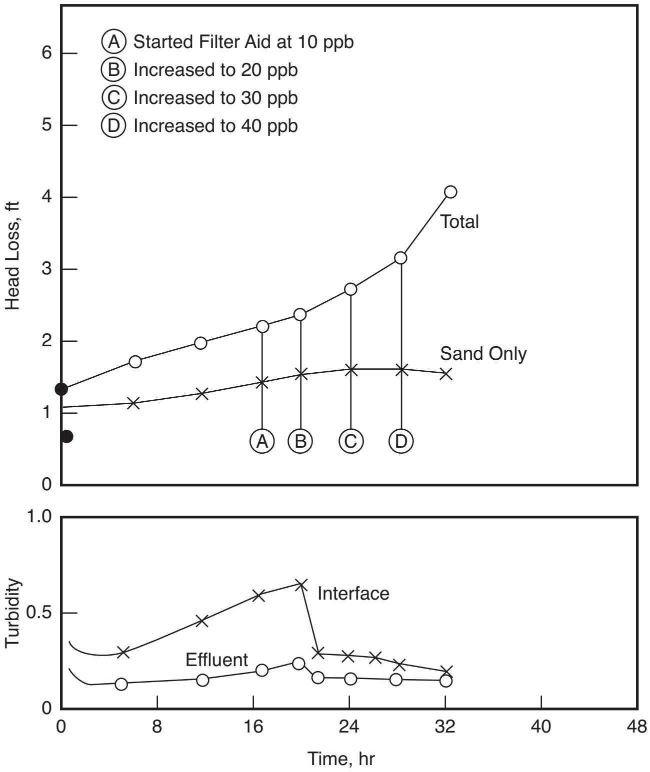
At water treatment plants using coagulation and granular media filtration, regulations require monitoring filtered water turbidity and recording the data every 15 min for each filter in operation. Monitoring and recording data without acting on filtration results when necessary will prevent production of high-quality filtered water. A system or hierarchy of appropriate alarms is needed to alert plant operators as turbidity begins to approach the upper limits for internal water quality goals and also the regulatory limits. To avoid exceeding either utility goals or regulatory limits, warnings are needed well before those are reached, to ensure that filtration plant staff have the necessary time to assess the situation and take corrective action to avert a regulatory violation or a breach of internal goals. In addition, any data that exceed regulatory limits will have to be flagged for reporting to the proper authorities.

A comparison should be made of filtrate turbidity produced by each filter in a plant over a period of several weeks to assess the performance capability and condition of each of the filters. Even if all of the filters in a plant have the same media design and underdrain design, conditions within a filter bed or in the underdrain and media support systems can change over time. If one filter is more likely to display turbidity spikes during a run or if it has higher filtrate turbidity after the initial improvement period has concluded, these behaviors can indicate the need for a filter inspection. Operators may develop an intuitive sense about a filter's weaker performance as compared to others in the plant; however, operators should confirm that one filter is not performing well by comparing and analyzing filtrate turbidity data and UFRV data on water production before doing a physical inspection of the filter.

The turbidity of water extracted from within the filter bed can be monitored to anticipate and prevent breakthrough. Continuously sampling filtered water from within a dual-media filter bed at the interface of the coal and sand layers was discussed at an AWWA annual conference in the early 1970s (Harris 1972), so this is not a new concept. Harris explained that interface turbidity monitoring, when combined with monitoring of head loss within the filter bed, could be useful for anticipating turbidity breakthrough and also for adjusting filter aid polymer dosage to prevent excessive turbidity from reaching the coal/sand interface in the filter bed. His figure, reproduced as Figure 8-1, also illustrates the effect of increases in filter aid dosage, both for lowering turbidity at the coal/sand interface and for increasing the total head loss in the filter. It should be noted that when filter aid polymer increased and floc strength became excessive, most of the head loss increase occurred in the upper layer of coal rather than in the sand. In Figure 8-1 the 40 ppb dosage of polymer was exhibiting a tendency to blind off the filter.

Measurement of turbidity of water extracted from within the filter bed has been used in more recent times for both dual media and deep bed monomedium filtration plants. The continuous extraction of a water sample from a location within the filter bed is done so turbidity removal at one or more specific locations within the bed can be evaluated. As turbidity increases within the bed, this signals the potential for turbidity to pass through the entire bed and out of the filter in the effluent. In a dual-media filter, excessive turbidity passing through the coal layer into the sand indicates weak floc and the need to modify pretreatment to strengthen floc reaching the filter.

At a filtration plant in California, sample taps were installed at 1-ft (0.3-m) intervals in a 6-ft (1.8-m) deep filter (see Figure 8-2) containing 1.5 mm e.s. anthracite filter material. Strainers are provided on sample taps to prevent media loss, and this detail is shown

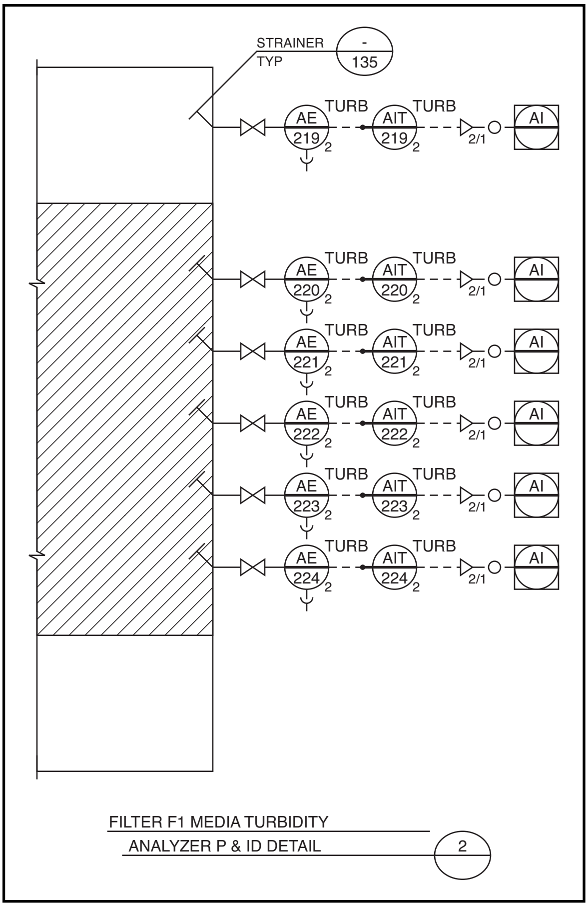


Source: Harris 1972.

Figure 8-1 Data for filtrate turbidity and filter head loss at interface of coal and sand and at filter effluent

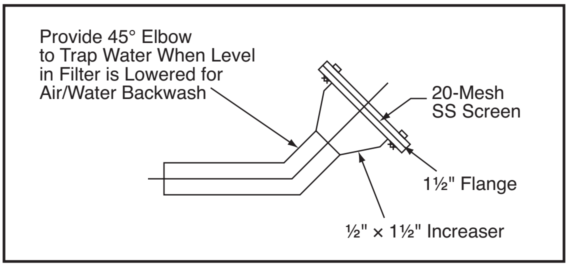
in Figure 8-3. A continuous supply of water to the turbidimeters enables plant staff to track the progress of floc penetration and removal within the bed. Data from this filter shown in Figure 8-4 demonstrated that over a 2.5-day filter run, turbidity remained well below 0.10 ntu at depths ranging from 4 ft to 6 ft (1.2 m to 1.8 m), even though turbidity rose to 1.5 ntu at the 1-ft (0.3-m) level when influent turbidity ranged from 1.7 ntu to 3 ntu.

If within-bed turbidity was monitored on a daily basis, large amounts of data would be generated. If a filter bed is provided with taps for extracting samples from within the bed, utility personnel can monitor the bed on an as-needed basis. Figure 8-5 shows sample lines set up for this purpose in a filter. Although not in use when the photograph was taken, the lines could be flushed and made operable if the need for a special study arose. It is much less expensive to place sample lines, such as these, during construction than to return to the filters to retrofit them. Figure 8-5 shows that the sample taps are



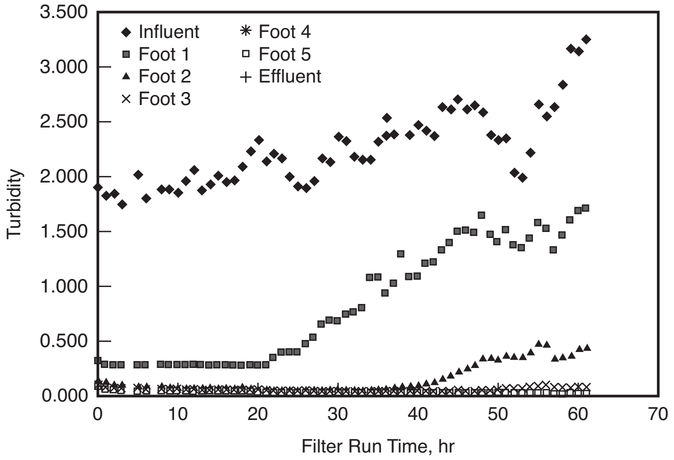
Source: Black & Veatch Corporation, *Filter Maintenance and Operations Guidance Manual.*

Figure 8-2 Turbidity sampling locations above and within filter bed for deep-bed monomedium filter



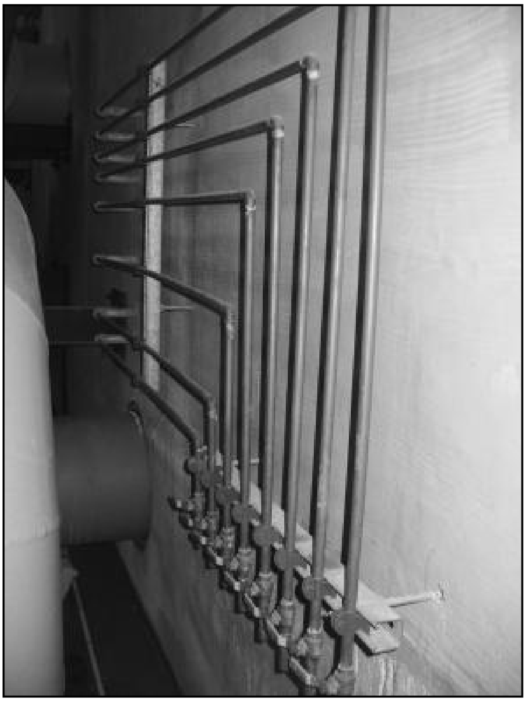
Source: Black & Veatch Corporation, *Filter Maintenance and Operations Guidance Manual.*

Figure 8-3 Strainer detail for within-bed turbidity sample lines for filter in Figure 8-2



Source: Modesto Irrigation District, *Filter Maintenance and Operations Guidance Manual.*

Figure 8-4 Turbidity versus time for filter influent water, water sampled from each foot of depth and filter effluent



Source: Logsdon.

Figure 8-5 Sample pipes installed to provide filter influent and effluent water and water from within filter bed

concentrated more in the upper part of the filter bed, where head loss is likely to accumulate more rapidly than farther down in the bed.

Particle Counts as Indicators of Filter Performance

Particle counters have been used in water treatment research and pilot-plant filtration studies for about five decades. For drinking water studies and plant monitoring, use of instruments that count particles and measure their size using the principle of light blockage began in the 1970s. In these particle counters, a particle casts a shadow on a photoelectric cell as it passes through the sensor, and the amount of light reaching the cell is used to calculate the equivalent diameter of a spherical particle. Particle counters can detect small differences in water quality as indicated by the particle count, whereas often a turbidimeter might show little or no change in turbidity. When filtered water is 0.10 ntu or lower, particle counters can be a more effective means of assessing subtle changes in filtered water quality. Breakthrough of particles during a filter run, i.e., the discharge of particles that were previously attached to filter material grains, is mostly caused by particles measuring several microns in size. Particle counters are more sensitive to this size range than turbidimeters.

Even though they are more sensitive than turbidimeters for detecting particles between 2 to 2.5 μm and larger, particle counters do have some limitations and disadvantages. Particle counters are more expensive than turbidimeters and may not be affordable for some utilities. Because of the complexity of using these instruments, a research project was funded by AwwaRF to develop practical guidance on using particle counters, and a report was published by Hargesheimer and Lewis (1995).

Particle counters also have limitations in analytical capability. They are not able to identify the type of particles, such as clay, *Cryptosporidium* oocysts, or *Giardia* cysts. Particle counters generally do not detect particles smaller than 1 μm, and often the minimum size detected is 2.5 μm. Particles in water have a variety of shapes, indices of refractions, and optical densities. If the properties of a particle in water are different from the properties of the particles used to calibrate the instrument, the size calculated for the particle may be inaccurate. Some raw waters have so many particles that the total count is an underestimate.

Another limitation of particle counters is the difficulty related to comparing data from different brands of these instruments. No standardized design for the sensor exists, whereas for turbidity, the nephelometric method has been accepted as the standard. *Standard Method* 2560 has been developed for light blockage particle counters, but as of the date of this publication, no regulatory performance requirement has been developed for analysis of filtered water by particle counting.

Particle count data can be very useful, but practical aspects should be addressed. If a filtered water particle count is 2 per mL in the size range of 2.5 to 150 μm, the number of particles in 1 L of water is 2,000. If all of these particles were infectious *Cryptosporidium* oocysts or *Giardia* cysts, this water would be unsafe to drink. The number of infectious pathogens a person needs to ingest to become ill can be small compared to the number of particles in finished drinking water, so particle counters cannot be used to indicate safety of the water. They can be valuable for assessing plant performance by comparing filtered water particle counts to the quality goal set for the plant.

Another practical limitation for particle counters is related to the size of the instrument's sensor orifice and flow rate. For example, in a counter with a sensor that detects particles sized between 2 to 70 µm, with a concentration limit of 15,000 particles per milliliter, a typical flow rate is 100 mL/min and a typical orifice size is 1 mm × 1 mm. At this flow rate, the velocity through the orifice is 5.5 ft/sec (1.7 m/sec). *Recommended Standards for Water Works* (Great Lakes–Upper Mississippi River Board of State Public Health & Environmental Managers 2003) suggests 1.5 ft/sec (0.46 m/sec) as the upper limit for the velocity of flocculated water in pipes in a treatment plant. Floc breakage is a concern if particle counters are used to compare clarified water and filtered water at a filtration plant. Another problem arises if particle counters are used to assess clarifier performance by counting flocculated water and clarified water in plants where sweep floc coagulation is practiced, especially if visible floc particles larger than 1 mm are seen in the water being sampled for particle counting. Breakage of floc in the counter sensor would indicate presence of a larger number of small particles rather than smaller numbers of large particles and would produce incorrect particle count data.

Assessing the removal percentage or *log removal* of particles from raw water to filtered water is problematic in plants that coagulate and filter water. As previously noted, the lower threshold for particle counters generally is over 1 µm; however, many particles in water are of a smaller size and are not counted. When coagulant is added to raw water, some of the submicron particles not included in the raw water particle count aggregate into larger sizes that can be detected, thus increasing the particle count. On the other hand, small countable particles in raw water can be coagulated and formed into larger aggregates, thereby decreasing the number of countable particles. With factors working to increase and also to decrease countable particles, assessing the true change in particle numbers through a filtration plant becomes difficult. At direct filtration plants and plants using DAF clarification, the objective of coagulation is particle destabilization, rather than the production of large flocs that will settle. At such plants, the particle count in flocculated water can be higher than the particle count of the raw water.

Particle counters can be very useful at filtration plants where producing very low filtered water turbidity is a goal. Particle counters can prove more effective than turbidimeters for assessing filter performance when filtered water turbidity is 0.10 ntu or lower, and small changes in turbidity become more difficult to discern. For example, at a Great Lakes filtration plant, particle count data were used to detect a problem that was not easily recognized by analyzing turbidity data. Filters at the plant have two independently operated effluent valves and headers. Flows from each portion of the filter are combined and conveyed to the clearwell. When one filter had slightly elevated particle counts (3 to 5 per mL) sized 2 µm and larger, as compared to other filters (1 to 2 per mL), plant staff investigated and found that one of the two effluent valves had not opened, causing one half of the filter to operate at a rate double that of other filters.

Online particle counters can produce overwhelming amounts of data in a single filter run. To handle the large amounts of data, values for the 10th, 50th, 90th, 95th, and 98th percentiles can be determined. It is not difficult to assess the data if particle count data are entered into a spreadsheet program that can tabulate data in their order of magnitude. Figure 8-6 presents data arranged in this manner. Another approach is to prepare a filter profile using particle counts, showing the counts per milliliter from the start of the filter run to its conclusion, as is done in Figure 8-7. This approach shows the effect of operating time, while the percentile analysis indicates the degree of variability of particle counts.

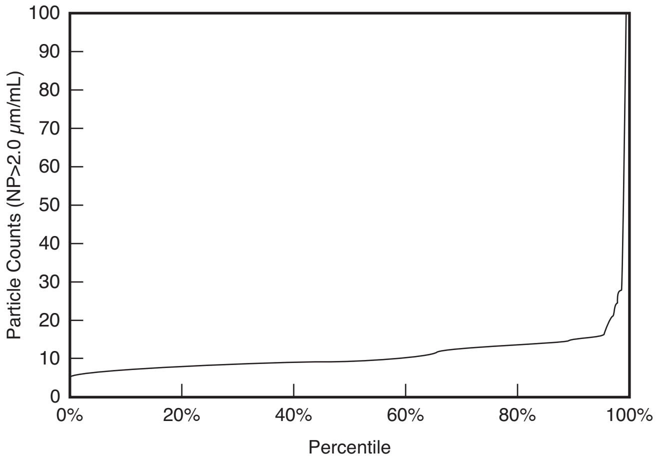
Other Water Quality Indicators of Filter Performance

Online turbidimeters and particle counters provide instantaneous results for filtered water quality. Other procedures can be used for special studies or for assessing specific water quality concerns.

Microbiological Sampling

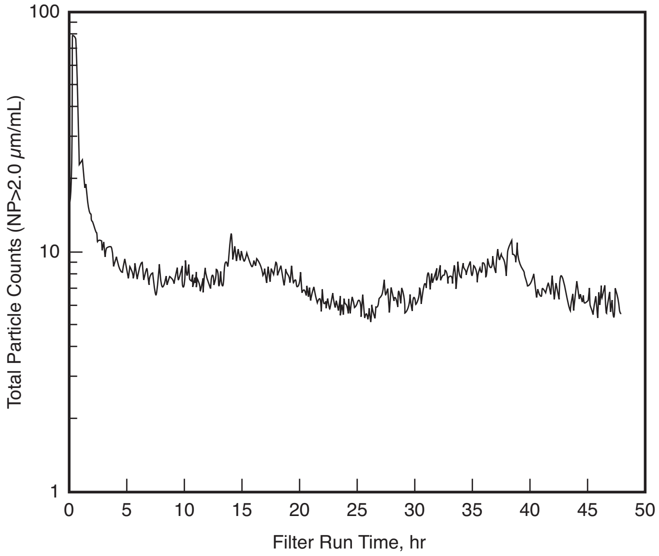
Filter performance can be evaluated by enumerating the number of microbes in raw water and in filtered water. Each method has some advantages and disadvantages.

The direct total microbial count procedure, Method 9216 in *Standard Methods*, is used to detect viable and nonviable bacteria in water; therefore, it can be used even if water is disinfected before filtration. An epifluorescence microscope with at least 1,000× magnification capability is required for the procedure. Because membrane filtration



Source: Calgary Water Utility, *Filter Maintenance and Operations Guidance Manual.*

Figure 8-6 Percentile plot of particle counts in filtered water for one filter run



Source: Calgary Water Utility, *Filter Maintenance and Operations Guidance Manual.*

Figure 8-7 Particle counts in filtered water versus time for duration of filter run

equipment is used, the microscope is the main capital expense at many water utility laboratories. The test can be performed in about a half hour, so results can be obtained quickly. In filters where biological growth is not encouraged on the media, the direct total microbial count can give a good estimate of the particle removal capability of filters if filter influent and effluent samples are obtained, or overall plant performance can be evaluated by sampling raw and filtered water. Filtration plants operating in a biological filtration mode may slough some bacteria out of the biologically active filters, which may understate filter performance.

At filtration plants treating river water subject to runoff containing soil particles, analysis for *Bacillus* spores by Method 9218 in *Standard Methods* can indicate the extent of microbiological contaminant removal. *Bacillus* spores are commonly found in soils, so runoff containing soil particles carries the spores to surface waters. In plants where disinfection is practiced after filtration, if source waters have high concentrations of the spores, log removal calculations can be performed. This was done by Rice et al. (1996). *Bacillus* spores do not reproduce in filter beds; therefore, the only source is the raw water. Also, the ambiguities associated with counting particles in raw and filtered water do not apply for the *Bacillus* spore assessment. When spore removal is used to evaluate filtration performance, the validity of the results rests on the quality of the sampling and analysis, and the extent to which spore inactivation might have occurred in the plant between the initial sample and the sample taken after filtration. This is a somewhat labor-intensive microbiological procedure that many plants are not equipped to perform, but the *Bacillus* spore analysis was performed by at least one commercial laboratory in 2008.

One technique used by some utilities for analyzing filter performance is the microscopic particulate analysis (MPA). Hancock et al. (1996) described a procedure for the MPA and concluded that this procedure is an effective tool for assessing plant performance. The MPA procedure provides data on the types of biological particles that are passing through the filter and the types that are removed, if both raw and filtered samples are obtained. Hancock et al. noted that reductions in MPA counts correlated with particle count reduction. They recommended using several tools to assess filtration efficiency, including MPA, as this provides a more comprehensive indication of performance than relying on a single monitoring method. The time and cost needed for this procedure would make it appropriate for special studies or periodic evaluations of filter performance rather than for day-to-day monitoring of filter performance.

Inspection of Membrane and Cartridge Filters

Filtered water samples are collected at some water filtration plants and then filtered through membrane filters so the residue can be inspected. At one eastern US utility, 1-L samples are filtered through 0.45 μm membrane filters placed on the filter apparatus with the plain side up. After the filter dries, it is taped onto a piece of white paper, and the color of the filter is evaluated. If the membrane is white, results are acceptable. A yellow tint can indicate passage of aluminum or iron through the filter. At another filtration plant, a similar test is used to detect passage of carbon fines, which would cause a gray tint on the white membrane filter. This procedure is applicable when a new GAC bed is put into service and anytime when PAC is used.

Cartridge filters of the type used for the microscopic particulate analysis can also be used by water treatment plant personnel for monitoring raw and filtered water quality. Hancock and Klonicki (2001) discussed the use of these filters for making qualitative judgments on water quality. Filter cartridges used for the MPA are white, so a change in the color of a cartridge used to monitor filtered water would indicate passage of particulate matter. Tan color may indicate floc passage, whereas gray may be a sign of passage of GAC fines, PAC, or anthracite fines through the full-scale filter. If a finished water filter has an unpleasant odor, this may indicate that algae or actinomycetes have passed through the full-scale filter. The advantage of using cartridge filters in this manner is that operators obtain data on a composite water sample, as the cartridge filters for finished water may be kept online for 24 hours before being removed for analysis. This gives a perspective of water quality over a long period of time rather than quality for an instant when a grab sample is obtained. These observations of cartridge filter characteristics, and inferences about the quality of filtered water that was produced by the plant during the interval when the monitoring was done, can be made by plant operations personnel without the level of scientific training needed for conducting the full MPA test.

SUMMARY

Monitoring filtration performance and treatment plant performance using multiple techniques provides treatment plant staff with a assortment of information that is very useful in assessing whether performance goals are met. It is advantageous to use a variety of monitoring methods if troubleshooting and plant investigations are needed to identify the cause of a problem revealed by the monitoring results.

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9

Quality Control for the Laboratory and Plant

INTRODUCTION

Process monitoring and plant operations are increasingly performed with the aid of instruments and electronics. These provide data about operations and online water quality at a central location in the plant. The person or persons responsible for plant operations have access to the maximum amount of up-to-date information available for treatment management. However, when the decision makers rely on instrumentation for information on plant operations, that information must be correct, or incorrect operating decisions could result. The increased reliance on instrumentation and electronics mandates an increased effort to verify that the data obtained are valid. Serious consequences can occur if incorrect water quality data, head loss data, or flow data are used when making decisions about plant operations. The importance of a good, practical program of quality control is discussed in this chapter.

Proper quality control and maintenance procedures are absolutely necessary for obtaining valid data from turbidimeters, pH meters, streaming current instruments, particle counters, flowmeters, and head loss instrumentation. Both bench instruments and online instruments must be operating properly if the instrument output is going to be useful. Sources of information on quality control and quality assurance procedures can be found in *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA, and WEF 2005) and from manufacturers of instruments. Additional information can be found in AWWA Manual M37, *Operational Control of Coagulation and Filtration Processes* (AWWA 2000).

QUALITY CONTROL IN THE LABORATORY

Chemical and Microbiological Analyses

Methods for measurement of chemical and microbiological constituents are described in *Standard Methods for the Examination of Water and Wastewater*. Standardized and approved methods must be used to obtain valid chemical, microbiological, and physical data. For small water systems with limited laboratory capability, analytical instrument manufacturers may have descriptions of methods appropriate for their instruments. For example, the Hach Company publishes the *Water Analysis Handbook* (Hach Company 2006), which covers photometric procedures, titration procedures, ion-selective electrode procedures, chemical procedures, microbiological procedures, and others. Some of these methods are approved or accepted by USEPA for reporting regulatory compliance data. An example is the nephelometric turbidity method, which meets or exceeds the criteria of USEPA Method 180.1. When water is analyzed for regulatory compliance purposes, methods that meet or exceed the criteria specified by USEPA must be followed.

Following standard procedures is important. Less obvious, although essential, is ensuring that all dry chemicals and solutions used in procedures are still within their shelf life. The use of old chemicals increases the potential for erroneous results. This applies both to chemicals used in analysis and to chemicals used for standardizing instruments. Careful collection and handling of samples also is necessary for obtaining valid analytical results.

At filtration plants, data useful for managing the filtration process include pH, alkalinity, hardness (at softening plants), and TOC. Iron and manganese are measured in plants removing those constituents. The appropriate frequency for performing nonregulatory measurements depends on the variability of the source water. If water quality changes are small and do not occur frequently, test procedures are not needed very often. When source water quality changes rapidly, such as on a river subject to periods of intense runoff, more frequent testing is needed so the guidance derived from analytical results can remain relevant.

Measurement of Physical Aspects of Water Quality

Turbidity, temperature, color, and particle counts are among the physical properties or constituents in water that are relevant to filtration. Of these, color typically is measured in the laboratory, whereas turbidity, particle counts, and temperature can be measured both at the laboratory bench and in the plant. Careful collection and handling of samples again must be given high priority.

If temperature of samples is measured in the laboratory, this must be done promptly after sample collection, before temperature change occurs.

When turbidity analysis is performed in the laboratory, most of the possible errors in procedure will cause the turbidity reading to increase. Dirty or scratched glassware, air bubbles in water, and fogging of the turbidity sample vials can increase the turbidity reading. If sedimentation occurs in the sample vial or in a sample container before water is poured into the sample vial, the turbidity reading could be lower than the actual turbidity.

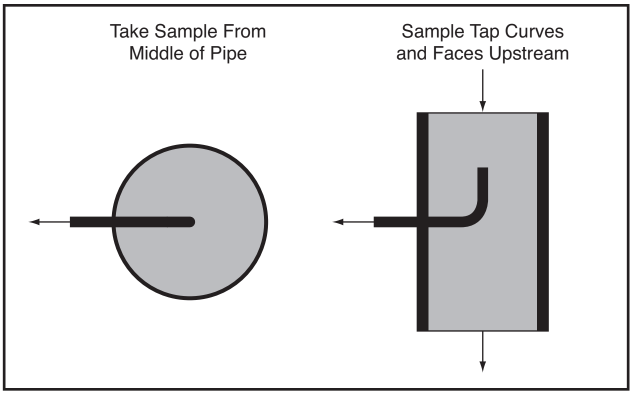
Particle counting is applicable for detecting small numbers of particles in water. Like other methods that are very sensitive and can detect very low concentrations of constituents, particle counting is susceptible to contamination problems. Particle concentrations of 1 or 2 per milliliter can be measured, so exposure of the sample water to a dusty atmosphere could result in serious contamination problems. Furthermore, glassware used for particle counting at the laboratory bench must be scrupulously clean to avoid sample contamination. For most water filtration plant purposes, using online counters to measure particles in filter effluent is considerably less labor-intensive and also less subject to contamination problems.

TREATMENT PLANT CONCERNS RELATED TO QUALITY CONTROL

Instruments Used for Chemical and Physical Analysis

Some general concepts apply to online instruments.

- The instrument must be installed according to directions provided by the manufacturer. Failure to do so can negate the value of any data collected from the instrument.
- The instrument should be located close to the sampling point, but situated for easy access for calibration, maintenance, and repair, to facilitate successful long-term use.
- Calibration must be performed at intervals no longer than those specified by the manufacturer.
- Periodic secondary checks of calibration between recommended calibration intervals are valuable for confirming that the instrument is still working acceptably.
- The sample extraction location is important. For sampling from a pipe, the middle of the pipe is preferred as this avoids possibility of obtaining samples having air bubbles at the top of the pipe or sediments at the bottom of a pipe. See Figure 9-1 for an illustration.
- Sample lines must not corrode, leach, or otherwise cause any change in the quality of the water conveyed to the online instrument.
- Within constraints of instrument accessibility for calibration and maintenance purposes, shorter piping is preferred rather than longer runs of piping, to minimize delay in sample analysis and opportunity for the quality of the sample stream to change.
- Sample stream handling must not change the characteristics of the constituent undergoing analysis; for example, pumping particle count samples to the particle counter must not be done for coagulated or filtered water.
- Rates of flow for online instruments must fall within applicable guidelines, if such have been formulated.



Source: Logsdon.

Figure 9-1 Recommended configuration for sample piping to collect filter effluent for particle counting and turbidity online measurement

Online Turbidimeters

Measurement of turbidity at each operating filter at 15-minute intervals is a regulatory requirement for coagulation/filtration plants treating surface water and groundwater under the influence of surface water. The only practicable approach for doing this is to use an online turbidimeter for each filter. Another regulatory requirement is that a turbidimeter used for collecting data to fulfill regulatory requirements must be calibrated using the procedure specified by the instrument manufacturer. This includes both the calibration method and the time intervals between calibrations, as recommended by the turbidimeter manufacturer. Proof of calibration must be kept so it is available if issues related to filtered water turbidity are raised by a regulatory agency. Small water systems may find it useful to contract for this service rather than use their own personnel.

Generally, online turbidimeters for filtered water are located in the pipe gallery as shown in Figure 9-2. Flow to the turbidimeter can be by gravity or under pressure. A flow control device is needed for adjusting the flow to maintain the range specified for the instrument. If air bubbles cause an analysis problem, using a bubble trap may resolve this. The turbidimeter should be close to the sample point, so the time interval between sample extraction and analysis is not excessively long. Furthermore, for some online turbidimeters, the volume of water within the instrument adds to the time lag between discharge from the filter to analysis of the water. For analysis of turbidity data during times of rapid change, such as when a filter is placed online after backwash, the residence time from the filter discharge to the point of measurement of turbidity should be identified. The waste line should be set up so the rate of discharge from the turbidimeter is easily measured using a stopwatch and graduated cylinder. If the discharge from the waste line

Source: Logsdon.

Figure 9-2 Turbidimeter mounted in pipe gallery

is readily visible, operators can detect an interruption of flow from the online turbidimeter if this should occur.

Occasionally, problems will develop with an online turbidimeter, and the data from the instrument will appear questionable. Online turbidimeters and bench-top turbidimeters will not necessarily give identical turbidity readings for the same water, even though both have been calibrated according to the instrument manufacturer's procedures. In spite of this limitation, if the output of an online turbidimeter is suspect, a grab sample of the discharged water should be taken from the online instrument, and an analysis at the bench should be performed. The bench-top instrument must be calibrated using a secondary standard before the comparative reading is made. Bench-top and online turbidity data for a given water sample may not be in agreement. Taking grab samples of water from other filters and comparing the online results to data from the bench-top turbidimeter being used as a reference instrument can indicate the relationship between results from the online and bench-top instruments. If other online turbidimeters produce data similar to results of the bench-top instrument, an online turbidimeter giving results not consistent with the bench-top results probably needs to be recalibrated.

One state drinking water regulatory agency has recommended that a check of turbidity by a bench instrument versus the online instrument be performed once per week to verify that the online instrument has not drifted excessively.

If raw water turbidity is monitored using an online instrument, the sample should be extracted before any coagulant chemicals are added to avoid the possibility of coagulation and changes in particle size by floc formation. At plants that add chemicals for zebra mussel control at the intake, it will not be possible to obtain a raw water sample with no added chemicals.

Particle Counters

It can be problematic to use particle counters to assess raw water. Some source waters contain so many particles that dilution is necessary before valid counts can be taken, because of the upper limits on the concentration of particles that can be counted accurately by such instruments. When the number of particles in raw water is high, grab samples should be collected and diluted in the laboratory to attain the number of particles within the countable range for an instrument, although this is a somewhat labor-intensive procedure.

Particle counters also are susceptible to problems caused by improper installation of sampling lines. If raw water is sampled for particle counting, the sample should be obtained before any chemicals are added. As with raw water turbidity, this may not be possible if chemicals are added at the intake for zebra mussel control. Note, however, that if potassium permanganate is added for this purpose, the presence of this chemical in the raw water can form a coating on the particle counter's sensor with the passage of time. Although pumping has the potential to change particle size distribution in a flowing sample, it may be necessary to pump raw water samples. Particle counters are expensive instruments; therefore, they should be sheltered in a protected environment near the intake, or kept in the treatment plant in clean, dry locations.

Generally, particle counters that analyze filtered water are located close to filter effluent piping in a position where sample pumping is not needed. If floc passes through a filter, pumping can cause the floc to break into smaller particles resulting in erroneous particle counts. Particle count samples should pass through a minimum of pipe bends that might induce flocculation. Preferred types of tubing for particle counters are copper, stainless steel, and polytetrafluoroethylene (PTFE), marketed as Teflon®. These do not exhibit biofilm buildup, which can give false positives for particle counts when biofilm sloughs off the sample line. As with online turbidimeters, the sample should be withdrawn from the middle of the pipe, not the top or the bottom.

Online particle counters are intended to operate at designated rates of flow through the sensors. Some means of maintaining a constant rate of flow in the proper flow range must be provided so the number of particles per milliliter can be calculated. A hydraulic weir device has proven effective. Water flow into the device must exceed the required flow to the instrument so some water can overflow at the control weir. As long as flow passes over the weir and deposits do not build up on the piping or tubing, the flow should remain constant because the sample that flows to the particle counter is withdrawn on the upstream side of the weir, which fixes the water surface elevation.

Particle counters must be calibrated periodically. Generally, this is done by the instrument manufacturer. Also, the rate of flow through the counter should be verified and kept within the specified range of the particle counter, and this can be performed periodically by treatment plant staff.

Streaming Current Instruments

These instruments are very helpful for optimization of coagulation, especially when source water conditions are variable over short periods of time. Data from a streaming current instrument are available within a few minutes of a water quality change; however, this depends on the time between coagulation and extraction of the sample for streaming current analysis, and the residence time in the sample line between the point of extraction and the instrument. For data to be of maximum value, some points must be observed.

- Water sampled must be representative of the monitored or controlled process.
- Sampling about 2 minutes after addition of coagulant is recommended, but sample at least 30 seconds after coagulant is added.
- The sample must not contain foreign matter that can damage the probe or block flow of the sample stream.
- Sampling must be continuous when the instrument is operating.
- The instrument must be as close as possible to the sampling point to minimize the delay between sample extraction and analysis.
- If the instrument is located outdoors, the sensor must be protected from rain, snow, direct sunlight, and spills; furthermore, the sensor and sample line must be protected from freezing.

The instrument manufacturer's brochures should be consulted for details on installation.

The water analyzed by streaming current instruments is coagulated, but it is not clarified; therefore, some source waters may contain fine, abrasive particles. These have the potential to damage the sensor. If the source water does at times contain particulate matter that can damage the sensor, a cyclone separator or small pressurized settling chamber should be used to protect the instrument. If the sample line clogs because of sediments, the sample line should be relocated. The sample lines should be periodically backflushed to maintain needed flow rates.

The sensor must be clean to work properly, so periodic cleaning is necessary. Cleaning solutions must NOT contain detergents because traces of detergent on the sensor will cause false readings. A solution of 10 percent household bleach can be used to remove organic coatings and alum precipitates. If iron or manganese deposits are present, a solution of RoVer™ Rust Remover can be used, at a strength of 30 g/L. Regardless of the kind of cleaning performed, the sensor must be rinsed very thoroughly afterward to remove all chemical traces that might cause false readings.

Streaming current instruments operate by giving a signal related to the current generated within the sensor. The value of this signal at optimum coagulation is not necessarily zero. The streaming current value reported when coagulation is optimized becomes the set point, or target value for future coagulation dosage adjustments. The set point value should be determined or verified periodically, perhaps on a seasonal basis. For example, if optimum coagulation in the fall has a different streaming current reading from the summer's set point, the fall value becomes the new set point. Complete documentation of each set-point determination should be kept for several years if source water quality tends to repeat itself on a seasonal basis.

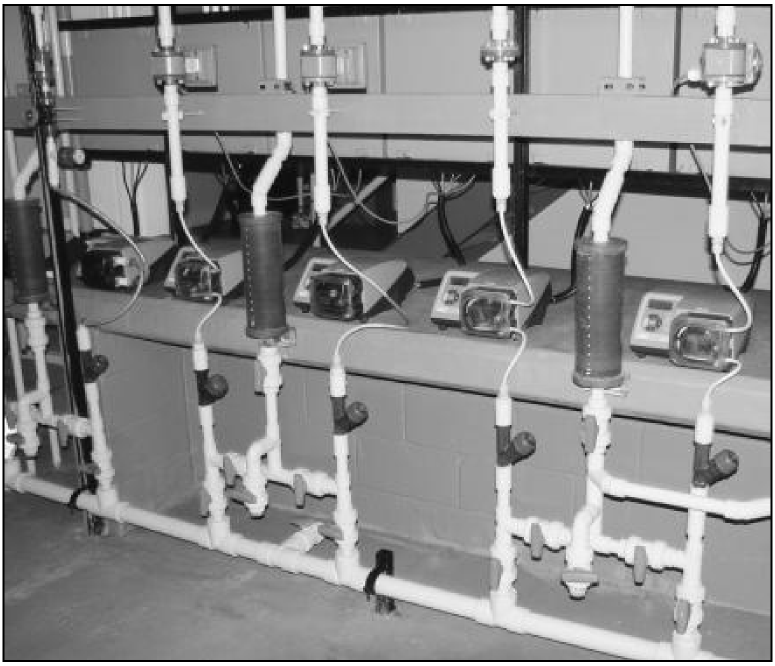
Online pH Instruments

It is necessary to control pH for optimal filter performance. At plants where pH is especially critical, either because lime softening is performed or because pH is critical for optimum removal of particles or TOC, online monitoring is very helpful to plant operations. If, however, the online pH data are inaccurate, the result could be inadequate removal of TOC or failure to properly stabilize lime-softened water resulting in precipitation of calcium carbonate in filter beds or water mains. In these situations, the online pH data MUST be accurate for good process control. The manual provided by the instrument manufacturer should be consulted for instructions on procedures and recommended frequency for calibration. If online pH measurement is used to provide data related to evaluation of Ct values, it is highly advisable to keep accurate records of instrument calibration and it is essential to ensure that the instrument uses a method approved by the USEPA.

Measurement of Flows, Pressures, Head Loss

Measuring Treatment Chemical Flows

Typically, chemical feed pumps are set using a calibration curve, but periodic checks of calibration are necessary to verify that settings have not changed. Calibration of diaphragm pumps can easily be checked if extra piping and valves are provided so that a graduated cylinder can be filled directly from the day tank, and then the chemical feed pump can pump from the cylinder for a brief period of time. Figure 9-3 shows piping and valves arranged so that a graduated cylinder can be used for checking calibration of either one or the other of two adjacent chemical feed pumps. By using a stopwatch to record time and recording the volumes in the cylinder at the beginning and end of the time interval, one can calculate the volume fed in a defined time and adjust the pump if necessary. A longer-term check on pump calibration is to determine the volume fed



Courtesy of James Van De Wege, Holland Board of Public Works, Holland, Mich.

Figure 9-3 Chemical feed pump calibration apparatus

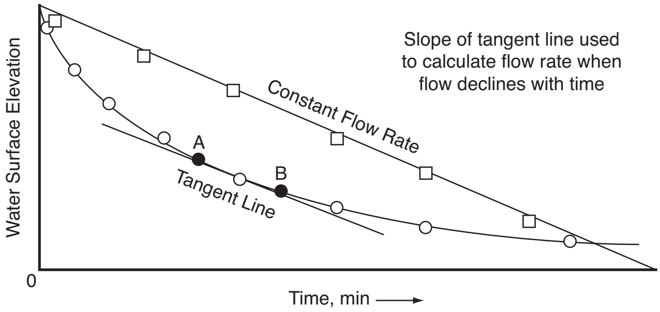
from the day tank over a number of hours; however, for this to be effective, the volume change in the tank must be known within ±5 percent or preferably ±2 percent.

Measuring Water Flow

Meters that measure the rate of flow of filtered water or backwash water can be checked by using the filter box as a measuring device. The procedures are somewhat similar in concept, but they are reverse in the sense that water flows out of the filter box for measuring filtered flow but into the filter box for measuring backwash rate of flow. A stopwatch and surveying rod or tape measure are needed, and at least two persons should perform these quality checks.

For the filtered water flow meter,

- After a clean filter is slowly backfilled with finished water, the flow of water into the filter should be shut off.
- The initial elevation of the water surface should be measured.
- The filter effluent valve should be opened to the desired rate of flow.
- The rate of flow should be determined by making periodic measurements of the water surface elevation, and the times coinciding with those measurements should



Source: Logsdon.

Figure 9-4 Measurement of water surface versus time to determine flow rate and check effluent flowmeter

be noted. Time intervals of about 30 seconds are appropriate. Flow meter readings at these times also are needed.

- This procedure should be continued for a fixed filter box area. Either the zone between the highest water level in the filter box and the top of the wash-water trough or gullet wall, or the zone below the bottom of the wash-water trough, down to the filter bed can be used. The key requirement is that the surface area of the water must be constant as depth changes.
- After the data have been collected, they are graphed on grid paper. The data points may describe a gently curving line as the driving head on the water decreased while its depth decreased. In this case, a tangent should be drawn to the curve at a point on the line where flow rate was measured and that is midway between times when the water depth was measured. The decrease in water volume during the time interval, divided by the time between elevation measurements, gives the rate of flow for that time interval. The flowmeter reading at the midpoint of that time interval should be a close approximation of the rate of flow. This is illustrated in Figure 9-4. An alternative approach would be to read both the flowmeter rate and the water surface elevation at a specified time and then after an interval long enough to obtain a second valid surface elevation, both the water surface elevation and the flowmeter rate should be obtained again. The two flowmeter rates should be averaged and compared to the calculated rate based on volume change over time.

When this procedure is done, the results should be saved for future reference.

Checking a backwash flowmeter or a surface wash flowmeter involves a similar procedure, except that the water level is measured over time as water rises, either from the top of the filter media to the bottom of the trough or from the top of the gullet wall to the highest level appropriate in the filter box, after the cross-section of the filter box above the gullet wall is full of water. The calculating procedure is the same as previously described but simpler if the rate of flow was constant during the calibration test.

Head Loss Instrumentation

Head loss gauges are used to indicate the extent to which a filter bed is clogged. Periodic checking of head loss instrumentation is recommended. For a zero head-loss check, the flow in the filter should simply be stopped. With a condition of zero flow, head loss is zero, and this should be the reading. If the layout of the plant permits it, a temporary piezometer tube made of clear plastic flexible tubing can be used to check head loss when the filter is operating. The tubing is connected to the discharge piping from the filter close to the tap for the head loss instrument. When no flow passes through the filter, the level to which water rises in the tube is the water level above the media. After this, the filter is returned to service and the head loss reported by instrumentation is compared to the difference in the level of water in the piezometer tube with zero flow versus the level when water is filtered. If the piezometer tubing is free of kinks or other flow obstructions, the difference in water levels for the filter at rest versus the filter during operation is the actual head loss.

SUMMARY

Basic laboratory quality control procedures have been known for a long time and should be practiced as a routine matter in water treatment plant laboratories. Modern methods of remote monitoring have enabled treatment plant staff to have more information on plant performance available in a continuous or online mode. The ease with which performance data can be attained releases operating staff from tedious measurement and data recording procedures, allowing more time for determining how the treatment process is working and how to manage any changes. Reliance on the analytical instruments providing the data must, however, be backed up with an effective program of quality control so plant staff know that the data provided are indeed valid and useful for making decisions about treatment.

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10

Filter Inspection and Maintenance

INTRODUCTION: THE NEED FOR FILTER INSPECTIONS

For any community, a water filtration plant represents a substantial investment of the community's resources, if the facility is publicly owned. The capital invested in privately owned water treatment plants also is a valuable resource. Regardless of the form of ownership, the investment should be protected by an effective program of inspection and maintenance. As an analogy, the owner of an automobile is responsible for its inspection and maintenance. If the owner never checks the engine oil level and never changes the oil and filter, the engine eventually will be seriously damaged at a great cost. Similarly, if maintenance at a filtration plant is neglected, facilities will become worn or damaged, and the ultimate cost for correcting neglected problems will be very high.

Some examples of severe filter problems are presented in Figures 10-1 through 10-6. Figure 10-1 is a photograph of a false floor that failed in uplift during backwashing. Figure 10-2 shows a tile block underdrain failure. Figure 10-3 illustrates the failure of underdrain blocks with attached porous plates. It should be noted that the entire block uplifted with the porous plate still attached. Figures 10-4 through 10-6 provide an example of a filter bed in a pressure filter that was not frequently inspected. When an inspection finally was done, significant portions of the bed had been cemented into a conglomerate rock by calcium carbonate precipitation. This damage to the media had occurred very gradually over time and was not detected by operating staff prior to the inspection. In Figure 10-4, the corrugated tube used for removing media to the vacuum truck is seen at the bottom of the figure. The large raised shapes above the corrugated tube are cemented mounds of media that were rock-hard. On the large mound in the right half of the photo, gouge marks caused by the air hammer used by a worker attempting to remove the cemented material are apparent. Figure 10-5 is a portion of the material removed from the filter. Figure 10-6 presents a close-up view of lumps of cemented sand and cemented anthracite removed from the filter. The light-colored objects in the dark pile in Figure 10-5 are the lumps of cemented sand.

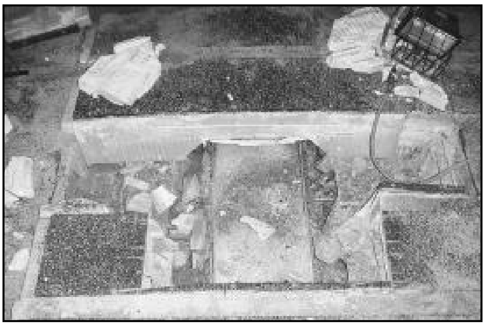
Operation staff at a water filtration plant want to prevent the catastrophic situations such as those illustrated in these figures. Routine observation of plant operations and a

Source: John L. Cleasby, *Filter Maintenance and Operations Guidance Manual.*

Figure 10-1 Uplift failure of false floor in filter

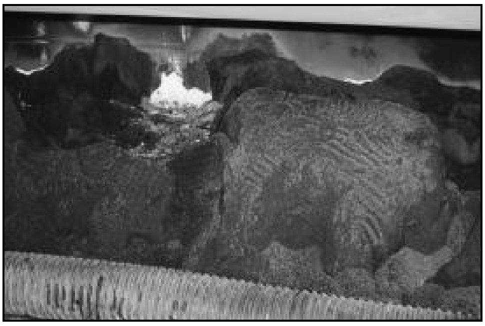
Source: John L. Cleasby, *Filter Maintenance and Operations Guidance Manual.*

Figure 10-2 Clay tile filter underdrain failure



Source: Logsdon.

Figure 10-3 Uplift failure of filter underdrain tile system with porous plate cap

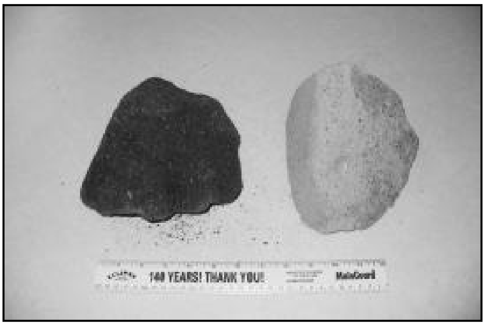


Source: Logsdon.

Figure 10-4 Cemented filter material mounds inside pressure filter

Source: Logsdon.

Figure 10-5 Filter media removed from pressure filter shown in Figure 10-4



Source: Logsdon.

Figure 10-6 Cemented lumps of anthracite and sand, removed from filter in Figure 10-4, shown next to a 12-in. ruler for size comparison

program of inspection and maintenance activities can identify potential problems before they grow into very expensive problems as illustrated in Figures 10-1 through 10-6. This chapter discusses recommendations for timing of plant inspections and procedures that can help identify the condition of filters so corrective actions can be taken if needed.

PREPARING FOR A FILTER INSPECTION

Performing either a quick filter inspection or a major filter inspection requires dedication of labor hours and removal of a filter from service for a period of time depending on the level of thoroughness of the inspection. Except in an emergency, an inspection should be planned in advance so it can be incorporated into the overall schedule for work and water production. Preliminary activities include selecting the inspection team, reviewing information obtained during prior inspections as well as plant operating records, planning for appropriate safety practices, and scheduling the work.

Information Review

Several kinds of documents can provide valuable guidance to the inspection team. These include

- Plant operating records for past year (filtration rate, water production per run, run length, percent wash water used).
- Water quality data for past year, including raw, settled, and filtered turbidity; coagulant dose; pH; alkalinity; temperature; and particle count, if available.
- Records of prior filter inspections, including notes on safety procedures.
- Specifications on filters from construction or rehabilitation projects.
- Standard operating procedures for plant (backwashing filter, placing filter in service, wash-water disposal or recycling).

In addition to documents, historical samples of filter media can be very useful for assessing the current condition of clean media. Samples of media should be saved and clearly identified when filter materials are placed in filters or during early years of operation, if new media samples were not saved. In later years, comparison of existing media condition versus the condition of new media can be can be helpful if questions arise about the condition of filter media and the need for media replacement. This is especially true for anthracite media, as with years of use it can become rounded on the edges, whereas new crushed anthracite is angular. If anthracite has worn excessively, utility management may consider replacing it.

Safety and Sanitation Considerations

Workplace safety is a highly important consideration. Inspections occur infrequently, so the inspection team members will be carrying out activities that are not routine. This can increase the opportunities for accidents. Also, filter inspections involve climbing in and out of filters and working within them. All appropriate safety precautions must be followed, whether the filters are open gravity filters or pressure filters.

Pressure filters are a confined work space and gravity filters also may fall into this category. Occupational Safety and Health Administration (OSHA) regulations apply to confined space activities. Whether OSHA's confined space working regulations apply to filters at a given plant has to be evaluated on a case-by-case basis. This determination must be made before any work inside filters begins so procedures for working in a confined space can be followed if required.

Even if confined space rules do not apply, basic aspects of workplace safety need to be applied. These include

- If the vertical distance down into the filter is over 6 ft (1.8 m), precautions to prevent falls may be needed.
- Lockout and tagout procedures must be initiated, so the filter cannot be placed into service accidentally while workers are in the filter box. When inspection procedures require a backwash, the lockout and tagout procedures should be discontinued temporarily.
- The filter bed has to be sufficiently dewatered before workers step onto the media. If the water has been drawn down to just below the top of the media, this may not provide secure footing.
- Working teams of two or more persons are a necessity, with one person remaining outside the filter to observe workers, secure assistance if needed, and help with providing tools and recording data.

Written procedures for inspections are strongly recommended, not to increase the burden of paperwork, but to ensure that procedures are documented and that all workers understand what the procedures are and that they must be followed. Information on safety procedures for confined spaces, lockout/tagout, and ladder safety can be found in AWWA Manual M3, *Safety Practices for Water Utilities* (AWWA 2002).

Planning for filter inspection should also include sanitary precautions in addition to workplace safety considerations. Disinfecting boots and equipment is an important preventative measure, particularly if boots and digging tools have been used outdoors where contamination might have occurred. Walking and working on pieces of plywood placed on the filter bed is recommended as a means of minimizing disturbance to filter media at locations not subjected to digging or other inspection procedures. Plywood disperses the weight and causes less disruption than walking directly on filter media. In the United States, where 4 ft × 8 ft sheets of plywood and oriented-strand board are the standard size, cutting a single sheet into three pieces 32 in. × 48 in. provides three work surfaces with no wood wastage. A similar metric-sized sheet could be cut into three useable pieces. At least one backwash should be performed as another sanitary precaution after completion of a filter inspection. This will restore the filter bed to an undisturbed state prior to placing it back in service.

Selecting the Team and Planning the Work

After a decision has been made to schedule a filter inspection, team members are selected and the work schedule is planned. Major filter inspections require multiple activities, and even with a crew of two or three persons, a filter might be out of service for one half or one day. If biological filtration is employed, it is imperative to perform the filter inspection as expeditiously as possible, because dewatering the filter for an extended period of time can result in die-off of microorganisms living on the filter media. When this occurs, recovery of biological activity could take days or weeks of operation following the inspection. If possible, a major filter inspection should be performed during a time when water demand is relatively low rather than high. This will be helpful both in terms of workload for staff at the treatment plant and because having a filter out of service when demand is low causes little or no interference with water production. Furthermore, inspection procedures result in the need for additional wash water, which is another reason for performing a major inspection when water demand is low.

A filter inspection should be conducted in a timely manner to minimize the hours of labor involved and to hasten the return of the filter to service if the inspection reveals that it can be used without risk to public health and without risk of damage to the physical facilities. Many tools and materials are needed for a major filter inspection; therefore, these should be assembled prior to the inspection to ensure that the work proceeds in an expeditious manner. Table 10-1 provides a list of materials and equipment that can be very useful when performing such an inspection.

Before an inspection begins, a brief review of the tasks and procedures that will be undertaken will eliminate confusion about what will be done, by whom, and when, after the inspection begins.

FILTER INSPECTION PROCEDURES AND FREQUENCY

The recommended frequency for filter inspections depends in part on the condition of the filter and past information on it. A filter that performs dependably, producing filtered water of low turbidity and yielding long runs, does not need to be inspected as often as one that has operating problems, filtered water quality problems, or a history of troubles. Table 10-2 provides recommended time intervals for inspection procedures. Some are done fairly often, but others may be undertaken between two to five years. A major filter inspection is recommended for one-year intervals until experience proves that year-to-year changes are minimal and inspecting at two-year intervals would result in no problems. Procedures recommended for a major filter inspection are listed in Table 10-3.

Sometimes a filter may appear to have problems but not of a sufficient magnitude to schedule a major inspection. In such a situation, a quick filter inspection should be performed, and this should take perhaps only two to three hours. Procedures to employ during a quick filter inspection are stated in Table 10-4.

Table 10-1 List of materials and equipment to obtain and assemble for major filter inspection (where metric sizes are not listed, use a metric size similar to the size listed in the table in English units)

Items
Three, 2-ft, 8-in. × 4-ft sections of ¾-in. plywood to stand on in filters
A 4-ft or a 6-ft level
25-ft tape measure
Flashlight
30 ft of heavy string or cord
Duct tape
0.5-L or 0.25-L wide-mouth plastic bottle
Cap for 1.5-in. galvanized pipe
25 to 35 plastic bottles with screw caps, 125 mL capacity, for turbidity samples
Light-weight aluminum pole, long enough to reach from filter operating floor to wash-water troughs (alternative to lowering bottle to trough by cord)
Bench-top turbidimeter
5-ft to 6-ft steel or metal rod for probing gravel (¼-in. diameter may be preferred for older filter beds of sand only. ⅜ or ½-in. diameter may be more appropriate for dual media or anthracite media.)
4-ft to 5-ft galvanized pipe, plastic pipe, electrical conduit, or copper pipe, or a special tool for core sampler (about 1 in. in diameter)
10 to 16 bottles, 1,000 mL capacity, for floc retention analysis
Two, 500-mL Erlenmeyer wide-mouth flasks with rubber stoppers
One, 500-mL graduated cylinder (clear plastic less susceptible to breakage than glass)
About twenty, 1-gal plastic food storage bags for filter media samples, per filter
Tablespoon
Four, 100-mL glass or plastic beakers
Filter media expansion tool
10 ft of ¾ in. galvanized pipe to support bed expansion tool
Twenty-four, 12-in. cable ties (to secure bed expansion tool)
Wash-water rise rate measuring tool (can use yardstick attached to long board)
Stop watch
Permanent ink marker
Labels
Surveyor's level or transit and level rod (optional for media elevation measurements)
Pan balance
Camera for taking pictures during inspection, for photographic records of what is found during the inspection.

Adapted from Smith, Wilczak, and Swigert 1997.

Table 10-2 Recommended frequency for observing and inspecting filters

- Daily to weekly for gravity filters
  - Observe at least one filter backwash and check flowmeter readings.
  - Over a period of one month, be sure to observe backwash of each filter at least once.
  - During backwash, observe surface wash to verify nozzles are not clogged and sweeps rotate, or observe air scour to be sure air is evenly distributed.
  - Draw down water in the filter and observe surface of filter bed before backwashing, checking for mounds, depressions, cracks, and mudballs. (Do this at least quarterly for pressure filters.)
- Quarterly or seasonally for both gravity and pressure filters
  - Check backwash rise rate and filter media expansion (for pressure filters treating ground water, annually should suffice if temperature changes are minor on a seasonal basis)
  - Conduct backwash turbidity profile
- Annually for both gravity and pressure filters
  - Probe gravel elevations
  - Inspect surface wash sweeps and nozzles if present
- Annually or once per 2 to 5 years, depending on past experience, for both gravity and pressure filters
  - Conduct major filter inspection for gravity filters; also use applicable procedures for pressure filters
  - Core media for acid solubility at 5-year intervals for coagulation plants and 2-year intervals for lime softening plants

Adapted from Logsdon et al. 2002. This table is applicable for new plants and plants not fully understood by operating staff or plants demonstrating operational problems. If plant performance is acceptable, time intervals between procedures may be longer. If filters are not susceptible to problems, the inspection interval can be as long as 5 years. Filters with continuing problems need to be inspected annually.

Regardless of the nature of the filter inspection, data and findings must be carefully and accurately recorded and saved for future reference. Water filtration plants are intended to provide decades of service, over which time the personnel at a facility may change numerous times. Records of work done on inspections and the findings must be kept to ensure that background information is available when future inspections are performed. Documented results are much more reliable than a person's memory, and if decisions are made about increasing or decreasing the frequency of inspections, it is necessary to have written information. Inspection results can be very helpful to plant operators and also to design engineers if a plant expansion is considered at a future time.

DETAILED DESCRIPTIONS OF FILTER INSPECTION PROCEDURES

Filter inspections employ a range of procedures that are described in this section. More detailed information on performing filter inspections is found in *Filter Evaluation Procedures for Granular Media* (Nix and Taylor, 2003).

Techniques described in this chapter are inspecting the condition of the filter box, troughs and piping; measuring the elevation of the filter media when the bed is at rest; probing support gravel if present; checking media for mudballs, media interface, and

Table 10-3 Major filter inspection program

- Draw down filter for first inspection
  - Check for cracks and depressions. The surface should be level and free of cracks or depressions.
  - Check condition of filter box, troughs, piping, and valve
  - Obtain media core samples before backwashing for floc retention analysis
- First backwash
  - Fill filter slowly up from the bottom to expel any entrapped air
  - Backwash filter, observing auxiliary scour (air scour or surface wash). Watch for boils or other evidence of uneven wash distribution and uneven air distribution if air is used.
  - During backwash, do a backwash turbidity analysis
- After backwash
  - Draw down filter for second inspection
  - Check to see if media surface is level as water reaches surface
  - Check troughs for media
  - Measure elevation of media in the bed at rest
  - Probe support gravel, looking for mounds or depressions in gravel
  - Inspect for mudballs, media interface (if applicable), and media depth
  - A media excavation procedure may be performed at this time for visual inspection of media after backwash, observation of interface in multimedia filters, and visual check of top layer of support gravel or nozzles if no support gravel is used
  - After first backwash, obtain clean media core samples for floc retention analysis and for other purposes such as sieve analysis, acid solubility test, etc.
- Second backwash
  - Fill filter slowly up from the bottom to expel any entrapped air
  - Perform another backwash with NO auxiliary scour and with bed expansion tool in place to measure filter media expansion. This backwash will also restore the bed to an undisturbed condition after the coring activities and excavation, if the latter was done.

Source: Logsdon et al. 2002.

depth confirmation; examining the underdrain; obtaining core samples; assessing effectiveness of backwashing, and checking for build-up of precipitates on filter media.

Box, Troughs, and Filter Piping

When the filter box has been drained for inspection, its condition should be evaluated. Cracks or spalling of concrete and failing paint or exposed steel reinforcing bars are signs of aging that indicate need for repairs. Rust on steel filter vessels is another indication of needed maintenance. Visible piping should be inspected for signs of corrosion and water leakage.

Filter troughs must be level across the top, and the top of each trough must be at the same elevation to attain uniform withdrawal of water and a uniform rise rate across the filter during backwash. To some extent, differences in trough elevation can be detected by carefully observing discharge of water over each trough during backwash.

Table 10-4 Quick filter inspection

- Draw filter down for first visual check
  - Look for cracks in filter bed and check to see if bed has pulled away from walls
  - As water surface reaches top of media, is media level? Watch for mounding or depressions.
- During backwash
  - Watch to see if surface wash or air scour is working properly
  - Look for boiling of media or dead spots
  - Watch for tilted wash-water troughs and for uneven flow with a trough having more water or less water than the others
- After backwash
  - Draw the filter down so operators can walk on it but do not dewater totally
  - Check troughs for media
  - Visually inspect media for cleanliness, presence of mudballs
  - Probe for gravel in middle of filter and near each corner, looking for mounds or depressions in gravel
  - Place pipe organ media expansion tool on media surface
- Second backwash
  - Fill filter slowly up from bottom to expel any entrapped air
  - Perform another backwash with water only; NO air and NO surface wash
  - Observe media expansion, and measure rise rate or backwash water flow
  - Measure water temperature
- After second backwash
  - Record media expansion and calculate percentage expansion, and assess adequacy of media expansion. Change wash-water rise rate to obtain appropriate media expansion if needed.

Source: Logsdon et al. 2002.

Another way to check trough elevation is to use a very slow rise rate after washwater reaches the bottom of the troughs. If they are level and all at the same elevation, water will begin to overflow all troughs uniformly at the same time. Each trough should be checked with a 4-foot carpenter's level during a filter inspection, and it can be done without great difficulty at most plants.

Examining Media, Support Materials, and Underdrains

When the filter is dewatered for the initial visual inspection, high spots and depressions in the media can be detected. Mudballs on the media surface can be seen if present. Also, cracks in the filter bed or areas where the media has pulled away from the filter wall can be detected. When filter materials are installed, they are placed at a specified elevation in the filter box, backwashed, and allowed to come to rest so the bed is level. As a filter is used, media loss takes place, and disruptions to the filter bed, or underdrain system, or both result in a media surface that is no longer level. Measurements taken during a filter inspection provide information on the depth of media and the depth of support gravel, if that is used.

Elevation of Media Surface

To determine the elevation of the top of the filter media, measurements can be taken from the tops of wash-water troughs at locations that are marked and identified on the inspection documents. With this method, a steel tape is used to determine the distance from the top of the trough to the top of the media. Using the known distance from the bottom of the filter box to the top of the wash-water trough, the total distance from the top of the media to the bottom of the filter box also can be calculated. For this method to give valid data, the tops of the troughs must all be level and at the same elevation.

Another approach is to establish a grid pattern and measure the elevation at every point on the grid using a surveyor's level and rod. This can be more labor-intensive than measuring only from the tops of troughs, but the results are more precise. Properly set-up surveying instruments are quite precise, and use of surveying equipment eliminates concerns about whether tops of wash-water troughs have identical elevations throughout the entire filter. One person uses the surveying instrument, another holds the rod, and perhaps a third person assists in positioning the surveyor's rod at the specified grid points.

The number of surface elevation measurements needed depends on the area of the filter. For small filters, five measurements are recommended, preferably with a measurement near each corner and in the middle. For medium-sized or large filters, measure media elevations along each trough at intervals of about 5 ft (1.5 m) or in a grid pattern with points at 5 ft (1.5 m) intervals.

Probing Filter Media

When filters are installed on porous plate bottoms or on tile underdrain systems having a porous plate cap, and if no torpedo sand is used on the porous plate or cap, the depth of filter media is the distance from the media surface to the filter floor. If support gravel or torpedo sand is used beneath the filter media, the depth of support materials must be determined, and this complicates determining media depth.

When support gravel or torpedo sand are present, for each location where the elevation of the media surface is determined, the depth to support materials must be measured by probing into the media. A steel rod about ⅜ in. or 10 mm can be used. The rod is prepared for probing by filing indentations on the length of the rod and marking them. The indentations can be made at every 1 in., with special markings at every 1 ft; or at every 2 cm with special markings every 20 cm. The markings are used to identify the depth to which the rod penetrates when it is gently pushed down into the media using short, repeated strokes, as shown in Figure 10-7.

The sound of the rod striking the filter material is different from the sound of the rod striking the gravel, and the feel is different. High noise levels will interfere with the use of this method of locating the top of the support gravel, so it is preferable that the filter area be quiet when this probing is performed. When support gravel is present, the probe should not be forced into the gravel.

Courtesy of Gerald H. Caron, City of Wyoming Utilities Department, Wyoming, Mich.

Figure 10-7 Probing to determine depth of filter media to support gravel

Another approach for determining the depth of penetration of the probing tool is to place masking tape around the rod at the media surface after the rod has reached the filter bottom or the support materials. After the rod is withdrawn, the distance from the bottom end to the tape on the rod is measured to determine the depth of penetration, which should be the depth of the media if the probing was done properly.

Probing to determine the depth to support gravel is not a precise measurement method, but a check on the quality of probing data is made by probing in the filter bed at a few locations that are adjacent to a wash-water trough. After the probing is done at those locations, the staff performing the probe should dig into the media at the places where probing was done. The size of the hole does not need to be large, and except for deep filter beds, digging by hand or with a small tool to extend one's reach into the hole beyond arm's length can expose the surface of the support gravel.

Next, a physical measurement is made from the top of the trough to the top of the support gravel. After subtracting the distance from the top of the trough to the top of the media, the tape-measure data for media depth is compared with the probing data. This will indicate how closely probing data are to the actual distance from the top of the media to the top of the gravel at each excavation site. Media depth determined by probing ought to be within ±1 in. (3 cm) of the depth determined by digging into the media to reach the support gravel.

After the quality of the gravel probing data has been determined to be satisfactory by the excavation, as previously described, the gravel depth data are compared to the design specification for the original or rebuilt filter. A deviation of ±30 percent from the design specification is considered serious and needs further investigation. Data needed for this comparison are the actual media elevation and media depth at each location where measurements were made, along with the elevation of the filter bottom.

With the availability of computer programs that are relatively easy to use, gravel surface profiles are plotted using a spreadsheet program. If this process is used, plant staff should be aware that spreadsheet programs used to depict the media surface may not have been developed by programmers who had experience with land surveying or were familiar with topographic maps. The actual support gravel surface may have hills and valleys resembling those in natural topography. The gravel surface is highly unlikely to have surface shapes resembling pyramids or solid polygons, even though that is how gravel profile data (a form of topographic data) might be depicted by spreadsheet figures. If graphic representations of gravel surfaces are shown to management or elective officials, plant staff need to be able to explain the difference between the computer-generated surface and the real surface profile, if asked.

Probing into the filter bed also is a way to locate large, hard lumps of material within the bed. Workers on plywood are doing this in Figure 10-8. This procedure involves less effort than using an excavation box, a technique described in the next portion of this chapter. Some of the lumps of anthracite, calcium carbonate, and cationic polymer bound together are shown in Figure 10-9.

Digging Into the Filter Bed

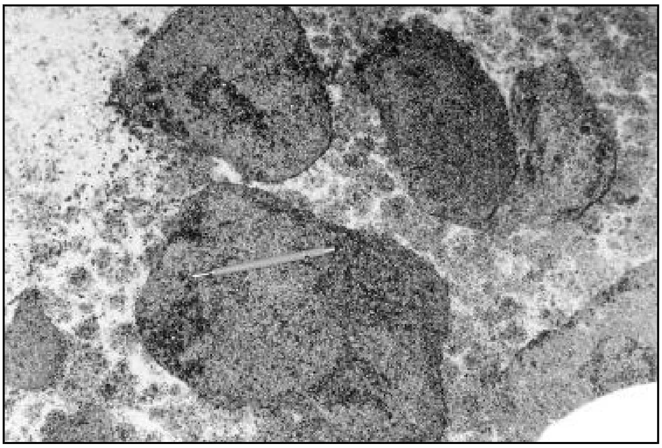
When visual indications of media and underdrain problems, such as filter boils or dead spots, are noted during backwashing, a filter excavation is necessary. An excavation box is used if the condition of an area of support gravel or condition of the underdrain is questionable. Using this device requires two or more workers and is likely to keep the filter out of service for a few hours if no problems are discovered, and longer if serious problems are found.

An excavation box is a four-sided box with no top and no bottom. It is a miniature version of a caisson. Figure 10-10 shows an excavation box positioned above a filter bed before being lowered into the bed. One way to use the box is to place it on the surface and gradually remove media from the area inside the box and along the edges of the box until it drops or can be pushed down to the bottom of the partial excavation. This is repeated until the box reaches the support gravel or the filter floor.

Another way to position the excavation box in the bed is to place it on the filter bed, held in position by ropes attached to the four corners. As the bed is fluidized, the excavation box is carefully lowered to the top of the support gravel or to the filter floor, if no

Source: Black & Veatch Corporation, *Filter Maintenance and Operations Guidance Manual.*

Figure 10-8 Probing filter media to locate large lumps of material in bed

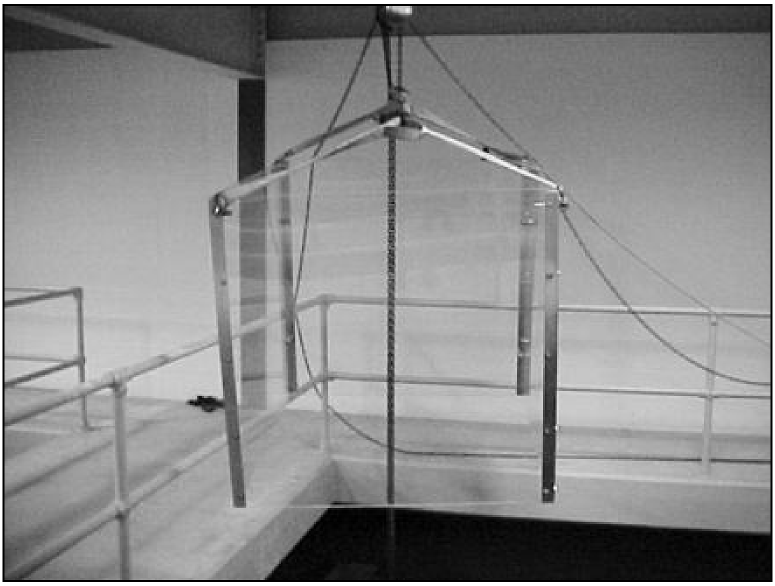


Source: Black & Veatch Corporation, *Filter Maintenance and Operations Guidance Manual.*

Figure 10-9 Lumps of media and $CaCO_3$ granules found in filter probed in Figure 10-8. A drafting pencil is on the largest lump for size comparison.

support gravel is present. Once the box is positioned there, backwash is ended, the filter is dewatered, and excavation can begin, as shown in Figure 10-11.

An excavation box must be large enough for a worker to stand inside and dig out filter media and gravel with a shovel or some other tool adapted for this purpose. This is likely to require a box about 3 ft × 4 ft (1 m × 1.3 m). The walls of this box must resist bending caused by the force of the media acting on them after the excavation reaches the full depth of the filter; however, the ability to look through a wall and view the media on



Courtesy of Black & Veatch Corporation.

Figure 10-10 Filter excavation box ready to be lowered into filter bed

Courtesy of Black & Veatch Corporation.

Figure 10-11 Digging media out of excavation box the other side of the box provides valuable information. A box made entirely out of ½ in. (12 mm) Plexiglas™ may bow because of the force of the media on the walls. One option is to use Lexan™ of sufficient thickness to resist bending, and another is to make a box having three sides of steel or aluminum with one side consisting of transparent materials, perhaps with metal braces at the top and bottom for added rigidity. Because the quantity of materials removed from inside the excavation box is large, tarps generally are placed beside the excavation box so filter materials can be placed on them and then returned to the hole after the box is removed from the bed.

Workers who dig media out of the excavation box have to be careful to avoid damaging the underdrain if excavation reaches that far. For example, if nozzles are used in the filter floor, they can be damaged by careless use of shovels. If the inspection box has one or more transparent walls, care also must be taken to avoid scratching or damaging those walls.

The person digging inside the box should be alert for presence of mudballs or other signs of problems. If a dual-media or tri-media filter is being inspected, carefully noting the location of the media interface and the extent of intermixing of two layers of different filter materials is an important aspect of the inspection. The interface can be seen through a transparent wall of the excavation box if the wall is clean. If a filter boil is the cause for the inspection, the media interface may not be representative of the rest of the filter, but it still should be noted. Also important to observe and record is the condition of the filter gravel, and the condition of the filter bottom, if the excavation reaches this area.

When the excavation is concluded, forces of the media pressing on the walls of the box may make removal difficult unless the bed is fluidized and the box is lifted out during a backwash. The excavation box requires both labor and time, but the level of effort is much less than what is required for removal of all of the media from the filter. If the findings indicate that only a small area of the filter needs repairs, using the box saves both time and labor in comparison to emptying the entire filter box and replacing all of the filter material after repair work is finished.

Obtaining Core Samples From the Filter

Core samples are taken from a filter so the media can be tested for size distribution (sieve analysis), acid solubility, or floc retention, for example. Because such testing is a follow-up activity to obtaining core samples, the samples must be representative of the media in the filter. This results in the need for careful sampling and for sampling from multiple locations within the filter for sieve analysis and for acid solubility testing. The AWWA *Filter Surveillance Video* recommends that core samples be collected at six different locations in the bed and combined for analysis. Floc retention is a special case in which it is best to analyze media separately for each location sampled, because backwashing may not be uniformly effective over the entire bed, and if locations of poor media cleaning exist, they should be identified. Before core sampling begins, locations in the filter bed are designated and recorded so future core sampling can be performed in the same places.

Core samples can be collected by gently inserting a tube with a diameter of 1 to 2 in. (2.5 to 5 cm) into a filter bed that has been drained but is still damp. Dry filter materials will not adhere to the walls of the sampling tube. If the filter is a rapid sand filter, a tube as small as ⅝ in. (1.6 cm) may be needed. For sieve analysis and for acid solubility, the tube is inserted to the bottom of the media; therefore, a core sampler made about 3 ft (0.9 m) longer than the depth of the media will cause the sampler to protrude above the media surface sufficiently to facilitate its manipulation to the bottom of the bed. Caution must be exercised as the core sampler nears the bottom of the filter bed. In filters with nozzles in the floor and no support gravel, striking a nozzle may damage it. The sampler should not penetrate the coarse sand and support gravel. Backwashing the filter prior to sampling for sieve analysis or acid solubility is good practice, as clean filter materials are needed for these tests. Core samples are collected both before and after backwashing for the floc retention analysis.

Core samplers can be made from PVC pipe, copper tubing, or metal electrical conduit. Tubing with a rough interior wall holds media better than tubing that is smooth, so if PVC pipe is used, swab the interior with PVC cement and shake in a small amount of very fine sand to roughen the surface. Metal conduit has surface roughness and is less expensive than copper, so conduit is a good choice if it is available.

If a core sampler is used for taking samples at successively greater depths within a filter bed, it is marked for those depths. A sampler used for the floc retention test is marked at distances of 2, 6, 12, 18, 24, 30, and 36 in. (5, 15, 30, 46, 61, 76, and 92 cm) from the end that penetrates the media.

A core sampler with a hinged tube that can be opened to permit examination of the media core can be made rather easily using a tube 1 to 2 in. (2.5 to 5 cm) in diameter, 2 to 3 ft (0.6 to 0.9 m) longer than the depth of the filter bed. To do this, a longitudinal cut (a cut along the axis of rotation of the tube) is made through both sides of the tube about 1 ft or 0.3 m longer than the depth of the media to be sampled. Then, the tube is cut across at the upper end of the longitudinal cut so half of the tube can be removed. Using an abundant amount of duct tape, refasten the cut-off portion of the tube back onto the larger piece. This will restore the cylindrical shape of the core sampler.

As the core sampler is push into the media, the person using it holds it about 3 ft (0.9 m) above the media surface and rotates the tube in a circle with a diameter of about 6 in. (15 cm), so the tube pushes media away from the hole that is left when the sampler is withdrawn. This will facilitate withdrawing the sampler, and if repeat samples are taken at different depths into the media instead of a single sample from the top to the bottom of the filter bed, pushing media away from the hole will prevent media at the top of the bed from falling into the hole and being sampled with media from a greater depth. When the sampler has penetrated to the intended depth, it is carefully withdrawn. If media has stayed in the lower end of the tube (the end that penetrated the bed), media has not been lost from the sampler.

After the hinged core sampler has been inserted into the bed to the appropriate depth and then withdrawn, it can be laid on a horizontal surface, allowing the duct tape on one side of the tube to be cut and the hinged portion of the tube opened to expose the media. This kind of sampler allows the user to see the various layers of media in the bed, as illustrated in Figure 10-12, although the force needed to penetrate into the bed and push media up into the sampler tends to compress the media somewhat. The length of the core removed from the filter will be shorter than the actual depth of the bed sampled, but the relative position of coal and sand in a dual-media filter will be kept intact by the hinged sampler. The core can be photographed to document the filter material layers (if any) found in the bed, and then the sample can be kept for further analysis or saved as part of the inspection record. If a plain tube is used, place the sample into a labeled plastic bag and save it for analysis as shown in Figure 10-13.

Assessing the Effectiveness of Backwash

Plant operators need to know if backwash is cleaning filter media effectively, and this can be assessed with data collected over the long-term or by a testing method that can be carried out during a filter inspection. Measuring the extent of bed expansion during backwash will verify that the rise rate used is actually attaining the desired bed expansion. Monitoring turbidity of spent backwash water will indicate when washing has continued long enough that only a small amount of particulate matter is being washed out of the filter bed. Testing media to estimate the amount of floc that can be released by vigorous agitation is another approach. Long-term accumulation of floc and other particles on grains of filter material will increase clean-bed head loss; therefore, monitoring this trend over several months gives insight into the condition of filter media.

Filter Bed Expansion

Measurement of filter bed expansion verifies that the expected expansion for a specified rise rate is attained when no auxiliary scour is operating. Relevant data include the amount of expansion measured as inches or centimeters, and expressed as a percentage of the filter bed depth, the water temperature, and the rise rate. After a sufficiently large data base is developed, past results indicating the rise rate that yielded a measured bed expansion at a given water temperature can be used as a guide to setting backwash rates.

Bed expansion can be measured in a number of ways. If a Secchi disk or similar target is mounted on a graduated pole and disappears from view when inserted into the bed, this would provide measurement of bed expansion at the full rise rate when the bed is clean and spent wash water is clear. When the filter media is barely visible on the top of the white portion of the Secchi disk, this indicates the upper boundary of filter expansion. Secchi disk measurements should be taken several times and averaged, because the method lacks precision.

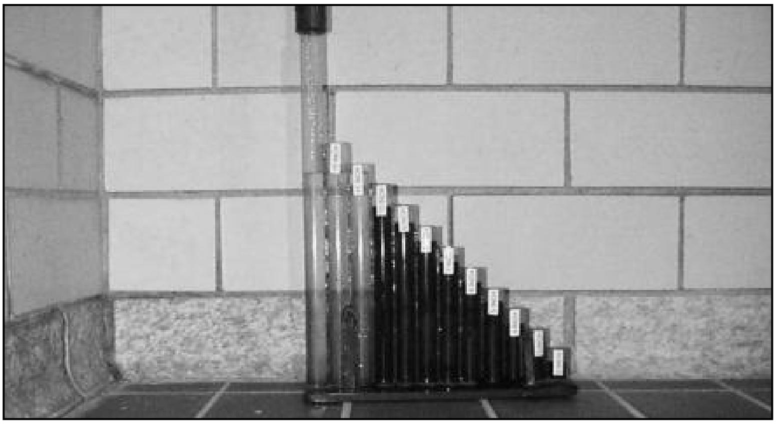
Courtesy of Filter Plant Programs Section, Pennsylvania DEP.

Figure 10-12 Hinged core samplers opened to permit examination of anthracite and sand layers extracted from filter bed

Courtesy of Filter Plant Programs Section, Pennsylvania DEP.

Figure 10-13 Pouring core sample into bag to save it for future testing

The *pipe organ* bed expansion tool is a device that can be built in a water utility shop by staff personnel with sufficient mechanical talent to work with plastic pipe. For a filter bed that is not expected to expand more than 10 in. (25 cm), translucent or clear PVC pipe with a diameter of about 1 in. or 2 to 3 cm is cut into lengths of 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 in., or 6, 9, 12, 15, 18, 21, 24, 27, and 30 cm. The pieces are fastened to



Source: Logsdon et al. 2002.

Figure 10-14 Pipe organ sampling device used to determine extent of bed expansion during backwash. Dark areas in translucent tubes are filter media caught during backwash.

an appropriately sized rectangle of PVC plate or sheet and fastened together with PVC cement. Another pipe piece is cemented to the assembly along with a threaded coupling so it can be mounted on a long pole, placed into the filter on top of the media at rest, and held there during the backwash.

The recommended procedure for using the pipe organ sampler is to wash the filter using the usual backwash procedure with surface wash or air scour, and complete the procedure as normally practiced. Then, the pipe organ sampler is installed by placing it on the filter media and securing the tool to prevent it from moving during backwash. Then again, the filter is backwashed *without* using air scour or surface wash, and after backwash has ended, the pipes are examined to determine which are full or partly full of media, and which are empty. Figure 10-14 shows the pipe organ sampler with anthracite in tubes ranging in height from 2 in. to 10 in. (5 cm to 25 cm). Little or no anthracite was in the 11-in. and 12-in. (28-cm and 30-cm) tubes, so the bed expansion during this wash was 10 in. (25 cm).

Spent Wash-Water Turbidity Monitoring

Monitoring turbidity of spent wash water indicates to operators the extent to which accumulated dirt and floc are removed from media. Typically, spent wash-water turbidity is very high for the first minute or two of backwash, and then it declines over the next several minutes. When the turbidity of spent wash water has decreased to about 10 ntu, additional backwashing is not likely to remove much more of the accumulated materials from the filter. If this test is performed, the filter should be at the end of a normal run, as the purpose of the test is to find out how long backwashing is needed for wash water to become clear after a typical filter run.

Spent wash-water turbidity generally changes rapidly during the first few minutes of backwashing, so before this evaluation proceeds, preparations have to be thorough and complete. Spent wash water is sampled every 30 sec for at least the first several minutes of the backwash. If a backwash lasts 12 min, sampling 2 times per minute for 6 minutes and once per minute for the duration would require 19 samples if the first sample is collected immediately when wash water begins to flow over the trough, i.e., at time zero. Plastic 125-mL screw-cap sample bottles of the type used for bacteriological samples are recommended for holding samples. Premark each bottle for a specific sample collection time. For sample collection, a plastic 0.5-L or 0.25-L bottle is fastened to the end of a pipe or pole long enough to reach from the operating floor to the wash-water trough. Two persons are needed for this test, with one collecting samples at designated times and a second person selecting the proper sample bottle to hold the just-collected sample and keeping track of time to tell the sampler when to take the next sample. Events take place at a fast pace when sampling is done on a 30-sec interval, making a two-person team essential.

After the samples are collected, they are analyzed for turbidity and data are recorded. The data are graphed on grid paper, with time on the X-axis and turbidity on the Y-axis. The first (time zero) spent wash-water sample probably will have low turbidity, but turbidity of subsequent samples will rise rapidly and then decline gradually. When turbidity changes are small from sample to sample, the sampling interval can be lengthened. A review of the graph reveals the amount time required for the dirt released from the filter to be washed away. As discussed in chapter 6, backwash can be terminated when spent wash-water turbidity declines to 10 ntu.

Floc Retention Analysis

A test for floc retention was developed by Kawamura (Kawamura 2000) to show how much floc and accumulated particulate matter has been trapped in the filter bed during a complete filter run and to indicate how much was removed during backwash. Performing this test requires the collection of core samples before a filter backwash and then again after the routine backwash. From the data developed, plant staff can determine the effectiveness of the backwashing , and if results indicate inadequate removal of particulate matter stored in the filter bed, changes in backwash procedure may be indicated.

This filter examination procedure (Kawamura 2000) requires collection of core samples from the same location at successive depths, and Kawamura recommended collection of samples at three representative locations within the filter. At a plant using surface wash with rotary sweeps, sampling near a corner of the filter, about 2 ft or 0.6 m out from each wall, midway along the wall, about 2 ft or 0.6 m from the wall, and in the middle of the filter is suggested. These three locations represent an area where surface wash may be weakest, one where action may be moderate, and finally one where surface wash ought to be most effective.

The following are steps for the floc retention analysis:

1. Drain the filter and begin the procedure so core samples can be obtained while the media is damp and will adhere to the core sampler. Prepare a minimum of six sample bags for each location sampled. Plastic Zip-lock bags will work well.
2. Place pieces of plywood as described previously in this chapter at the coring location to minimize media disturbance.
3. Collect core samples at depths of 0 to 2 in.; 2 to 6 in.; 6 to 12 in.; 12 to 18 in.; 18 to 24 in.; 24 to 30 in.; and 30 to 36 in. (0 to 5 cm; 5 to 15 cm; 15 to 30 cm; 30 to 46 cm; 46 to 61 cm; 61 to 76 cm; and 76 to 91 cm) (depending on the depth of the media). For beds deeper than 36 in. (91 cm), continue collecting core samples at 6-in. (15-cm) increments until the bottom of the filter is reached. Place each core sample into a separate bag marked to indicate the depth and location within the filter from which it was withdrawn.
4. While pushing the core sampler into the media for each sample, hold it slightly inclined from vertical and rotate the top of the sampler in a circle about 6 in. (15 cm) in diameter to gently push media away from the hole that will be created when the core is withdrawn. This prevents media from the upper part of the bed from falling into the hole and being sampled in a deeper sample.
5. When the core sampling is completed, backwash the filter.
6. After the backwash is finished, drain the filter completely and repeat the core sampling procedure at the locations where it was done before the backwash.
7. From each sample bag, prepare a 50 mL sample by lightly tamping core samples into a 50 mL graduated cylinder. A plastic spoon can be used to transfer the media from the bag into the cylinder. Transfer the 50-mL media sample from the graduated cylinder into a 500-mL wide-mouth Erlenmeyer flask. Add 100 mL of tap water and shake vigorously for 30 seconds. Drain the turbid water, but none of the media, into a 500 mL beaker.
8. Repeat this procedure four more times, until a turbid water volume of 500 mL has been collected in the beaker.
9. Gently swirl the turbid water in the beaker, being careful to avoid aerating the sample. Then measure the turbidity of the sample. Measurement of turbid water can be problematic, so measure the turbidity three times as a check on the quality of the data.
10. Multiply the average turbidity by 2 so the final turbidity tabulated will be on the basis of a 100 mL sample of the original filter media (because the particulate matter causing the turbidity was washed off a volume of 50 mL of media). This step is done so the results can be interpreted using Kawamura's evaluation criteria.

The criteria suggested (Kawamura 2000) for evaluating the cleanliness of a filter after it has been backwashed is

- 30 to 60 ntu indicates a clean filter and a ripened bed.
- 60 to 120 ntu indicates a slightly dirty, less than ideal bed, but not yet a concern.
- over 120 ntu indicates a dirty bed with need for evaluating the filter washing system and the backwash procedure.
- over 300 ntu could indicate a mudball problem.

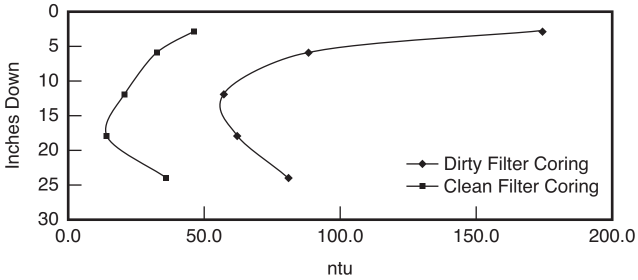
When floc retention data indicate the need for evaluation of filter washing, a review of the existing backwash procedure and modification to increase the scouring action are recommended. One backwash using a more vigorous auxiliary scour is not adequate to cure a problem that developed over weeks or months. After the plant has been operated for a month or two with the modified backwash procedure used at the end of each filter run, another floc retention test can be carried out in the same locations that were tested previously to learn if the media have been cleaned more effectively. If improved backwashing does not result in cleaner media, chemical cleaning may be needed.

When floc retention data indicate a potential mudball problem, the area in the filter where the media samples had the most dirt and floc is a candidate for the use of the filter excavation box. Excavating the media will allow plant staff to determine the extent to which mudballs exist down in the filter media, out of sight. If mudballs are so large and abundant that extended washing and auxiliary scour and special techniques for eliminating mudballs are not capable of restoring the filter bed to its proper mudball-free condition, chemical treatment of the media or excavation and cleaning of the media may be necessary.

Data obtained by the floc retention analysis procedure also can be used in an alternate way. For the core samples collected before the filter was backwashed, the value of the turbidity extracted from each filter core sample can be graphed, with turbidity on the X-axis and depth of the core on the Y-axis. The graph of turbidity extracted versus bed depth (Figure 10-15) will show the depth of penetration of the floc into the bed and will indicate whether or not most of the floc is held near the top of the filter bed. The turbidity data from samples obtained after the filter has been backwashed are again graphed, as previously described. The change in turbidity removed from the media before and after backwash for each core sample indicates the relative amount of floc stored and then removed by backwashing. If most of the turbidity removed by backwashing is coming from the first, or first and second core samples (from the surface to 6 in. below the surface), this indicates most of the floc is being removed at the top of the bed and may be a sign of excessive floc strength and overdosed filter aid.

Clean-Bed Head Loss Trend Analysis

This indirect approach for assessing cleanliness of the filter bed was discussed in chapter 8. It relies on interpretation of the trend of standardized clean-bed head loss data.



Courtesy of Gerald H. Caron, City of Wyoming Utilities Department, Wyoming, Mich.

Figure 10-15 Floc retention test data for filter before and after backwash

The clean-bed head loss data are collected over several months of operations. This approach does not require physical inspection of the filter. If the trend for standardized clean-bed head loss shows an increase over time, this could signal the need for a physical inspection using Kawamura's floc retention analysis procedure to assess media condition.

Acid Solubility

The acid solubility test is described in AWWA B100-01 Standard for Filtering Material (AWWA 2001). Before sampling media to perform this test, the filter is backwashed so clean filter material can be tested to measure the extent to which it has been coated with acid-soluble materials. At lime softening plants, if the filter material is coated, the coating is very likely to contain calcium carbonate. Growth of calcium carbonate on filter media is a symptom of inadequate recarbonation and softened water that is unstable with respect to calcium carbonate saturation. Acid solubility test data provide a long-term indication of how well recarbonation is working. At coagulation plants, acid solubility testing can be used to measure the accumulated particulate material on filter media such as iron precipitates and iron floc, manganese precipitates, and alum floc.

Checking Integrity of Valves

Filter influent and effluent valves and backwash valves can be checked by static testing procedures. To check the valve that shuts off influent water to the filter, the filter is drained to the top of the media, and the water surface elevation is measured. The filter should remain this way for 24 hours to determine whether water leaks into the filter box.

To check the effluent valve to the clearwell (and to filter-to-waste, if present), the filter is filled until the water surface is at the usual high level, and the valves are shut off. The water surface is measured and the filter remains full for 24 hours to determine if the water surface drops in that time.

To check the valve controlling the flow of backwash water into the filter, the filter is drained until the water is at the top of the filter media and the valve to the pipe

Courtesy of Filter Plant Programs Section, Pennsylvania DEP.

Figure 10-16 Small mudballs removed from a filter

going to the clearwell is closed. With the wash-water valve closed, the filter is observed to determine whether the water slowly rises above the media surface while other filters are backwashed. If filter-to-waste facilities are provided at the plant, the filter waste flow should be zero while filtered water is discharged to the clearwell. These checks should be performed when major filter inspection procedures are carried out.

FILTER MAINTENANCE PROCEDURES

Activities such as eliminating mudballs, cleaning filter media and underdrains, and cleaning filter boxes or vessels are considered maintenance procedures that may need to be undertaken from time to time. Typically, these procedures are used if a filter inspection indicates the need.

Eliminating Mudballs

Mudballs can form when filters are not backwashed adequately. Leftover floc, polymer, and dirt can stick to grains of filter material, and as the accumulation grows, mudballs increase in size and are progressively more difficult to wash out of the filter. Small mudballs placed on a food storage bag are shown in Figure 10-16. The prevention of mudball formation is the best approach to mudball control. Overdosing of coagulant or polymer can promote their formation, so careful management of chemical dosing is an effective way to deal with mudballs. If they do form, however, a number of procedures are available for removing them from the filter bed, either by breaking them up or by taking them out of open, gravity filters. These procedures usually are not applied to pressure filters.

Physical removal of mudballs can be accomplished in small filters by using a garden rake to remove those on top of the media when the filter is at rest. This procedure should be effective for removal of mudballs about 1 in. or 2 cm in size, and larger. The garden rake (perhaps equipped with an extended handle) also could be used in small filters during backwash, *if the surface wash sweeps are turned off.* The operator can stand along the filter wall and dip the rake into the media to loosen it at the corners of the filter, where rotary sweeps are not as effective (Figure 10-17). Using a garden rake to provide extra agitation to media can be done occasionally, perhaps once per month, to enhance cleaning during backwash.

If the garden rake method is used to remove mudballs or to agitate filter media, the operator must follow safety precautions to avoid falling into the filter. The design of most filters is such that a lone person who falls into a filter cannot climb back out. At a plant so small that only one operator is on duty, an extra person should be available when this procedure is performed.

A mudball net can be used to physically remove mudballs when the bed is fluidized. Again, surface sweeps must be off when this method is used. As constructed at an Oregon water utility, the mudball net is made with ½ in. (about 1 cm) wire screen or hardware cloth having dimensions of 11 in. × 21 in. (28 cm × 53 cm), mounted on a long pole and resembling a swimming pool skimmer net. The mudball net shown in Figure 10-18 was used in Pennsylvania and appears to be about the same size. A mudball net is used in a manner similar to the way a landing net is used to boat a large fish. When the bed is fluidized, the mudball net is gently swept through the water and media. Mudballs larger than the mesh size are caught and pulled up out of the bed. The mesh size previously described is large enough to permit fluidized media to pass through easily, but small enough to catch mudballs before they grow large enough to cause severe problems.

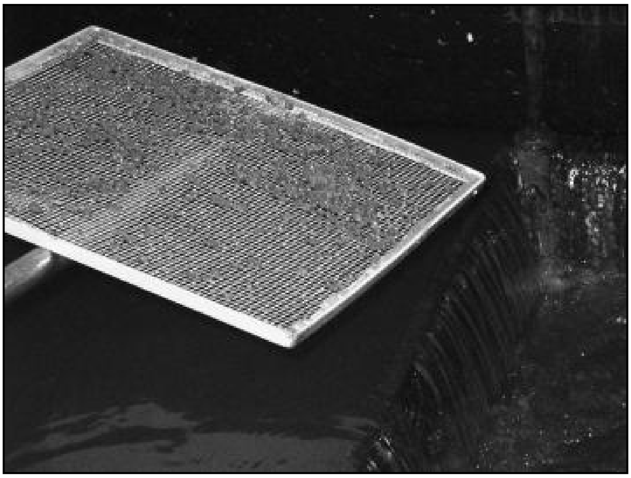
Mudballs can be broken up by high-velocity jets of water, which is the intention of surface wash. Sometimes extra agitation is needed, and this can be provided by using a large hose, such as a 2-in. (5-cm) hose with a 1-in. (2.5 cm) nozzle. Before the hose is used, water level in the filter box is reduced to 1 to 2 in. (2.5 to 5 cm) above the media surface. Then water is sprayed on the media surface to break up mudballs, as depicted in Figure 10-19. At a California water utility where the hose and nozzle used are as previously described, with a water pressure of 80 to 90 psi (550 to 620 kPa), operators take about an hour to hose a 1,000 ft^2 (93 m^2) filter. Depending on the size and location of the access hatch or hatches and the size of the filter vessel, this method might be applicable to a pressure filter.

Chemical Cleaning of Filter Media and Underdrains

When backwashing is not sufficiently effective to prevent accumulation of deposits of floc on filter media, or when calcium carbonate precipitates on filter media, chemical cleaning procedures are employed to restore the media to its proper condition. Filter

Courtesy of Filter Plant Programs Section, Pennsylvania DEP.

Figure 10-17 Mudball rake to remove mudballs from a small filter



Courtesy of Filter Plant Programs Section, Pennsylvania DEP.

Figure 10-18 Mudball net after removal of small mudballs from filter during backwashing

materials are cleaned by using acids, caustic chemicals, and proprietary cleaning chemicals sold for that purpose.

Preparation for Chemical Cleaning

Prior to performing any chemical cleaning, careful planning and analysis must be undertaken. If cleaning is needed, one or more core samples should be obtained so a laboratory

Courtesy of Black & Veatch Corporation.

Figure 10-19 Hosing a filter to break up mudballs

analysis of cleaning can be done on a known volume of media. By determining the quantity of cleaning chemical needed for a measured volume of media, the quantity needed to clean an entire filter can be estimated.

Cleaning chemicals will nearly always, if not always, require special safety precautions. When plant staff perform the cleaning procedure, Material Safety Data Sheets must be obtained, and all safety precautions must be followed. Safe handling of acids and caustic chemicals is mandatory to avoid injury on the job. Protective goggles and clothing are required. Furthermore, if calcium carbonate is removed from filter media by dissolving it with acid, carbon dioxide (CO_2) will form. The quantity of CO_2 that will be produced by cleaning can be estimated if the mass of calcium carbonate is known or estimated closely. If large amounts of calcium carbonate are present in a filter inside a building, extra ventilation might be needed. Chemical cleaning procedures are multi-person tasks, for safety reasons, and must never be done alone.

Another potential safety issue and public relations issue is to ensure that during the chemical cleaning, the chemical cleaning solution in the filter cannot leak past a valve and into the clearwell. Valve integrity should be checked before acids, caustic, or dispersing agents are put into the filter unless this was recently done during a major filter inspection.

When cleaning chemicals are used, they will be most effective if they are mixed thoroughly into the filter bed. This is challenging at plants equipped with surface wash, but it might be accomplished to some degree by adding the chemical to the surface of a drawn-down filter, then applying surface wash and briefly fluidizing the bed to try to attain some mixing. The water level is kept below the top of the wash-water trough during this time.

Another approach is to inject chemical into the backwash water so the chemical solution is forced up through the filter bed. In a filter equipped with air scour, the chemical is added to a filter with the water surface just above the media, and then the air scour is turned on. The agitation caused by the rising air bubbles will help disperse the chemical. Dispersal can be more thorough if a short application of wash water is applied so the media mixes within the bed as air is added. Again, water should not be discharged over the wash-water troughs until cleaning is completed.

Disposal of residuals after chemical cleaning is another aspect of the overall project that must be planned in advance. The spent cleaning chemical solution and materials removed from the media must be washed out of the filter. Backwash continues until the bed is thoroughly clean and the pH of spent wash water is the same as the pH of wash water applied to the filter. When filters are chemically cleaned, the backwash water must not be returned to the head of the plant. Disposal to the sewer in many cases is the preferred approach. When acid cleaning is done on media coated with calcium carbonate, the acid is neutralized; therefore, disposal is not as challenging unless excess acid was used. If an alkaline chemical is used to soak filter media, neutralization of the spent chemical solution might be needed before discharge to a sewer is allowed. These matters must be resolved in advance to prevent the filtration plant from having a filter full of some chemical solution with no method of disposal provided.

Cleaning Media at Lime Softening Plants

Plants using lime softening are more likely to encounter situations requiring chemical cleaning than coagulation plants, as precipitated calcium carbonate can be tightly bound to media. The need for chemical cleaning can be identified by observing the long-term trend of head loss data, by implementing the floc retention test, by measuring the effective size of filter media, and by administering the acid solubility test. The first two approaches have been discussed previously.

Lime softening plant staff can assess the need for cleaning by means of size analysis. Typically, when filter media are purchased, the size may vary within a ±10 percent range. If anthracite media is purchased with a specified effective size of 1.0 mm, the range that is provided is 0.9 to 1.1 mm. If sieve data on the purchased media or a more recent analysis are absent, a 20 percent increase in effective size compared to the 1.0 mm specified size signals an increase in media size caused by calcium carbonate precipitation. This indicates the need to perform an acid cleaning on the media.

The significance of the presence of a coating of calcium carbonate on anthracite filter material (commonly used in filters at the present time) is better understood by considering the effect of an increase in media size caused by a coating of calcium carbonate. The density of anthracite commonly used in the United States is 1.7 g/cm^3, whereas the density of calcite (calcium carbonate) is 2.71 g/cm^3. Although crushed anthracite is never spherical in shape, spherical filter grains are used for calculation. If a 1.0 mm sphere of anthracite with an original density of 1.7 g/cm^3 is coated with a layer of calcium carbonate

0.1 mm thick, the new diameter would be 1.2 mm. The overall density of the 1.2 mm sphere would increase to slightly over 2.1 g/cm^3. This calcium-carbonate-coated filter material would have a substantially greater tendency to intermix with sand in a dual-media filter.

For most utilities, an acid solubility test provides less expensive and more precise results than a sieve analysis procedure for assessing the need to clean media at a lime softening plant. The acid solubility test can be performed at many water treatment plant laboratories. AWWA B100-01 specifies that the acid solubility for filter materials should not exceed 5 percent. A substantial increase in this value indicates the presence of a layer of calcium carbonate over the anthracite or sand. In the previous hypothetical example with a 20 percent increase in the diameter of an anthracite sphere caused by a calcium carbonate coating, 54 percent of the mass of the coated particle is calcium carbonate; therefore, the acid solubility would be 54 percent. The acid solubility analysis also is sensitive for evaluating the extent to which filter sand is coated with calcium carbonate.

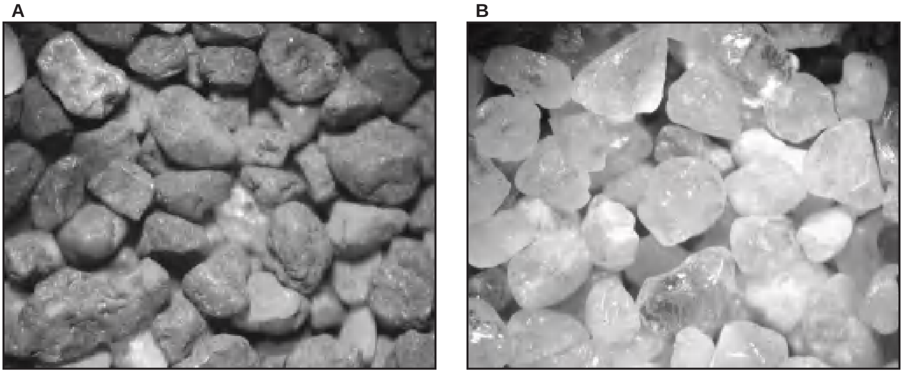
Acids that have been used to clean filters include 3 percent food-grade phosphoric acid and NW-310 dispersant cleaner, food-grade glacial acetic acid, muriatic (hydrochloric) acid, and citric acid. These vary in cost, but the higher cost for food-grade chemicals is weighed against the higher potential for public relations problems that might be associated with the use of hydrochloric acid when deciding which chemical to use.

In some instances, filter material in a lime softening plant is not merely coated with calcium carbonate, but also the precipitation has been so problematic that filter material is incorporated into a limestone conglomerate "rock" in the filter bed. This material can be so hard that an air hammer is required for physical removal. In this situation, the choices are to use an air hammer and "mine" the conglomerate material for removal from the bed or to use acid and dissolve it. Neither approach is easy, as one involves dust and high noise levels, while the other requires use of acid. Both have been used at plants where media became incorporated into precipitated calcium carbonate that was like limestone conglomerate. When the air hammer method is used to dislodge solidified materials, care must be used to avoid penetrating the underdrain tiles or otherwise damaging the underdrain, if the tool is used near the filter floor.

Cleaning Media at Coagulation Plants and Iron and Manganese Removal Plants

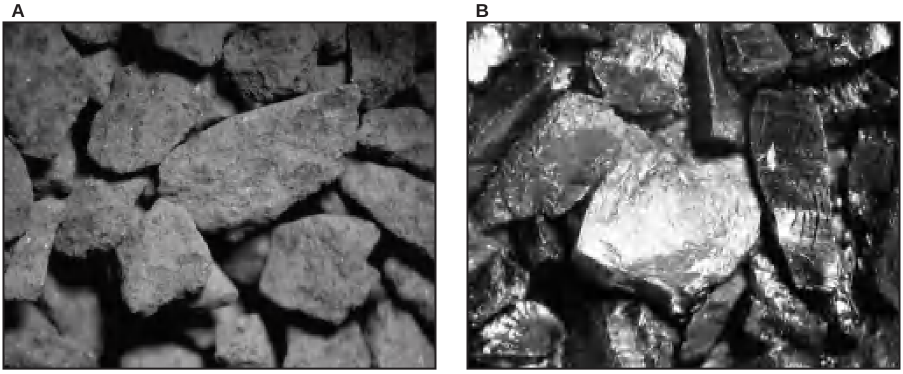
The use of chemical cleaning agents at plants that practice chemical coagulation or removal of iron and manganese offers a number of benefits. Clean media have lower clean-bed head loss than media coated with inorganic or organic films. Filter run times may be increased, and effectiveness of backwash may be improved. Also, chemical cleaning can help to disintegrate mudballs and facilitate their removal from the filter bed by backwashing.

Several chemical cleaning methods are used at plants that employ coagulation and filtration, and at those that remove iron or manganese. Precipitated iron is dissolved at low pH; however, care must be exercised so the acid does not damage concrete filter boxes. For alum floc and for accumulations of organic matter on filter media, an alkaline soak is used for cleaning. During a New England filter investigation project in which the author participated, anthracite filter material was coated with substances that made it so sticky that it could be formed into a ball. When the coated anthracite was placed in a laboratory beaker and an alkaline solution was added, the liquid became dark brown, resembling the color of strong coffee. After extended backwashing and agitation with garden rakes failed to clean the media sufficiently, an alkaline soak was used with success. Sodium hydroxide (caustic soda) can be used at a dosage of 1 to 3 lb/ft^2 (5 to 15 kg/m^2). Proprietary chemicals that are certified under the NSF International's Standard 60 program for direct additives to drinking water also are available. Figures 10-20a (before cleaning) and 10-20b (afterward) illustrate the extent to which filter sand is cleaned by chemicals. Figures 10-21a and 10-21b show the effect of chemical cleaning on anthracite filter media.



Courtesy of Floran Technologies, Inc.

Figure 10-20 Filter sand before chemical cleaning (A) and after cleaning (B)



Courtesy of Floran Technologies, Inc.

Figure 10-21 Anthracite filter material before chemical cleaning (A) and after cleaning (B)

When chemicals are used to clean filter media, testing the chemical on a measured sample of media can provide data needed to estimate the approximate dosage of chemical and thus the quantity of chemical that is necessary. At one utility where this was performed, testing showed that a caustic soda solution of 50 mg/L was sufficient to dissolve materials adhering to filter media. Caustic soda at a concentration of 50 mg/L was used in the filtration plant, with the filter left to soak overnight, followed by extensive backwashing the next day to thoroughly clean the media.

Another aspect of chemical cleaning that has to be considered in the planning stage is the removal of manganese by filter media. If the plant's source water contains manganese, chlorination just ahead of the filter will carry a free chlorine residual onto the filters resulting in manganese removal in the long-term. Soluble manganese (Mn^{+2}) sorbs onto filter media coated with manganese dioxide, and long-term exposure to free chlorine oxidizes the Mn^{+2} to manganese dioxide so sorption of soluble manganese can continue. It is not advisable to remove all of the manganese dioxide coating at a plant where manganese removal has occurred, because manganese will pass through the filters until the media once more is coated with manganese dioxide. After chemical cleaning is performed at such a plant, soaking the clean filter media in a potassium permanganate solution will quickly re-establish a manganese coating so removal of manganese will be effective and customer dissatisfaction will be minimized. A procedure for performing a potassium permanganate soak was presented by Knocke et al. (1990) and is provided in the sidebar.

Keeping Filter Vessels Clean

At some filtration plants, accumulations of scum form on filter walls from time to time. At one plant on Lake Michigan, operators fastened pulsating sprinkler heads to the top of surface wash pipes. When surface wash was operating, the sprinklers sprayed the filter box walls to keep them clean. Once the sprinklers were positioned to spray water at the intended location. the procedure was automatic and needed no operator attention.

In regions having a warm climate, filters are often open to the atmosphere rather than located within buildings. This saves money on construction, but open filters in a warm, sunny location can become sites for algae growth. Algal growths have the potential to cause T&O problems, and if mats of algae break off the walls, fall onto the filter bed, and sink into the media when the filter is backwashed, they can promote mudball formation.

Removing algae from filter walls is challenging. High-pressure washing can be used and is less labor-intensive than manual scraping. If the algae and other debris removed from the filter walls are not broken up sufficiently to be removed by backwashing, however, the potential for creation of mudball problems exists. Regardless of the method used to clean the walls, backwashing the filter thoroughly afterward is necessary.

Procedures for Conditioning Filters for Manganese Removal

This method for conditioning filter media is from Knocke, William R., Susan Occiano, and Robert Hungate, 1990, *Removal of Soluble Manganese From Water by Oxide-Coated Media*, Awwa Research Foundation, Denver, Colo. They included as Appendix A of their report, a procedure prepared by Mr. Thomas Bailey, Department of Water Resources, Durham, N.C.

"Manganese is removed by adsorption and oxidation on the filters in most water plants removing manganese. The oxidized manganese coating on the filter media has an affinity for soluble manganese. The soluble manganese is adsorbed on the media and oxidized by chlorine or some other oxidant. A coating of oxidized manganese on the filter media is essential for the process to work.

"If the manganese in the unfiltered water is less than 0.05 mg/L, the process may be initiated by only adding chlorine. The low level of manganese allows the process to slowly begin without nuisance effects of manganese in the filter effluent. However, if the manganese is greater than 0.05 mg/L, the filter must be preconditioned to remove manganese.

"The following procedure may be used to condition the filter:

1. Thoroughly backwash the filter.
2. With the filter full of water, dose the filter with 100 mg/L potassium permanganate. If the filter is new, 'disinfection' may be done simultaneously by adding 100 mg/L chlorine (HTH). The chemicals may be applied by broadcasting the potassium permanganate and HTH into the water on the filter. Always use a dust mask, rubber gloves, and rain gear when broadcasting the potassium permanganate or HTH. If the pH of the filter water is less than 6, 10 mg/L of sodium hydroxide may also be added to the filter.
3. Draw the chemical into the filter by operating in a filter-to-waste mode until 6 in. of water remains above the media.
4. Let the filter stand for 24 hours.
5. After 24 hours, initiate filter operations in a filter-to-waste mode to remove any excess potassium permanganate and HTH. Appropriate environmental precautions should be exercised regarding the disposal of this waste water.
6. Thoroughly backwash the filter.
7. Begin filtering the settled water in a filter-to-waste mode. Be sure that the filter influent has a pH greater than 5.5 and a free chlorine residual greater than 1.0 mg/L.

Procedures for Conditioning Filters for Manganese Removal (continued)

8. After one hour of filter-to-waste operations, collect a bacteriological sample. If the sample is positive for coliform count, repeat steps 2–7.
9. Test for manganese in the filter effluent. If manganese is less than 0.05 mg/L, and coliform concentrations are acceptable, place the filter online.

"This procedure will enable manganese to be removed in 48 hours. The process will not need to be repeated as long as the filter is kept in an oxidized state and the pH of the filter-applied water is above 5.5. To keep the filter in an oxidized state, avoid prolonged shut-down and maintain a free chlorine residual at all times during filter operations. After shut-down, always backwash the filter before putting online.

"During backwash, oxidized manganese is scrubbed from the media. Therefore, to prevent this manganese from entering the distribution system, operate in a filter-to-waste mode for a minimum of 30 minutes after backwashing the filter."

Author's Note: In absence of filter-to-waste capability, backwash the filter with a subfluidized rise rate for the equivalent of three filter box volumes (from the bottom of the underdrain to the top of the wash-water troughs) or until permanganate is not detected in the spent wash water in Step 5. When filter-to-waste is not available, be sure to backwash with chlorinated water in Step 6 before placing the filter into service, and after one hour of filter operation with chlorinated filter influent water, collect a bacteriological sample as directed in Step 8. If the sample is positive for coliform, remove the filter from service and disinfect it again using 100 mg/L HTH as described in Step 2.

Proprietary chemicals certified under the NSF International Standard 60 are available for cleaning basin walls, filter box walls, wash-water troughs, and other surfaces exposed to water and coated with deposits of biological matter or inorganic substances.

Special Techniques for Pressure Filters

As compared to gravity filters, pressure filters are difficult to inspect. Observation of backwashing is strongly recommended for gravity filters, but this may be impossible for many pressure filters. Therefore, it is unlikely that checking for even distribution of wash water, for filter boils, or for dead zones within the filter will be done for pressure filters. The difficulty or impossibility of performing simple observation tasks for pressure filters places the burden of detecting problems at an early stage on physical inspection procedures. These involve entering the pressure vessel and examining the media surface profile of a drained filter, probing to detect the transition from filter material to support materials, and taking core samples for evaluation of media size and especially for chemical analysis, such as acid solubility.

Logsdon et al. 2002 recommends performing a short inspection inside a pressure filter on a quarterly basis, or perhaps more frequently. Observation of the media surface to determine whether it is level and to check for mudballs can provide some helpful information for operators. Obtaining core samples once per year and performing a floc retention analysis both before and after backwash is a means of checking on the adequacy of backwash. It is also advisable to test for acid solubility.

The failure to inspect pressure filters periodically and determine the condition of filter media can have expensive consequences. At one midwestern iron removal plant treating hard water from a confined aquifer, aeration was used to oxidize the iron. Aeration also decreased the concentration of CO_2 in the water, very slightly raising the pH. The increase in pH was sufficient to cause very slight and gradual precipitation of calcium carbonate. Routine chemical testing did not reveal a potential problem, but eventually the original pressure filters were not as effective as newer filters. When the older filters were inspected, they were found to have a conglomerate of anthracite filter material and precipitated calcium carbonate (in effect, a limestone conglomerate). An earlier inspection with core sampling might have revealed the precipitation problem before it had progressed so far and the remedy had become so expensive. Although inspecting pressure filters may be more difficult than inspecting gravity filters, periodic evaluation of the condition of pressure filters is no less important than such evaluations for gravity filters.

SUMMARY

Water utility personnel and other trained specialists can use a wide variety of procedures to inspect, evaluate, and maintain filters. Although some small utilities may need outside assistance for inspection and maintenance programs, many utilities should be able to perform needed activities with existing staff, perhaps supplemented by staff working as consultants and contractors. Because of the large expense associated with construction of filters, a good program of inspection and preventive maintenance has the potential to offer large cost savings as compared to the cost of replacing filter media, or the cost of replacing ruined filter bottoms and underdrain facilities.

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11

Slow Sand Filtration

INTRODUCTION

Slow sand filters were used successfully to treat municipal water supplies on a sustained basis beginning in 1829 at the Chelsea Water Works Company in London, according to M.N. Baker (Baker 1981). James Simpson had studied water filtration facilities used mainly to provide water for industries rather than for municipalities, and he concluded that filtering water through a bed of sand prepared so that filtered water could readily drain out of the bottom would be successful. Simpson first evaluated slow sand filtration on an experimental basis before the Chelsea filters were built. In modern day, it would be said that he used a *demonstration filter*, as Baker reported that Simpson's filter had an area of 1,000 ft^2 (about 93 m^2) at the surface. According to Baker, the filter produced about 3.9 mgd/acre, which is the equivalent of an approach velocity of 0.15 m/hr. Simpson's filter was cleaned by scraping off a thin layer of sand when terminal head loss was reached.

In concept, Simpson's filter had numerous similarities to slow sand filters that are used at the present time, and operation was similar. When a slow sand filter is used by itself with no pretreatment, source water is applied to the filter and very slowly passes through a bed of fine sand. After weeks or even months of operation, when head loss builds up to a terminal value, a typical cleaning operation consists of draining the supernatant water and the filter sufficiently so operators can remove a thin layer (up to 1 in. or 1 to 2 cm) of sand from the top of the bed. Generally, this cleaning restores the head loss to a value close to the original clean-bed head loss, and another run is begun.

Slow sand filtration technology was introduced to the United States by James P. Kirkwood, who immigrated to the United States from Scotland. During the latter part of his engineering career, he traveled to the United Kingdom and Europe to study and observe slow sand filters and infiltration galleries. Kirkwood's book on filtration of municipal water supplies was published in 1869 and was the authoritative source on water filtration for about 30 years, until Allen Hazen published his first edition on this topic.

The first municipal slow sand filter used in the United States was placed into operation at Poughkeepsie, N.Y. in 1872. Other installations followed in New York and New England. Typically, these were used to treat low-turbidity waters and were successful.

Farther to the west, when slow sand filters were built at places such as Indianapolis, Ind., they proved unable to cope with the fine clay in runoff from farmlands. After the successful application of conventional filtration plants at locations such as Cincinnati, Ohio and Louisville, Ky. in the early 1900s, interest in slow sand filtration waned and most municipal filters built after this time employed coagulation and rapid rate filtration.

The renewed interest in slow sand filtration in the United States was a result of the need for an uncomplicated filtration process that could be used by small systems in rural areas where supposedly pristine water had been treated only by chlorination, resulting in waterborne disease outbreaks of giardiasis in the late 1960s, 1970s, and early 1980s. Research undertaken or sponsored by the USEPA in the 1980s showed that *Giardia* cysts could be removed effectively by properly designed and managed slow sand filters. Since then, the capability of slow sand filtration for removal of *Cryptosporidium* oocysts has been demonstrated, and the process has been adapted to a wider range of source water quality by coupling it with various processes for pretreatment or posttreatment.

HOW SLOW SAND FILTERS WORK

Slow sand filters rely on biological action for much of their removal capability, but filtration by particle straining and perhaps particle attachment also plays a role. Particle

Slow Sand Filter Design Basics

Slow sand filters are the least complex type of granular media filter. Figure 11-1 is a schematic diagram of a slow sand filter plant. These filters consist of a basin with underdrain piping and support gravel to support a bed of relatively fine sand. The basin can be a concrete filter box or an earthen embankment. In modern designs, the embankment and basin bottom may have an impervious liner to prevent water loss through the bottom of the basin and erosion of the basin slopes. During normal operating procedure, influent water is introduced above the filter bed in a way that does not disturb the sand, but for the initial filling and after the bed has been dewatered, water must be introduced from beneath the filter to drive air out of the bed as it is filled. At the bottom of the filter box or basin, collector piping is surrounded by support gravel about 1.3 ft to 2 ft (0.4 m to 0.6 m) deep. Above the gravel layer is the filter sand, typically having an effective size of about 0.15 mm to 0.30 mm, with the UC less than 5 and preferably less than 3. The depth of the sand bed is about 2.7 ft to 4 ft (0.8 m to 1.2 m) when the bed has been constructed, and the water depth over the sand at that time is about 3 ft (1 m). Generally, no pretreatment is applied to the influent water, and the filtration rate may range from 0.04 to 0.12 gpm/ft^2 (0.1 to 0.3 m/hr). The very low filtration rates require filter bed areas 20 to 40 times larger than filter areas for rapid rate filtration for production of the same quantity of water per day. For many small installations in rural removal mechanisms and other aspects of the slow sand filtration process are discussed in the following section.

Biological Activity Necessary for Effective Filtration

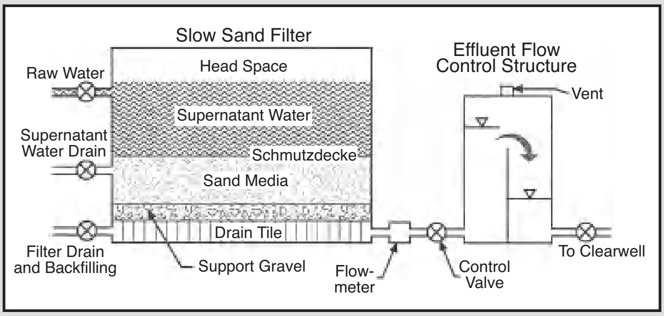
Biological action is the key to removal of microbes and influences turbidity removal. This is one very important difference between the operation of rapid rate filters and slow sand filters. The operation of slow sand filters has to be consistent with the objective of maintaining an active biological population within the sand bed.

The Organisms in a Slow Sand Filter

In a biologically active slow sand filter, the kinds of organisms found change as water flows deeper into the sand bed. At the surface of the filter bed, a layer of decaying biological matter and bacteria called the *schmutzdecke* develops. This is a German word for *dirty skin*. Some straining occurs in the schmutzdecke. Algal mats of filter-clogging species may form at the schmutzdecke, and some algal cells may penetrate into the top 1 in. (about 3 cm) of the sand in large numbers. The ecology of slow sand filters was studied in facilities owned by Thames Water Utilities (Duncan 1988) and was reviewed in detail by Haarhoff and Cleasby (1991). Bacteria are most numerous within the top 2 in. (5 cm),

Slow Sand Filter Design Basics (continued)

areas, however, the much larger filter area needed for slow sand filter beds does not present a siting problem because of the availability of land. Good design practice provides multiple filter beds that are sized so that when one filter is removed from service for cleaning by removal of a thin layer of sand or for replacing sand to restore the initial bed depth, the other filter or filters can produce sufficient water to meet the needs of the community.



Source: Fox et al. 1994.

Figure 11-1 Effluent-controlled slow sand filter

decreasing at lower depths. In a biologically mature filter, protozoa can be found from near the surface to depths of 2 to 4 in. (5 to 10 cm). They feed on bacteria and also on algae cells. Among the largest organisms that are found in a slow sand filter bed are round worms, flatworms, and segmented worms, which can be as large as a few millimeters in size. Some of the worms feed on detritus, i.e., fragments of organic matter, and tend to be deeper in the bed than bacteria and protozoa.

Knowing the details of the ecology of a slow sand filter is not necessary for its successful operation, but understanding that the sand bed is inhabited by living organisms is very important. Bacteria, protozoa, and worms need both food and oxygen to metabolize the food they ingest, and a steady input of food and oxygen to the filter bed stabilizes the population of organisms within the bed. Long-term interruptions of flow can lead to depletion of oxygen in the filter bed and to die-off of organisms that are the key to effective slow sand filtration. Drying a slow sand filter bed has even more serious consequences and could lead to elimination of most or all of the biota in the bed. Therefore, the flow of influent water should be continuous, and filter bed maintenance activities should be performed in a prompt manner to minimize down time and harmful effects to the biota.

Removal of Microorganisms

Microorganism removal is the strength of slow sand filtration. This process was effective in removing pathogens and reducing the incidence of waterborne disease in London and other cities in the 1800s before scientists understood that microbes could cause communicable diseases, such as cholera and typhoid fever. Removal of bacteria was studied by Allen Hazen in the 1890s at Lawrence, Mass., and by others after slow sand filter studies were renewed in the 1980s. Bacteria removal can be as great as 3-$\log_{10}$ to 4-$\log_{10}$ (Bellamy et al. 1985a, 1985b; Fox et al. 1984; Cleasby et al. 1984). Following the discovery of waterborne viral illnesses, researchers at the Metropolitan Water Board in London (now Thames Water Utilities) evaluated virus removal and again reported values as high as 3-$\log_{10}$ to 4-$\log_{10}$ (Poynter and Slade 1977). Research sponsored by the USEPA in the 1980s demonstrated that *Giardia* cyst removal could also be in the range of 3-$\log_{10}$ to 4-$\log_{10}$ (Bellamy et al. 1985a, 1985b; Pyper 1985). Similar removals have been attained for *Cryptosporidium* oocysts in studies done in the 1990s (EES and Thames Water Utilities 1996). Mature slow sand filters evaluated at the University of Waterloo (Anderson and Huck 2005) also performed in this range, and sometimes better for removal of *Giardia* and *Cryptosporidium*. These results have been attained with filters having a developed, or mature, biota.

Removal of microorganisms can decline when water is very cold and the metabolism rate of the biota facilitating microbial removal slows greatly. *Giardia* cyst removal by a small slow sand filter not being used to provide water to a public water system was in the range of 3-$\log_{10}$ to 4-$\log_{10}$ when water was 45° to 70°F (7.5° to 21°C). When water was 33°F (<1°C), cyst removal generally was in the 2-$\log_{10}$ to 3-$\log_{10}$ range (Pyper

1985). The decline in efficiency for removal of microbiological contaminants can be offset somewhat if water demand during times of cold water is substantially lower than the peak demand for which a slow sand filter is designed, as the lower filtration rate can help to offset the cold temperature effect.

Removal of Inorganic Particles

Removal of organic particles in a slow sand filter is explained in part by predatory action of the larger organisms as they use smaller ones for food. Removal of inorganic particles such as clays can occur, but removal is variable, as indicated by data on turbidity removal by slow sand filters. Clearly, clay particles are not an organic food source, so some other explanation is required for the removal of turbidity-causing particles.

Experiments at CSU, in which Horsetooth Reservoir water originating high in the Rocky Mountains was used during testing, showed that turbidity removal and total coliform removal were lower in a slow sand filter that had been chlorinated between filter runs to minimize biological activity, as compared to a control filter operated in the normal manner. On the other hand, a slow sand filter treating water with supplemental sterile nutrients for promotion of biological growth removed both turbidity-causing particles and total coliform bacteria more effectively than the control filter. This work (Bellamy et al. 1985a) indicated that biological action played an important role in turbidity removal.

An explanation for removal of inorganic particles by slow sand filtration was found in literature on the activated sludge wastewater treatment process and discussed by Bellamy et al. (1985a). Researchers studying activated sludge found that some kinds of bacteria can release exocellular polymers that can flocculate not only bacteria in the activated sludge liquor but also clay particles. If higher levels of bacterial growth result in release of higher concentrations of exocellular polymers that make the surfaces of sand grains more "sticky," this could enhance clay particle removal by attachment to the sand. This concept has not been verified experimentally, but the results from CSU do reinforce the importance of maintaining a healthy and active biological population in the filter bed and strongly suggest a role for exocellular polymers in slow sand filters.

Biological Filtration for Removal of Dissolved Organic Matter

Some removal of dissolved organic matter can be attained in slow sand filters. The extent to which this occurs depends on the biodegradability of the dissolved organics. Although readily degradable organic matter could be effectively removed by the biota in a slow sand filter, biota also exist in natural waters and utilize organic matter there. An example of this is the biodegradation of sewage. In the era when sewage was discharged to rivers after receiving only primary treatment (sedimentation), the oxygen demand resulting from biological degradation of the sewage, which could occur in a matter of days, sometimes was sufficient to deplete the oxygen in the receiving water downstream from the sewage outfall. Readily degraded dissolved organic matter is most likely used as a food source before source water is extracted for treatment by slow sand filtration. Organic matter that is not readily degraded in natural waters and is thus persistent, such as color, is not likely easily utilized as a food source by the biota in a slow sand filter. Water sources with potential to have high concentrations of color include marshes, swamps, and lakes with large quantities of vegetation.

Changing the nature of dissolved organic constituents can increase their biodegradability. This is most readily accomplished by use of ozone for pretreatment ahead of a slow sand filter. Preozonation has been shown to increase the biodegradability of dissolved organics in biologically active rapid rate filters, and it does the same for slow sand filters. The extra microbiological growth resulting from increased availability of food can result in formation of biofilms on slow sand filter media to the extent that head loss may increase at a faster rate than if ozone were not used. Adapting ozone to an existing slow sand filter might decrease filter run times, whereas for a new filter with

Design of Rate Control and Relationship of Rate Control for Slow Sand Filters and Available Finished Water Storage

Rate Control

Slow sand filters can be designed to operate with influent rate control or with effluent rate control. Effluent rate control was illustrated in Figure 11-1, while Figure 11-2 shows influent rate control. Influent rate control can be applied very simply using an influent valve to adjust the rate of flow into an influent water channel and a weir at each filter in plants with multiple filters, with each weir having the same design and elevation for equal flow splitting. It should be noted that a splash plate is provided to prevent erosion of the sand as it falls from the weir into the sand filter. For filter effluent rate control, rate changes must be made gradually and as seldom as possible. A practice to avoid in this mode of rate control is to maintain the desired supernatant water level in the filter by frequently opening and closing the effluent valve. Frequent on–off operation is not acceptable, and shut-downs of filter flow are to be avoided except for filter maintenance.

When filtered water storage is sufficient, adjustment of filtration rate can be made as infrequently as once per day, which is appropriate for small systems that are operated by part-time personnel who have only an hour or two each day to devote to water treatment operations. Sizing finished water storage so it is sufficient to account for hourly fluctuations in demand throughout the day enables the filter to operate throughout the day at a production rate similar to the total water demand for that day.

preozonation, designers can consider using a slightly larger media size to compensate for the possibility of added head loss caused by more biofilm formation.

INFLUENCE OF FILTER DESIGN AND OPERATION PARAMETERS ON FILTER PERFORMANCE

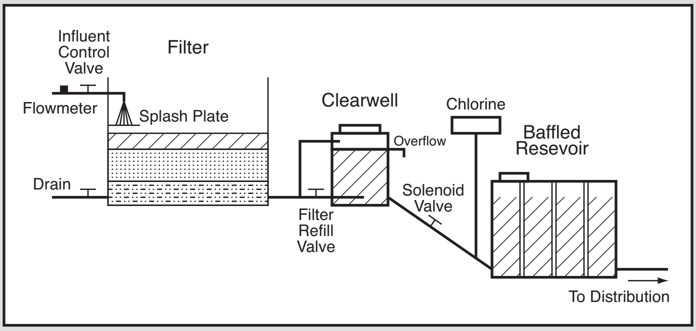
Factors that influence the performance of slow sand filters include aspects of the filter design, manner of operation, and environmental factors, such as water temperature, water quality, and sunlight.

Media Size and Bed Depth

The size of sand in the filter bed, and the bed depth both affect filter performance. As with rapid rate filtration, smaller sand size gives better particle removal; however, it causes higher clean-bed head loss and possibly a greater rate of head loss increase during filter operation. Before 1900, Allen Hazen performed filtration tests at the Lawrence

Design of Rate Control and Relationship of Rate Control for Slow Sand Filters and Available Finished Water Storage (continued)

When slow sand filtration was first used in the United States, intermittent operation of slow sand filters was tried, but this procedure was abandoned in favor of continuous operation. As no coagulant chemicals are used in slow sand filters during typical operation, forces that hold attached particles to sand grains are expected to be weak, and rapid rate changes or frequent rate changes have the potential to be very disruptive to filtered water quality and thus should be avoided.



Courtesy of Stephen Tanner, Idaho DEP.

Figure 11-2 Slow sand filter with influent rate control

Experiment Station in Massachusetts and showed that removal of bacteria was more effective when sand size was smaller. Bellamy et al. (1985a) also studied the effect of sand size and reported that total coliform removal was 96 percent for a filter having an effective size of 0.6 mm and 99.4 percent when the effective size was 0.1 mm. A typical sand effective size recommended for use in slow sand filters is 0.15 to 0.30 mm, with a UC < 5 and preferably < 3. Slow sand filters are not backwashed and restratified, so a low UC value is not necessary, in contrast to media used for rapid rate filtration.

Bed depth influences slow sand filter performance only if the sand bed has become too shallow as a result of multiple scraping activities performed to restore clean-bed head loss. A new filter bed may have a depth of 2.7 to 4 ft (0.8 to 1.2 m), and after the bed depth has decreased to 1.6 to 2 ft (0.5 to 0.6 m), the depth needs to be restored to the original value in a process called *resanding*, which is described in a later section of this chapter. This minimum depth provides a margin of safety with regard to removal of bacteria by a slow sand filter.

Filtration Rate

The filtration rate at which a slow sand filter operates influences removal of microorganisms and also may influence turbidity removal. In research performed at CSU (Bellamy et al. 1985b), average total coliform removal was 99.67 percent for a filter operated at 0.12 m/hr versus 98.98 percent for a filter operated at 0.40 m/hr, based on 243 analyses. Turbidity removal declined from 32.14 percent to 27.24 percent for rates of 0.12 m/hr versus 0.40 m/hr, respectively, for 891 analyses. Several decades earlier, Allen Hazen also reported declining rates of removal for bacteria when higher filtration rates were used.

Water Temperature

Filter efficacy is influenced by water temperature as a consequence of the importance of biological action for removal of microbes and particles causing turbidity. Temperature influences the metabolic rate of the biota in a slow sand filter and in the schmutzdecke, so biological activity is more intense in warm water, and impeded or slowed by cold water. As a result of the temperature effect, removal of microbiological contaminants is reduced somewhat in water when the temperature is near freezing. Operating at a slower filtration rate can help to counteract this decrease in filtration efficiency. In many communities, water demand peaks in warm weather when lawns and gardens are watered. An exception to this could be a community that has a heavy influx of tourists for winter sports, such as skiing and snowmobiling. By being aware of the potential for lowered filtration efficiency when water is very cold, operators will understand the special importance of careful filter operation at such times.

SOURCE WATER QUALITY FOR SLOW SAND FILTERS

Slow Sand Filters Used Alone

When slow sand filters are used without pretreatment or posttreatment other than disinfection and corrosion control, source water quality must be very good, based on how

Covered Slow Sand Filters

Slow sand filters designed for operation in cold regions generally are covered because scraping sand at an ice-covered slow sand filter cannot be done until the ice layer is removed from the water. Providing structures to cover filter beds requires additional capital investment, so some exceptions have been made to this general concept of covering the filters when extended freezing conditions are expected. An open slow sand filter that formerly was used in Colorado treated source water of such high quality that filter runs during winter were long enough to continue from the last scraping in fall until after the ice on the filter melted in spring. Of course, the supernatant water had to be deep enough so that ice could not form all of the way down to the sand bed. A second reason for covering slow sand filters to prevent freezing is the possible damage that may be caused if a thick layer of ice forms on the supernatant water and pushes against the filter walls. Figures 11-3 and 11-4 show the same slow sand filter facility with one photo taken in summer and another in winter from a different perspective. At this facility, the top of the covered filter boxes is slightly above ground level, and a small access building is provided to cover the access hatch to the filters. Note that if filters are covered, it is very important that sufficient headroom for maintenance workers be provided between the surface of the sand bed and the bottom of the roof structure covering the filter boxes.

Courtesy of Gordon Pyper, USEPA Cooperative Agreement.

Figure 11-3 Covered slow sand filter in Vermont during warm weather

Courtesy of Gordon Pyper, USEPA Cooperative Agreement.

Figure 11-4 Covered slow sand filter in Vermont during winter with snow cover, illustrating reason for covering filter in region with cold winters

these filters work. Cleasby (1991) has recommended the following guidelines for source water ideal for slow sand filters:

- Turbidity < 5 ntu
- Algae—no heavy seasonal blooms occur, and chlorophyll-*a* < 5 µg/L
- Iron < 0.3 mg/L
- Manganese < 0.05 mg/L

His recommendations did not cover synthetic organic contaminants or inorganics such as arsenic. Even though the capability of slow sand filtration is excellent for removal of microbiological contaminants, it is most suited for application without treatment other than disinfection when source waters are considered "pristine." It should be understood, however, that waters that were considered to be pristine in the 1970s and 1980s sometimes were contaminated with pathogens such as *Giardia*, so clarity does not equate with purity.

Attempts to treat turbid, clay-bearing waters on a long-term basis by slow sand filtration unaided by pretreatment have failed for more than a century. If the suitability of source water cannot be demonstrated by prior slow sand filter experience or by pilot-plant studies, pretreatment may be necessary.

Modifications to Slow Sand Filtration for Enhanced Performance

When source water quality is beyond the range recommended for slow sand filters used alone, pretreatment can extend the capability of this process so a wider variety of source waters can be treated. Higher turbidity, color, NOM, and synthetic organic chemicals can be removed when pretreatment or posttreatment processes are added.

For some source waters, roughing filters (preliminary filters with coarse media) and infiltration galleries or infiltration wells in or near streams or rivers can remove sufficient turbidity that the remainder can be dealt with in a slow sand filter. Although chemical pretreatment is usually not used, an emergency pretreatment practice using chemical coagulation followed by flocculation and sedimentation in channels and basins at Salem's slow sand filter facility on Geren Island was performed during and following a major flood in Oregon in early 1996. This ad-hoc pretreatment attained turbidity reductions between 80 percent to 90 percent and enabled the filters to continue operating without plugging over a period of several weeks of abnormally high turbidity (Krueger et al. 1999).

Slow sand filtration is a biological process, and organic constituents that are biodegradable can be removed in this process. Persistent organics, or those that are not readily biodegraded, can be broken down by ozone and changed to biodegradable substances. Just as preozone can enhance biologically active rapid rate filtration, it can also enhance slow sand filtration by increasing the amount of organic matter that can be used as food by the biota in the filter bed. In slow sand filtration studies performed in the UK, reduction of true color by slow sand filtration alone was about 20 percent, whereas reduction by preozonation and slow sand filtration was almost 75 percent (Greaves et al. 1988). In addition, preozonation increased removal of TOC from 8 percent to 15 percent for slow sand filtration alone to 25 percent to 35 percent, indicating that ozone was breaking apart organic molecules that were not readily biodegradable and creating substances that were more easily used as food by organisms living in the filter bed.

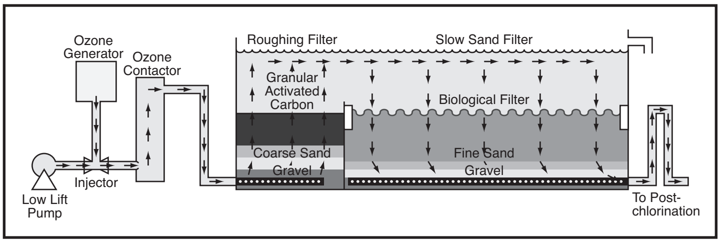
To enable slow sand filter plants to effectively treat source water containing pesticides and satisfy the European Community limit of 0.1 µg/L for individual pesticides, Thames Water Utilities Ltd. developed the GAC Sandwich™ filter (Bauer et al. 1996). A full-scale filter consisting of a layer of 300 mm of filter sand as the bottom layer, 150 mm of Chemviron 400 GAC in the middle, and 450 mm of filter sand on top was operated at filtration rates ranging from 0.1 to 0.3 m/hr and demonstrated excellent removal of pesticides.

Treatment with slow sand filtration supplemented by preozonation, a roughing filter for enhanced particle removal, and a GAC filter following the slow sand filter was evaluated at the University of Waterloo in Canada (Anderson and Huck 2005). Source water was the Grand River, which has a watershed in agricultural and urban areas in Ontario. When the roughing filter and slow sand filter were biologically mature, filtered water turbidity was maintained below 0.3 ntu, even when source water turbidity exceeded 25 ntu and even though the slow sand filter was operated at a rate of 0.4 m/hr. TOC removal for the entire process train was 58 percent to 65 percent, compared to about 15 percent for a slow sand filter operated in parallel but with neither pretreatment nor posttreatment. The pretreatment processes combined with slow sand filtration reduced THM formation by 58 percent to 60 percent. The test results demonstrated that pretreatment compatible with slow sand filtration can substantially extend its capabilities for removal of turbidity and organic contaminants.

Pre-engineered slow sand filtration plants similar in design to the process train studied at the University of Waterloo, but with the GAC filter placed between the roughing filter and the slow sand filter, have been fabricated and are in use in several Canadian provinces and in some states in the United States. A schematic diagram is presented in Figure 11-5. As of 2007, more than two dozen of these full-scale pre-engineered (package) slow sand filtration plants had been installed or were under construction in the United States and Canada (Jobb et al. 2007).

OPERATION, MONITORING, AND MAINTENANCE OF SLOW SAND FILTERS

By nature, slow sand filters are different in some aspects of operation, monitoring, and maintenance from those employed for rapid rate filtration. Two factors responsible for these differences are the absence of coagulant chemicals and the very slow rate of filtration, which results in changes in water quality occurring slowly. In addition, the passive nature of slow sand filtration facilitates operation by part-time staff. As a result, staff can observe operating conditions and change them as necessary on a daily basis, plus they can monitor plant operation and record data in a matter of an hour or less at small plants.



Courtesy of MS Filter, Inc.

Figure 11-5 Pre-engineered slow sand filtration process train with pretreatment including ozonation, roughing filter, and GAC filtration

This is an advantage of the process for small communities where water treatment operators may have general public works duties including wastewater treatment and road maintenance, and all tasks must be done on a part-time basis.

Placing a New Filter Into Service

When a new slow sand filter is placed into service, development of the biota within the sand bed will require a period of weeks. With passage of time, the schmutzdecke develops, a variety of organisms grow within the filter bed, and effective treatment is attained. Among the approaches taken for evaluation of slow sand filter efficacy are measurement of turbidity, *E. coli*, total coliform bacteria, viruses, and *Giardia* cysts in filter effluent (Haarhoff and Cleasby 1991). In their review of slow sand filter literature, Haarhoff and Cleasby reported five studies in which a new filter bed was reported to have matured between 35 to 60 days. In three of the five studies, the monitoring done for filter maturity was for total coliform bacteria or *E. coli*. Colder water would slow the development of biota in the bed and the maturation time, and in one study performed in Vermont, it was reported by Haarhoff and Cleasby that the filter had a 100-day initial operating period before erratic removal results were no longer observed.

Locally obtained sands have been used for the filtering material in some slow sand filters. When the local sand has not been not thoroughly washed before being placed in the filter, turbidity in filter effluent has exceeded that of the filter influent during start-up. Tanner and Ongerth (1990) reported that a new slow sand filter with beds of locally obtained sand that initially contained 4 percent clay fines by weight produced filtered water turbidity that generally exceeded raw water turbidity from 3 months to 15 months of operation after start-up. Filtered water turbidity at this plant exceeded the MCL during 6 of the 12 months of Tanner and Ongerth's study. This performance was attributed to incomplete washing of the filter sand before it was placed in the beds. The gradual discharge of fine particles that cause turbidity has the potential to lengthen the time between starting the initial flow of water through the filter and the acceptance of the filter as being capable of producing potable water for public consumption.

Recommended Operating Procedures

A key factor in operating slow sand filters is to minimize the rate increases applied to the filters, and when rate increases are made, to apply them gradually. The need for care when increasing rates is caused by the absence of chemical coagulation and the expectation that particles in a slow sand filter may be less tightly attached to media grains than particles in rapid rate filters. Along with avoiding rate increases, there is the need to have abundant finished water storage so the filter does not have to produce water at a rate similar to the rate of use in the water system. When treated water storage is sufficiently great that filtered water production can be managed at a rate close to the daily average for water use in the system, with hourly differences either withdrawn from or added to finished water storage, rate changes can be held to perhaps only one or two per day. If multiple stages of treatment are employed at a slow sand filter plant, minimizing the number of rate changes per day also minimizes the need for changes or adjustments to other processes.

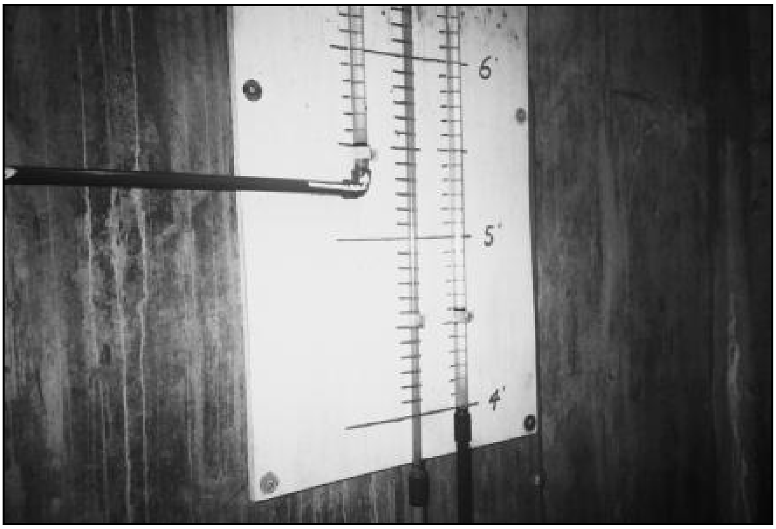
As previously discussed in this chapter, slow sand filters SHOULD NOT be operated in a stop–start mode. They do not require around-the-clock staffing, therefore they can operate unattended except for daily periodic monitoring and operational tasks.

Performance Monitoring

As a result of the very low filtration rate, monitoring of slow sand filter performance can be done on a daily basis, in contrast to the regulatory requirement in the United States that filtered water turbidity must be monitored at 15 min intervals for rapid rate granular media filtration. Furthermore, whereas a filter run at a rapid rate filtration plant can sometimes last less than 24 hours, slow sand filter runs can last for days, weeks, or even months, except for unusual events such as an algae bloom that results in formation of a mat of filter-clogging algae on top of the filters. Because head loss increases very slowly, monitoring head loss once per day is adequate, and this can be done by use of water piezometers as shown in Figure 11-6 rather than with sophisticated instrumentation and electronics. If the filter effluent passes through a totalizing water meter that also has a rotating dial that can be used to calculate a flow rate, this is sufficient for obtaining instantaneous filtration rate data. Total gallons filtered per day for each filter also would be included in daily operating data. Other regulatory requirements related to disinfectant residual and coliform sampling need to be met.

Maintenance Procedures

Slow sand filter maintenance procedures are not complicated, and this is another process advantage for small water systems. Two procedures unique to slow sand filters are methods to restore clean-bed head loss and resanding to restore the original depth of the filter bed.



Source: Pyper 1985.

Figure 11-6 Water piezometers used to measure head loss in Vermont slow sand filter

Cleaning to Restore Clean-Bed Head Loss

When head loss through a slow sand filter reaches terminal value, the upper half-inch or 1 in. (1 to 2 cm) of media can be scraped to remove the clogged sand. When this cleaning method is used, sand can be washed and stockpiled for future use, or it can be discarded. A sand washer is shown in Figure 11-7. If sand is washed and stockpiled after filter scrapings, it should be protected from dirt, dust, and bird droppings until it is reused. Discarding the sand is not desirable, as that results in the need to purchase more sand after repeated scraping operations have caused the bed to reach its minimum acceptable depth. In small plants, sand can be scraped into windows as illustrated in Figure 11-8 and removed from filter beds by wheelbarrows or by lawn tractors and trailers. A scraping technique used in the Rocky Mountain region is the use of an asphalt rake (a tool resembling a garden rake but with a wood blade and rubber squeegee, used to distribute an emulsion topping on asphalt driveways). The asphalt rake is capable of moving about 1 in. (2 cm) of sand into a windrow pattern, where shovels can be used to place the material in a device to convey it out of the slow sand filter. Sand scraping machines have been developed to remove a thin layer of sand from large slow sand filters.

Another approach to cleaning a slow sand filter bed is wet harrowing. This method of cleaning has been used with success at a large slow sand filter plant in New England (Collins et al. 1991). To accomplish wet harrowing, the supernatant water is drained from the filter down to a depth of about 12 in. (30 cm). Then a rubber-tired tractor equipped with a comb-tooth harrow is used to stir the top 12 in. (30 cm) of sand while

Courtesy of Ted Wixom, Doe Bay Water Users Assoc.

Figure 11-7 Sand washer for cleaning sand before it is replaced in a slow sand filter bed

Courtesy of Stephen Tanner, Idaho DEP.

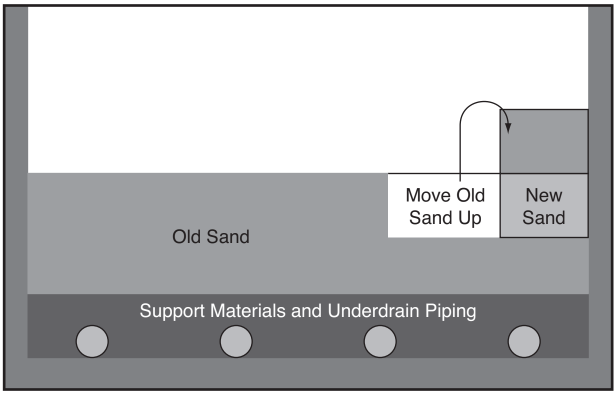
Figure 11-8 Manual cleaning of a slow sand filter

the remaining supernatant water is allowed to drain to the side of the filter bed. The horizontal flow of water carries away the dirt and schmutzdecke that were stirred into the supernatant water by the harrowing. If the harrowing is not completed by the time the water level drops to 3 in. (8 cm) over the bed, harrowing is stopped and the bed is refilled to about 12 in. (30 cm) so the harrowing can resume. This cleaning method extends the time for removing sand from the beds for a thorough cleaning to as long as 8 to 10 years.

After filter cleaning or scraping, operating the filter and wasting filtered water for a day, or perhaps longer, may be appropriate. A conservative approach would be to test for coliform bacteria in filter effluent and filter to waste until coliform data are acceptable. The time needed to verify that filtered water quality is satisfactory after scraping promotes the need for having multiple filter beds.

Replacing Sand When Bed Level Reaches Minimum Depth

Adding sand to the filter bed (resanding) is done when a minimum acceptable bed depth is reached after repeated filter scrapings. To do this, the bed must be dewatered and then scraped to remove the schmutzdecke and accumulated dirt. Next, starting at one wall of a rectangular or square filter bed, a trench parallel to the wall is excavated about 3 ft or 1 m wide, equal to the depth of the layer of sand that needs to be added to restore the filter to



Source: Logsdon.

Figure 11-9 Replacement of sand in slow sand filter to keep sand exposed to biota at top of filter bed

its original surface elevation. The excavated sand can be set aside for use at the completion of the resanding task. New sand or cleaned, recycled sand that had been scraped off the filter previously is placed in the trench, and then a trench of old sand is excavated adjacent to the previous trench. This is shown in the diagram in Figure 11-9. The old sand removed from the second trench is placed on top of the new sand that was placed in the first trench. This procedure results in placing sand from the lower part of the filter onto the top portion of the bed in the resanded filter. The pattern is repeated across the entire filter. When the last trench is excavated adjacent to the far wall (the wall opposite from the first excavation), the sand that was excavated first is then placed in over the new or reused sand that was placed into the last trench.

Use of the trenching procedure is more laborious than merely putting sand on the top of a filter needing a deeper bed; however, advantages can result from trenching. If the resanding is done in a prompt manner, especially in smaller installations, some of the biota in the sand bed may survive the resanding procedure and serve as a source for organisms in the resanded bed. Also, trenching will prevent development of a less-pervious layer of sand in the upper zone of the undisturbed sand. If a filter is repeatedly resanded when the depth decreases to two-thirds of the original depth, the sand just below the two-thirds level may become clogged, resulting in increased clean-bed head loss.

Letterman (1991) has indicated that resanding can require as much as 53 hr of labor per 1,000 ft^2 (50 hr/100 m^2) of filter area. This is a procedure that calls for advanced planning, and for a small system with limited staff, finding extra workers on a temporary basis will accomplish the procedure in a more timely manner. Washing used sand again just before resanding will prevent dirt and contamination from entering the filter bed.

After resanding, the renovated filter may need to be run to waste for a few days. Letterman (1991) reported that previous literature suggested a period of 1 to 2 days for ripening of the filter bed. Monitoring filtered water turbidity and coliform bacteria will provide information on the quality of water produced after resanding and will indicate when filter effluent can again be sent to the distribution system.

Recommended Standards for Water Works (Great Lakes—Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers 2003) states that slow sand filters shall be operated to waste after scraping or resanding until the filter effluent turbidity is consistently less than the standard required for the system. For slow sand filters, the SWTR requires that representative samples of filter effluent should be equal to or less than 1 ntu (1.4 ntu or less) in 95 percent of measurements taken each month (USEPA 1989). Therefore, an appropriate turbidity goal is 1 ntu.

When coliform bacteria monitoring is done to assess the ripening of a filter bed, coliform bacteria density in undisinfected filtered water samples during the ripening period can be compared to data for similar samples prior to termination of the filter run for scraping or resanding. Comparable numbers of bacteria in the effluent after filter maintenance, or comparable removal percentages, would indicate that the filter had returned to its previous capability for removal of microbiological contaminants.

SUMMARY

Slow sand filtration is a biological process as well as a physical process. Without the biological effects, slow sand filters are not very effective. Therefore, these filters must be managed and operated with the goal of maintaining an active biological system within the bed so all of the benefits of this process can be realized.

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12

Precoat Filtration

INTRODUCTION

The Drinking Water Dictionary (Symons et al. 2000) defines precoat filtration as, "A process designed to remove particulates by applying the water to be treated to a membrane or fabric coated with a very fine granular medium, such as diatomaceous earth." Precoat filtration was investigated as a process for treating potable water during World War II when the need to remove amoebic cysts from water provided to troops in the Pacific islands became apparent. The cysts were much more resistant to chlorine than bacteria, and they were large enough to be filtered out of the water using precoat filtration with DE or diatomite filter aid. Investigations by the Engineer Board of the US Army and the US Public Health Service demonstrated that filtration through a thin layer of diatomite filter aid was effective for removing cysts of *Endamoeba histolytica* from contaminated water (Black and Spaulding 1944). In the years following WWII, research on precoat filtration for public water systems was continued. By 1977, over 145 precoat filtration plants had been built to treat municipal drinking water supplies (Fulton 2000), with a total treatment capacity estimated at 180 mgd (680 ML/d).

Interest in precoat filtration was further stimulated in the late 1970s and early 1980s, when outbreaks of waterborne giardiasis were occurring in places where the source waters were considered pristine and disinfection was the only treatment provided. Research sponsored by the USEPA demonstrated that *Giardia* cysts could be removed reliably by precoat filtration. Research performed more recently showed that excellent removal of *Cryptosporidium* oocysts could be attained. AWWA has developed Manual of Water Supply Practices M30, *Precoat Filtration* (AWWA 1995) and Standard B101-01, *Precoat Materials* (AWWA 2001).

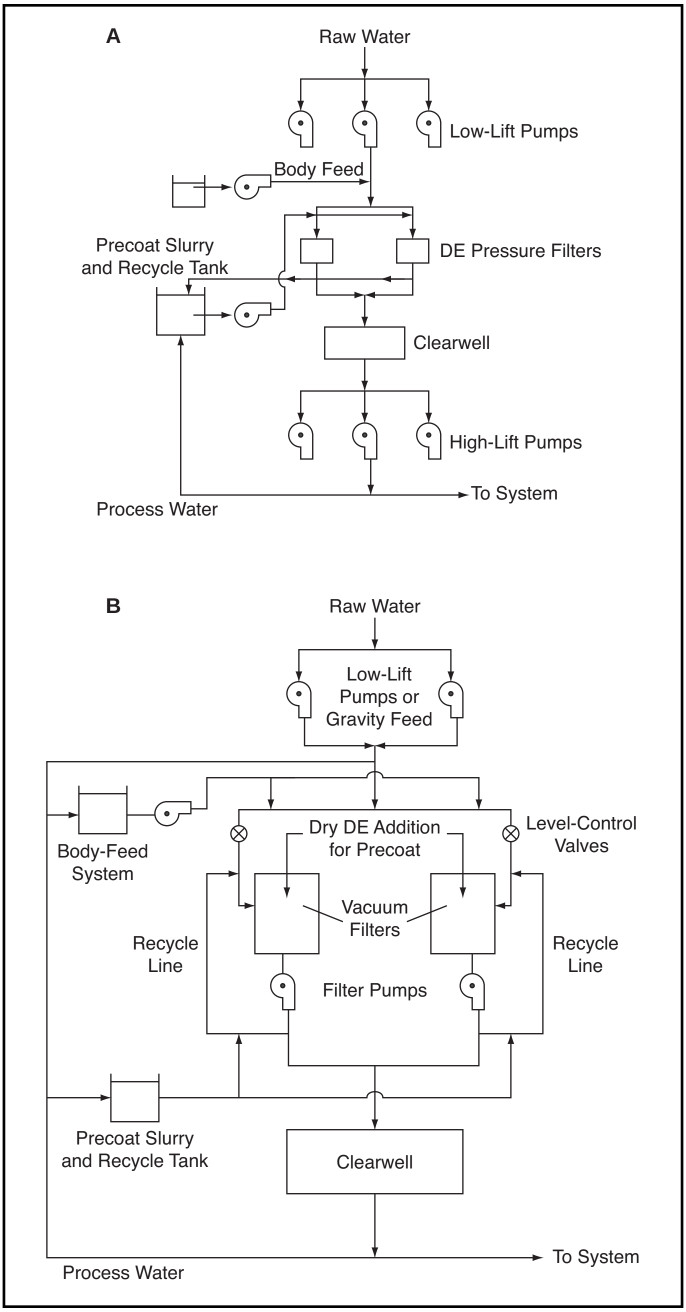
PRECOAT FILTRATION CONCEPTS

Precoat filtration shares the general characteristics of other filtration processes but differs substantially in the mechanism by which particles typically are removed. Common features include initiating a filter run with low head loss across the filter, gradual increase in head loss as the run progresses and particles are removed by the filter, and finally stopping the run to clean the filter and prepare it for another run.

In the granular media filtration process, the filtration step is preceded by coagulation of particles to be removed. During filtration, removal of the coagulated particles occurs by attachment of coagulated particles to grains of filter material, and media sizes range from 0.5 mm up to 2 or 3 mm. Filter beds range from 2 ft to 6 ft (0.6 m to 2 m) deep. Head loss develops into the depth of the filter bed to facilitate longer filter runs. Filter media, such as sand or anthracite, would not be added to a filter bed during the filter run. At the end of the filter run, the filter is backwashed to clean the filter media so it can be used again. Granular media filtration can occur in pressure vessels or in filters open to the atmosphere, with gravity providing the driving head to push the water through the filter.

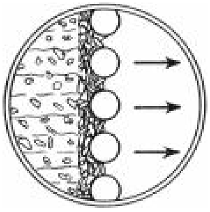
Precoat filtration equipment consists of a vessel that contains multiple filtration devices called *filter elements* or *leaves*. These are rigid structures that support the membrane or fabric (septum) that holds the filter cake, and are designed so filtered water can flow easily within the filter leaf to the discharge piping. Precoat filtration utilizes pressure vessels or open filters with pumps on the effluent side to create a pressure differential across the filter. A flow schematic for a precoat pressure filter is shown in Figure 12-1a. Figure 12-1b is a flow schematic of a precoat vacuum filter. The main particle removal mechanism in precoat filtration is straining. The filter medium (or *filter aid,* as it is commonly called) that is used in precoat filtration is either diatomite or perlite instead of sand or anthracite. To prepare for a filter run, the clean filter leaves or elements in the filter are coated with a thin layer of filter aid called the *precoat,* as illustrated in Figure 12-2. The filter aid can have a median size as small as 0.02 mm, and the filter cake through which filtration occurs may be as thin as ⅛ in. (3 mm) at the beginning of a filter run just after precoating is completed. Precoat filtration can exhibit a rapid increase in head loss when nonrigid particles are filtered out; therefore, a small dosage of filter aid (body feed) is continuously added to the filter influent (see Figure 12-3) during the run to maintain the porosity of the filter cake while at the same time increasing the thickness of the filter cake. Finally, at the end of a run, the used filter aid is removed for disposal, whereas rapid rate filters are backwashed and the media is used for many years. Thus, some very important differences need to be understood by those who operate precoat filters.

Precoat filtration equipment is designed to hold the cake of filter aid, to allow water to pass through the cake to the interior of the filter leaves, and then to permit filtered water to flow out of the filter. The pressure differential that drives water through the filter is provided by influent pressure when filter elements are enclosed in a pressure vessel, or by vacuum (pressure less than 1.0 atmosphere) on the effluent side when filter elements are in open vessels. Figures 12-4 and 12-5 show examples of filter leaves.



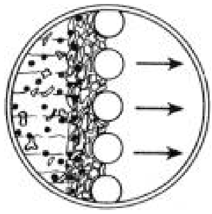
Source: AWWA Manual M30 *Precoat Filtration*.

Figure 12-1 Typical precoat filtration equipment schematic diagram



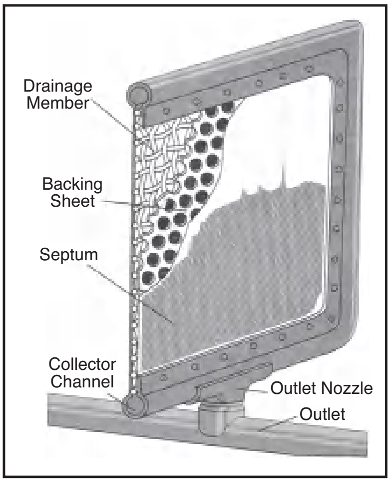
Adapted from G.R. Bell, *Jour. AWWA*, 1962.

Figure 12-2 Diagram of precoating diatomite on filter septum



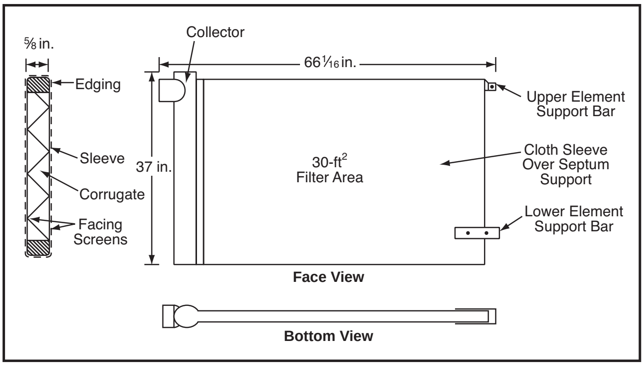
Adapted from G.R. Bell, *Jour. AWWA*, 1962.

Figure 12-3 Diagram of precoat filtration, showing influent particles (black dots) and filter aid being added as body feed



Source: AWWA Manual M30 *Precoat Filtration*.

Figure 12-4 Cutaway view of filter leaf showing support for septum



Courtesy of Westfall Manufacturing Company.

Figure 12-5 Typical construction of vacuum filter leaf element

Design of Precoat Filters

Pressure and Vacuum Filtration

Precoat filters are purchased from filter equipment manufacturers. The devices for measuring and controlling the rate of flow are specified by the design engineer and supplied by manufacturers of such equipment. Precoat filters are made in two types of units—pressure filters and vacuum filters. These differ in a number of ways with advantages and disadvantages for each, just as pressure filters and open gravity filters at rapid-rate granular media filtration plants have important differences.

Pressure Filters

Pressure filters used for precoat filtration can be operated to a higher pressure differential (head loss) than vacuum filters, with operating pressures as high as 30 to 40 psi (210 to 280 kPa). Because of the higher head losses, pressure filter runs can be longer than vacuum filter runs so more water can be produced for a given quantity of precoat filter aid.

Pressure filters can be installed between a higher elevation water source and a lower elevation community using the water, without breaking head in the transmission main. Pressure filters also discharge water at 1.0 atmosphere or higher, so degassing in the pressure filter is unlikely when the source water is supersaturated with dissolved air.

A disadvantage for pressure filters is the difficulty of observing the condition of the filter cake on the filter elements when filtration is occurring. Some pressure filters have been designed in such a manner that gaining access to the filter elements for inspection or extra cleaning is a difficult task that may require loosening and removal of large bolts or nuts and physical removal of one end of the pressure vessel. Some cylindrical pressure vessels positioned in a vertical manner are configured this way, such as the filter pictured in Figure 12-6.

Other pressure filter vessels are designed so they are positioned on a horizontal axis, and the removable end of the vessel resembles the door on an autoclave. This kind of pressure filter can be opened rather quickly, and the filter elements may be designed so they move out of the pressure vessel for cleaning when the end is removed. Another quick-opening configuration is for one end of the vessel and the filter elements to be fixed, with the remainder of the filter vessel or shell moving away from the elements for cleaning. Examples of these two types of horizontal pressure filters are shown in schematic diagrams in Figure 12-7.

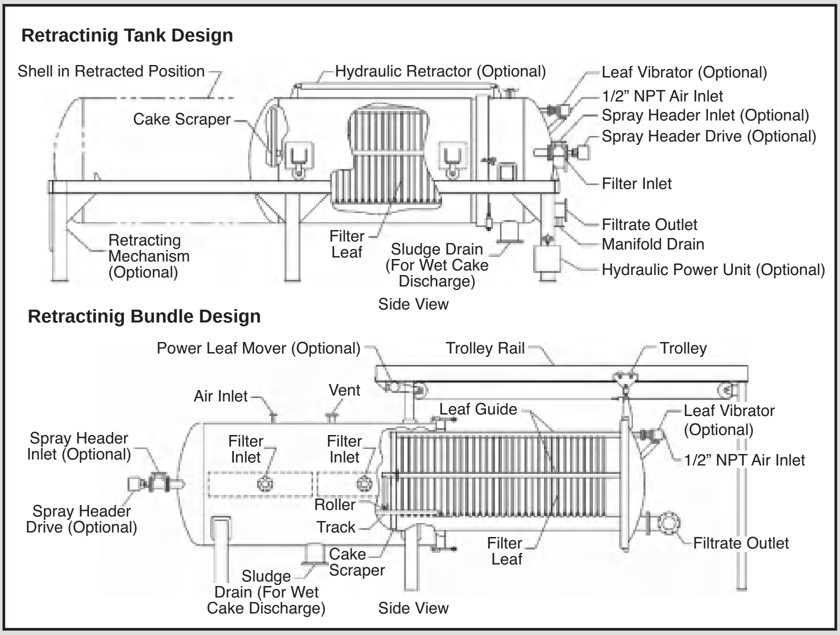
Vacuum Filters

Vacuum filters usually employ an open rectangular tank in which the filters are placed. The pressure differential across these filters is less than 0.7 atmosphere (10 psi

Design of Precoat Filters (continued)

Source: Logsdon.

Figure 12-6 Pressure filter installation



Courtesy of Whittier Filtration, Veolia Water Solutions & Technologies.

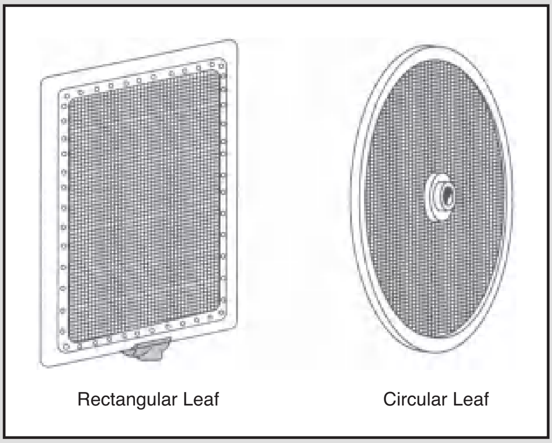
Figure 12-7 Diagrams of quick-opening pressure filters with retracting tank design and retracting bundle design

Design of Precoat Filters (continued)

or 70 kPa). Inspection of the filter elements during operation is possible because the tanks holding filter elements are open. Although the pressure differential is less for vacuum filters than for pressure filters, vacuum filters have the potential to be operated by siphon action rather than by pumps, with energy savings attained by operating in this manner. This arrangement could be considered when the water source and plant site are higher than the community to be supplied with filtered water. A disadvantage to applying reduced pressure on the effluent side of a vacuum filter is that if the differential is sufficient and if dissolved air in the influent water is supersaturated, air bubbles can form within the filter cake as a result of the lower pressure. Collapse of the bubbles can disrupt the filter cake and possibly permit previously trapped particles to pass into filtered water.

Filter Elements or Leaves

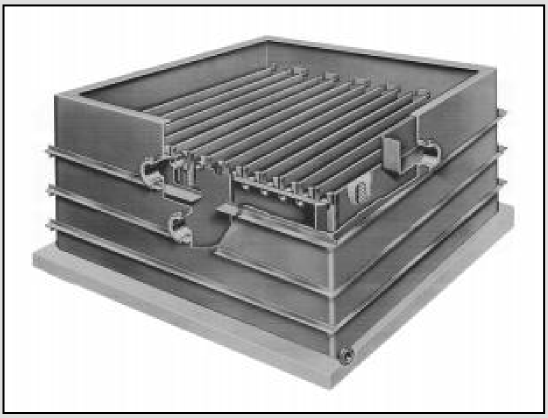
Filter leaves are pancake-shaped, circular, rectangular, or square (Figure 12-8), and generally are placed in a vertical position in the filter vessel (Figure 12-9). They must be structurally strong so they can support the septum, a fabric onto which the filter aid material is coated, and they need to facilitate the flow of water inside the filter leaf to its discharge point with low head loss (somewhat analogous to low clean-bed head loss in granular media filtration).



Source: AWWA Manual M30 *Precoat Filtration.*

Figure 12-8 Flat filter elements

Design of Precoat Filters (continued)



Courtesy of Westfall Manufacturing Company.

Figure 12-9 Cutaway view of vacuum filter

The septum that covers the structural portion of the filter leaf is made of woven synthetic fiber cloth or stainless-steel wire cloth. It must be strong enough to maintain its integrity in spite of a pressure differential that can be as high as 30 to 40 psi (210 to 280 kPa). The septum fabric can be obtained with fine pore openings or with somewhat larger pore openings. Smaller pore openings provide support for filter aid having smaller median particle sizes. If the openings in the septum fabric are so large that the filter aid being used for precoating does not effectively *bridge* the openings, filter aid can leak through the septum into filtered water. On the other hand, if the septum fabric has openings that are smaller than needed, this creates some additional but unnecessary head loss when water is filtered. For the integrity of the filter cake, it is very important that the septum and filter leaf not flex and permit cracks to form in the filter cake when a high differential pressure is reached near the end of a filter run.

Cleaning the Filter Leaves

Cleaning the filter leaves of both pressure filters and vacuum filters usually is accomplished by washing, and this may be accompanied by sprays to exert extra cleaning action on the filter leaves. When the filter is cleaned, used filter aid is washed out of the vessel for dewatering and disposal. An operating advantage of pressure vessels that open for cleaning and of vacuum filters is the opportunity for the plant operator to visually inspect the condition of filter leaves at the end of the run after the cleaning cycle is complete. A pressure filter with leaves extended out from the pressure vessel for cleaning and inspection is shown in Figure 12-10.

Design of Precoat Filters (continued)

Courtesy of G. Pyper, USEPA Cooperative Agreement.

Figure 12-10 Pressure filter with filter elements retracted from filter shell, showing some filter aid remaining on filter elements because of incomplete cleaning

Rate of Flow, Head Loss, Rate Control

Filtration Rate and Rate Control

Precoat filters traditionally were designed for a filtration rate of 1 gpm/ft^2 (2.4 m/hr). Research on precoat filtration for removal of *Giardia* cysts and *Cryptosporidium* oocysts has shown that precoat filters can be operated at 2 gpm/ft^2 (5 m/hr) and be very effective for removal of these pathogens, exceeding the log removal credits allowed by the USEPA's drinking water regulations for precoat filtration. Based on testing done in the 1980s and 1990s and discussed in this chapter, operating precoat filters at the higher rate seems appropriate, if other aspects of source water quality make the 2 gpm/ft^2 (5 m/hr) rate feasible. The principal concern would be the presence of compressible particulate matter that would result in rapid accumulation of head loss at the higher filtration rate. Whether this would be a problem could be evaluated during pilot testing.

Rate of flow control in older plants involved the use of a constant speed pump and a valve to control the flow rate on the discharge side of the filter. A more energy-efficient approach to rate control is to use a high efficiency electric motor and a variable-frequency drive for energy efficiency while varying the flow rate as needed, with a flow control valve on the effluent. This approach to controlling flow rate also can be used for recirculation of filtered water through the filter at a low-flow rate sufficient to maintain the cake on the filter leaves when production of filtered water is not needed but plant staff do not want to terminate flow into the filter and lose the filter cake.

Design of Precoat Filters (continued)

Head Loss

Head loss information indicates how closely vacuum filters are approaching the maximum practical head loss. For pressure filters, both the influent pressure and the head loss through the filters need to be known, as pressure vessels have an upper limit on operating pressure, and the differential pressure across the filter leaves needs to be limited to an amount that is within manufacturer's specifications. For both types of filters, the pattern of head loss accumulation during a filter run is useful for interpreting whether the body-feed rate is adequate, as discussed in the portion of this chapter devoted to operation.

Auxiliary Facilities and Equipment for Precoat Filters

Storage and Handling

Diatomite and perlite are abrasive inorganic materials that are produced in the form of powders that can cause dusty conditions if not stored and handled properly. These products can be purchased in 50 lb (22.7 kg) bags and in 900 lb (408 kg) bags and also can be delivered in bulk by truck or rail. Diatomite contains crystalline silica, and perlite may contain this substance. AWWA Manual M30 *Precoat Filtration* recommends that personnel handling these filter aids should be supplied with goggles, gloves, and respirators. Also, a dust collector system should be provided where slurry is prepared.

Pumps and Piping

Diatomite is an abrasive material, so pumps and piping that convey the precoat slurry must be designed to resist erosion. Broder and Byron (2005) recommend that case-hardened centrifugal pumps and abrasion-resistant chemical feed pumps be used for pumping diatomite slurries at concentrations of 4 percent or lower. Peristaltic pumps or rubber-lined centrifugal pumps are needed for slurries with concentrations greater than 4 percent. Because of the abrasive tendencies of the slurries, sharp bends or short-radius 90° turns in piping are to be avoided if possible. Piping is less likely to wear at gradual bends than at sharp bends where centrifugal force pushes more of the diatomite in the slurry against the pipe wall.

Diatomite particles have a specific gravity of between 2.0 and 2.3. Therefore, they can settle relatively quickly in water. If flow of diatomite slurry is stopped, the filter aid will settle to the bottom of the pipe. Providing cleanouts at critical points in a body-feed line may be helpful for operations if clogged pipes are encountered. Flow velocity ranging from 3 to 8 ft/sec (0.9 to 2.4 m/sec) is recommended for pipes carrying slurries of diatomite (Broder and Byron 2005). In pilot-plant testing

Design of Precoat Filters (continued)

with diatomite filtration done by the USEPA in the late 1970s, the author observed that body-feed piping carrying flow slightly downhill is less likely to clog. AWWA Manual M30 recommends that body-feed slurry piping be sloped slightly downhill if possible, and the use of flexible, transparent tubing is suggested as a means of locating and breaking up an area of clogged filter aid.

Precoating Apparatus

To prepare a filter for a new run, a coating of diatomite or perlite must be applied to the filter leaves after they have been cleaned following termination of the prior run. To do this, a slurry of filter aid is prepared in a precoat tank. Fulton (2000) explained that the volume of water involved in precoating is about 125 percent of the volume of the filter vessel and associated piping, so the precoat tank is sized to be about one fifth to one fourth of the size of the filter vessel. The slurry in the precoat tank is gently stirred, with enough agitation to maintain the filter aid in suspension but not so much vigor that the filter aid particles will be broken up by the mixer.

During precoating, the filter aid slurry is recirculated through the filter and back to the precoat tank. The precoat pump should be sized to provide a filtering rate similar to the conservative 1 gpm/ft^2 filtration rate that has been used for standard precoat filter operations. The change-over from precoating to filtering must be made smoothly, with no interruption in flow. Otherwise, a loss of flow could cause some of the precoat cake to slough off the filter leaves.

Body Feed

The body-feed system consists of a slurry tank with stirrer, metering pump, and piping. Precoat filters not equipped with some form of rate-of-flow control will operate in a declining rate mode. In a single filter without rate control, the highest rate of flow will occur at the beginning of the filter cycle, with rate of flow gradually diminishing as the filter cake thickness increases as a result of body feed, and as particles are removed from the influent water. Adding body feed at a constant rate of flow and constant concentration of filter aid would be wasteful of filter aid if the flow through the filter diminished during the run. This also could result in use of insufficient body feed if a flow increase took place. Thus, if a precoat filter is not operated in a constant rate mode, the body-feed pump should be proportioned to the rate of flow through that filter to maintain a constant concentration of body feed during the run. When multiple filters are used, a body-feed pump can be provided for each filter.

Design of Precoat Filters (continued)

Design Aspects Causing Short Filter Runs

Some mechanical or design features of precoat filtration plants that result in short filter runs:

- Poor hydraulics within filter leaves, resulting in high head loss as filtered water passes through the interior of filter leaves and out of the filter piping.
- Inability to provide sufficient amount of body feed.
  - Feed pump capacity not sufficient.
  - Excessively high back pressure on pump providing body feed to pressure filters.
  - Body-feed lines too small to carry needed flow.

As particulate matter is removed by a precoat filter, the filter cake becomes clogged. Gelatinous and compressible particles tend to clog the filter cake quickly, whereas rigid particles clog the cake much more slowly. To counteract the effect of this clogging, a small quantity of filter aid material called *body feed* is continuously fed into the raw water during filtration to extend the filter run. The nature of the particles being removed will determine the concentration of body feed needed to achieve a long and economical run. Straining is the major mechanism for particle removal; therefore, selection of a filter aid with the proper median particle size is important for attaining the desired filtered water quality. Filter aids with small particle sizes will form cakes with small pore spaces and can remove smaller particles than filter aid consisting of larger-size particles that form larger pores. On the other hand, the larger pore spaces associated with larger filter aid give it a lower resistance to flow, and consequently the possibility of a lower rate of head loss increase and longer filter runs.

Particle capture by straining rather than by attachment to filter media prevents turbidity breakthrough associated with filtration rate increases. If, however, the filter cake is disrupted by formation of air bubbles within the cake or by flexing of the filter septum, breaks in the cake could dislodge previously trapped particles and allow influent particles to pass through the cake.

FILTER AID MATERIALS

DE (diatomite) and perlite are used as filter aids for precoat filtration, with diatomite being more commonly used for water filtration. Both are inorganic mineral products. Diatomite is a silica material consisting of skeletal remains of diatoms, and is found in large deposits in some states in the western United States. Diatomite is mined, milled, calcined or flux calcined, and classified into various size grades. In the calcining process, milled diatomite is heated in a rotary kiln to a temperature high enough to cause particles to fuse together in larger sizes. A flux, such as soda ash, can be added before calcining to promote formation of still larger particles (Hendricks 2006), which results in formation of a more porous filter cake. Perlite, which is used less commonly than diatomite, is mined as glassy volcanic rock, crushed, calcined, milled, and classified into various size grades.

The size or grade of filter aid has a very strong influence on the particle removal capabilities of the filter cake in precoat filtration, as pore size in the filter cake is related to the size distribution of the filter aid particles. Information on the size of particles in various grades of filter aids can be obtained from producers of these filtering materials.

In some situations, it may be useful to modify the surface properties of diatomite by precipitating aluminum hydroxide onto diatomite in dilute slurry form. This is done by adding alum at a concentration of about 0.05 g of alum as $Al_2(SO_4)_3 \cdot 14\ H_2O$ per 1 g of diatomite in water containing the stirred diatomite slurry to form aluminum hydroxide on the surface of the diatomite (Hendricks 2006). Depending on the alkalinity of the water used to make up the slurry, soda ash might need to be added also. As the precipitate forms, it coats the diatomite and enhances the capability of the filter aid to remove particles that are smaller than the sizes removed by straining alone. This preparation technique, if used, would be performed onsite at the water treatment plant before a filter is precoated or before filter aid is put into a tank used to supply body-feed material. The alum coating tends to increase head loss through the filter aid cake, so generally this procedure is used with larger, more porous grades of filter aid.

Filter aid materials come in a range of grades with varying particle size. As previously noted, the coarser grades have large particles that form a cake with larger pores that cause lower head loss during filtration but have less ability to strain out small particles. The finer grades of filter aid form filter cakes with smaller pores that can remove microbes and finer inorganic particles, but such cakes create higher head loss during filtration. Selecting a filter aid that balances particle removal with acceptable head loss properties is a challenge for plant operators. Tables 12-1 and 12-2 are examples of the grades of diatomite provided by two suppliers of this product.

APPROPRIATE SOURCE WATER QUALITY AND PROCESS CAPABILITIES

Precoat filtration generally has been used with high-quality source waters of the type appropriate for direct filtration and slow sand filtration. High concentrations of organic matter and high turbidity are problematic for this filtration process.

Generally, no chemical coagulants are used with precoat filtration, so little removal of dissolved substances takes place. True color should be low, and the concentration of TOC should be sufficiently low that compliance with the DDBP Rule will not present difficulties.

Turbidity in source water should be low, ranging up to about 10 ntu. Turbidity removal can vary, depending on the nature of the turbidity-causing particles. Very small,

Table 12-1 Properties of Celatom filter aids*

Grade	Median Particle Size, µm	Permeability, da	pH of 10% Slurry
FW-6	18.0	0.480	9.0
FW-12	24.0	0.800	9.5
FW-14	28.0	0.800	9.5
FW-18	31.0	1.300	9.5
FW-20	33.0	1.700	10.0
FW-40	40.0	2.100	10.0
FW-50	42.0	3.500	10.0
FW-60	48.0	5.000	10.0
FW-80	77.0	12.000	10.0

*Data from Technical Data Sheet, EaglePicher Filtration & Minerals, Inc. 2007.

Table 12-2 Properties of Celite filter aids*

	(Data From Johns-Manville Filtration & Minerals Division Product Bulletin, 1981)	Data From World Minerals, 2007 (Successor Corporation to J-M Filtration & Minerals)
Grade	Median Particle Size, µm	Median Particle Size, µm
Filter Cel	7.5	19
Standard Super Cel	14	21
Celite 512	15	24
Hyflo Super Cel	18	30
Celite 503	23	34
Celite 535	25	43
Celite 545	26	46

*Data provided in1980s differ from present data on median particle size.

submicron particles require the use of finer grades (smaller particle sizes) of filter aid than do larger particles in water. Turbidity removal is not easy to predict in advance, and removal of larger biological particles may be much more effective than removal of small particles causing turbidity in water (Langé et al. 1986), because particles are removed by straining action unless an alum-coated filter aid is used. Such a procedure generally is not used at municipal filtration plants, although it has been shown by Langé et al. (1986) to enhance removal of fine particles that might otherwise pass through the filter cake. Particulate contaminants can be removed by precoat filtration, whereas dissolved contaminants pass through the filter cake. In this respect, precoat filtration resembles microfiltration or ultrafiltration.

Conversion of dissolved contaminants, such as iron and manganese, to precipitated forms by oxidation can be used as pretreatment to enable precoat filtration to remove these substances. Precoat filtration yields longer runs, however, when the particles being removed are rigid rather than gelatinous and compressible, as precipitated iron and manganese would be. Depending on the concentration of iron or manganese or both in the influent water, removal of these contaminants would have the potential to cause shorter filter runs. Short runs might occur either because of the need to use larger amounts of body-feed filter aid to maintain good porosity in the filter cake, or because the compressible precipitates, or iron or manganese blinded off the filter cake.

Because precoat filtration had been shown to be effective for *E. histolytica* cyst removal, the capability of this process for removal of 9 μm microspheres and *Giardia* cysts was evaluated (Hoye 1979). Giardia cysts are round to oval, about 8 to 18 μm long and 5 to 15 μm wide, so the 9 μm spheres were an appropriate surrogate for cysts. When a precoat thickness of 0.2 lb/ft^2 (1 kg/m^2) was used, along with body feed, microsphere removal was greater than 99.9 percent in 17 of 19 filter runs performed at 1.0 to 1.1 gpm/ft^2 (2.4 to 2.7 m/hr). Three of those runs met or exceeded 99.999 percent removal. In subsequent studies (Logsdon et al. 1981), 11 precoat filtration runs at filtration rates of 0.9 to 1.4 gpm/ft^2 (2.2 to 3.5 m/hr) resulted in removal of 99.36 percent to 99.993 percent of *Giardia muris* cysts. These filter runs used a filter aid (Celite 535) with a median particle size of 25 μm and a median pore size of 13 μm. For the testing with *Giardia muris*, precoat thickness was 0.2 lb/ft^2 (1 kg/m^2), and body feed was used.

Extended testing of precoat filtration at rates of 1 to 4 gpm/ft^2 (2.4 to 9.8 m/hr) at CSU (Langé et al. 1986) again demonstrated very good cyst removal capabilities, with *Giardia* cysts being recovered in filtered water in only one run out of 31. Cyst removal always exceeded 99 percent and was greater than 99.9 percent in 15 of the 31 runs. Comparative removal percentages for turbidity, bacteria, and cysts by several grades of diatomite are presented in Table 12-3, adapted from Langé et al. (1984). Results for removal of bacteria depended on the grade of filter aid used, as bacteria are smaller than cysts, and smaller filter aid particle sizes and pore sizes are necessary for effective removal of bacteria. Horsetooth Reservoir at Fort Collins, Colo. was the source of the water used for filtration testing, and the water contained very fine clays that caused turbidity. Most of the fine clay particles were smaller than 1 μm and were not removed effectively by grades of diatomite commonly used in drinking water treatment, so turbidity removal was much less effective than cyst removal. Generally, as median pore size of the filter aid being used decreased, turbidity removal and total coliform bacteria removal increased. It should be noted that in some instances where Table 12-3 does not show this trend, the data presented are related to the detection limit for the analysis involved rather than actual filter efficiency because no bacteria or cysts were detected in those filtered water samples.

The capability of precoat filtration for removal of *Cryptosporidium* oocysts was demonstrated in research by Ongerth and Hutton (1997, 2001). As with bacteria, removal of *Cryptosporidium* was a function of the size distribution or grade of the filter aid particles, as shown in Table 12-4. Fine filter aids produced higher removals (6 $\log_{10}$)

Table 12-3 DE filtration test results from CSU

Grade of Diatomaceous Earth Used	Median Particle Size, µm	Percentage Removal Attained		
		Turbidity, %	Total Coliform Bacteria, %	*Giardia* Cysts, %
Filter Cel	7.5	99	>99.8	Not done
Standard Super-Cel	14	51	>99.9	Not done
Celite 512	15	28	97	Not done
Hyflo Super-Cel	18	18	83	>99.4
Celite 503	23	11	68	>99.7
Celite 545	26	17	28	>99.7

Adapted from Langé et al. 1984.

Table 12-4 Average removal of *Cryptosporidium* oocysts by diatomite filtration

Filter Aid Name and Grade	Median Particle Size of Filter Aid, µm	Average $\log_{10}$ Removal at 1 gpm/ft^2 (2.4 m/hr)	Average $\log_{10}$ Removal at 2 gpm/ft^2 (4.9 m/hr)
Celite 512	16	6.24	6.33
Hyflo Super-Cel	22	6.00	6.31
Celite 535	34	3.84	5.64
Celatom FW-6	18	6.31	6.68
Celatom FW-12	24	5.93	6.23
Celatom FW-50	42	3.94	5.38

Adapted from Langé et al. 1984.

of oocysts, which are 4 to 6 µm in size, and coarser grades of filter aid were somewhat less effective, yielding log removals ranging from 3.6 $\log_{10}$ to over 5.0 $\log_{10}$. The latter results are typical of what would be attained with grades of DE commonly used at water filtration plants.

Data presented in Tables 12-3 and 12-4 illustrate the dependence of particle removal on the size of filter aid used. Fine grades of diatomite are effective for removal of coliform bacteria and *Cryptosporidium* oocysts. A grade of diatomite typically used for water treatment, Celite 535, gave very good results for oocysts removal but not very good results for removing coliform bacteria, which are much smaller. As previously noted, turbidity-causing particles, often smaller than bacteria, can pass through a precoat filter even when *Giardia* cysts are removed. Thus, the size of a particle in water and the size distribution of filter aid particles determines whether or not the particle in water is removed in the filter.

RECOMMENDED OPERATING PROCEDURES

Precoat filtration involves three steps: precoating the filter, operating the filter and managing body feed, and cleaning the filter when a run is terminated. As explained in the section on filter aids, a variety of filter aid materials are available. Selection of the appropriate filter aid for the water being treated is the first step toward achieving successful treatment.

Evaluating Filter Aids

When the source water quality changes very little over time, plant operators can determine the appropriate grade of filter aid that provides sufficiently long runs while achieving desired filtered water quality. When water sources undergo changes in quality from time to time, the use of the same filter aid over the long term may not result in the most effective treatment. One example of a quality change that might require evaluation of filter aids is a change in the concentration, type, or size of the particles that are causing turbidity in the source water.

To handle turbidity episodes in the source water, more than one grade of filter aid should be available for use, depending on the quality of the water being filtered. If fine particulate matter is causing turbidity, the use of a finer grade of filter aid than the one usually employed may lower the filtered water turbidity. At smaller plants where filter aid is kept in sacks, storing more than one grade of filter aid is a practical approach to occasional episodes of turbidity that is difficult to remove with the filter aid generally used.

Testing of different grades of filter aid can be done at the laboratory bench, with a Buchner funnel, an aspirator to create vacuum, and the coarsest grade of filter paper available for use with the funnel. This testing should be performed when the turbidity in the source water is difficult to remove with the filter aid customarily used. First, measure the turbidity of the source water, and then filter it through the Buchner funnel with only filter paper applied and wetted with tap water to seal the paper to the funnel. If very little turbidity reduction occurs during filtration through the coarse filter paper, then turbidity reduction attained when the filter paper is precoated with filter aid can be attributed to the filter aid. After verifying that the filter paper causes little turbidity removal, place filter paper on the funnel, wet it, and then apply a filter aid slurry in a sufficient amount to precoat the filter paper to a thickness of about ⅛ in. or 3 mm. Then filter water through the filter cake at a rate of about 1 to 2 gpm/ft^2 (2.4 to 4.9 m/hr). To relate the 1 gpm/ft^2 (2.4 m/hr) filtration rate to laboratory equipment, 2.4 m/hr equals 2,400 mm/hr or 40 mm/min. Thus, if the water level in the Buchner funnel drops 40 mm in 1.0 min, this is equivalent to a filtration rate of 1 gpm/ft^2. The coarsest grade of filter aid that gives desired turbidity removal in the bench testing should also work in the full-scale filter if the particle size range is appropriate for the pore spaces in the septum and the filter aid will bridge the pore spaces during precoating.

Precoating the Filter

Precoating must be managed carefully, and an adequate depth of filter cake must be established before the filter is placed into service. Based on the surface area of all of the leaves in the filter to be precoated, an appropriate amount of filter aid is added to water in the precoat tank. For diatomite filtration, a filter cake thickness for the precoat of ⅛ in. or 3 mm is recommended, based on research for removal of *Giardia*-sized 9 µm microspheres (Logsdon et al. 1981). This amounts to about 0.2 lb/ft^2 (1 kg/m^2). Multiplying the total filter leaf area by 0.2 lb/ft^2 (1 kg/m^2) gives the quantity of diatomite needed for precoating the filter.

The grade of precoat must be selected so it is appropriate for mesh (pore) size of the septum on the filter leaf. If the pore spaces in the septum are too large in relation to the filter aid used for precoating, filter aid particles will not bridge well across the septum pores. This can cause difficulties in establishing the precoat, as well as filter aid leakage problems during the run if undue pressure fluctuations occur on the influent side of the filter.

After the filter aid slurry is prepared, it is pumped through the filter and recycled back to the precoat tank. With each pass of filter aid slurry through the filter, more filter aid catches on the septum or on previously deposited filter aid on the septum, and gradually a precoat cake builds up on the filter leaves. Eventually, all of the filter aid is deposited on the septum and the water in the precoat tank becomes clear. The flow of water from the precoat tank must be maintained while filtration is initiated. The filter cake is held against the septum by the pressure of water passing through the cake, into the filter leaf, and out of the filter. Interrupting this flow of water removes the forces holding the filter cake against the septum and allows it to fall off the filter septum. If this occurs, the filtering capability of the filter leaf is lost.

An alternative approach for precoating to facilitate the use of a finer grade of precoat and body-feed filter aid is to employ a two-stage precoating process. In the first stage, a filter aid grade coarse enough to coat on the filter leaves is applied at a thickness about half of the recommended amount, followed by application of a second layer of precoat using a finer grade of filter aid, again at about half the thickness recommended for a usual precoat. Two-stage precoating was used in Duluth during pilot-plant testing of diatomite filtration for asbestos particle removal (Logsdon 1979).

Yet another approach for attaining lower filtered water turbidity while maintaining good flow and a low rate of head loss accumulation through the filter cake is to use alum-coated diatomite in the second layer or stage of a two-stage precoating process and follow up with alum-coated diatomite for body feed. The aluminum hydroxide coating on the filter aid facilitates some particle attachment and thus produces lower turbidity than could be attained by using uncoated filter aid of the same grade. This procedure was used to improve removal of turbidity and total coliform bacteria in research performed at CSU (Langé et al. 1986).

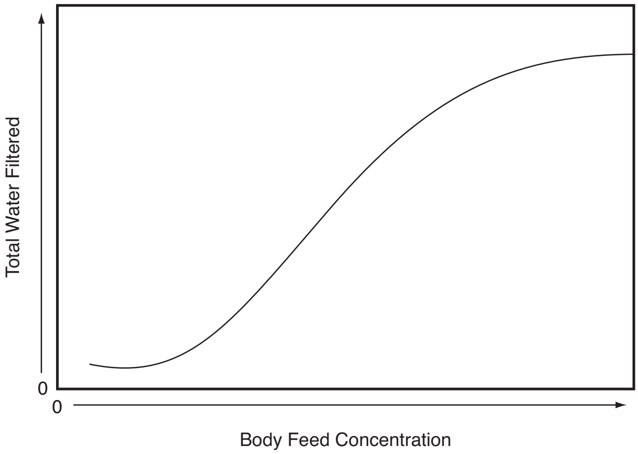
Operating the Filter—The Importance of Body Feed

After filter operation has changed from precoating to filtration with a minimum of disruption of flow through the filter, flow must be maintained in the filter to hold the filter cake on the filter leaf. The porosity of the filter cake is high when the run begins, and to maintain that high porosity, body feed is added. The amount of body feed that will yield a long filter run depends on the characteristics and concentration of particles in the influent water. Rigid, or noncompressible particles like clay have a lower tendency to block the pores of the filter cake than compressible particles. Algae, organic matter such as leaf fragments and rotting vegetation, precipitated iron or manganese, and floc formed by iron or alum coagulants all tend to be compressible and, if present, can cause head loss to increase at a high rate. When compressible particulate matter is present in the source water, the ratio of body-feed filter aid to turbidity might be on the order of 10:1. However, if turbidity is caused by rigid particles such as clay or silt, the ratio of filter aid to turbidity may be as low as 3:1. The concentration of body feed does not need to be as high when rigid particles are removed, in contrast to dosages required for compressible particles.

Algae in source water can be problematic for precoat filters. Algae are compressible and will blind off the filter cake if they accumulate on the surface of the cake. Using more body feed may help to cope with algae, but if the body-feed rate is high, the increase in thickness of the filter cake itself may cause head loss to rise too rapidly. In this situation, changing to a coarser grade of body-feed filter aid to reduce head loss may be helpful.

Precoat filtration removes particles mainly by straining, so turbidity breakthrough seldom happens unless the filter cake is disturbed. Rate increases can be tolerated and should not cause increased filtered water turbidity, if they are made gradually. A plant with only two filters would have one filter operating at twice its normal rate when the other was taken out of service for removal of spent filter cake and precoating unless the rate of raw water pumping could be decreased by half. Even in this situation, increasing the filtration rate should have minimal effect on filtered water quality if the increase is not made so abruptly as to shock the filter in a manner similar to the effect of water hammer, as that could disrupt or crack the filter cake.

Reviewing the nature of head loss increase during a filter run can be instructive for making decisions about body-feed rate. A precoated filter operated with zero body feed will display an exponential rise in head loss as particles are removed on the surface of the filter cake and cake filtration through the fine particles trapped on the surface ensues. With an adequate body-feed rate, the increase in head loss over time will be closer to a straight line rather than to a curve that is concave upward. Overfeeding the body-feed filter aid, however, will cause the filter cake to increase in depth too rapidly, and whereas the graph of head loss versus time will still approach a straight line, the rate of accumulation will be more rapid, so the filter run will end prematurely as a result of terminal head loss.



Adapted from McIndoe 1972.

Figure 12-11 Relationship of body-feed rate to total water production by precoat filter

The effect of increased amounts of body feed on total water production during a filter run was presented by McIndoe (1972) and is shown in Figure 12-11. According to McIndoe's explanation of this figure, when an inadequate amount of body feed is used, the body-feed filter aid particles are surrounded by the particulate matter being removed from the water, so body-feed merely adds to the bulk of the filter cake without improving the porosity of the cake. As more body feed is added, cake porosity increases, and total water production increases. Ultimately, a sufficient amount of body feed is used, resulting in peak water production. Further increases in the amount of body feed merely add thickness to the filter cake without noticeable improvement in cake porosity, but because the cake is thicker, the head loss rises, and this eventually results in a decrease in water production.

Monitoring Precoat Filter Performance

As with other filtration processes, monitoring the performance of a precoat filter during the run is an essential operations task, but with precoat filtration, the monitoring should start with the precoating step. If the time required for precoating to be accomplished is longer than normal, this can be an indication that troubleshooting is needed, as described later in this chapter. During filter operation, monitoring for influent turbidity, filtered water turbidity, head loss through the filter, pressure in a pressure filter vessel, rate of head loss gain, and body-feed flow are all important.

Turbidity monitoring is essential to surface water filtration. Filtered water turbidity monitoring is required by regulations, and knowing the influent water turbidity is helpful for managing body-feed dosage, if the typical characteristics of source water turbidity-causing particles are known. That is, if turbidity generally is caused by rigid particles such as soil particles rather than by compressible particles, increases in turbidity may not call for such high dosages of body feed as would be needed for compressible particles. Filtered water turbidity is required to be equal to or less than 1 ntu in 95 percent of measurements taken each month, and records of these data must be kept for regulatory compliance purposes (USEPA 1989).

Head loss and pressure data are important for practical considerations. In pressure filters, the pressure within the vessel must not exceed limits specified by the equipment manufacturer. Doing so could risk damage to filtration equipment. The head loss incurred during filtration increases as the run progresses, and at a predetermined maximum head loss, the run should be ended. Knowing the rate at which head loss increases can aid operators in planning for ending the run, cleaning the filter, and starting a new run.

Understanding the pattern of head loss development also can be helpful to filter operation. If head loss is increasing at a moderate rate but then increases at a considerably higher rate, this could indicate either a change in the quantity or nature of the particles being removed, with compressible particles being a concern. Alternatively, the sudden increase in the rate at which head loss is rising might indicate a loss of body feed into the filter influent, with formation of a filter cake having very poor filtration properties.

Body feed has to be continuous during a filter run, and it needs to be adequate to maintain a porous filter cake even if the nature or quantity of the source water particles changes. Periodic checks are useful for verifying that the body-feed equipment is working and that filter aid slurry is flowing through the body-feed line. If loss of body feed occurs and causes a more rapid accumulation of head loss, the best course of action is to end the filter run, clean the filter, fix the body-feed system, and start a new run because restoring the body feed will not restore the formerly good head loss accumulation properties of the existing filter cake.

Cleaning the Filter to Prepare for Another Run

After a filter run has been ended, regardless of the cause for termination, the spent filter cake must be thoroughly cleaned off of the filter leaves. In addition, if the filter run is interrupted for any reason and flow through the filter stops, the filter must be cleaned. Attempting to recoat the filter leaves by restarting the filter and coating it with filter aid that fell off the leaves when flow stopped is likely to result in an uneven and spotty filter cake, with gaps or thin areas. This could permit passage of pathogenic microbes through the filter.

Failure to carefully clean the filter also could result in accumulation of dirt and organic matter on the filter leaves. This would then cause uneven precoating, with possible passage of particles through areas where the filter cake was not sufficiently thick.

Disposal of Spent Filter Aid

Precoat filter media settles very rapidly in still water. Therefore, a low-cost approach to disposal of this material is to discharge spent filter aid to a holding basin, allow it to settle, and decant the supernatant water. Dried spent filter aid could be worked into soil as a soil amendment, or it could be landfilled.

Troubleshooting Precoat Filtration

Fulton's book, *Diatomaceous Earth Filtration for Safe Drinking Water* (Fulton 2000) lists possible causes for problems in precoating. The following text is adapted from Fulton and supplemented by the author.

If the precoat slurry does not clear in the time typically needed to establish a filter cake on the leaves, this indicates failure to form the cake. Several causes can be considered.

Operational problems with precoating include the following:

- Not enough filter aid is put into the slurry tank to fully coat the filter leaves.
- Rate of precoat slurry recirculation is too low, resulting in failure of filter aid to rise through the entire filter leaf area and cover the leaves.
- Flow rate within the is filter too fast, washing precoat filter aid off the leaves.
- Filter leaves are dirty and the resulting low flow in dirty areas is insufficient to hold filter aid on the leaves.
- Air enters the filter vessel because of vortex formation in precoat tank.
- The operator has used a grade of filter aid for precoating that is too fine to bridge over the openings in the filter septum.

Mechanical problems that cause difficulties in precoating include

- Pressure filter is not properly vented, resulting in the vessel partly filled with air.
- Filter cake is washed off leaves because of inadequate internal baffling.
- Weave of septum is too open, i.e., pore spaces too large for precoat filter aid to bridge across and form a stable cake when appropriate drinking-water grade of precoat filter aid used. (This could happen with a precoat filter designed for swimming pool use, but used for a small water system.)
- Leaks occur in seals or at connection of septum cloth to filter leaf frame.

Plant operators should be aware of the amount of time usually needed for the filter cake to form and precoat slurry to clear, indicating that the filter aid has been deposited on the filter leaves and the filter is ready for the next run. If the slurry takes an unreasonably long time to clarify, the operator should evaluate the list of possible causes. Some problems, such as using insufficient filter aid to form the filter cake, could be a one-time error, whereas some of the other operational problems, such as dirty filter leaves, might be repeated in future runs. Identifying the cause of precoating difficulties and correcting the problem is necessary for attaining effective filtration.

Fulton's book lists causes for failure to attain the desired low turbidity in filtered water. Operational causes adapted from Fulton include

- Operating the filter at a rate that causes internal velocity high enough to wash filter aid off the filter leaves.
- Dirty filter leaves that did not precoat adequately and thus permit fine turbidity-causing particles to pass through.
- Filter aid used is too coarse, with filter-cake pore spaces large enough to permit very small turbidity-causing particles to pass through.
- Improper manipulation of valves when changing from precoating to filtration caused some loss of filter cake from leaves.
- Air binding in vacuum filter followed by collapse of air bubbles in filter cake and passage of particles into filtered water.

All of the mechanical issues listed as potential causes of difficulties in establishing a precoat can also be causes for failure to meet the filtered water turbidity goal during filtration. In addition, warped screens on filter leaves and a septum that is too loose and flexible can result in passage of turbidity into filtered water.

In addition to the problem of high filtered water turbidity, short filter runs can cause problems in filter operation, whether the process is slow sand, rapid rate, or precoat filtration. Short filter runs were addressed by Fulton. The potential causes are adapted from his book and supplemented by the author.

Operational causes of short filter runs include

- Operating precoat filters at a filtration rate that is too high.
- Using no body feed, or an inadequate body-feed rate, resulting in build-up of a cake of compressible particles that cause an exponential increase in head loss during the run.
- Use of an excessive rate of body feed, causing the filter cake to increase in thickness too rapidly, with head loss caused by the thickness of the filter cake.
- Erratic or interrupted body feed caused by a malfunctioning or plugged body-feed slurry pump or plugged body-feed piping, which causes cake filtration to be established in a some or all of the filter cake.
- Improper combination of precoat and body-feed grades. Fine body-feed filter aid can penetrate into pores of a coarse precoat and increase flow resistance. Coarse body feed can allow particles to penetrate body-feed filter cake and be removed on the fine precoat filter cake, thus causing head loss to increase more rapidly.
- Use of unfiltered water for precoating, with particles in the water being trapped in the precoat cake.

- Excessive recirculation during precoating, resulting in breakdown of filter aid into smaller particle sizes.
- Particle concentration in source water is too high (high turbidity) or consists of compressible particles that require high rates of body feed in proportion to particle concentration.

If short filter runs are encountered, and source water quality does not seem to be the cause, reviewing recent operating experience in the context of the previous bullet items may help with identification of the cause of short runs.

INSPECTION AND MAINTENANCE ACTIVITIES

Inspection and maintenance of precoat filters is a necessary activity, just as those activities are needed for rapid rate and slow sand filters. Length of time in service since the last inspection, quality of the water being treated, and precoat filter performance all may influence the timing of inspections.

Build-up of organic particulate matter, such as algae or rotted vegetation on the septum, can clog septum pores and result in incomplete coverage of the septum surface during precoating. This can lead to poor filtration results. Therefore, a periodic inspection of filter leaves should be undertaken after cleaning. This is especially important when influent water contains organic debris that may stick to the septum; therefore, even if a periodic inspection schedule is maintained, an extra inspection might be useful after an algae bloom on a reservoir or lake, or after runoff containing suspended organic matter had been encountered.

The abrasive nature of diatomite necessitates periodic inspection of the precoat recirculating pump, body-feed pumps, and piping associated with precoat recirculation and body feed. Replacement of parts or piping may be needed if excessive wear is detected. Good engineering practice includes providing spare equipment for facilities that are vital to successful plant operation.

As with plants employing other filtration processes, a regular program of inspection, calibration, and maintenance procedures for head loss instrumentation, turbidimeters, flow measurement instruments, and body-feed pumps should be planned and carried out.

SUMMARY

Precoat filtration for drinking water was developed during WW II and has been used for municipal water treatment since the late 1940s. This filtration process typically accomplishes particle removal by straining action in the filter cake, which consists of DE or perlite. It is most appropriately applied for treatment of source waters with low turbidity and low TOC and color, and with no dissolved contaminants exceeding MCLs. Precoat filtration is very effective for removal of microbiological contaminants larger than bacteria, and because no coagulant chemicals are used in most applications, it is an appropriate technology for small water systems.

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Glossary

The main source for the definitions in this glossary is *The Drinking Water Dictionary*, edited by James M. Symons and published by the American Water Works Association. Additional definitions appeared in the Awwa Research Foundation's *Filter Maintenance and Operations Guidance Manual*, or were provided by the author.

acid solubility – The susceptibility of filtering material or of substances precipitated onto filtering material to being dissolved in acid.

acid solubility test – A filter media test described in AWWA B100, used to determine the percentage by weight of filter media that can be dissolved in acid. This test can be used to determine the proportion of calcareous material in filtering material or in support gravel before these are placed in a filter. The test also can be used to evaluate the extent of weight gain caused by the precipitation of calcium carbonate on filtering material at a lime softening plant.

air backwash – A process for cleaning filtration media in which air is introduced into a liquid backwash flow to assist in dislodging particles entrapped in the media. Air backwash is typically used for backwashing either pressure or gravity media filters.

air binding – (1) The clogging of a filter, pipe, or pump as a result of the presence of air released from water. Air can prevent the passage of water during the filtration process and can cause the loss of filter media during the backwash process. (2) Displacement by air of water from the top portion of a precoat filter pressure vessel, which reduces the area available for filtration of water through the filter elements.

air bubble volume – The volume of air bubbles present in a dissolved air flotation clarifier, in proportion to the total volume of air and water in the clarifier. As air bubble volume is increased in a dissolved air flotation clarifier, the solids separation capability of the clarifier increases.

air scour (air scouring) – The practice of admitting air through the underdrain system to ensure complete cleaning of media during filter backwash. *See also* air backwash.

air water backwash (air–water wash) – A method of backwashing granular filter media in which both air and water are used. The air is entrained under pressure into the backwash water in the underlying media support structure and is released as the water flows upwardly through the granular media. The purpose of the air is to provide additional energy and some buoyancy that increases the scouring action and enhances the release of particles attached to the granular media.

alarms – Mechanisms used to alert operators when monitoring data have reached a preset limit. Alarms may be used in conjunction with online turbidimeters or particle counters to alert operators to a rise in turbidity or particle counts to an unacceptable level or to a level that requires action to prevent a further rise in the parameter being monitored.

algae – The simplest plants that contain chlorophyll and require sunlight; they vary from microscopic forms to giant seaweed.

alkalinity – A measure of the capacity of a water to neutralize strong acid; in natural waters this capacity is usually attributable to bases such as bicarbonate $(HCO_3)^-$, carbonate $(CO_3)^{-2}$, and hydroxide (OH^-) and to a lesser extent silicates, borates, ammonia (NH_3), phosphates, and organic bases. It is expressed in milligrams of equivalent calcium carbonate per liter (mg $CaCO_3$/L).

alum ($Al_2(SO_4)_3 \cdot 14\ H_2O$) – The common name for aluminum sulfate, a chemical used in the coagulation process to remove particles from water. *See also* aluminum sulfate; coagulation.

aluminum sulfate ($Al_2(SO_4)_3$ – An inorganic compound commonly used as a coagulant in water treatment. It contains waters of hydration, $(Al_2(SO_4)_3 \cdot X\ H_2O)$ (where X is a variable number.) Aluminum sulfate is often called alum.

anionic polymer – A negatively charged polymeric compound used to assist in removing particles from water. Anionic polymers are most typically used as flocculant aids; they bridge floc particles and thereby generate larger particles that can be removed by sedimentation, flotation, or filtration.

ANSI – American National Standards Institute.

anthracite (coal) – A particulate form of coal that is used in granular media filters to remove particles from water. Anthracite coal is typically used in dual-media filters in combination with sand.

APHA – American Public Health Association.

approach velocity – Another term for filtration rate. The rate of filtration in gallons per minute per square foot can be converted to an approach velocity, i.e., the rate of flow of the water toward the top of the filter bed as it flows down in the filter box. 1 gpm/ft^2 = 8.02 cubic feet per square foot per hour (8.02 ft^3/ft^2/hr) or 2.44 m/hr.

auxiliary scour – *See* filter agitation.

available head – The head, or pressure, available to drive water through a granular media filter. Available head depends on the design of the plant and of the filter. When the available head is provided in large measure by using a deep filter box with 6 to 8 feet of water over the filter media, this reduces the tendency for air binding to occur in the filter bed. On the other hand, when a major portion of the available head is provided below the filter media, pressure within the filter bed may decrease to less than one atmosphere, which can cause air binding.

AWWA – American Water Works Association, a professional association representing the drinking water supply profession.

AWWA B100 – The AWWA *Standard for Filtering Material*. This standard describes properties of various types of filtering material, gives test procedures, and tells how to place filtering materials. It does NOT contain design standards for filter beds.

AwwaRF – Awwa Research Foundation, the only nongovernmental organization that sponsors research for the drinking water profession. It is independent of, but related to, the American Water Works Association.

backwash – (1) The process of cleansing filter media of particles that have been removed during the filtration or adsorption process. Backwashing involves reversing the flow through a filter to dislodge the particles. Backwash water is either treated and returned to the plant influent or is disposed. (2) The passing of a fluid (feedwater, treated water, air, or other fluid) through an ion exchange column or some type of microporous membrane for cleaning purposes to remove particles.

backwash volume – The volume of water used to backwash a filter during the filter cycle. As this volume increases, the net productivity of the filter will decrease unless the total volume of water filtered during the run has increased in proportion to the increase in the backwash volume.

baffle – A metal, wooden, or plastic plate installed in a flow of water to slow the water velocity and provide a uniform distribution of flow.

ballasted floc clarifier – A clarifier used for suspended solids separation assisted by weighted or ballasted flocs.

ballasted flocculation – A water treatment process in which very fine sand is incorporated into flocs to hasten their settling. By increasing the density of floc particles, the settling of flocs can be accomplished in a fraction of one hour as compared to a detention period of as long as four hours for a conventional settling basin. After sludge is removed from the settling basin, the floc and sand are separated, and the sand is reused.

bed expansion – The effect produced during backwashing when the filter medium becomes separated and rises in the tank or column. It is usually expressed as a percentage increase of bed depth, such as 25 percent, 50 percent, or 75 percent.

biodegradability – The susceptibility of a substance to decomposition by microorganisms.

biological filtration – The process of filtering water through a filter medium that has been allowed to develop a microbial biofilm that assists in the removal of fine particulate and dissolved organic materials.

biota – living organisms, including bacteria, plants, and animals, in a given ecosystem.

body feed – In precoat filtration, the continuous addition of filter aid (diatomaceous earth or perlite) during the filtering cycle to provide a fresh filtering surface as the suspended material clogs the filter aid precoat.

boil – A rise in the water surface caused by the turbulent upward movement of water.

breakthrough – (1) The point in a filtering cycle at which turbidity-causing material starts to pass through the filter. (2) The time in the cycle of a treatment bed when an increase, sometimes defined as an unacceptable increase, in the effluent concentration occurs for the contaminant being controlled.

bubble volume – *See* air bubble volume.

Buchner funnel – A funnel with a flat bottom containing pores for passage of liquid, and a cylindrical wall. Buchner funnels are used in the laboratory for tests involving vacuum filtration.

CAC – *See* contact adsorption clarifier.

calcine – Heat a substance to a high temperature but below its melting point, to drive off water or decompose carbonates; to change the physical or chemical constitution. Calcining is often done in a rotary kiln.

Caldwell–Lawrence diagram – A diagram illustrating a series of relationships associated with the chemical equilibrium of calcium carbonate ($CaCO_3$) as a function of pH, alkalinity, and calcium hardness for a solution of given temperature and ionic strength.

carbonate alkalinity – Alkalinity caused by carbonate ions (CO_3^{2-}) and expressed in terms of milligrams of equivalent calcium carbonate ($CaCO_3$) per liter.

cationic polymer – A polymeric substance with a net positive charge, used in coagulation, flocculation, flotation, or filtration processes to improve the removal of negatively charged particles from natural waters. Cationic polymers can be used to destabilize negatively charged particles or to form a bridge between destabilized floc.

chlorine demand – The quantity of chlorine consumed in a specified time period by reaction with substances present in water that exert an oxidant demand (e.g., natural organic matter, ammonia [NH_3], hydrogen sulfide [H_2S]). The chlorine demand for a given water varies with both contact time and temperature.

chlorine residual – A concentration of chlorine species present in water after the oxidant demand has been satisfied. Chlorine residual can be determined and expressed in a number of ways. Commonly used analytical techniques include a colorimetric method using the reagent N,N-diethyl-p-phenylenediamine and a volumetric method using an amperometric titration. The concentration is often expressed in terms of free chlorine, total chlorine, or combined chlorine.

clarification – Any process or combination of processes that reduces the amount of suspended matter in water. At rapid rate, granular media filtration plant's clarification often is accomplished by using gravity sedimentation. Other clarification processes used include dissolved air flotation and preliminary filters.

clean-bed head loss – The head loss that occurs after a filter has been backwashed and restored to a clean condition. Clean-bed head loss is measured at the start of a filter run, and is also known as starting head loss.

clearwell – A tank or vessel used for storing treated water. Typical examples of storage needs include (1) finished water storage to prevent the need to vary the rate of filtration with variations in distribution system demand, and (2) backwash water for filters. Clearwells are located onsite at a water treatment plant. A clearwell is also called a filtered-water reservoir.

coagulant – A chemical added to water that has suspended and colloidal solids to destabilize particles, allowing subsequent floc formation and removal by sedimentation, flotation, filtration, or a combination of these processes (e.g., the use of alum or iron salts for removing turbidity in a water treatment process).

coagulation – The process of destabilizing charges on particles in water by adding chemicals (coagulants). Natural particles in water have negative charges that repel other material and thereby keep it in suspension. In coagulation, positively charged chemicals are added to neutralize or destabilize these charges and allow the particles to accumulate and be removed by physical processes such as sedimentation or filtration. Commonly used coagulants include aluminum and iron salts and cationic polymers.

color unit – The unit used to report the color of water. Standard solutions of color are prepared from potassium chloroplatinate (K_2PtCl_6) and cobaltous chloride ($CoCl_2 \cdot 6\,H_2O$). Adding the following amounts in 1,000 mL of distilled water produces a solution with a color of 500 color units: 1.246 g potassium chloroplatinate, 1.00 g cobaltous chloride, and 100 mL hydrochloric acid (HCl). Other terms used for color units include Pt-Co color units, and in the U.K. and Europe, Hazen units, and degrees Hazen.

contact adsorption clarifier – A filter used in a water treatment plant for the partial removal of turbidity (clarification) before final filtration, also called a contact filter, roughing filter, or preliminary filter.

combined air and water wash – A filter backwashing technique that employs a gentle, nonfluidizing upflow of wash water simultaneously with air scour. For filters employing media consisting of fine sand, dual media, mixed media, or coarse anthracite monomedium, combined air and water wash are used until the level of water in the filter approaches (about 6 in. or 15 cm) the top of the wash-water trough. Then air scour is ended and water backwash completes the cleaning of the bed and restratification of media, if necessary. For filters consisting of coarse sand with an

ES of 1.0 mm or larger, the combined air and water wash may be used for about 10 minutes and some water will overflow the wash-water trough.

constant rate filtration – The most common method of filter operation, in which the filters are operated at a constant rate. The rate is controlled either by (1) an effluent valve that is gradually opened as head loss increases throughout the filter run, or (2) a variable water surface above the filter media that gradually rises to increase the applied head as head loss accumulates.

conventional water treatment – The use of coagulation, flocculation, sedimentation, filtration, and disinfection, together as sequential unit processes, in water treatment. This process is also called complete treatment.

core sample – A sample of the medium obtained to represent the entire bed depth when the bed is being analyzed for capacity or usefulness. A hollow tube is sent down through the bed to extract the sample.

cracks [in filter] – Crevices or cracks that develop in filter media as a result of dirty media or excessive polymer dosages. Cracks may develop within the filter bed itself or at the wall, between the filter wall and the bed. As the dirty, cohesive filter media is packed together because of the pressure drop (head loss) that occurs in the bed, shrinkage of the bed may cause cracks to appear. Water can pass through the cracks much more readily than through the porous bed, so poor filtered water quality can caused by development of cracks in the filter bed.

Ct – residual concentration C, mg/L × contact time t, minutes.

DAF – *See* dissolved air flotation.

DBP – *See* disinfection by-product.

DE – *See* diatomaceous earth.

dead zone – An area or zone in a tank or basin where little or no flow or mixing occurs.

declining rate filtration – A filtration process in which the filter rate gradually decreases throughout the course of the filter run. A flow-restricting orifice is used in the effluent piping to control the maximum rate when the filter is clean. As the filter clogs with solids, resistance through the filter bed increases, which causes the flow rate to decrease as flow is shifted to other, cleaner filters in the treatment plant.

delayed start – Starting a filter after backwash, with a period of time of perhaps one half hour or more between the backwash and startup. Also referred to as *resting* a filter. If done for a time that is not excessive, resting a filter can in some plants enable the filter to produce better quality water when it is started, reducing the magnitude of the initial turbidity spike, or its duration, or both.

depth filtration – A filtration process in which particles are removed as water flows through the pore spaces in a filter media bed. Depth filters are designed to entrap particles throughout the mass of filter media, as opposed to a surface filter, where only the surface layer does the actual filtering. Particle removal occurs mainly by attachment onto grains of filtering material or by attachment onto other particles previously removed in the filter bed, rather than by a straining or screening action.

detritus – Finely divided, nonliving, settleable material that is suspended in water.

diatomaceous earth (DE) – The microscopic remnants of the discarded outer surface of diatoms. DE is also called fuller's earth. It is the medium most commonly used in precoat filtration.

diatomaceous earth (DE) filter – A filter using a medium made from diatoms. The water is forced through the diatomaceous earth by a pressure differential, with inlet pressure higher than atmospheric on the inlet side in a pressure DE filter, and outlet pressure less than 1 atmosphere in a vacuum DE filter.

diatomaceous earth (DE) filtration – A filtration method in which diatomaceous earth is used as the filtering medium. *See also* precoat filtration.

direct filtration – A method of filtration in which coagulated and flocculated particles are applied directly to a filtering medium from the flocculation basin without settling or flotation. It is not to be confused with direct in-line filtration.

direct in-line filtration – A method of filtration in which coagulated particles are flocculated *in-line* prior to and during direct application to a filtering medium. Neither a dedicated basin for flocculation nor settling is provided. Direct in-line filtration is not to be confused with direct filtration (which uses a dedicated flocculation basin). It is also called in-line filtration (also known as contact filtration).

direct total microbial count – An analytical method for assaying bacteria in water. The total numbers of bacteria are determined by membrane filtration, staining, and UV-illuminated microscopy. This procedure is described in *Standard Methods for Examination of Water and Wastewater*, No. 9216. It is a technique that can be used to evaluate the passage of bacteria through filters. The technique detects both viable and nonviable bacteria.

disinfectant – An agent that destroys or inactivates harmful microorganisms.

disinfection – (1) The process of destroying or inactivating pathogenic organisms (bacteria, viruses, fungi, and protozoa) by either chemical or physical means. (2) In water treatment, the process in which water is exposed to a chemical disinfectant—chlorine ($HOCl$, OCl^-), chloramines ($NHCl_2$ or NH_2Cl), chlorine dioxide (ClO_2), iodine, or ozone (O_3)—for a specified time period to kill pathogenic organisms.

disinfection by-product – A chemical by-product of the disinfection process. Disinfection by-products are formed by the reaction of the disinfectant, natural organic matter, and the bromide ion ($Br–$). Some disinfection by-products are formed through halogen (e.g., chlorine or bromine) substitution reactions, i.e., halogen-substituted by-products are produced. Other disinfection by-products are oxidation by-products of natural organic matter (e.g., aldehydes—RCHO). Concentrations are typically in the microgram-per-liter or nanogram-per-liter range.

dissolved air flotation – A process in which air is dissolved into water under high pressure and is subsequently released into the bottom of a treatment unit to float solids. On release, the lower pressure in the unit results in the formation of bubbles that collect particles as they rise to the surface. The floated particles are then skimmed for subsequent processing. This process is effective in removing low-density solids and algae.

dissolved oxygen (DO) – The concentration of oxygen in aqueous solution, which is often expressed in units of milligrams per liter. It is usually determined by one of two methods: a dissolved oxygen probe or Winkler titration.

DOC – dissolved organic carbon.

dual-media filter – A filter containing two types of granular filtering media with different sizes and specific gravities to maintain media stratification after backwashing. Anthracite coal and sand are the most commonly used media in dual-media filters.

effective size (ES) – The size opening that will just pass 10 percent (by dry weight) of a representative sample of the filter material; that is, if the size distribution of the particles is such that 10 percent (by dry weight) of a sample is finer than 0.45 mm, the filter material has an effective size of 0.45 mm. It is also called the effective grain size or the d_{10} size. Common units are millimeters.

electrokinetic potential – The electrical difference between the firmly bound water layer surrounding a charged particle and the bulk water solution. This is often called the zeta potential. It can be computed operationally from the electrophoretic mobility. Zeta potential is used in water treatment as a way of optimizing coagulation.

electrophoretic mobility – A measure of the ability of an ion or particle to migrate in an electric field. The electrophoretic mobility is equal to the migration velocity per unit field strength. The units are often expressed as microns per second per volt per centimeter. This term is often used in colloid analysis and coagulation. Electrophoretic mobility is related to the electrokinetic potential on a particle.

equalization basin – *See* equalizing reservoir.

equalizing reservoir – A reservoir interposed in a water supply system (or other hydraulic system) at any point between source and consumer to furnish elasticity of operation to the distribution system so that different portions of the system may be more or less independent of each other. An equalizing reservoir is also called a balancing reservoir.

ES – *See* effective size.

exocellular polymer – Any of several types of macromolecular polymeric materials released extracellularly by microbial cells.

exopolymer – *See* exocellular polymer.

ferric chloride ($FeCl_3$) – An iron salt used as a coagulant in water treatment. The iron has a valence of +3.

ferric sulfate ($Fe_2(SO_4)_3$) – An iron salt used as a coagulant in water treatment. The iron has a valence of +3.

filamentous algae – Algae that grow in a thread-like manner, having either single or branched strands. Filamentous algae may form wiry growths or tangled mats in source waters, and some attach to reservoir walls or to basin walls in water treatment plants.

filter – (1) In the laboratory, a porous layer of paper, glass fiber, or cellulose acetate used to remove particulate matter from water samples and other chemical solutions. (2) The screening, removal, or both of harmful pollutants, as through respirators and dust masks. Many filters are compound specific. (3) A unit process containing a small-diameter medium, such as sand, that is designed to remove particulate matter from a liquid stream. Filters may operate by gravity or by externally applied pressure.

filter agitation – A method used to achieve more effective cleaning of a filter bed. It usually involves using nozzles attached to a fixed or rotating pipe installed just above the filter media. Water or an air–water mixture is fed through the nozzles at high pressure to help agitate the media and break loose accumulated suspended matter. Filter agitation can also be called auxiliary scour or surface washing.

filter aid – (1) Polymer or other chemical added to pretreated water to improve its filtering properties. Typically high molecular weight polymers are used. (2) Diatomaceous earth or perlite filtering material, in the context of precoat filtration.

filter alum – commercial-grade aluminum sulfate, $Al_2(SO_4)_3{\cdot}14\ H_2O$ used as a coagulant chemical at water filtration plants. This chemical typically has a strength of 15 percent to 17 percent as Al_2O_3.

filter boil – *See* boil.

filter cake – The layer of fine material that deposits on the upgradient (upstream) side of any filter. Over time, the filter cake increases the head loss and decreases the performance of the filter. In precoat filtration, the filter cake initially consists of diatomaceous earth or perlite filter aid, materials with good filtration properties. During filter operation, body feed consisting of filter aid is added to maintain good filter cake porosity and thus extend the length of the filter run.

filter element – A device that provides structural support for a septum of porous fabric, which holds the precoat filter cake, and within the element provides for collection of filtered water and its flow out of the filter element into the effluent piping. Filter elements are manufactured as flat filter leaves or cylindrical (tubular) elements. *See* filter leaf.

filter excavation box – A box with four sides but with no top and no bottom. This box is placed in a granular media filter bed and used as a caisson in which a worker can stand and excavate filter media with a shovel to perform an inspection of the filter bed, or of the filter support material, or filter bottom at a particular location within a filter. A filter excavation box would typically have an area of about 10 square feet, to provide sufficient working room for the person who excavates the media from within the box.

filter floor – The concrete floor above the plenum into which filter nozzles have been placed. The filter floor supports the support gravel, if gravel is used, and the filter media.

filter leaf – A flat filter element having a circular or rectangular shape, used in precoat filtration.

filter rate-of-flow controller – A valve or orifice plate on the effluent line from a filter, used to control the flow rate through the filter. A valve can be modulated by a flow-measuring device to select the flow rate desired, whereas an orifice plate has a fixed opening and can control the maximum flow rate through the filter only when the filter is clean.

filter resting – *See* delayed start.

filter ripening – A process by which granular media filter performance gradually improves at the beginning of a filter run as particles are deposited and act as collectors for subsequent particles applied to the filter. Filter ripening can last anywhere from a few minutes to more than an hour depending on the characteristics of the filter influent and the filter design. It is desirable for filters to ripen in less than 15 minutes because filtered water during the ripening process is often wasted.

filter to waste – Filtering and wasting the initial water produced by a filter after it has been backwashed and a new run has been initiated. This is one technique for dealing with the initial high spike of turbidity that results when a filter is restarted after backwashing.

filter underdrain – A system in a filter designed to collect filtered water and evenly distribute backwash water. Typical underdrain designs include perforated pipe systems, precast or plastic blocks, strainers, and porous plates, among others.

filter washtrough – A set of conduits, located above the filter media and open at the top, that are designed to collect filter backwash water. The bottoms of filter troughs should be at an elevation that permits the filter media to expand adequately during backwashing without coming in contact with the bottom of the trough.

fines – The finer-grained particles of a mass of soil, sand, or gravel. When new filter media are placed in a filter bed, the filter is backwashed to stratify the fines at the top of the bed, and then the fines are scraped off to avoid excessive clean-bed head loss.

fixed nozzle – An immovable nozzle used in filter backwash to introduce backwash water or surface wash. Fixed nozzles can be connected to piping in the gravel support layer of a rapid granular filter to provide even distribution of backwash water over the entire area of the filter. Fixed nozzles also can be attached to a piping grid above the filter media to provide surface wash during the backwash cycle.

floc – Collections of smaller particles that have come together (agglomerated) into larger, more separable (settleable, floatable, or filterable) particles as a result of the coagulation–flocculation process.

floc blanket clarifier – An upflow tank in which flocs are formed and retained in a fluidized bed (the *blanket*) of existing flocs prevented from settling by the upflow of the incoming water.

floc retention test – A procedure used to assess the cleanliness of filter media after backwashing, and the amount of floc and dirt contained in a filter bed before backwashing. In the floc retention test, core samples of filter media are shaken in filtered water to remove floc and dirt retained in the filter bed. This test was developed by S. Kawamura, who recommended a scale of values for interpretation of the turbidity resulting from shaking the core samples in water to wash off the floc and dirt.

flocculant aid – A chemical added during coagulation to improve the process by stimulating floc formation or by strengthening the floc so it holds together better. Such a chemical is also called a coagulant aid.

flocculation – The water treatment process following coagulation that uses gentle stirring to bring suspended particles together so they will form larger, more separable clumps called floc. Flocculation also is used to form small flocs appropriate for removal in direct filtration or in a dissolved air flotation clarifier.

flow-normalized head loss – Head loss in an operating filter, with the data adjusted (normalized, or standardized) to a standard rate of filtration. When clean-bed head loss data are normalized for flow and water temperature, data collected from different seasons and at different filtration rates can be compared.

fluidization – The process of suspending a particulate medium such that the particles are mobile and are not continually in contact with each other. For example, filter media are fluidized during backwashing to remove entrapped particulates. *See also* backwash.

fluidization velocity – The upward velocity that is sufficient to fluidize a filter bed.

fluidized – Pertaining to a mass of solid particles that is made to flow like a liquid by injection of water or gas. In water treatment, a bed of filter media is fluidized by backwashing water through the filter. *See also* backwash.

FTW – *See* filter to waste.

G – *See* velocity gradient.

GAC – *See* granular activated carbon.

garnet – A dense granular filter medium (specific gravity of 3.6–4.2) that is the bottom layer in multimedia, triple-media, or mixed-media filters. Garnet is often used in rapid granular filters, with anthracite as the top layer, then sand, then garnet.

gpm/ft^2 – gallons per minute per square foot.

granular activated carbon – A form of particulate carbon manufactured with increased surface area per unit mass to enhance the adsorption of soluble contaminants. Granular activated carbon is used in water filters and fixed-bed contactors in water treatment.

gravity filter – A rapid granular filter of the open type for which the operating level is placed near the hydraulic grade line of the influent and through which the water flows by gravity.

Gt – A dimensionless flocculation parameter obtained by taking the product of the velocity gradient, G in reciprocal seconds, and the time of mixing or flocculation, t in seconds. The Gt product is sometimes used as an overall indication of the mixing or flocculation energy imparted to water in a process.

hardness – A quality of water caused by divalent metallic cations and resulting in increased consumption of soap, deposition of scale in boilers, damage in some industrial processes, and sometimes objectionable taste. The principal hardness-causing cations are calcium, magnesium, strontium, ferrous iron, and manganese ions. Hardness may be determined by a standard laboratory titration procedure or computed from the amounts of calcium and magnesium expressed as equivalent calcium carbonate ($CaCO_3$).

head loss – A reduction of water pressure (head) in a hydraulic or plumbing system. Head loss is a measure of (1) the resistance of a medium bed (or other water treatment system), a plumbing system, or both to the flow of the water through it, or (2) the amount of energy used by water in moving from one location to another. In water treatment technology, head loss is basically the same as pressure drop.

heterotrophic plate count – A bacterial enumeration procedure used to estimate bacterial density in an environmental sample, generally water. Other names for the procedure include total plate count, standard plate count, plate count, and aerobic plate count.

HTH – High test hypochlorite, which is calcium hypochlorite, a disinfectant with approximately 70 percent available chlorine.

hydraulic flocculation – Flocculation attained by the flow of water through a baffled basin or channel. No mechanical stirring is used in hydraulic flocculation.

hydraulic grade line – A line (hydraulic profile) indicating the piezometric level of water at all points along a conduit, open channel, or stream. In a closed conduit under pressure, artesian aquifer, or groundwater basin, the line would join the elevations to which water would rise in pipes freely vented and under atmospheric pressure. In pipes under pressure, each point on the hydraulic profile is an elevation expressed as the sum of the height associated with the pipe elevation, the pipe pressure, and the velocity of the water in the pipe. In an open channel, the hydraulic grade line is the free water surface. Hydraulic profiles are commonly used to establish elevations through the processes that make up a treatment facility under maximum and minimum flow conditions.

hydraulic gradient – The change in static head (pressure) per unit of distance in a pipeline in which water flows under pressure.

hydraulic profile – *See* hydraulic grade line.

hydrolysis – A chemical reaction in which water molecules react with a substance to form two or more substances.

ilmenite – A high-density filtering material having a specific gravity of 4.2–4.6, sometimes used in mixed-media filters. Ilmenite ($FeTiO_3$) is an iron titanium ore associated with hematite and magnetite.

inclined plate settler – A unit constructed of multiple parallel plates, approximately 2 in. (5 cm) apart and oriented at a 45° to 60° angle from the horizontal, to improve settling in a sedimentation basin. The units are placed at the end of a sedimentation basin (across the entire width), and flow travels upward through the plates and exits at the top prior to being discharged from the basin (a configuration called *counterflow*). Co-current and cross flow may also be used. The inclined plates provide a much shorter distance for particles to settle prior to being captured and are often used to maintain particle removal at higher flow rates, thereby reducing the need to construct additional basins.

inclined tube settler – A unit constructed of multiple parallel tubes approximately 2 in. (5 cm) apart and oriented at a 45° to 60° angle from the horizontal, to improve settling in a sedimentation basin. The units are placed at the end of a sedimentation basin (across the entire width), and flow travels upward through the tubes and exits at the top prior to being discharged from the basin. The inclined tubes provide a much shorter distance for particles to settle prior to being captured and are often used to maintain particle removal at higher flow rates, thereby reducing the need to construct additional basins.

infiltration gallery – A horizontal subsurface tunnel for intercepting and collecting groundwater by gravity flow.

initial improvement period – The period of operation after backwashing and the start of a new run, in which the quality of water produced by a granular media filter may deteriorate and then improve until acceptable filter effluent quality is attained. Often referred to as *ripening*.

initial turbidity spike – The high turbidity observed at the start of a filter run after backwashing. *See* initial improvement period.

in-line filtration – *See* direct in-line filtration.

interface turbidity – Turbidity of filtered water at the interface of two layers of filtering material, such as at the interface of the anthracite and sand layers in a dual-media filter. Measurement of interface turbidity can provide plant operators with an advanced indication of possible turbidity breakthrough.

jar test – A laboratory procedure for evaluating coagulation and rapid mix, flocculation, and sedimentation or flotation processes in a series of parallel comparisons.

jetting – *See* boil.

lateral – (1) Directed toward, coming from, or situated on the side. (2) A secondary conduit diverting water from a main conduit for delivery to distributaries. (3) In a granular media filter, the laterals are perforated pipes that carry filtered water to the main collector pipe for discharge from the filter. During filter backwash, laterals distribute the clean wash water into the bottom of the filter box from the supply line. Ideally, the support gravel further distributes the flow of wash water, so a uniform upward flow of wash water can be attained.

lateral floor – A filter underdrain system consisting of parallel pipes (usually plastic or older earthenware designs) coming out of a central header and traversing the width of the filter, with a capped end. These pipes may have holes drilled in them to collect water and allow backwash water out, or there may be nozzles screwed into the pipes for this purpose. The pipes must be rigidly fixed to the filter floor. They may be embedded in concrete or be packed around by stones and gravels. The nozzles and gravels must prevent sand entering the pipes. *See also* nozzle floor, filter underdrain.

launder trough – A trough in a basin designed for evenly distributing or collecting the flow to or from the unit.

L/d – The ratio of granular media filter bed or layer depth divided by effective size of the media.

lime softening – The process of removing water hardness by adding lime to precipitate solids composed of metal carbonates and hydroxides. Clarification may or may not also occur.

liquid alum – liquid commercial-grade aluminum sulfate, $Al_2(SO_4)_3 \cdot 49.6\ H_2O$ used as a coagulant chemical at water filtration plants. This chemical typically has a strength of 7.5 percent to 8.5 percent as Al_2O_3, or about half the strength of dry alum.

log removal – A shorthand term for $\log_{10}$ removal, used in reference to the Surface Water Treatment Rule and the physical–chemical treatment of water to remove, kill, or inactivate pathogenic organisms such as *Giardia lamblia* and viruses. A

1-log removal equals a 90 percent reduction in density of the target organism; a 2-log removal equals a 99 percent reduction; a 3-log removal equals a 99.9 percent reduction; and so on.

MCL – maximum contaminant level.

mechanical flocculation – A flocculation process in which mechanical devices, mixers, or stirrers are used to impart a gentle motion to coagulated water and thus cause formation of floc particles.

media interface – The interface between two different layers of filtering material. Depending on the grain sizes and specific gravities of the materials in each layer, after backwashing a sharp delineation may be noticed at the interface of the layers, or on the other hand, substantial intermixing of the two different filtering materials may occur. If a layer of small filtering material intermixes excessively with a layer of larger filtering material, the small grains may occupy pore spaces between the grains of large material. This can cause excessive clean-bed head loss in the intermixing zone.

metallic coagulant – Various formulations of iron or aluminum, used for chemical coagulation.

MFL – million fibers per liter.

mgad – million gallons per acre per day.

mgd – million gallons per day.

m/hr – meters per hour.

microscopic particulate analysis – The use of any one of several methods to identify and size particles in water. Several versions of analytical methods are available that can identify *Giardia*, *Cryptosporidium*, algae, nematodes, and other microorganisms. Particles from large volumes of water are isolated onto a cartridge filter with a typical pore size of 1 µm. Microscopic particulate analyses are used to assess the performance of water filtration plants, as well as to help identify groundwater that may be under the influence of surface water.

mixed-media filter – A filter containing three filter materials—typically anthracite coal, supported by sand, supported by garnet or ilmenite—that stratify after backwashing according to their respective specific gravities.

ML/d – million liters per day.

monomedia filtration – A method of filtration in which particles are removed with a single media type. Monomedia filters are often deeper than conventional filters, up to 6 ft (1.8 m), and use large-diameter media (from 1.2 to more than 1.8 mm in effective size) to reduce head loss. The deeper monomedia can provide additional storage for collected particles. Often used with ozone, monomedia configurations use anthracite or granular activated carbon as a result of their larger particle size compared to sand.

MPA – *See* microscopic particulate analysis.

mudball – (1) A clump of granular media that stuck together during backwashing of a rapid granular filter, often caused by uneven distribution of backwash water. Because of their size—from that of a pea up to 1 or 2 in. (2.5 to 5 cm) or more in diameter—they sink during backwashing and become very difficult to remove. Surface wash or air wash is usually effective in preventing their formation. (2) A ball of sediment sometimes found in debris-laden flow and channel deposits.

multimedia filter – A filtration device designed to use three or more different types of filter media. The media types usually used are silica sand, anthracite, and garnet or ilmenite sand. This type of filter can sometimes be operated at flow rates higher than 2 gpm/ft^2 (5 m/hr).

natural organic matter (NOM) – A heterogeneous mixture of organic matter that occurs ubiquitously in both surface water and groundwater, although its magnitude and character differ from source to source. Natural organic matter contributes to the color of a water, and it functions as disinfection by-product precursors in the presence of such disinfectants as chlorine (HOCl). Humic substances (e.g., fulvic acid) represent a significant fraction of natural organic matter in surface water sources.

nephelometer or **nephelometric turbidimeter** – An instrument that measures turbidity by measuring the amount of light scattered by particles in a water sample. It is the only instrument approved by the US Environmental Protection Agency to measure turbidity in treated drinking water. It operates by passing light through a sample and then measuring the amount of light deflected (usually at a 90° angle).

nephelometric turbidity unit (ntu, NTU) – A unit for expressing the cloudiness (turbidity) of a sample as measured by a nephelometeric turbidimeter. A turbidity of 1 ntu is equivalent to the turbidity created by a 1:4,000 dilution of a stock solution of 5.0 mL of a 1.000-g hydrazine sulfate ($(NH_2)_2 \cdot H_2SO_4$) in 100 mL of distilled water solution plus 5.0 mL of a 10.00-g hexamethylenetetramine ($(CH_2)_6N_4$) in 100 mL of distilled water solution that has stood for 24 hr at 25 +3°C.

NOM – *See* natural organic matter.

nonionic polymer – A polymer that has no net electrical charge.

normalized head loss – Head loss in an operating filter, with the data adjusted (normalized, or standardized) to a standard rate of filtration and a standard water temperature. When clean-bed head loss data are normalized for flow rate and water temperature, data collected from different seasons and at different filtration rates can be compared.

nozzle – (1) A short, cone-shaped tube used as an outlet for a hose or pipe. The velocity of the emerging stream of water is increased by the reduction in cross-sectional area of the nozzle. (2) A short piece of pipe with a flange on one end and a saddle flange on the other end. (3) A side outlet attached to a pipe by such means as riveting, brazing, or welding.

nozzle floor – A filter floor designed for emplacement of filter nozzles, when nozzles are used in the underdrain system. This is one design that is used for filters employing air scour for media cleaning.

nutating-disk meter – An instrument for measuring the flow of a liquid. Liquid passing through a chamber causes a disk to nutate, or roll back and forth. The total number of rolls is then counted.

OSHA – Occupational Safety and Health Administration.

oxidant – Any oxidizing agent; a substance that readily oxidizes (removes electrons from) something chemically. Common drinking water oxidants are chlorine (Cl_2), chlorine dioxide (ClO_2), ozone (O_3), and potassium permanganate ($KMnO_4$). Some oxidants also act as disinfectants.

ozone – An unstable gas that is toxic to humans and has a pungent odor. It is a more active oxidizing agent than oxygen. It is formed locally in air from lightning or in the stratosphere by ultraviolet irradiation; it inhibits penetration of ultraviolet light from the sun to the Earth's surface. It also is produced in automobile engines and contributes to the formation of photochemical smog. For industrial applications, it is usually manufactured at the site of use. It serves as a strong oxidant and disinfectant in the purification of drinking water and as an oxidizing agent in several chemical processes.

PAC – *See* powdered activated carbon.

PACl – *See* polyaluminum chloride.

particle attachment – Attachment of particles to filter grains in a granular media filter. Most of the particles in filter influent water are small enough to pass through the pores of the filter bed, so removal must occur by attachment rather than by physical straining. *See* physical straining.

particle count – The results of a microscopic examination of treated water by a particle counter that classifies suspended particles by number and size.

particle counter – An instrument that measures the number of particles within a given size range. These instruments have been used to optimize the performance of filters in water treatment plants.

Partnership for Safe Water – A volunteer initiative by the US Environmental Protection Agency, the Association of Metropolitan Water Agencies, the Association of State Drinking Water Administrators, the National Association of Water Companies, the American Water Works Association, and the Awwa Research Foundation to optimize water treatment to better protect the public from *Cryptosporidium* oocysts. The program began in September, 1995, and commits participating water utilities to a four-phase self-assessment program for optimizing their operations. Phase I of the program consists of the agreement to participate and requires the water supplier to have met the Surface Water Treatment Rule for at least 6 months and to pledge to complete phases II and III of the partnership. Phase II consists of data collection, and Phase III consists of a comprehensive water treatment self-assessment package. Phase IV is a third-party assessment via the US Environmental Protection Agency Composite Correction Program.

percentile – A point on a frequency distribution indicating what percentage of values are less than or equal to the value being considered. For example, the tenth percentile is the point in a cumulative frequency distribution for which 90 percent of the observations are greater and 10 percent are lesser or equal. Someone who scored in the 78th percentile on a test would have a higher grade than all but 22 percent of those taking the test.

percentile data – The percentile values that are obtained after data have been arranged in ascending or descending order so that percentiles can be calculated. Percentile data for online filtered water turbidity results or online filtered water particle counts can be used as a means of evaluating filter performance. Use of percentiles enables one to analyze a large mass of data in a rapid fashion and is a good way to learn about the frequency and magnitude of extremes or peaks in turbidity and particle counts.

perlite – (1) A form of volcanic rock that, when processed, yields various grades of filter media. (2) The filter media so obtained. Perlite is used in precoat filtration.

permeability – A measure of the relative ease with which water flows through a porous material. A sponge is very permeable; concrete is much less permeable. Permeability is sometimes called *perviousness*.

pH – A measure of the acidity or alkalinity of a solution, such that a value of 7 is neutral; lower numbers represent acidic solutions and higher numbers, alkaline solutions. Strictly speaking, pH is the negative logarithm of the hydrogen ion concentration (in moles per liter). For example, if the concentration of hydrogen ions is 10^{-7} moles per liter, the pH will be 7.0. As a measure of the intensity of a solution's acidic or basic nature, pH is operationally defined relative to standard conditions that were developed so that most can agree on the meaning of a particular measurement. The pH of an aqueous solution is an important characteristic that affects many features of water treatment and analysis.

physical straining – Removal of particles in a granular media filter bed caused by the inability of a particle to pass through a pore space in the bed that is smaller than the particle itself.

piezometer – An instrument for measuring pressure head in a conduit, tank, or soil by determining the location of the free water surface.

piezometric tube – A tube open at both ends, with one end that is placed into a liquid flow system, such as a filter bed. The height of the water in the tube measures the energy in the liquid due to pressure (pressure head) and elevation (elevation head). The difference in the elevation of the water surface over an open, gravity filter and the elevation of water in a piezometric tube that has an opening within the filter bed is the head loss within the filter at that location in the filter.

pilot filter – A small tube containing the same media as plant filters and through which coagulated plant water is continuously passed, with a recording turbidimeter continuously monitoring the effluent. The amount of water passing through the pilot filter before turbidity breakthrough can be correlated to the operation of the plant filters under the same coagulant dose.

plain sedimentation – The sedimentation of suspended matter without the use of chemicals or other special means.

plant optimization – In the context of this handbook and in the context of the Partnership for Safe Water, the continuous effort to improve filtered water quality and plant performance so that filtered water turbidity and particle counts (if the latter are measured) are as low as the plant can reasonably attain through the efforts of the operating staff.

plate settler – *See* inclined plate settler.

plenum – The space under a filter floor where filtered water is collected before it exits through the header, and where air or water or both can be introduced and then flow upward through the filter nozzles into the filter bed.

polyaluminum chloride (PACl) $Al(OH)_x(Cl)_y(SO_4)_z$ with y typically from 1 to 2.5 and z from 0 to 1.5 – A hydrolyzed form of aluminum chloride ($AlCl_3$) that is used for coagulation, typically in low-turbidity or cold waters. As a result of its polymeric form, lower dosages can be used compared to metal coagulants.

polymer – A synthetic organic compound with high molecular weight and composed of repeating chemical units (monomers). Polymers may be polyelectrolytes (such as water-soluble flocculants), water-insoluble ion exchange resins, or insoluble uncharged materials (such as those used for plastic or plastic-lined pipe).

porosity – The ratio of void volume to bulk volume in a sample of rock, sediment, or filter pack material.

potassium permanganate ($KMnO_4$) – A substance in the form of dark purple crystals used as an oxidant in drinking water treatment. Potassium permanganate is used for taste-and-odor control and for iron and manganese removal. Unlike other oxidants, potassium permanganate has not been associated with the production of disinfection by-products.

powdered activated carbon – Activated carbon composed of fine particles and providing a large surface area for adsorption. Powdered activated carbon is typically added as a slurry on an intermittent or continuous basis to remove taste-and-odor-causing compounds or trace organic contaminants and is not reused.

precoat – A very fine granular filter medium, such as diatomaceous earth or perlite, applied (usually by slurry) to a retaining membrane of fabric surface prior to a service run. At the end of each service run, the precoat medium is rinsed off and disposed of prior to application of a new precoat to the filter septum.

precoat filtration – A process designed to remove particles by applying the water to be treated to a membrane or fabric coated with a very fine granular medium, such as diatomaceous earth or perlite. *See also* diatomaceous earth, perlite, precoat.

precoating – The process of applying a precoat to a support surface called a septum. *See also* precoat.

preliminary filter – A filter used in a water treatment plant for the partial removal of turbidity prior to final filtration. Such filters are usually of the rapid type, and their use allows final filtration at a more rapid rate or reduces or eliminates the necessity of other preliminary treatment of the water. A preliminary filter is also called a contact filter, contact roughing filter, primary filter, or roughing filter.

preoxidation – Application of an oxidant prior to a water treatment step. Better usage is to specify where the oxidant is added, e.g., source water oxidation or prefiltration oxidation.

pressure filter – (1) An enclosed vessel having a vertical or horizontal cylinder of iron, steel, wood, or other material containing granular media through which liquid is forced under pressure. (2) A mechanical filter for partially dewatering sludge.

pressure filtration – A filtration process in which the media are completely enclosed and the operation takes place under pressure greater than 1 atmosphere on the influent side of the filter. Typically, pumps provide the pressure, but raw water piped to the pressure filter from a higher source may have sufficient pressure that pumping is not needed.

pretreatment – At a plant employing rapid rate granular media filtration, pretreatment consists of all processes that are used to prepare the source water so that it can be filtered effectively, yielding the desired water quality.

productivity – As a measure of filter performance, productivity is the total number of gallons of water produced per square foot of filter area during a filter run (cubic meters of water per square meter of filter area). Net productivity is determined by subtracting the volume of water used to backwash the filter from the total water production to determine net water production, and then calculating the volume produced per unit area.

PVC – Polyvinyl chloride, an artificial monomer made from vinyl chloride and used in pipes, sheets, and vessels for transport, containment, and treatment in water facilities.

quality assurance – (1) An overall system of management functions designed to provide assurance that a specified level of quality is being obtained. It can be thought of as being composed of quality control (QC) and quality assessment (QA). (2) The management of products, services, and production or delivery processes to ensure the attainment of operational performance, product, or both in keeping with quality requirements.

quality control – A system of functions carried out at a technical level for the purpose of maintaining and documenting quality. It includes such features as personnel training, standard operating procedures, and instrument calibrations.

rate controller – *See* filter rate-of-flow controller.

reactor–clarifier – A device in which both flocculation and particle separation occur. The "reaction" occurs when water to which coagulants have been applied is flocculated in a conically shaped compartment, with mechanical mixing, in the center of the clarifier. The flocculated water flows outward into the settling zone, in which solids settle and clarified water is collected at the surface. The advantage of using reactor–clarifiers—as opposed to a separate flocculator and settling tank—is that area requirements for treatment can be reduced. These devices enhance floc-to-floc contact to form more separable flocs.

recarbonation – The introduction of carbon dioxide (CO_2) into the water, after precipitative softening using excess lime for magnesium removal, to lower the pH of the water.

recycle – To use something over again. At water filtration plants, recycle of residuals streams such as spent backwash water typically involves returning the residual stream to the beginning of the treatment train and blending it with influent raw water. In some cases, residual streams are treated before being recycled.

restratification – The act of returning a multimedia filter bed to its stratified condition, with larger filtering material on the top layer and the smaller filtering material beneath. Restratification is accomplished by backwashing the filter and while the bed is fluidized, gradually reducing the rise rate as the fluidization ceases and the filter bed settles back to its position at rest.

rewash – *See* filter to waste.

rising rate or **rise rate** – In filter operation, this is the backwash rate. In a granular media filter box, when backwash water only is used (no air scour and no surface wash) the backwash rate is literally the rate of rise of the water between the top of the filter media and the bottom of the wash-water trough. In a solids-contact unit or reactor–clarifier, the rise rate is the rate of operation in the plane at the separation line. Rise rates are typically expressed in units of gallons per minute per square foot or meters per hour.

rotary surface washer – A device used to clean the surface of filter media, typically used in the first stages of a backwash cycle. A rotary surface washer has arms connected radially to a mounted rod and rotates in a plane parallel to the surface of the media. The rotating arms, typically located less than 6 in. (15 cm) above the surface of the media to be cleaned, rotate as a result of water pressure exerted when water flows into the arms and is forced out, downward into the media surface, through small openings along one side of each arm.

roughing filter – *See* preliminary filter.

saturator – In the dissolved air flotation process, a pressure vessel used to produce clarified or filtered water saturated typically at 60 to 80 psi (420 to 560 kPa). When the high pressure is released on entry to the DAF clarifier, a fine cloud of air bubbles forms.

SCADA – Supervisory control and data acquisition.

schmutzdecke – The layer of solids and biological growth that forms on the top of a slow sand filter, aiding in the removal of turbidity without chemical coagulation.

Secchi disk – A circular metal plate, 8–12 in. (20–30 cm) in diameter, that is painted in black and white quadrants. A Secchi disk is used to measure the clarity of water and determine visible light extinction coefficients.

sedimentation – A treatment process using gravity to remove suspended particles.

septum – The fabric that coats the filter element frame and supports the precoat filter cake. Septum materials typically are woven of synthetic fiber or fine stainless steel wire.

sequester – To keep a substance (e.g., iron or manganese) in solution through the addition of a chemical agent (e.g., sodium hexametaphosphate) that forms chemical complexes with the substance. In the sequestered form, the substance cannot be oxidized into a particulate form that will deposit on or stain fixtures. Sequestering chemicals are aggressive compounds with respect to metals, and they may dissolve precipitated metals or corrode metallic pipe materials.

serpentine flow – A back-and-forth pattern used in chlorine contact basins for wastewater treatment, and in some flocculation basins. Serpentine flow basins, properly designed, can attain a very close approximation to plug flow.

set point – The position at which a process controller is set. The set point is the same as the desired value of the process variable.

shear forces – Forces acting on floc and particles attached to filter media grains. Flocs and particles that are attached to filter media grains in an operating filter are able to withstand the existing shear forces that would tear them away from the filter grains at that moment. If, however, the interstitial velocity within the filter bed is increased, the shear forces increase, and the previously attached flocs may be detached from the filter grains. Shear forces increase when the rate of filtration is increased, and as the pores of the filter bed are filled with flocs, leaving a smaller cross-sectional area for water flow and thus increasing the interstitial velocity.

short-circuiting – A hydraulic condition in a basin in which the actual flow time of water through the basin is less than the design flow time (i.e., less than the tank volume divided by the flow).

sieve analysis – An analytical procedure used to determine the size distribution of filtering materials.

silica sand – A filtering material commonly used in granular media filters.

slow sand filter – A filter consisting of a sand bed and underdrain, through which water typically is filtered at a rate of about 0.04 to 0.12 gpm/ft^2 (0.1 to 0.3 m/hr) with no chemical pretreatment.

slow start – A technique used to reduce the peak and duration of the turbidity spike when a filter is placed into service after being backwashed. In the slow start, the filter is brought into service at a fraction of the full filtration rate and the rate is gradually increased using small, incremental rate increases and multiple rate increase steps. This reduces the magnitude of each individual rate increase and thus has the potential to cause less disturbance to any floc or particles that may be deposited in the filter bed.

sludge blanket clarifier – A clarifier designed to maintain a zone in which sludge accumulates and concentrates. As flocculated water passes through the sludge blanket, influent flocs attach to the flocs present in the sludge blanket, promoting efficient clarification (sometimes referred to as a floc blanket clarifier).

slurry – A mixture of liquid and solids that can be pumped and transported by liquid-handling equipment. Examples are lime slurry used to raise pH in precipitative lime softening and diatomaceous earth or perlite slurry used in precoat filtration.

solids contact clarifier – A unit process in which both flocculation and particle separation occur. Coagulated water is passed upward through a solids blanket, allowing flocculation and particle separation to take place in a single step. The solids blanket is typically 6 to 10 ft (2 to 3 m) below the water surface, and clarified water is collected in launder troughs along the top of the unit. Solids are continually withdrawn from the solids blanket to prevent undesired accumulation. *See also* launder trough.

specific ultraviolet absorbance (SUVA) – The ultraviolet absorbance at 254 nanometers (measured in units of per meter) divided by the dissolved organic carbon concentration (in milligrams per liter). Typically, a specific ultraviolet absorbance less than 3 L/m-mg corresponds to largely nonhumic material, whereas a specific ultraviolet absorbance in the range of 4–5 L/m-mg corresponds to mainly humic material. Because humic materials are more easily removed through coagulation than nonhumic substances, higher specific ultraviolet absorbance values should indicate a water that is more amenable to enhanced coagulation.

spent wash water – Dirty backwash water discharged from a filter during backwashing.

sphericity – For filter media, a measure of the bead roundness or "whole bead" count of beads in an ion exchange resin product or other bead-form absorbent or filter medium.

stratification – The layering of granular media on the basis of grain size.

streaming current – A current gradient generated when a solution or suspension containing electrolytes, polyelectrolytes, or charged particles passes through a capillary space, as influenced by adsorption and electrical double layers. This phenomenon is used in monitoring and controlling coagulation and flocculation processes. Streaming current is typically measured with online streaming current monitors or streaming current detectors (commercial terms often used interchangeably for streaming current instruments).

subcritical fluidization backwash – A procedure to clean a filter in which backwash water is added at a rate that does not completely fluidize the bed, i.e., the particles are not freely supported by the liquid. Under a subcritical fluidization regime, the media are in greater contact, potentially "scouring" difficult-to-dislodge particles. When combined with air, this flow regime can implement a collapse pulsing backwash. Subcritical fluidization may be followed by full fluidization to allow the scoured particles to be released from the media bed for complete cleaning.

subfluidizing velocity – A backwash rise rate insufficient to fluidize granular filter media.

supernatant – Located above or on top of something else, such as the supernatant water located above the bed of filter media.

support gravel – The layer or layers of gravel that support the filtering material in a granular media filter.

surface sweep – *See* rotary surface washer.

surface wash – *See* filter agitation.

surface wash nozzles – Nozzles on a fixed grid of pipes or on rotary surface washers. The nozzles are designed to deliver high-velocity jets of water onto the surface of the filter media and into the media after it has been fluidized during backwashing. These nozzles are used to provide auxiliary scour and aid in cleaning dirt from the filter media.

SUVA – *See* specific ultraviolet absorbance.

THM – trihalomethanes.

TOC – *See* total organic carbon.

total alkalinity – *See* alkalinity.

total organic carbon (TOC) – A measure or the concentration of organic carbon in water, determined by oxidation of the organic matter into carbon dioxide.

tube settler – *See* inclined plate settler.

turbidimeter – An instrument that measures the amount of light scattered by suspended particles in a water sample, with a standard suspension used as a reference. If the scattered light is measured at an angle of 90° to the incident light, the instrument is a nephelometer. *See also* nephelometric turbidimeter.

turbidity – (1) A condition in water caused by the presence of suspended matter, resulting in the scattering and absorption of light. (2) Any suspended solids that impart a visible haze or cloudiness to water and can be removed by treatment. (3) An analytical quantity, usually reported in nephelometric turbidity units, determined by measurements of light scattering. The turbidity in finished water is regulated by the US Environmental Protection Agency.

turbidity breakthrough – Passage of turbidity all the way through a filter such that a measurable change in turbidity can be detected. In the filtration process, a filter ripening period occurs in which turbidity declines, followed by an operating time when the turbidity is typically less than the goal value and is relatively stable, followed by a steady increase. Under ideal conditions, terminal head loss should precede breakthrough, thereby protecting the filtered water quality from a sharp increase in particulates.

turbidity spike – An abrupt increase in turbidity, generally used to describe a sudden rise of filtered water turbidity.

turbidity unit – A measure of the degree of turbidity (cloudiness) of the water. Turbidity units typically also include the name of the method by which turbidity was measured or the standard on which the turbidity is based. *See also* nephelometric turbidity unit.

UC – *See* uniformity coefficient.

UFRV – *See* unit filter run volume.

ultraviolet (UV) absorbance at 254 nanometers (UV-254 or $\mathbf{UV_{254}}$) – A measure of water's ultraviolet absorption at a wavelength of 254 nanometers. This value is an indirect measure of compounds containing double bonds (including, but not limited to, aromatic compounds). Therefore, this measurement has been considered representative of the humic content of natural organic matter, as well as acting as a surrogate for disinfection by-product precursors.

underdrain – *See* filter underdrain.

uniformity coefficient (UC) – A measure of how well a sediment is graded. The coefficient may be calculated as follows:

$$\text{uc} = d_{60}/d_{10}$$

Where:

d_{60} = the grain size, in millimeters, for which 60 percent (by weight) of the sediment's grains are finer, as shown on the sediment's grain size distribution curve

d_{10} = the grain size, in millimeters, for which 10 percent (by weight) of the sediment's grains are finer, as shown on the sediment's grain size distribution curve

unit filter run volume (UFRV) – The volume of water that is processed through a filter in a single filter run between backwashes. The purpose of determining the unit filter run volume is to compare the throughput of a filter under different filtration rates. Although filter run times will decrease as filtration rate increases, the unit filter run volume may stay the same or increase because of the higher filtration rate.

USEPA – United States Environmental Protection Agency.

UV absorbance – *See* ultraviolet (UV) absorbance at 254 nanometers (UV-254 or UV_{254}).

velocity gradient – A measure of the mixing intensity in a water process. The velocity gradient, which is expressed in units per second, is dependent on the power input, the viscosity, and the reactor volume. Very high velocity gradients (greater than 300 per second) are used for complete mixing and dissolution of chemicals in a coagulation process, whereas lower values (less than 75 per second) are used in flocculation to bring particles together and promote agglomeration.

velocity of minimum fluidization – The minimum backwash velocity or rise rate needed to fluidize a bed of granular media in a filter.

viscosity – A measure of the capacity of a substance to internally resist flow. Viscosity is the ratio of the shear stress rate to the rate of shear strain. Absolute viscosity is expressed in units of stress-time.

$$\mu = \tau(du/dy)$$

μ = viscosity, in pound force seconds per foot squared (newton seconds per meter squared or pascal seconds)

τ = shear stress, in pound force per foot squared (newtons per meter squared)

du/dy = rate of shear strain, rate of angular deformation, or velocity gradient, in 1/second

Kinematic viscosity is absolute viscosity/water density

$$\nu = \mu/\rho$$

ν = kinematic viscosity, in units of square feet per second or square centimeters per second

ρ = density in slugs per cubic foot or kilograms per cubic meter

Water at 68°F (20°C) has a viscosity of 0.0208 pound force seconds per foot squared (1.002×10^{-3} pascal-seconds, or 1.002 centipoise).

V_{mf} – *See* velocity of minimum fluidization.

wash water – Water that is used to clean a unit process. Wash water is typically identified as backwash water and is associated with the wastewater resulting from the cleaning of filter media to remove attached particles.

wash-water trough – A trough placed above filter media to collect backwash water and carry it to the drainage system.

WEF – Water Environment Federation.

weir – A dam-like device with a crest and some side containment of known geometric shape placed perpendicular to flow to measure or control the flow rate of water in a channel.

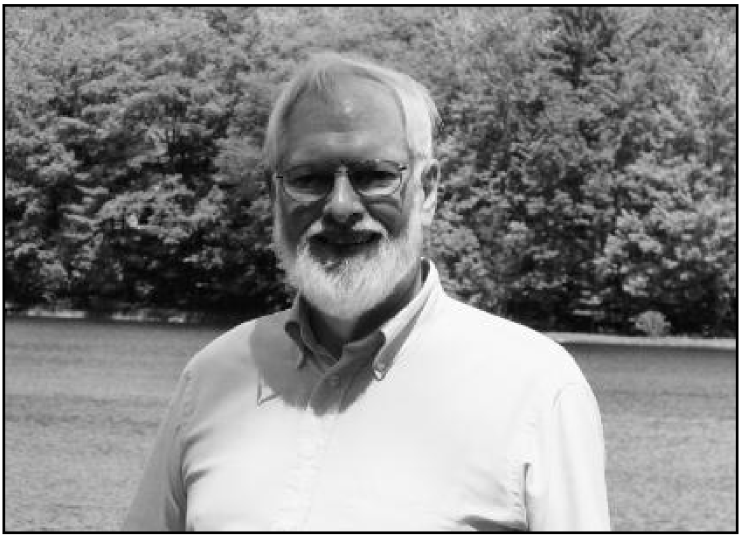
zeta potential – *See* electrokinetic potential.

90% values – 90th percentile values, typically the value exceeded by 10 percent of the data, that is, the value for which 90 percent of the data are equal to or less than.

Index

Note: *f.* indicates figure; *t.* indicates table.

About the Author



Gary S. Logsdon, PE, received his Bachelor of Science in Civil Engineering and Master of Science in Sanitary Engineering from the University of Missouri and his Doctor of Science in Environmental Engineering from Washington University. He is a retired US Public Health Service (USPHS) Commissioned Officer. For 19 years, Logsdon was detailed from the USPHS to the US Environmental Protection Agency, where he performed and directed research on drinking water treatment with a strong emphasis on water filtration. Following retirement, he worked with Black & Veatch Engineers for more than 14 years and directed water filtration pilot-plant studies; he also evaluated water filtration plant operations before retiring again.

Logsdon is a Board Certified Environmental Engineer with the American Academy of Environmental Engineers, an Honorary Member of AWWA, and recipient of AWWA's A.P. Black Research Award. The author believes that persons who operate and manage water treatment plants provide important public health protection to those who are served by water systems. This book was prepared with the goal of assisting water treatment plant operators and managers to do their best as they strive to produce safe drinking water.