Filter Maintenance and Operations Guidance Manual

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Filter Maintenance and Operations Guidance Manual

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FOREWORD

The Awwa Research Foundation is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of a Strategic Research Plan, the Research advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The foundation also sponsors research projects through the unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various joint research efforts with organizations such as the U.S. Environmental Protection Agency, the U.S. Bureau of Reclamation, and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the foundation's staff and large cadre of volunteers who willingly contribute their time and expertise. The foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering firms. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The foundation's trustees are pleased to offer this publication as a contribution toward that end.

Water utilities are facing increasingly stringent water treatment regulations and public health goals for known contaminants. In order to meet tougher regulations, it is imperative that water utilities

optimize unit processes. Conventional rapid gravity filtration is the heart of the water treatment processes. The Foundation undertook this research project to provide guidance to filter operators and engineers in order to optimize the operation and maintenance of conventional filtration systems.

Edmund G. Archuleta, P.E.
Chair, Board of Trustees
Awwa Research Foundation

James F. Manwaring, P.E.
Executive Director
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EXECUTIVE SUMMARY

INTRODUCTION

Customers, municipal authorities, and regulators demand safe drinking water. Failure to provide it can have serious consequences to the health of the local community, and the reputation of a water supplier can be damaged. Water plant operators have long worked in a world where they must comply with legislative requirements. Now they also need to demonstrate that they understand best operating practice for filters, and that they have benchmarked their filtration plants against best practice and have developed their own documented best operating procedures. This manual provides a tool kit of practical resources that enable water suppliers to get the best out of their plants and the people that operate them. In developing procedures based on this manual, water suppliers can demonstrate to their customers and managers, and to regulatory authorities that they provide good customer service by reducing the risk of producing poor quality water.

This manual was developed to provide guidance on techniques and procedures for maintenance and operation of water filtration plants and to provide background information and advice on where to find additional information. It was written with the intention of strengthening and promoting the enthusiasm and initiative shown by plant operators. The manual is intended to be a practical complement to other readily available excellent reference sources such as AWWA Manuals of Water Supply Practice and other AWWA books and journals. Awwa Research Foundation reports also serve as reference in this manual, although they may be available for purchase for a period of time, but become unavailable after the supply is exhausted.

This manual is a reference document. It is a compilation of ideas, concepts, and practical approaches to treatment, operations, and maintenance that have been compiled to assist the operator in doing tasks related to maintaining and operating a water filtration plant using granular media filters. It provides filter plant operators with a number of practical tools to determine current conditions and performance, identify deficiencies, and optimize the operation and maintenance of the rapid gravity filtration or pressure filtration process. Many of the ideas contained in this manual were provided by water utilities and have been proven in actual practice by utilities. Other sources of information for this manual include peer-reviewed literature and AWWA conference proceedings. Finally, some of the concepts in this manual were provided by the Project Advisory Committee, the Technical Review Group

members who advised the Project Team, and the Project Team members at Black & Veatch Corporation and Thames Water Utilities, Ltd.

This manual is not a document that must be read from cover to cover, as one would read a good novel or a biography. It is not a universal manual for all kinds of filtration, as it does not cover the topics of slow sand filtration, diatomaceous earth filtration, or membrane filtration. It is not the only book or information source a water treatment plant operator will need to do his or her job. Finally, this manual is not a substitute for the solid training and education needed by filtration plant operators. Instead, it is a tool for the trained and educated operator.

In the United States and Canada, three dozen water utilities participated in sharing operating and maintenance knowledge in the first phase of the project, so a draft manual could be developed in Phase 1 of the project. The treatment plants represented cover the spectrum of raw waters encountered in North America and include both large and small water systems. Information on 49 filtration plants was submitted, covering a very wide range of source water and process design, as some participating water utilities had more than one filtration plant. Most plants treated surface water, with quality ranging from nearly pristine to very turbid. Plants employing chemical coagulation and plants using lime softening are included in the study.

The 600+ page draft guidance manual was evaluated in the field by over forty Participating Water Utilities, by the AWWARF Project Advisory Committee, and by Thames Water at several of their plants in Phase 2. The very extensive field review of the manual text and procedures improved the final product by ensuring that the water utility perspective was maintained in the document.

CONTENTS OF THE MANUAL

The focus of the manual is on rapid gravity and pressure granular media filtration. Filtration through beds of granular media is ineffective, however, if water is not properly pretreated. For this reason, two chapters of the manual deal with pretreatment, with the emphasis on maintaining effective pretreatment so the filters will work as intended. The manual has 16 chapters, and about 600 pages, of which approximately 100 are figures. The figures illustrate filter inspection procedures, tools used for inspecting filters and measuring backwash expansion, process diagrams, and filter media. Included are numerous examples of conditions operators hope they will never see in their plant, such as big mudballs, an upset filter bottom, a blown out filter bottom, gravel migration, leakage of sand into the filter plenum, a failed nozzle and underdrain system, and calcium carbonate cementation of media and pipes. Pictures

are included to show how to carry out procedures, to illustrate special tools and equipment, and to depict problem situations so operators will recognize the problems in their plant, if the problems do occur. The manual is organized in the following manner:

CHAPTER 1. INTRODUCTION TO MANUAL: This tells the user what the manual is and what it is not, and states that the manual was produced for water treatment plant operators and managers, state drinking water agency staff who interact with and provide technical assistance to water utilities, trainers who work with plant operators, and engineers who design filtration plants.

CHAPTER 2. HOW TO USE THIS MANUAL: Chapter 2 explains how to use this guidance manual as a reference document, with emphasis on troubleshooting and solving treatment problems. Symptoms of problems that may be encountered at filtration plants are listed, with possible causes and page numbers in the manual where the user can find advice that may help in solving the problems. The manual contains approximately a dozen pages that list symptoms or problems with possible causes and references to portions of the manual that address those specific issues. Filter turbidity profiles (graphs of filtered water turbidity versus time) provided by the Pennsylvania Department of Environmental Protection are included to aid operators in the interpretation of filter behavior.

CHAPTER 3. THE REGULATORY ENVIRONMENT: In Chapter 3 readers will find a brief summary of regulations related to water filtration. The regulations discussed are those of the United States Environmental Protection Agency, Canadian Provinces, the World Health Organization, Europe and the United Kingdom, Australia, and New Zealand.

CHAPTER 4. FILTER OPERATION AND OPTIMIZATION: Chapter 4 has daily operational tips and methods of optimizing filter operation. This chapter deals with routine filter operation, with operation during conditions that stress filter performance, and summarizes treatment strategies for water quality episodes, as reported by participating water utilities. The need for careful management of filtration plant operations is discussed, and emphasis is placed on increasing filtration rates in a way that impairment of filtered water quality is minimized.

CHAPTER 5. FILTER PERFORMANCE MONITORING: Monitoring instruments and meters, sampling locations and configurations as well as monitoring frequency, and data handling/trend analysis

are covered in this chapter. Measurement of turbidity, particle count, head loss, and rate of flow are discussed. Filter performance monitoring is necessary because filtration is a dynamic process, with conditions changing over time. Operators need current information on the performance of filters so they can make intelligent decisions to manage the filtration process and the treatment plant.

CHAPTER 6. BACKWASH MANAGEMENT AND OPTIMIZATION: Chapter 6 focuses on a key aspect of filter operation that has to be done right in order to maintain the physical facilities and to produce good water. Both air assisted backwash and backwash with auxiliary water scour are covered. Failure to backwash filters effectively can lead to problems with filtered water quality and to problems with the filter beds. Expensive repairs can result from improper backwashing, so an entire chapter is devoted to backwashing filters.

CHAPTER 7. FILTER RIPENING AND CONTROLLING THE INITIAL TURBIDITY SPIKE: The first minutes or hours of a filter run may be the most challenging from the perspective of filtered water quality, so this chapter provides information on how to quickly attain high-quality filtered water. Techniques include filter to waste, gradual start, delayed start, adding coagulant or polymer to backwash water, and adding coagulant or polymer to pretreated water entering the filter box when it is refilled after backwash. Typically water utilities that reported they were able to maintain filtered turbidity below 0.3 nephelometric turbidity units (ntu) when starting a filter after backwash also reported that they used a combination of the above-mentioned procedures rather than just one of the procedures described in Chapter 7. These procedures have been demonstrated to improve filtered water quality, although results have been plant-specific for some of the techniques discussed. Therefore this chapter urges that methods of controlling the initial turbidity spike be evaluated with care if they are not being used at present, and if appropriate, drinking water regulatory officials may need to be included in discussions and planning for trials of the techniques.

CHAPTER 8. PRETREATMENT: CHEMICAL DOSAGE, SELECTION, AND MIXING: Chapter 8 explains how to determine and maintain correct chemical pretreatment, as chemical pretreatment has a very substantial effect on the quality of water produced by rapid rate filtration of water through a bed of granular filtering materials. This chapter presents information on a variety of approaches for determining and for monitoring the efficacy of chemical dosages to attain effective coagulation and lime softening process performance. These include jar tests, historical charts on historical water quality and

dosage, zeta potential, streaming current instruments, dosage based on pH or alkalinity, pilot filters, visual observation, and measurements of natural organic matter (typically UV absorbance). Generally the water utilities participating in this manual development project reported that they use more than one technique for assessing the efficacy of coagulation and determining the appropriate coagulant dosage.

CHAPTER 9. PRETREATMENT: FLOCCULATION AND CLARIFICATION: This chapter discusses approaches to flocculation, and describes operation and maintenance of sedimentation basins and dissolved air flotation clarifiers. The importance of well-baffled flocculation basins is emphasized as a means of attaining effective flocculation.

CHAPTER 10. FILTER INSPECTION AND MAINTENANCE: Much of the chapter is devoted to procedures for inspection of filters and filter media. Methods for probing media, measuring media expansion during backwash, and evaluating the cleanliness of filter media before and after backwash are presented. Techniques for chemical cleaning of media are discussed. This chapter covers much of the information presented in the Filter Surveillance Video developed by the American Water Works Association. Use of the written material in Chapter 10 in conjunction with the video would be a very effective way for water utility personnel to develop and carry out plans for filter inspections.

CHAPTER 11. FILTER MEDIA CHARACTERISTICS, SELECTION, AND REPLACEMENT: Chapter 11 discusses filter media properties, tests for properties of filter media, and media replacement. This information is provided so water utility employees will have a greater understanding of filter material properties and the significance of those properties in the filtration process.

CHAPTER 12. QUALITY CONTROL AND INSTRUMENTATION ISSUES: Because of the necessity that monitoring data be accurate, Chapter 12 contains information operators need on how to maintain and calibrate instruments and monitoring devices so the information they are using as the basis for making operating decisions will be valid information. Among the instruments and devices covered in this chapter are on-line turbidimeters, on-line particle counters, on-line pH meters, streaming current instruments, flow meters, and head loss instrumentation.

CHAPTER 13. CASE STUDIES: Manual users will find text on water utility experiences related to various aspects of pretreatment and water filtration in Chapter 13. This information supplements the material presented in earlier chapters. The following case studies are included in this chapter:

- Addition of Alum to Settled Water Flowing into Filter Box: summarizes Greenville Water System's engineering study for reducing the initial turbidity spike.
- Determining Profiles and Contours of Filter Media and Support Materials in Filter Beds: describes procedures used and data collected at Austin, Texas; Calgary, Alberta; Modesto Irrigation District, California; and Southern Nevada Water Authority, Nevada.
- Monitoring Water Quality within the Filter Bed: presents data on monitoring turbidity within the filter bed to provide early warning for impending turbidity breakthrough at Swift Creek Water Treatment Plant and the Modesto Irrigation District.
- Filter Inspection and Maintenance at a Lime Softening Plant: reviews filter rehabilitation work and maintenance procedures used the Elm Fork Water Treatment Plant operated by Dallas Water Utilities.
- Monitoring and Review of Rapid Gravity Filter Performance Using On-line Particle Counters at Hope Valley Water Treatment Plant, Adelaide, South Australia: this study demonstrated that prechlorination resulted in lower filtered water particle counts when it was used.
- Implementing Optimization at Filtration Plants: optimization programs are described, and results are presented for the Elm Fork Water Treatment Plant at Dallas, Texas; a 2.0 mgd (7.6 ML/d) direct filtration plant at Leavenworth, Washington; and the conventional filtration plant at Fort Collins, Colorado.
- Chemical Cleaning of Filter Media: reviews technique used to clean filter media at a lime softening plant at Chanute, Kansas.
- Application of Streaming Current Instruments at Philadelphia: experiences, both positive and negative, with use of streaming current instruments at Philadelphia's Samual S. Baxter Water Treatment Plant are described.
- Rehabilitation of Filters at Brick Utilities: experience with a filter rehabilitation program is reviewed.
- Case Study of Modifications to Air Scour System: operational difficulties led to improvements in filters equipped with air scour.

- Improved Filtered Water Turbidity by Continuous Dosing of Supplementary Coagulant at Thames Water Utilities: supplemental dosing of ferric chloride at the weir where clarified water was discharged to the filter flume improved filtered water turbidity at the Shalford Works.
- Shortening Filter Ripening Time by Short Term Additional Coagulant Dosing: initial turbidity spike can be reduced by adding ferric chloride when the filter box is refilled, in full-scale study at Thames Water Utilities' Shalford Works.
- Coring of Dual Media Leads to Identification of Cause of Media Loss: apparent loss of filter media from beds was revealed instead to be a failure to place all of required media during construction.

CHAPTER 14. EQUATIONS AND EXAMPLE PROBLEMS, AND JAR TEST PROCEDURES: Equations related to filtration are presented and used in Chapter 14, with solutions worked out step by step in metric units and in foot-pound-second units. In many instances, these equations and example problems will be of interest to engineers who work with water filtration rather than to plant operators. This chapter also presents an extended discussion of jar test information and procedures that operators may find useful when they evaluate water treatment using jar tests.

CHAPTER 15. RESEARCH NEEDS: Ideas about research needed for various aspects of the maintenance and operation of granular media filters are given in Chapter 15.

GLOSSARY: The Glossary lists commonly used water treatment terms contained in this manual, with about two thirds of the definitions based on the *AWWA Water Dictionary* edited by Dr. James Symons. The project team developed definitions for terms not found in the *AWWA Water Dictionary*.

ANTICIPATED USERS OF THE MANUAL

This manual was prepared for a variety of users, both water filtration plant operators and those who interact with operators. Those who may use this manual include:

- Water treatment plant operators
- Water filtration plant managers
- State regulatory staff who visit and inspect filtration plants and work with plant operators
- Consultants and design engineers who are interested in the maintenance and operational aspects of water filtration plants, and how maintenance and operation are influenced by design.
- Trainers who work with filtration plant operators.

CHAPTER 1
INTRODUCTION TO MANUAL

PURPOSE OF MANUAL

This guidance manual is dedicated to the water treatment plant operators who actually make the plants work and produce the water their customers drink. One treatment plant manager expressed it this way, "Operator dedication in the performance of their duties is perhaps the most important contribution to the successful optimization of the MRWTP. Given the necessary resources and direction, the operators are constantly looking for that slight adjustment or procedural change that will further optimize the plant performance. Their enthusiasm and initiative are the difference!"

This guidance manual was developed to provide guidance on techniques and procedures for maintenance and operation of water filtration plants and to provide background information and advice on where to find additional information. We hope that it will strengthen and promote the enthusiasm and initiative shown by plant operators. The manual favors the use of readily available sources such as AWWA Manuals of Water Supply Practice, the AWWA *Principles and Practices of Water Supply Operations Series*, *Opflow*, and *Journal AWWA*. Additional reference sources include AWWA publications such as *Water Quality and Treatment, 5th Ed.*; *Filtration Strategies to Meet the Surface Water Treatment Rule; Handbook of Chlorination and Alternative Disinfectants, 4th Ed.*; *The Chlorine Dioxide Handbook*; and *Water Treatment, 2nd Ed.* AWWA Research Foundation reports also serve as reference material in this manual, although they may be available for purchase for a period of time, but become unavailable after the supply is exhausted.

WHAT THIS MANUAL IS

This manual is a reference document. It is a compilation of ideas, concepts, and practical approaches to treatment, operations, and maintenance that have been compiled to assist the operator in doing tasks related to maintaining and operating a water filtration plant using granular media filters. Many of the ideas contained in this manual were provided by water utilities and have been proven in actual practice by utilities. Other sources of information for this manual include peer-reviewed literature and AWWA conference proceedings. Finally, some of the concepts in this manual were provided by the

Project Advisory Committee, the Technical Review Group members who advised the Project Team, and the Project Team members at Black & Veatch Corporation and Thames Water Utilities, Ltd.

This manual contains the following chapters:

CHAPTER 1. INTRODUCTION

CHAPTER 2. THE REGULATORY ENVIRONMENT – Has a brief summary of regulations, with emphasis on those related to filtration.

CHAPTER 3. HOW TO USE THIS MANUAL – Explains how to use this guidance manual as a reference document, with emphasis on troubleshooting and solving treatment problems.

CHAPTER 4. FILTER OPERATION AND OPTIMIZATION – Focuses on daily operational tips and methods of optimizing filter operation.

CHAPTER 5. FILTER PERFORMANCE MONITORING – Monitoring instruments and meters, sampling locations and configurations as well as monitoring frequency, and data handling/trend analysis are covered in this chapter.

CHAPTER 6. BACKWASH MANAGEMENT AND OPTIMIZATION – Focuses on a key aspect of filter operation that has to be done right in order to maintain the physical facilities and to produce good water.

CHAPTER 7. FILTER RIPENING AND CONTROLLING THE INITIAL TURBIDITY SPIKE – The first minutes or hours of a filter run may be the most challenging from the perspective of filtered water quality, so this chapter provides information on how to quickly attain high-quality filtered water.

CHAPTER 8. PRETREATMENT: CHEMICAL DOSAGE, SELECTION, AND MIXING – Briefly discusses various pretreatment processes and presents information on a variety of approaches for determining chemical dosages to attain effective coagulation and lime softening process performance.

CHAPTER 9. PRETREATMENT: FLOCCULATION AND CLARIFICATION – Flocculation and clarification processes, when part of the treatment train, must be managed properly to attain the best filtration performance.

CHAPTER 10. FILTER INSPECTION AND MAINTENANCE – Describes O&M techniques and inspection procedures to help operators keep the filtration plant fully functional for the long term.

CHAPTER 11. FILTER MEDIA CHARCTERISTICS, SELECTION, AND REPLACEMENT – Provides information on properties of filter media and how to evaluate, test, and replace media.

CHAPTER 12. QUALITY CONTROL AND INSTRUMENTATION ISSUES – Contains information operators need on how to maintain and calibrate instruments and monitoring devices so the information they are using as the basis for making operating decisions will be valid.

CHAPTER 13. CASE STUDIES – Presents water utility experiences related to various aspects of pretreatment and water filtration operation and maintenance.

CHAPTER 14. EQUATIONS AND EXAMPLE PROBLEMS – Equations are presented and used, with solutions worked out step by step in metric units and in foot-pound-second units.

GLOSSARY. Commonly used water treatment terms contained in this manual, with definitions based on the *AWWA Water Dictionary* edited by Dr. James Symons.

As shown in Figure 1.1, the main focus of the manual is on rapid gravity and pressure granular media filtration. Filtration through beds of granular media is ineffective, however, if water is not

properly pretreated. For this reason, two chapters of the manual deal with pretreatment, with the emphasis on maintaining effective pretreatment so the filters will work as intended.

WHAT THIS MANUAL IS NOT

This manual is not a document that must be read from cover to cover, as one would read a good novel or a biography. It is not a universal manual for all kinds of filtration, as it does not cover the topics of slow sand filtration, diatomaceous earth filtration, or membrane filtration. It is not the only book or information source a water treatment plant operator will need to do his or her job. This first edition may not be the last and final version of the manual. Drinking water regulations can be expected to change over time, and portions of the manual will therefore need to be revised. New findings related to the operation or maintenance of granular media filters may come to light, and technical information may need to be updated. Therefore portions of this manual may need to be revised and updated by the AWWA Research Foundation in the future. Finally, this manual is not a substitute for the solid training and education needed by filtration plant operators. Instead, it is a tool for the trained and educated operator.

WHO THIS MANUAL IS FOR

This manual was prepared for a variety of users, both water filtration plant operators and those who interact with operators. Those who may use this manual include:

- Water treatment plant operators
- Water filtration plant managers
- State regulatory staff who visit and inspect filtration plants and work with plant operators
- Consultants and design engineers who are interested in the maintenance and operational aspects of water filtration plants, and how maintenance and operation are influenced by design.
- Trainers who work with filtration plant operators

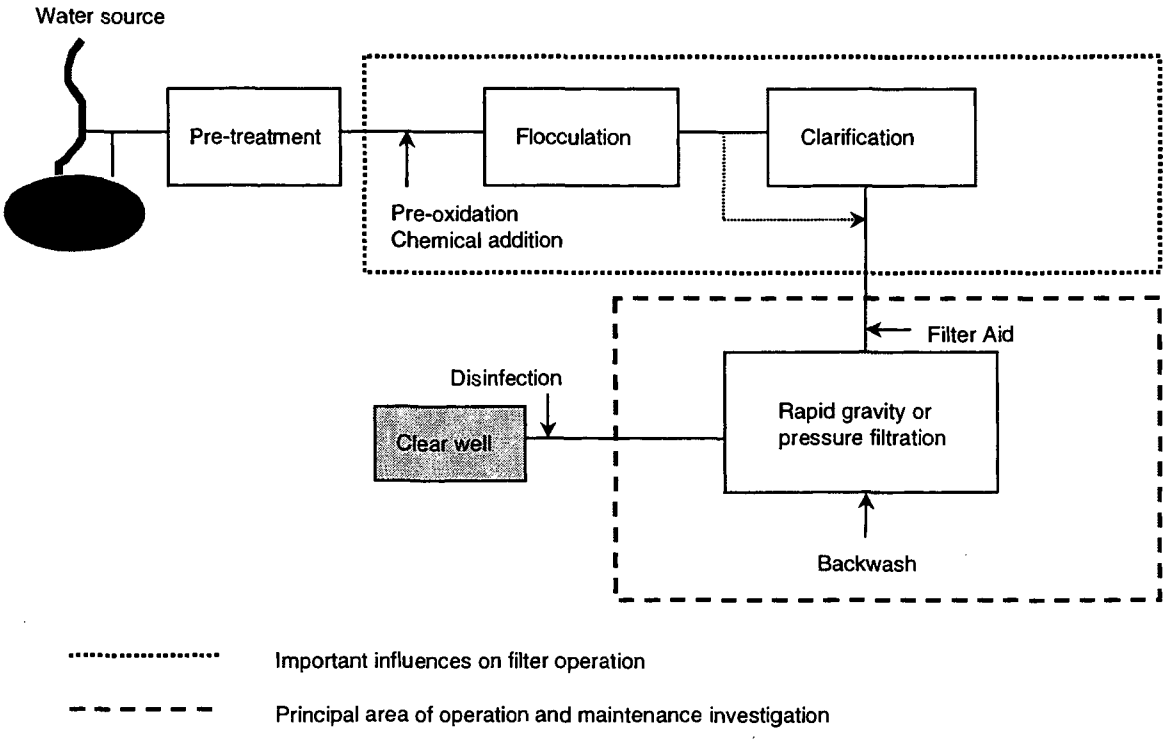

Figure 1.1 Scope of the manual

CHAPTER 2

HOW TO USE THIS MANUAL FOR ROUTINE OR PERIODIC OPERATIONS AND TROUBLESHOOTING

INTRODUCTION

Chapter 2 has been prepared as a guide to the contents of the manual for routine operations and for periodic activities such as filter inspection, and as an aid for troubleshooting and solving problems related to pretreatment and filtration. This chapter presents lists of potential water quality problems and O&M problems, and symptoms of problems, along with references to portions (chapters and pages) of the manual that contain potentially useful information for solving those problems. For additional guidance on troubleshooting, users of this manual may refer to *WATER TREATMENT Troubleshooting and Problem Solving* (Tillman 1996).

This manual provides information on the maintenance and operation of granular media water filtration plants that employ chemical coagulation or precipitative lime softening as pretreatment. Both open, gravity filters and closed vessel, pressure filters are covered in this document. The manual has been produced as an information resource for water treatment plant operators and managers and persons who provide technical assistance to water treatment plant staff.

As an information resource, this manual is not intended to be read in its entirety. Instead, the intention of the manual's authors is that users will go to the manual for information on specific, identifiable topics; or the manual will be used for trouble-shooting at plants when problems are encountered. In general only a small portion of the information in the manual would be needed to resolve a specific problem or to learn about a specific topic. Therefore reading the entire manual is neither practical nor recommended.

Figure 2.1 depicts the concept of factors involved in a plant audit or evaluation. Instrumentation, pretreatment, operation, and maintenance are all interrelated, and all influence the quality of water produced by the plant. Overlaid on these four factors is the design of the plant, which except for minor aspects, can not be changed by the operator. Plant design influences all four factors in various ways. The extent of instrumentation provided, and the ease of installing more, may be influenced by the plant design. Pretreatment used is determined by design. The ease of operation and the capability to make gradual changes in filtration rate are both influenced by the design of the plant. The amount of maintenance needed at a plant can be influenced by plant design, and accessibility of equipment and

facilities for maintenance is certainly determined by the design. Even though the plant design is established and operators may be constrained to work with the plant as it is configured, much can be accomplished by creative use of instrumentation, pretreatment, operational procedures, and a good maintenance program. This chapter tells how the four factors overlain by design in Figure 2.1 may be interrelated, and how operators can use the interrelationships to diagnose problems and improve plant performance.

Figure 2.1 illustrates the principle that at the core of filter plant operation the filter design may be fixed, there are large areas where the Operations & Maintenance (O&M) team have opportunities to improve matters: the areas of instrumentation, operation, maintenance and pre-treatment. These areas form the subject matter of this manual.

In this guidance manual, strong emphasis is placed on operating and maintaining filters so the quality of filtered water will be equal to or better than the goals set by the utility and by the applicable regulatory agency. If a filtered water quality problem is noted, it could be related to the physical condition of the filter bed, support materials, or underdrain. Sometimes there is no water quality problem, but analytical methods have given false readings. Other times a filtered water quality problem may be the result of incorrect or inadequate pretreatment. The main focus of this manual is on filtration, but pretreatment can be a performance-limiting factor in attaining acceptable filtered water quality, so two chapters are devoted to pretreatment issues. One chapter on quality control issues has been developed as a guide to operators.

ORGANIZATION OF THE MANUAL

Manual users who know what they plan to do and know the type of information they are seeking can use the table of contents and index guides to locating information in the manual. For example, if installation of on-line particle counters is being contemplated at a filtration plant, plant staff may wish to read about particle counters in Chapter 5, Filter Performance Monitoring, and in Chapter 12, Quality Control and Instrumentation Issues. When a specific topic has been identified and information is needed, using the manual should be straightforward.

A schematic presentation of the organization of Chapters 2 and 4 through 12 is presented in Figures 2.2 through 2.6. Chapters 1, 3, and 13 through 16 are not depicted in Figures 2.2 through 2.6. Chapter 1 is the introduction, and Chapter 3 is a review of regulations related to water filtration. Chapter 13 consists of case studies related to materials presented earlier in the manual. Chapter 14

contains examples of formulae and equations that have been worked out, generally in both metric and customary foot-pound-second units. Chapter 15 is a glossary of terms, and Chapter 16 presents research needs identified in the project. In Figure 2.2, the interrelationship of Chapters 2 and 4 through 12 is depicted. Figures 2.3 through 2.6 are a graphic presentation of approaches to managing filtration and solving problems.

Figure 2.2 shows how the chapters in the manual are organized to guide the reader with filtrate quality problems. Each of the potential areas that indicate or cause filter problems is examined in greater depth in figures 2.3 to 2.6.

Figure 2.3 presents the actions to take to ensure that data indicated by instruments are truly representative of what is happening in the filter.

Figure 2.4 indicates steps to be taken to ensure that the poor filter performance is not caused by problems with pre-treatment or significant changes in raw water quality.

Poor filter performance may be caused by improper operating procedures. Figure 2.5 depicts actions to take to ensure that poor filter performance is not due to poor filter operation.

Ensure that a maintenance program is in place to check the filters thoroughly and regularly. Elements of such a maintenance program are depicted in Figure 2.6

GOOD PRACTICE FOR FILTER OPERATION AND MAINTENANCE PROCEDURES

The following sections of Chapter 2 are written with the presumption that each filter at an operating filtration plant is equipped with an on-line turbidimeter. In the United States, all public water systems serving at least 10,000 persons must be so equipped on January 1, 2002 in accordance with the Interim Enhanced Surface Water Treatment Rule (IESWTR). All public water systems serving fewer than 10,000 persons must monitor each filter with an on-line turbidimeter 36 months after publication of the final Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR), or about January 1, 2004, based on the monitoring date selected for the IESWTR and expected promulgation date for the LT1ESWTR.

Monitoring turbidity of water produced by each filter by use of an on-line turbidimeter has been recommended as best practice by numerous water treatment engineers for one or two decades, or longer, so this is not a revolutionary concept. Water utilities lacking an on-line turbidimeter for each filter are strongly encouraged to equip their filters with these instruments as soon as possible, and certainly should do this well before the required regulatory compliance deadlines. At treatment plants not equipped with

on-line turbidimeters for each filter, staff will have to take grab samples from individual filters to carry out some of the recommended trouble-shooting procedures and filter monitoring activities presented in this manual.

Top 6 Recommended Procedures and How to Find Help in this Manual

The authors of this manual recommend that water utility managers, plant supervisors, operators and water quality staff develop a documented set of filter operating and maintenance procedures for each filtration plant within a utility. This manual can assist in the development of these plant specific procedures. The procedures should be available and followed by all operators and water quality staff associated with the defined water filtration plant.

Defined and audible records that the procedures have been followed, together with monitoring and inspection results, should be kept for a regulatory, management, long-term filter optimization and future design upgrade purposes. Key data from filter inspections, plant operating conditions and performance data under "normal" and unusual events should be kept for at least 10 years, preferably longer to assist future operators.

1. **Regulation:** Obtain and keep up to date national and regional regulations pertinent to water treatment. Define how they will be applied, monitored and reported for each plant. Include in training programs. See Chapter 3, Regulatory Environment for information pertinent to USA, Canada, U.K., Australia and New Zealand as current in 2001.

2. **Monitoring instrumentation:** Install on-line turbidity monitoring of filtered water quality, and monitoring of filter flow and head loss, for each filter within a filtration plant. Define and document how the monitoring instrumentation will be regularly maintained and calibrated. Keep defined records of maintenance and calibration and audit them regularly. Continuously display and preferably, continuously record readings of on-line turbidity, flow and head loss with records not more than 15 minutes apart. Consider on-line particle counters for additional monitoring and optimization. See Chapter 12, Quality Control and Instrumentation for recommended practices and include appropriate material in your procedures and training programs.

3. **Monitoring filter run performance:** Visually inspect the filtered water turbidity, flow and head loss trends for all filters every day and compare with defined goals and "normal" performance of the plant. Characterize and document "normal" filter performance including typical seasonal variation for each plant. If filter performance is trending towards unacceptable water quality and/or filter performance, take corrective actions and record both actions and plant response. Learn from "events" and incorporate learning in revised procedures. Seek to keep filtered water quality below 0.1 ntu, minimizing the extent of the initial turbidity spike after backwashing. Managing flow and rate of change of flow through a filter is a vital operational procedure. See Chapter 5 for Filter Performance Monitoring, Chapter 4 for Filter Operation and Optimization and Chapter 7 for Filter Ripening and Controlling the Initial Turbidity Spike. Include appropriate material in your procedures and training programs.

4. **Managing pretreatment:** Managing optimal pretreatment is a vital operational activity to enable subsequent good filter operation. Selection, maintenance and control of chemical dose and mixing, assisted by regular jar testing are the key operational activities. Documented procedures for operators and water quality staff should be developed for each plant under "normal", seasonal variation and "event" conditions and records kept to show that procedures are followed. The results of jar tests and chemical dose changes should be kept to assist filter optimization and problem diagnosis. It is important to understand that overdosing with chemicals, in particular polyelectrolytes may enhance clarifier performance but can lead to long-term filter media problems. See Chapter 8 for Pretreatment: Chemical Dosage, Selection and Mixing and Chapter 9 for Pretreatment: Flocculation and Clarification. Include appropriate material in your procedures and training programs.

5. **Optimizing backwashing:** Documented procedures for backwashing filters, to remove deposited solids and maintain good filter media condition, are required for each plant and media configuration. Optimal backwash conditions can vary with season and require testing and establishment by operators. Regular observation of backwash operation is an important diagnostic for detecting potential major problems with filter media and filter under-drains that can lead to filtered water quality failures. As a general rule dirty filters should never be brought into service without prior backwashing. See Chapter 6 for Backwash Management and Optimization. Include appropriate material in your procedures and training programs.

6. **Inspecting filter media condition:** Maintaining filter media in good condition is a key long-term role for filter operators to ensure that good filtered water quality can be achieved. Regular visual inspection for media loss and filter bed cracking is vital together with an annual planned program of filter coring and media condition assessment to determine whether backwashing requires optimization or new media is required. See Chapter 10 for Filter inspection and Maintenance and Chapter 11 for Filter Media Characteristics, Selection and Replacement. Include appropriate material in your procedures and training programs.

TROUBLESHOOTING, DIAGNOSING PROBLEMS, AND LINKS TO INFORMATION IN THE MANUAL

The remaining portion of this chapter lists problems that may be encountered at a filtration plant and lists possible corrective actions with references to other places in the manual where detailed information related to the corrective actions may be found. NOTE: THE TECHNIQUES DESCRIBED IN THIS MANUAL MAY WORK FOR SOME FILTERS BUT NOT FOR OTHERS. USERS SHOULD NOT EXPECT THAT ALL TECHNIQUES IN THE MANUAL WILL WORK IN EVERY WATER FILTRATION PLANT.

Filtered Water Quality Problems

Filtered water quality problems addressed in this manual will consist mainly of problems related to high turbidity or high particle counts. In this chapter reference is made only to turbidity, to avoid repetition. If you are monitoring particle counts in filtered water at your filtration plant, in general you may substitute the words "particle count" and "particle counter" for "turbidity" and "turbidimeter" in the following text. This does not mean that turbidity and particle counts are the same; instead, an increase in particulate matter passing through a filter, whether measured by a turbidimeter or by a particle counter, can be a symptom of a problem and a signal for taking corrective action. One exception to this concept relates to calibration and QA checks for particle counters, which are different from those for turbidimeters. In particular, particle counter calibration is not a procedure that was done routinely at water treatment plants by water utility personnel in the year 2000, so you will have to adapt recommendations on particle counter QA to the existing realities for those instruments.

Another aspect of filtered water quality that is dealt with in this manual is the quality of water treated by precipitative lime softening. This section of Chapter 2 also deals briefly with softened water.

I. Turbidity inconsistent, with one or more filters high while others meet turbidity goal

A. Confirm high turbidity of filtered water by obtaining a grab sample and testing at bench turbidimeter after the bench turbidimeter has been checked with a secondary standard.

1. If turbidity of grab sample is normal, not high, on a bench turbidimeter with acceptable results from secondary calibration, recheck filtered water turbidity with both the on-line turbidimeter and the bench turbidimeter. Confirmation of normal turbidity by bench turbidimeter signals need for calibration of on-line turbidimeter [Chapter 12, pp. 9-10] or cleaning of supply line to the on-line turbidimeter. [Chapter 12, pp. 7 and 9]

2. If turbidity of grab sample is high and bench turbidimeter is in agreement with on-line turbidimeter, check this filter.

a. Has the filter recently been returned to service so the turbidity represents the initial improvement period? [Chapter 7, p. 1 and Figures 7.1 and 7.2 at end of chapter] The use of cationic polymer as the only coagulant can result in long initial improvement periods.

b. Has the filter recently been subjected to a substantial rate increase that could cause high turbidity? Turbidity breakthrough following a rate increase can be a sign of weak floc and the need for using a filter aid. [Chapter 8, p. 47] Excessively high flow through a filter also might be caused by a rate controller failure. A quality control procedure for checking rate of flow in a filter is explained in Chapter 12, p. 22.

c. Is the filter operating under high head loss, near the end of the run, and experiencing turbidity breakthrough? [Chapter 4, p. 5, Fig. 4.2]

d. Is this a new problem or has it been occurring? Check data sheets or other operating records to learn how long this has been happening.

e. If this filter is equipped with a rate controller, is the controller "hunting"? That is, does the controller frequently and repeatedly change rates, rather than just settling in on a rate and holding it? [Chapter 5, p. 16]

3. If turbidity of grab sample is high and bench turbidimeter is in agreement with on-line turbidimeter, and problems are not found with the filter, investigate influent water quality.

a. Is the quality of pretreated water going to this filter the same as the quality applied to other filters, or has short-circuiting or some other problem caused a different quality? [Chapter 9, p. 9]

b. If a filter aid is used, where is it applied? Is filter aid dosed individually to each filter, or to settled water that goes to all filters? For the former (not usually done) be sure dosing is same for all filters. For the latter case, does the filter with highest turbidity have a very short time between filter aid dosing and application to filter? Sometimes conditioning time after addition of filter aid can make a difference in performance. [Chapter 8, p. 45]

4. If poor filtered water turbidity is not related to filter operation or applied water quality, inspect the condition of the filter bed, underdrain, and the piping and valves. [Chapter 10]

a. Backwash filter and watch for boils, which would indicate disrupted support gravel or underdrain problems. Also watch for dead spots with no backwash activity, which would indicate badly gummed up media or clogged underdrain in the dead area. If observed, this dead area is causing filtration to take place on the portion of the filter that still is able to pass water through the bed. [Chapter 6, pp. 1-3, and Chapter 10, p. 20]

b. Inspect media for mudballs, as extensive deposits of mudballs can decrease effective area of filter and result in higher filtration velocities through the clean portions of the bed. [Chapter 10, pp. 9-20]

c. Drain the filter and inspect, looking for media mounding or depressions in filter media [Chapter 10, p. 9]

d. If media appears level, check depth and compare to other filters. Has this filter bed lost a considerable amount of media? [Chapter 10, pp. 9-12]

II. Turbidity high from all filters

A. Confirm high turbidity by obtaining a grab sample and testing at bench turbidimeter. It is highly unlikely that all on-line turbidimeters could be reading high, but confirm by checking a single filter before investigating pretreatment. When all filters have high turbidity, the problem probably has originated in pretreatment.

B. Check pretreatment train for chemical dosages and dosage monitoring. [Chapters 8 and 9]

1. Verify addition of pretreatment chemicals. Are chemical feeders operating and feeding chemical? Verify chemical feed rates by pumping from graduated cylinder or measuring flow of chemical over a few minutes. [Chapter 8, pp. 33-34] Check delivery of chemical to point of addition, to determine if chemical feed line has been broken.
2. If pH is important for your treatment process, check on-line pH meter (if used) versus a bench model pH meter that has just been calibrated with appropriate buffers. Verify that pH of the coagulated water is appropriate. [Chapter 12, pp. 19-21]
3. If streaming current instrument is used as a guide for adjusting chemical dosages, has this instrument been responding well to changes in coagulated water quality or has it been sluggish? Review its performance and consider cleaning the streaming current instrument if needed. [Chapter 12, pp. 16-19]
4. If coagulant dosage charts are used to set dosages for coagulation, do you have correct raw water quality data? Recheck raw water quality parameters that are used in your charts and verify you are employing the proper strategy. Are you using the same coagulant chemical and the same chemical strength that were used when the coagulant dosage chart was developed? [Chapter 8, pp. 24-26]
5. Review rate of head loss increase experienced in this situation. For the raw water quality being experienced at present, if head loss gain seems to be very low or minimal, this can be a symptom of underdosing coagulant so that particulate matter passes on through the filter instead of being caught in the filter bed. [Chapter 5, pp. 18-20]
6. If clarified water turbidity is low but turbidity removal in the filter is inadequate, this may be a sign of weak floc. Consider using a filter aid or floc aid to strengthen floc. [Chapter 8, pp. 44-48] If a filter aid is used the dosage may be wrong. Pilot filter testing may be needed to learn the correct dosage.
7. Has source water quality changed? If so, jar tests may be needed to identify the proper pretreatment chemical dosages. [Chapter 8, pp. 12-32]

8. Are large numbers of algae present in the source water? Algae can be difficult to remove by coagulation, sedimentation and filtration, and can cause elevated turbidity and more rapid gain of head loss in filters.

B. Check pretreatment train for mixing and flocculation equipment. Are rapid mixers and flocculators operating? [Chapter 8, pp. 48-51 and Chapter 9, pp. 1-8]

C. Check condition of filters for air binding. If the rate of gain of head loss suddenly becomes higher with no increase in filtration rate, air binding could be the cause. Operating air-bound filters can cause higher turbidity [Chapter 4, pp. 56-58]

D. Is lime being added after sedimentation to adjust pH? Addition of lime can cause elevated turbidity.

III. Calcium carbonate is precipitating in filter beds and causing mineral deposits on media or is passing through filter beds and precipitating in the distribution system in excessive quantities as shown by pipes removed during repairs or coupons removed during main tapping

A. Obtain a core sample of filter media and check for precipitation of calcium carbonate deposits on filter media by acid solubility test. [Chapter 8, pp.36-41 and Chapter 10, pp. 31-38]

B. Check pH of recarbonated and filtered water using a properly calibrated bench model pH meter and verify that on-line pH meter (if used) is properly calibrated. [Chapter 12, pp. 19-21]

C. Using standard procedures for your plant, determine proper pH and alkalinity for recarbonated water. [Chapter 8, pp. 36-41]

D. If using polyphosphates to sequester calcium and prevent precipitation of calcium carbonate on filter media or on water main walls, review this practice to be sure the chemical is being applied appropriately.

IV. Iron, manganese, or both passing through filters

A. Confirm chemical analysis to be sure there is a problem before undertaking more work.

B. Identify source of iron and plan corrective action

1. Natural, in source water

a. Verify that oxidant dosage and type, contact time, and pH are correct for precipitation of iron

b. Even if treatment conditions seem to be correct, iron may be complexed with organic matter, and this can make iron removal more difficult.

2. Iron from ferric or ferrous coagulant

a. If no recycle practiced, are the coagulation conditions (pH and iron dosage) those that will cause precipitation of essentially all of the iron coagulant?

b. If backwash water is recycled, or if sludge is returned to source water, could soluble iron be formed from recycled floc in washwater or from sludge? If so the solution may be to change residuals disposal practice.

C. Identify source of manganese and plan corrective action.

1. Natural, in source water

a. Verify that oxidant dosage and type, contact time, and pH are correct for manganese treatment.

b. If prechlorination for manganese removal onto manganese-coated filter media is practiced, have the filter media been changed out so the new media lacks the manganese dioxide coating that is needed for removal of manganese when chlorine is the oxidant?

2. Manganese arising from use of permanganate in treatment

a. Verify that permanganate use for manganese removal, taste & odor control, oxidation of natural organic matter, or zebra mussel control is correct and not excessive.

b. Consider effects of recycle of backwash water and possibility for manganese recycle. Also consider sludge. Is sludge removed from sedimentation basins on a periodic but frequent basis by sludge removal equipment or are basins cleaned manually, with long time intervals for sludge to become anoxic (no dissolved oxygen) so manganese could revert to its soluble form? Where is sludge sent after removal from sedimentation basin? If recycled to source water, could manganese later reappear in raw water?

Poor Water Quality Produced by Pretreatment

When pretreatment is not effective and poor water quality is produced by pretreatment processes, filtered water quality also is likely to suffer. Sometimes though, operators may notice a problem while examining pretreatment facilities. For some of the pretreatment problems, troubleshooting procedures are those recommended when filtered water quality problems are encountered. If this is the case, a prior troubleshooting procedure is referred to instead of being repeated here verbatim.

I. Hazy, cloudy, or turbid water produced by pretreatment processes

A. Take a grab sample of clarified water and check to confirm high turbidity using bench turbidimeter.

If turbidity of grab sample is normal, not high, on a bench turbidimeter with acceptable results from secondary calibration, recheck clarified water turbidity by both the on-line turbidimeter (if used) and the bench turbidimeter. Confirmation of normal turbidity by bench turbidimeter indicates the need for calibration of on-line turbidimeter for measuring turbidity of clarified water [Chapter 12, pp. 6-9]

B. Likely causes of haze in settled water include underdosing coagulant, or pH too low. Refer to **Filtered Water Quality Problems, II,** B, items 1, 2, 3, 4, and 7.

C. Hazy, cloudy or turbid water could be caused by inadequate mixing or inadequate flocculation.

1. Is rapid mixer working and dispersing coagulant quickly and thoroughly? [Chapter 8, pp. 49-51]
2. Is flocculator operating and causing particle-to-particle collisions to build flocs from particles that were destabilized by adding the coagulant chemical? [Chapter 9, pp. 1-4]

D. When coagulation is correct, increases in flow rate in sedimentation basins can cause carry-over of turbid water. Upflow clarifier or sludge blanket clarifier processes used for coagulation of low-turbidity or highly colored waters are especially vulnerable to being upset with the subsequent washout of floc, as coagulation of such source waters tends to form light, fluffy floc. [Chapter 9, pp. 10-13]

E. Failure of mechanical sludge removal equipment to function properly or failure to remove sludge frequently enough when manual removal is necessary can result in

accumulation of sludge deposits in sedimentation basins to the extent that removal of floc can deteriorate. Furthermore, improper operation of mechanical sludge removal equipment or broken sludge removal equipment can cause disturbances to settled sludge in sedimentation basins, resulting in episodes of high turbidity in settled water.

1. If the sedimentation basin does not have sludge removal equipment, check sludge depth with a "Sludge Judge" or similar device to learn if excessive sludge has accumulated. If so, drain the basin and remove the sludge.
2. For a sedimentation basin with mechanical sludge removal equipment observe settled water turbidity before, during, and after operation of sludge removal equipment. Increases in turbidity following operation of sludge removal equipment suggest a need to drain the basin and inspect the sludge removal equipment to learn if problems exist. [Chapter 9, pp. 15-16]

II. Mixture of clear water and large flocs discharged from sedimentation basin

A. Coagulant dosage might be too high or polymer usage may be incorrect. Refer to **Filtered Water Quality Problems, II,** B, items 1, 2, 3, 4, and 7.

B. If coagulant dosage is correct, short circuiting may be a problem [Chapter 9, pp. 9-13]

1. Check operating records for an increase or decrease in raw water temperature a few hours before the appearance of the problem.
2. Check operating records for a very large increase or decrease in raw water turbidity a few hours before the appearance of the problem.
3. Has a high and steady wind set up an adverse current pattern in settling basins?

If this problem is causing short filter runs, reducing the filtration rate may be necessary. There is little an operator can do to stop short-circuiting in a basin when it is caused by wind or by density differences in water being treated.

III. Clear water and floc from dissolved air flotation (DAF) clarifier

A. Check removal interval for taking floated floc off the surface of the water in the DAF clarifier basin. If floated floc remains on the surface too long it can break up and sink. [Chapter 9, pp. 20]

B. Observe removal of floated floc during removal cycle. Is all floated floc pushed across the water surface and onto to the clarifier beach, or floated over the clarifier weir without

breaking up, or does some of the float break up with some floc sinking during removal? [Chapter 9, pp. 18 and 20]

C. If DAF clarifier is not in a building, does wind or rain cause floated floc to sink? [Chapter 9, p. 20]

Filters Have Head Loss Problems

I. Rapid head loss gain caused by large amounts of visible floc and particulate matter in the filter influent

A. If clarified water turbidity is excessively high and floc carryover is happening, check clarification. [Chapter 9]

1. Is short circuiting happening in sedimentation? [Chapter 9, pp. 9-12]

a. Abrupt water temperature changes can create density differences and cause short-circuiting. [Chapter 9, pp. 9-10]

b. Sudden major changes in turbidity of the source water can change the density of the water and cause short-circuiting [Chapter 9, pp. 10]

c. Increases in flow can wash coagulation floc out of upflow clarifiers and sludge blanket clarifiers. [Chapter 9, pp. 10-12]

2. If DAF is used, is sufficient bubble volume being added to the flocculated water? Check recycle ratio and operating pressure in the saturator. [Chapter 9, pp. 20-21]

3. Is the clarifier being operated at an overflow rate that exceeds its capacity? [Chapter 9, pp. 11-12]

B. Excessive filter aid dosages can cause floc to be too strong and carry-over floc will form a mat on the top of the filter bed. Surface filtration causes much higher rates of head loss gain than depth filtration. [Chapter 4, p. 1 and Chapter 8, p. 47]

C. Filter clogging algae are difficult to remove in sedimentation pretreatment. They can result in high rates of head loss gain. [Chapter 4, pp. 35-36]

II. Head loss rate of increase is moderate and later is high, with no increase in filtration rate

A. If the increase is somewhat gradual this could indicate surface filtration and floc removal at top of filter bed. [Chapter 4, p. 1 and Chapter 8, p. 45]

B. An abrupt increase in head loss rate of increase, part of the way into a filter run, can signal air binding of a filter.

III. Clean Bed Head Loss is Higher than Normal

A. Conduct a limited filter inspection. [Chapter 10]

1. Probe for mudballs
2. Take several core samples to inspect filter media for mudballs and dirt.
3. Do a floc retention analysis of media after backwashing.

Filter Backwash Seems to be Ineffective

I. Evaluate backwash cleaning efficacy

A. During backwash watch for dead zones where no wash water upflow is apparent [Chapter 6, pp. 1-2]

B. Check auxiliary scour

1. Are surface wash nozzles clogged or in need of replacement? [Chapter 10, pp. 24-25]
2. Is air distribution uniform during air scour? [Chapter 10, pp. 25-26]

C. Evaluate cleaning efficiency by performing floc retention test before and after backwash [Chapter 10, pp. 29-31 and Figure 10.21]

D. Is backwash performed for a sufficiently long period of time? Perform a backwash turbidity profile. [Chapter 10, p. 28-29]

II. Check flow rates applied during backwash

Are backwash water flows adequate? Is the flow meter accurate? Check by performing a rise rate test. [Chapter 12, pp. 24]

A. Check the flow meter for surface wash by performing rise rate test. [Chapter 12, p. 25]

III. Evaluate filter bed expansion

A. Test for backwash expansion by using a bed expansion measuring tool. [Chapter 10, pp. 26-28]

B. Calculate minimum fluidization velocity for the media in the bed. [Chapter 14, p. 7-10]

Filter Media Is Disappearing

I. Inspect filter to learn why and how media loss happening

A. Check records of prior filter inspections and note media elevation at last inspection. [Chapter 10, pp.2- 4]

B. Drain media to surface and inspect. [Chapter 10, p. 13]

1. Check elevation at several locations to determine extent of loss.
2. While bed is drained, check media for mounds or depressions that could indicate a disrupted underdrain through which media loss is happening.

C. Backwash filter and observe carefully, watching for boils or other signs of disrupted underdrain. [Chapter 10, p. 26]

D. Check spent washwater storage basin or spent washwater lagoon for media. Also check sludge for presence of filter media if clarifier sludge and spent washwater are kept in a common basin or lagoon. [Chapter 6, p. 42]

E. If dual media or mixed media filters are used, check core sample records or take a few core samples to learn whether one filtering material or all are being lost. [Chapter 10, pp. 21-24]

II. Filter inspection for underdrain problems

A. Go forward with this procedure if evidence for underdrain problems were found.

B. Use filter excavation box and inspect any area where media depressions are found or where boils were seen during backwashing. Use great care if digging near filter nozzles that could be damaged by workers' tools. [Chapter 10, pp. 18-21]

C. If plenum is accessible, inspect for accumulations of filter media.

D. If damaged nozzles or underdrain damage found, filter needs to be rebuilt. [Chapter 10, pp. 33-35]

III. Evaluating backwash for filter media loss

A. Test for backwash expansion by using a bed expansion measuring tool. [Chapter 10, pp. 27-29] However if surface wash is used and media loss is occurring during backwash, operate the surface wash when doing the backwash expansion test, contrary to directions for backwash expansion test when purpose is to assess adequacy of backwash.

B. Calculate minimum fluidization velocity for the media in the bed. [Chapter 14, pp. 7-10]

C. Inspect filter troughs to see if media found in troughs after backwash has been completed.

E. If media loss caused by backwashing, review procedures used during backwash. In particular if air scour is used, is air on when water is flowing over washwater troughs. Media loss is more likely during this phase of backwashing. [Chapter 6, pp. 28-29]

ACTIONS FOR PLANT AUDIT AND TROUBLESHOOTING

Tables 2.1 through 2.4 present actions to take during a plant audit or troubleshooting exercise. Recommended actions are referenced to pages in the O&M manual that describe these actions in detail.

Table 2.1.

Plant audit check #1 – turbidity instrumentation.

Turbidity Instrumentation basic checklist: ensure you can trust what your instrument tells you!	
Action	Chapter-Page
Is water flow getting to sensor at the correct rate?	12-7
Check sensor ntu value against grab sample	12-8,9
Is sensor dirty?	12-19,20
Is anything blocking sensor? (e.g. spiders, condensation, algae)	12-20
Is computer screen showing the same value as instrument local indicator?	12-8,9
Are the sampling arrangements satisfactory?	12-4, 5, 6

Table 2.2

Plant audit check #2 – pretreatment.

Pretreatment issues that may cause filter turbidity problems. Check pH correction, check coagulant and check polymer systems	
Action	Chapter-Page
Check if anything is blocking chemical addition points?	8-37
Check for proper chemical mixing	8-51 to 8-54
Check preoxidation is operating correctly	8-2 to 8-10
Check pH set point is at required value	8-12 to 8-27 and 12-22, 23
Check coagulant dose set point is at required value	8-12 to 8-31
Check polymer dose set point is at required value	8-12 to 8-31 and 8-47 to 8-51
Check for poor floc retention in clarifier	9-7, 8
Check all chemical dosing pumps and valves are set correctly to achieve dose and pH set points	8-43 to 8-51
Check chemical feed day tanks are not empty	8-37
Check dilution / carrier water supplies are functioning	8-37

Table 2.3.

Plant audit check #3 – operation.

Operating issues that may cause filter turbidity problems.	
Action	Chapter-Page
Check current position in filter cycle	4-3 to 4-6
Check backwash operation: take filter out of service if previous backwash was not performed correctly	6-1 to 6-4, 6-14 to 6-19, 6-26 to 6-29
Check that flow rate is set correctly and not fluctuating outside set limits	5-23, 24 and 12-23 to 12-26
Check filter-to-waste is functioning correctly	7-8 to 7-10
Carry out techniques for managing filter ripening	7-8 to 7-22
Check filter recycles are being managed correctly	6-42 to 6-46
Check filter is not being operated at excessive head loss	5-18 to 5-21
Check filter run length is not excessive	6-18
Carry out backwash to end filter run	6-14 to 6-19, 6-26 to 6-29

Table 2.4.

Plant audit check #4 – maintenance.

Maintenance issues that may cause filter turbidity problems. Check filter media depth and condition, observe backwash and check bed expansion during backwash	
Action	Chapter-Page
Check filter contains correct depth of media	10-18 to 10-22
Check filter media condition: look for even flat surface, watch out for mudballs and cracks	10-16, 17
Watch filter backwash: look for correct functioning of surface wash, check for even distribution of air scour and backwash water	6-1 to 6-4
Check backwash bed expansion	10-30 to 10-32

INTERPRETATION OF FILTER TURBIDITY PROFILES

In producing this manual the authors are aware of a wide range of potential readers, with different interests, experience and time available. An excellent means of understanding and optimizing filter behavior is by plotting trends of the filtrate turbidity from individual filter runs and comparing these with an ideal filter run. Where there is a difference there is an opportunity to improve filter operation. Filter effluent flow rate measurement and head loss are also valuable data to help determine what is going on. This section of the manual has incorporated some very valuable diagnostic tools provided by the Pennsylvania Department of Environmental Protection (Chescattie 2001).

The Pennsylvania Department of Environmental Protection (PADEP) has developed filter profiles that depict trends of filtered water turbidity following the initiation of a filter run. The filter profile figures also have text that explains a probable cause for the shape or pattern of the turbidity through the run. These explanations can aid operators in understanding the nature and causes of high-turbidity episodes or turbidity breakthrough problems. In addition, some of the figures provide guidance on how to undertake troubleshooting when problems with filtered water turbidity are encountered. To supplement the turbidity profiles prepared by the PADEP, the project team developed additional filter profiles, and these are also presented in this section of the manual.

The following advice was provided by PADEP. "Individual filter profiles can be a valuable tool and provide very useful information. For a profile to be useful, it must be representative of the performance of a particular filter. Figure 2.7 shows an example of a representative filter profile. Note that events and times in this example are clearly labeled. Sample intervals (how often turbidities are recorded and graphed) should be between 2 and 15 minutes. It is a good idea to use more frequent intervals (2 minutes) when turbidities are not stable. Times on the X-axis should be labeled at least every 30 minutes. The profiles should include an entire filter run – several minutes prior to a backwash, an entire backwash, and should continue until the next backwash."

In Figure 2.7 only a portion of the full filter run is shown, to show backwash and ripening in detail. Exactly what the turbidimeter shows during a backwash depends on the position of the turbidimeter sample point in relation to the positions of the filter outlet valve, the backwash water inlet valve, the filter-to-waste system (if present) and any pipe work that they have in common. The filter backwash started at 07:56, filter-to-waste started at 08:14, and the filter was placed on line at 08:28.
PADEP continue "Once you have created a representative profile for each filter in your plant, you should interpret each profile, attempting to determine if any potential problems exist. The following nine figures are examples of some of the most common filter profiles and possible interpretations of each."

Figure 2.8 is described by PADEP as "Excess filter run-time: filter should have been washed when a noticeable ntu increase occurred, in this case near 70 hours." It shows a filter run which continues into the breakthrough phase. Filter wash should be initiated sooner, either by a filtrate turbidity trigger (say 0.1 ntu or a noticeable increase from the base line value) or by shortening the run length trigger to around 70 hours. A similar curve with a shorter run time might be indicative of a weak floc, an excess coagulant dose, or too shallow a depth of media.

Figure 2.9 shows a disturbed filter curve. PADEP described this as probably being caused by hydraulic surging, i.e. rapid changes in flow rates. "Often this type of profile is caused by a "seeking [i.e., hunting]" valve or valves – valves continuously open and close to try to maintain a particular flow." The answer to this may be in adjusting the valve hardware or the control set points that adjust the valve position.

In Figure 2.10, PADEP showed a graph where the filter-to-waste time was too short. The backwash commenced at 8 minutes, and the filter-to-waste started at the peak around 18 minutes. The filter was back online at the peak at 23 minutes into the trend. The explanation and suggestion were "Filter-to-waste time too short: extend until turbidity is < 0.1 ntu. The filter-to-waste time for this plant

was about 6 minutes; extending the filter-to-waste time for another 6 minutes would have reduced the on-line turbidity to below 0.1 ntu. It is important to note that many variables affect the amount of time needed for a filter to recover after backwashing. Consequently, it is likely that filter-to-waste times will often need to be adjusted. Therefore it is important for operators to monitor turbidities and adjust / extend filter-to-waste until turbidities fall below the 0.1 ntu goal."

A secondary spike is shown in Figure 2.11. Filter-to-waste started at 16 minutes and the filter returned to service at 23 minutes. PADEP's view was that "increasing filter-to-waste probably won't eliminate this spike. Possible solutions may include increasing backwash rates and / or duration, or allowing filter to rest offline for at least 15 minutes before returning to service. Also, a plant may consider adding Alum to their backwash water during the last few minutes of the backwash sequence or adding a filter aid / polymer. It is important to note that it is often not necessary for a plant to implement all of the above-mentioned solutions. Evaluate the duration and severity of the backwash spike; then use some judgment when making recommendations." The aim of this manual is to expand on the views and techniques mentioned here by PADEP.

In Figure 2.12 the filter starts backwashing at 5 minutes, starts filter-to-waste at 33 minutes and is put back on line after 1 hour. The trend is described by PADEP as having "excessive recovery time: something is significantly wrong with this profile. Begin by thoroughly evaluating the backwashing procedures and pretreatment chemical feeds. Look at performance of upstream unit processes – rapid mix, flocculators, settling. Perform a thorough filter and media inspection. Try to determine where in the treatment process things are going wrong. Often, there are several causes combined; such as lack of rapid mixing + improper chemical doses + excessive filter run times + inadequate backwash rates. This type of profile is not always caused solely by poor filter performance." Prolonged ripening times may be a sign of excessively good clarifier performance, since too few particles remain in the water to ripen the filters. It is better to optimize the combined performance of the clarifiers and the filters as one, and achieve the desired filtrate turbidity than to consider each stage in isolation. Alternatively the filter may have been backwashed too long and there are no backwash remnants to help ripen the filter.

In Figure 2.13 backwashing starts at 5 minutes, filter-to-waste at 40 minutes, and the filter is on line at 50 minutes. In this case the filter appeared to be clean after the backwash but quickly starts to deteriorate progressively. PADEP suggest that there may have been a breakdown in a chemical feed pump to cause this profile. They also recommend that causes be investigated as for Figure 2.12.

Two spikes of different height and intensity are presented in Figure 2.14. It is not the objective of this to state what is an acceptable or an unacceptable spike but to help focus attention into ensuring

that each spike is looked at and causes determined, so that appropriate action can be taken. What are acceptable values will need to be determined by each utility. The opinion of PADEP was that the spike at 25 minutes "isn't really of major concern. However you should note the time and attempt to determine the cause. Also, remember that if this same event were to occur when the filter had more run time (elapsed), the severity and duration of the spike may be greater." The spike at 120 minutes "is more significant and a thorough attempt should be made to determine the cause. Possible causes include backwashing another filter or back flushing an adsorption clarifier. Could also be caused by opening / closing of valves – changing hydraulic flows."

The event pictured in Figure 2.15 was described by PADEP as possibly being "caused by increasing the plant flow rate for a period of time. Or, it may be caused by recycling wastewater. Note that sometimes recycling causes this pattern due to increased turbidities; however sometimes it may be the increased recycle flow rate itself that hydraulically causes this pattern. Either way it is a significant problem. When investigating this type of event pay close attention to the start and stop times and try to correlate them with events on SCADA, strip charts, or the operators' log books." A change like this may be associated with a temporary change in pretreatment at 40 minutes, which is corrected at about 130 minutes. This might be, for example, a change in coagulant dose, loss of polymer, or change in mixing conditions. Sharp step up and step down changes like this may also result from the loss and restarting of preoxidants such as chlorine or ozone.

A particular example of a case where the turbidimeter stops recording when the filter is off line is shown in Figure 2.16. In this example the "profile is caused by the start / stop operation of a plant. Filter-to-waste should be implemented whenever a "dirty" filter (filter with run time) is placed on line. Also, operating the plant at a lower flow rate would enable the plant to dun longer with fewer shut downs / start ups and better overall process performance." Note how as the filter run gets longer, each start up produces worse filtrate. This is a practice to be avoided.

Figure 2.17 shows an example of very unstable filtrate quality. There could be many causes of such a trend and a full plant investigation is required. In Figure 2.18 a steady state is reached in both examples, however the steady state above 0.3 ntu is not in keeping with modern best practice. In Figure 2.19 a regular pattern of spikes is seen. This is likely to be caused by hydraulic surges, as other filters are routinely backwashed at regular intervals.

If a filter is allowed to start entering breakthrough, then even small adjustments in effluent flow rate can produce a spike. The magnitude of this spike increases the longer the filter run continues (Figure 2.20).

Water filtration plant staff are encouraged to review the turbidity profiles depicted in this chapter when filtered water turbidity is unsatisfactory, as the examples presented herein may provide clues to the nature of the problems being encountered.

REFERENCES

Chescattie, E. 2001. Personal communication.

Tillman, G. M. 1996. *WATER TREATMENT* Troubleshooting *and Problem Solving*. Boca Raton, Florida: Lewis Publishers

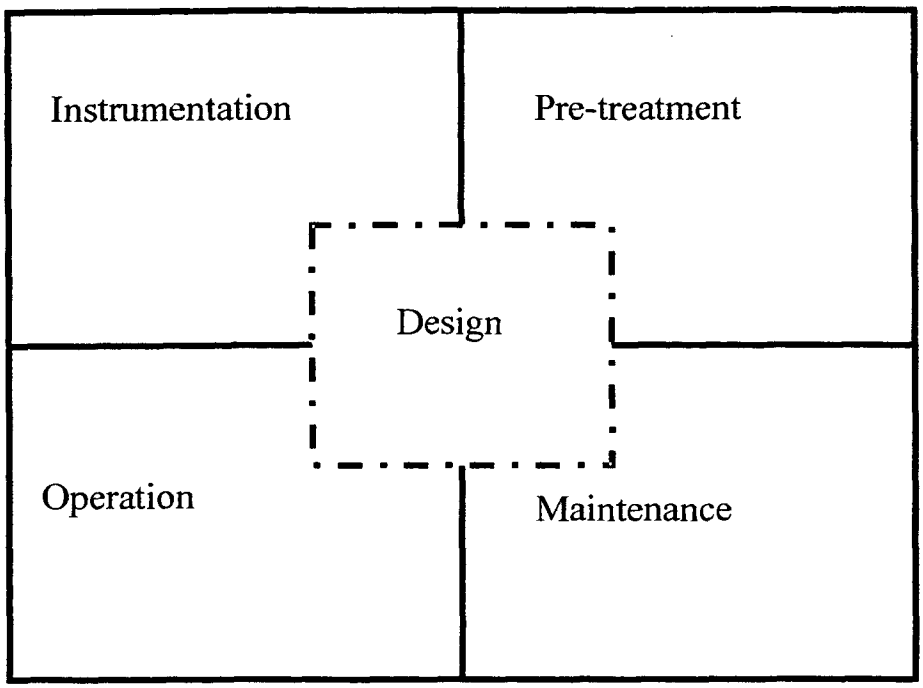

Figure 2.1 Filter O&M areas for improvement

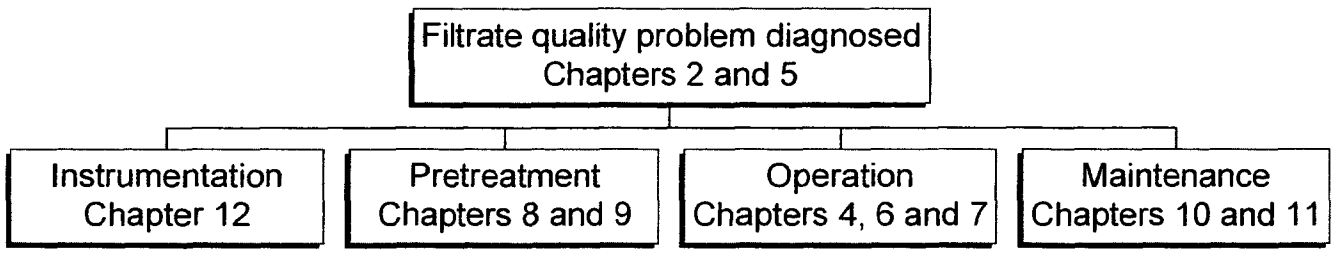

Figure 2.2 Layout of the Filter O&M Guidance Manual

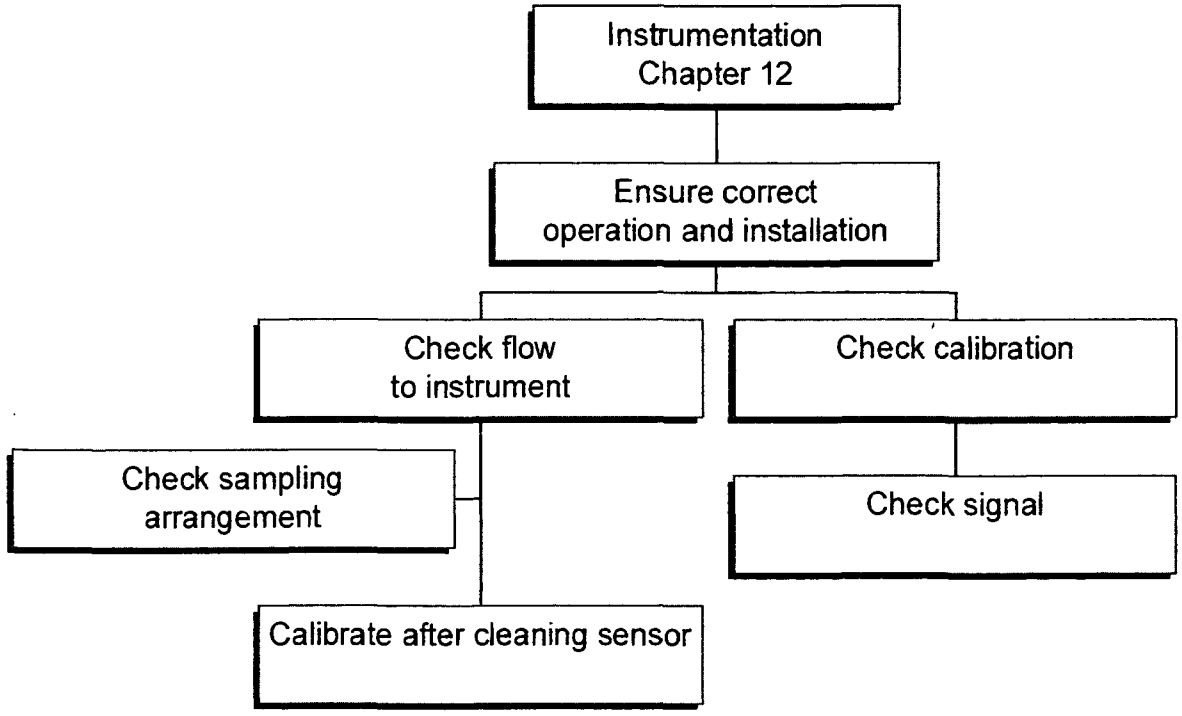

Figure 2.3 Steps in checking instrumentation

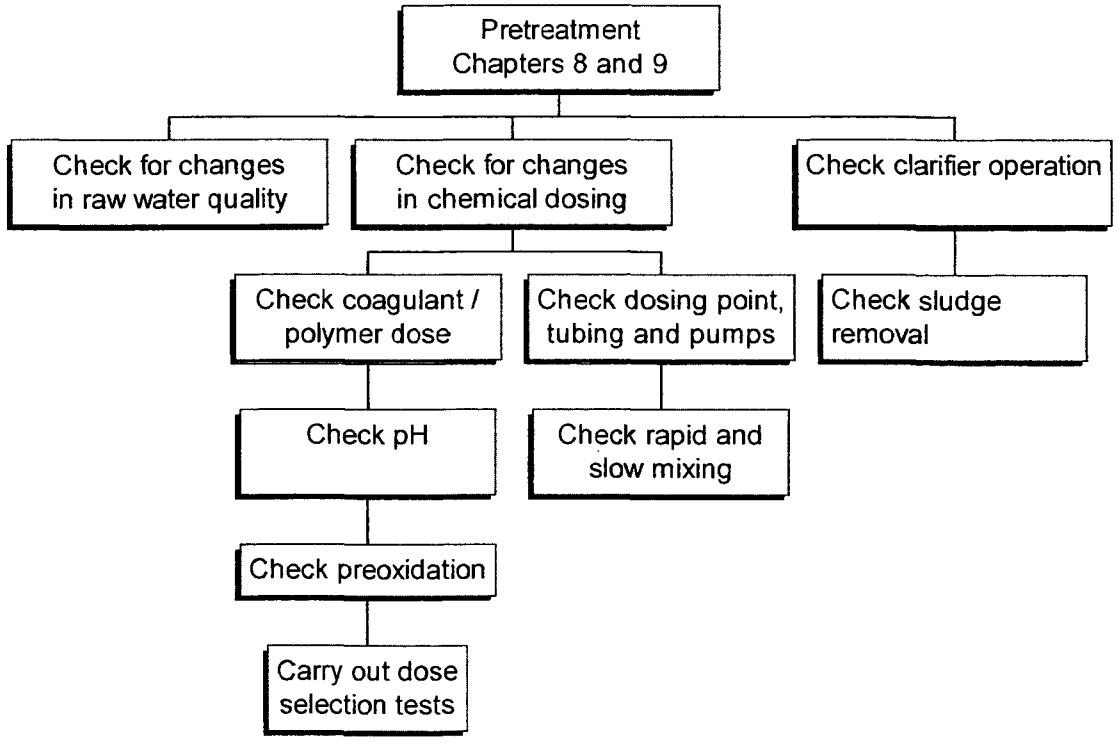

Figure 2.4 Diagnosis of pretreatment

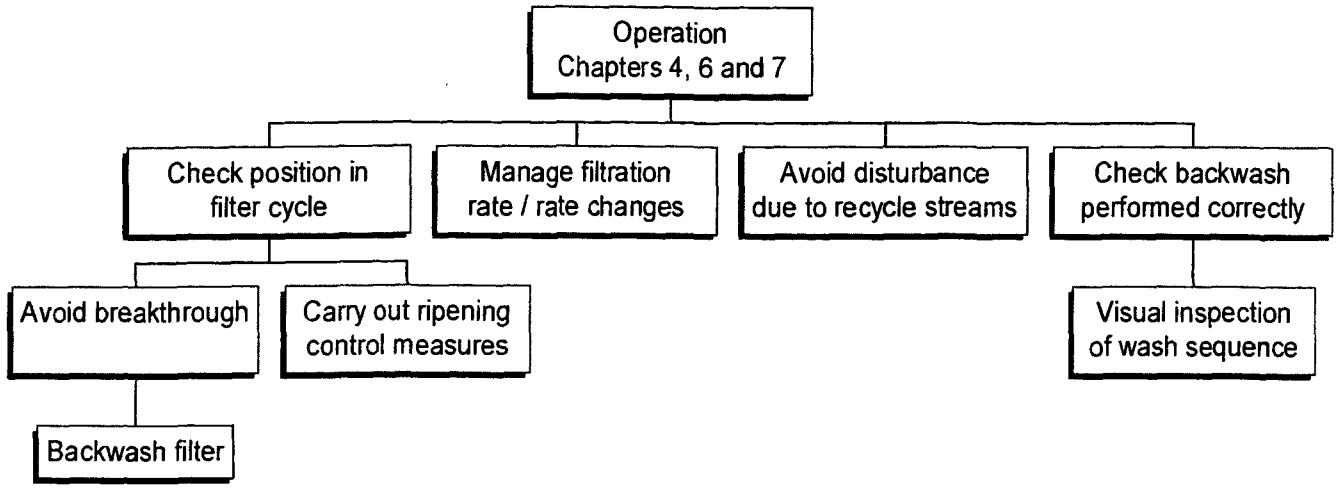

Figure 2.5 Actions for assessing effect of filter operation on filter performance

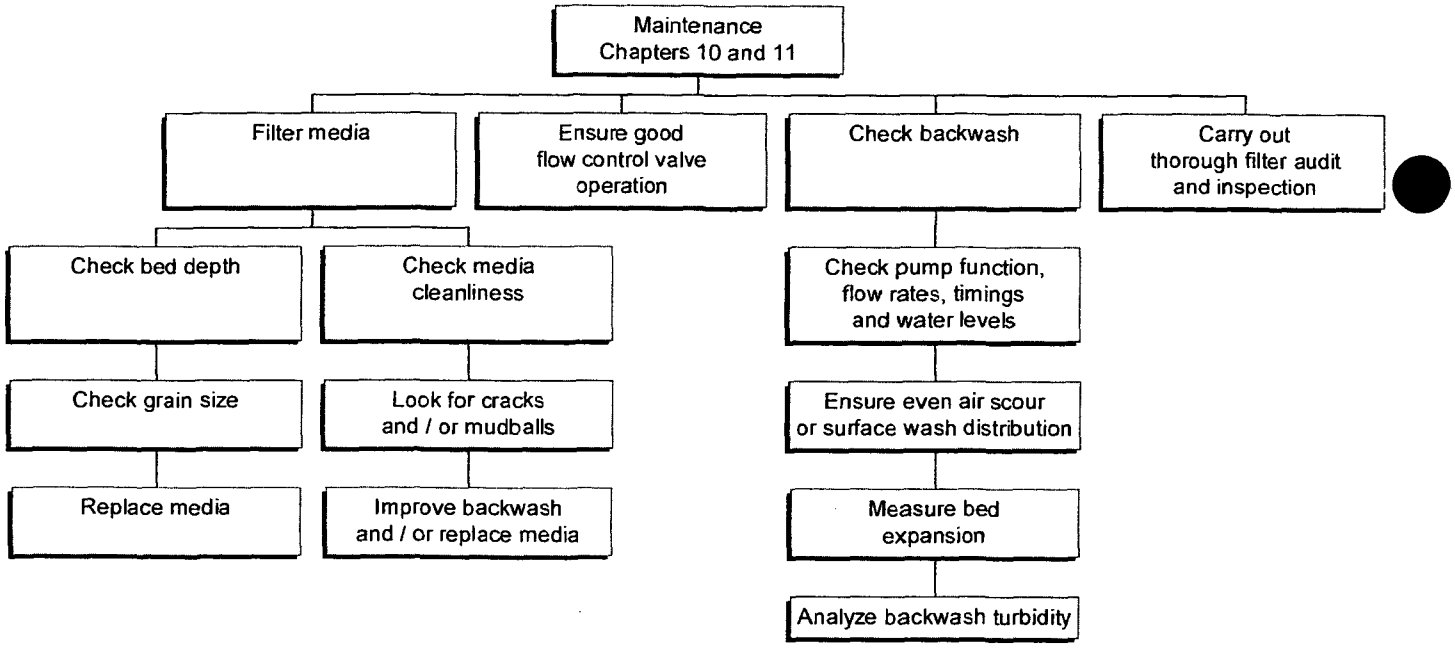

Figure 2.6 Filter maintenance program

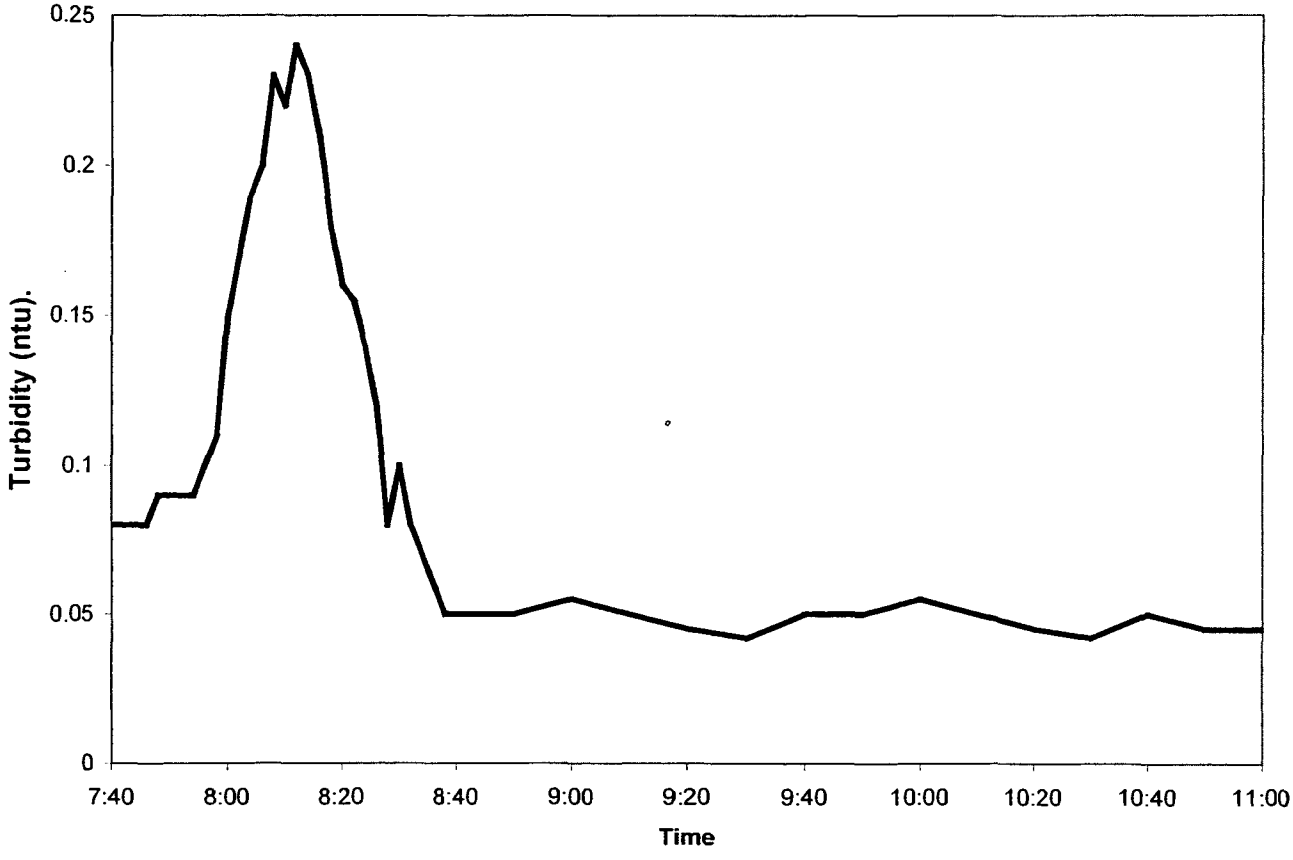

Figure 2.7 Typical filter backwash and ripening sequence. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

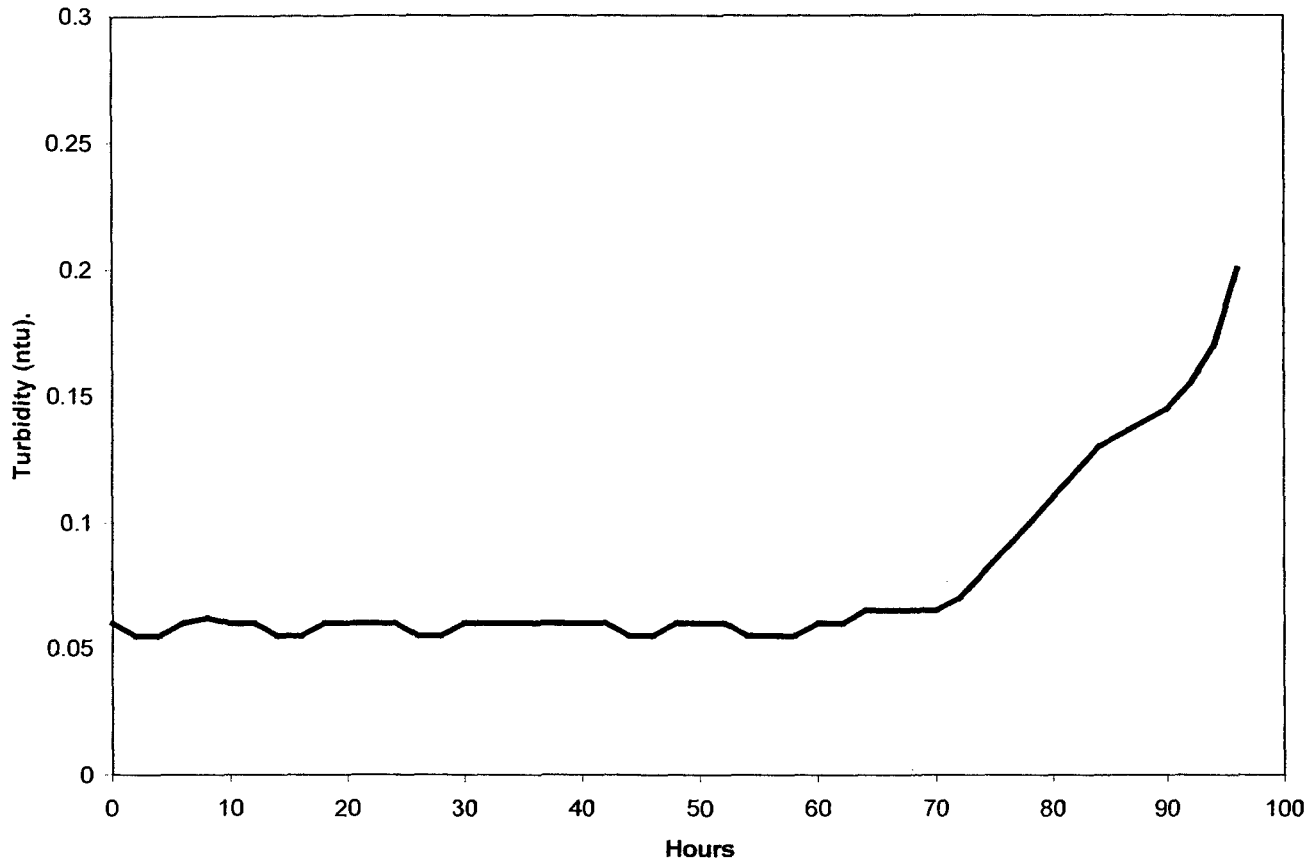

Figure 2.8 Excess filter run time. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

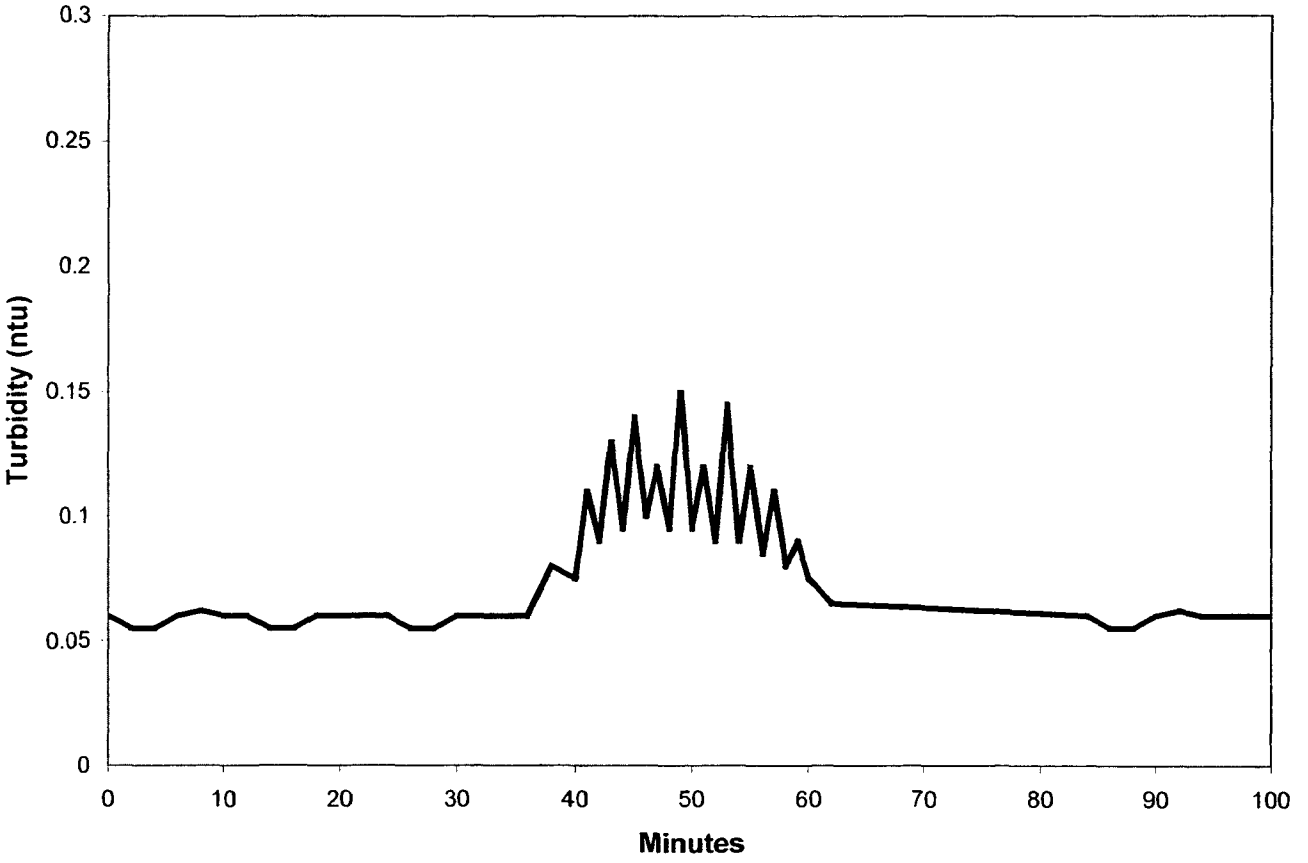

Figure 2.9 Filtrate disturbed by surging or hunting outlet valve. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

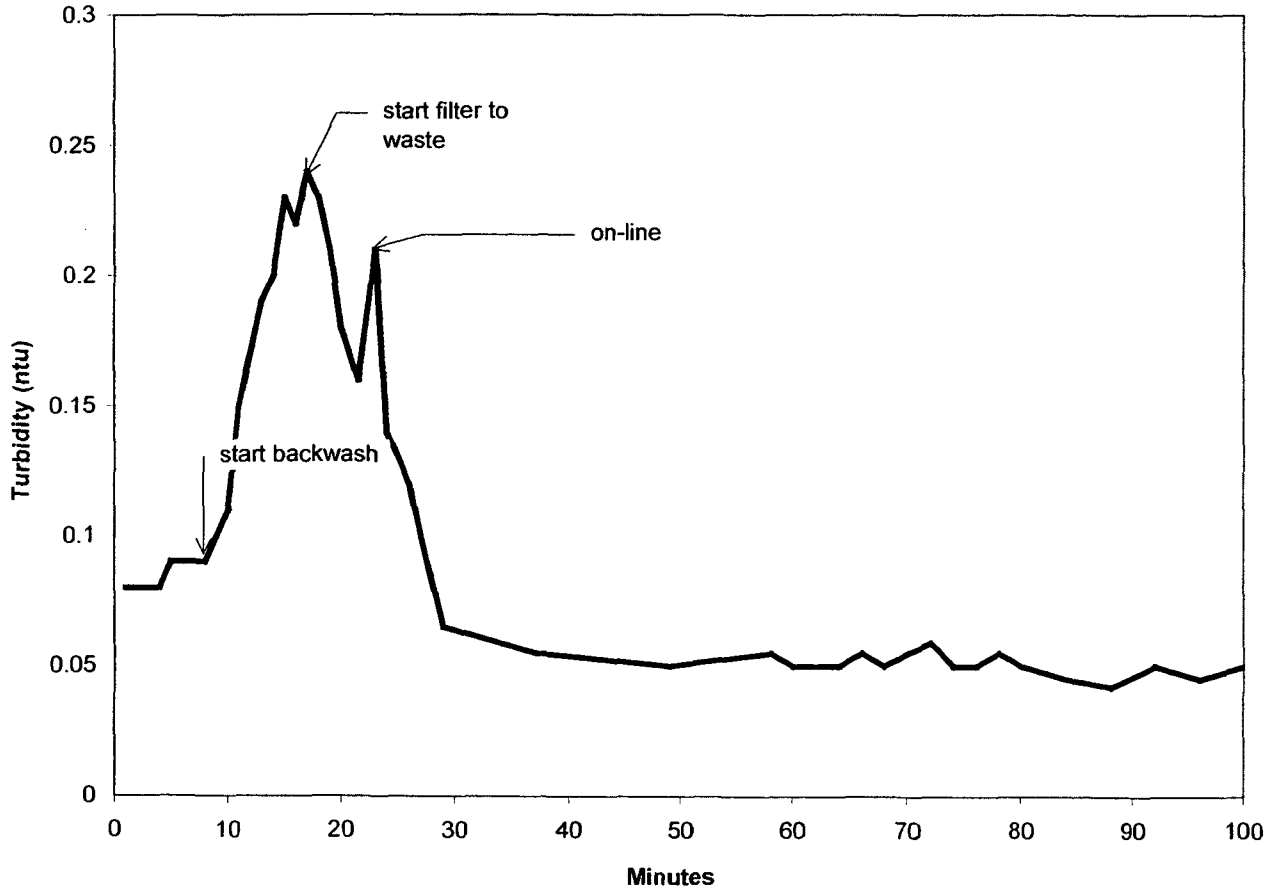

Figure 2.10 Filter-to-waste time too short. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

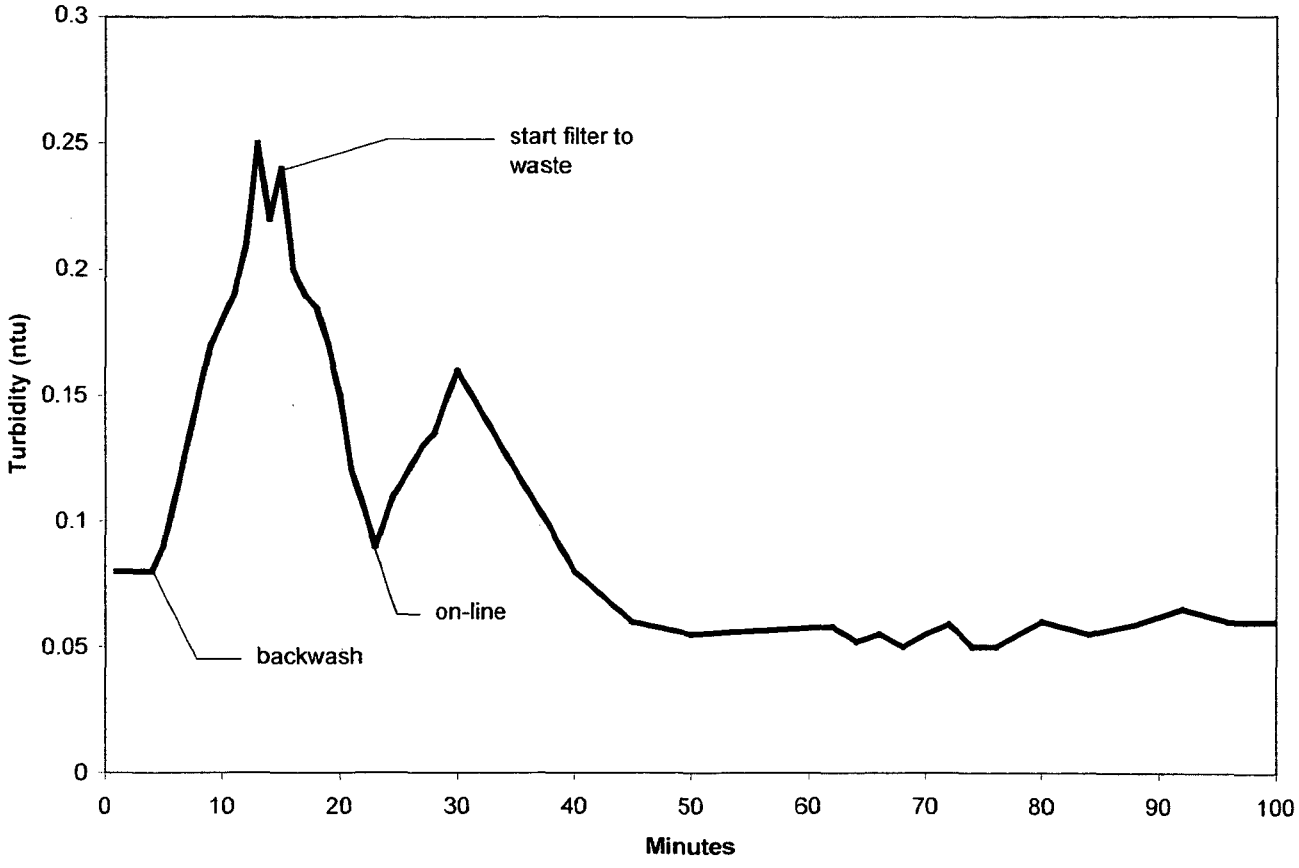

Figure 2.11 Secondary spike. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

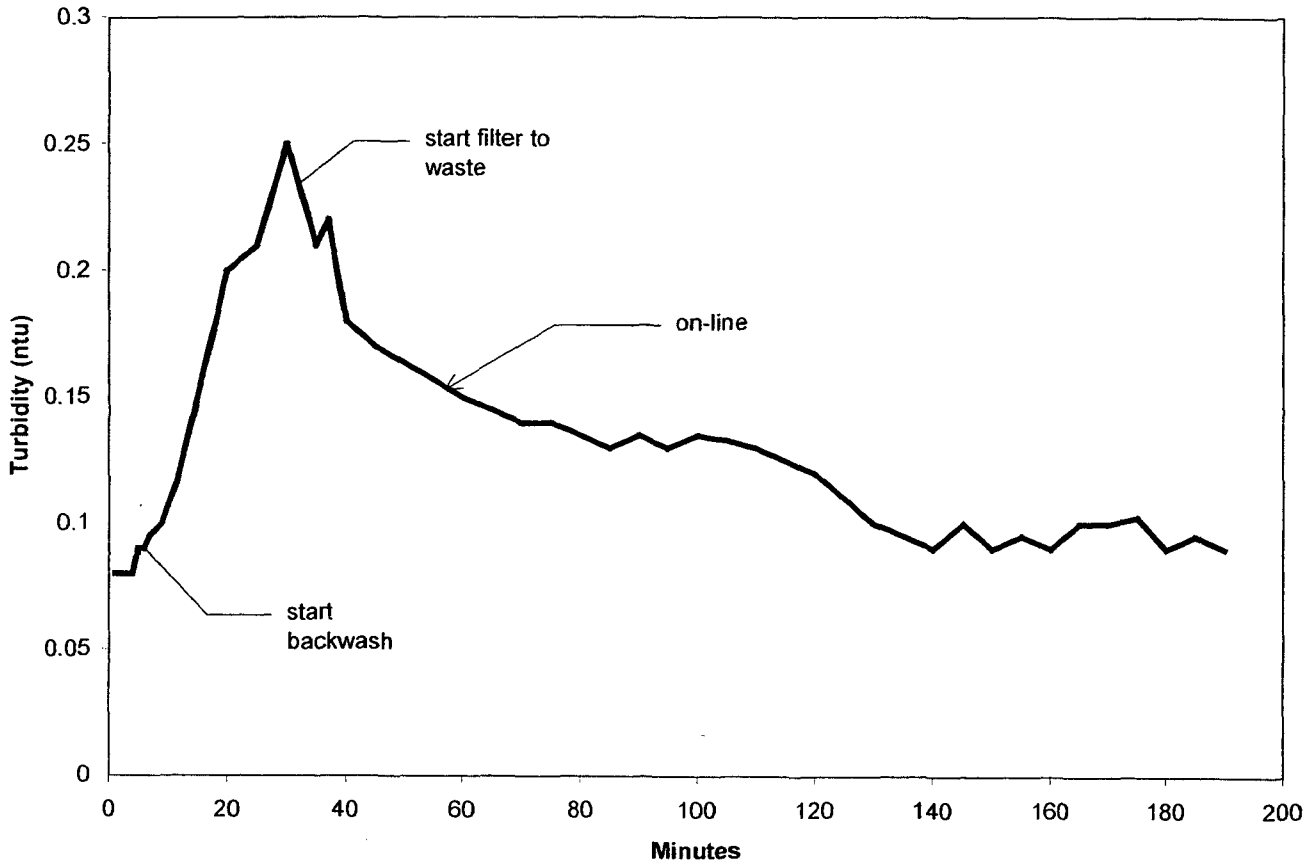

Figure 2.12 Excessive ripening period. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

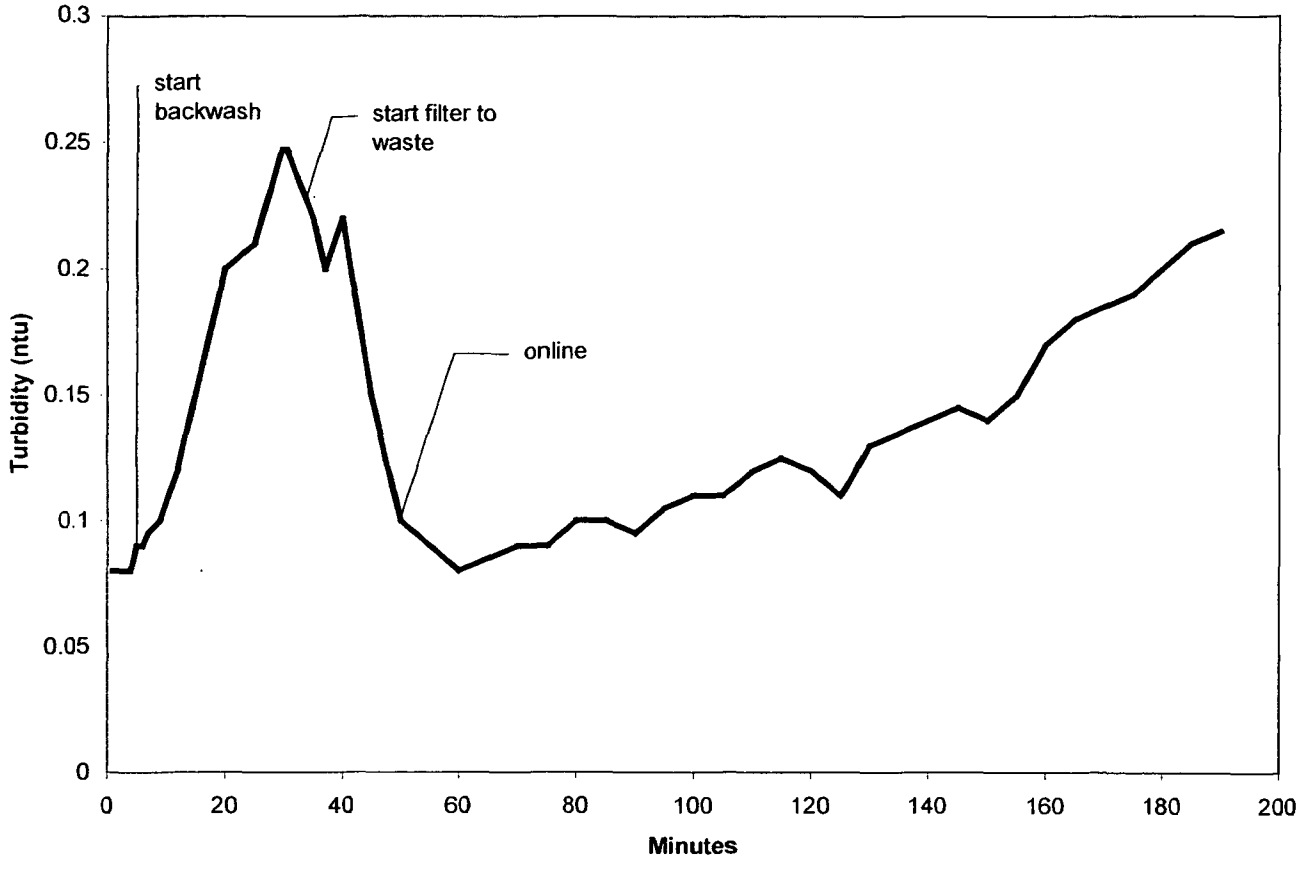

Figure 2.13 Rapidly deteriorating filtrate quality. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

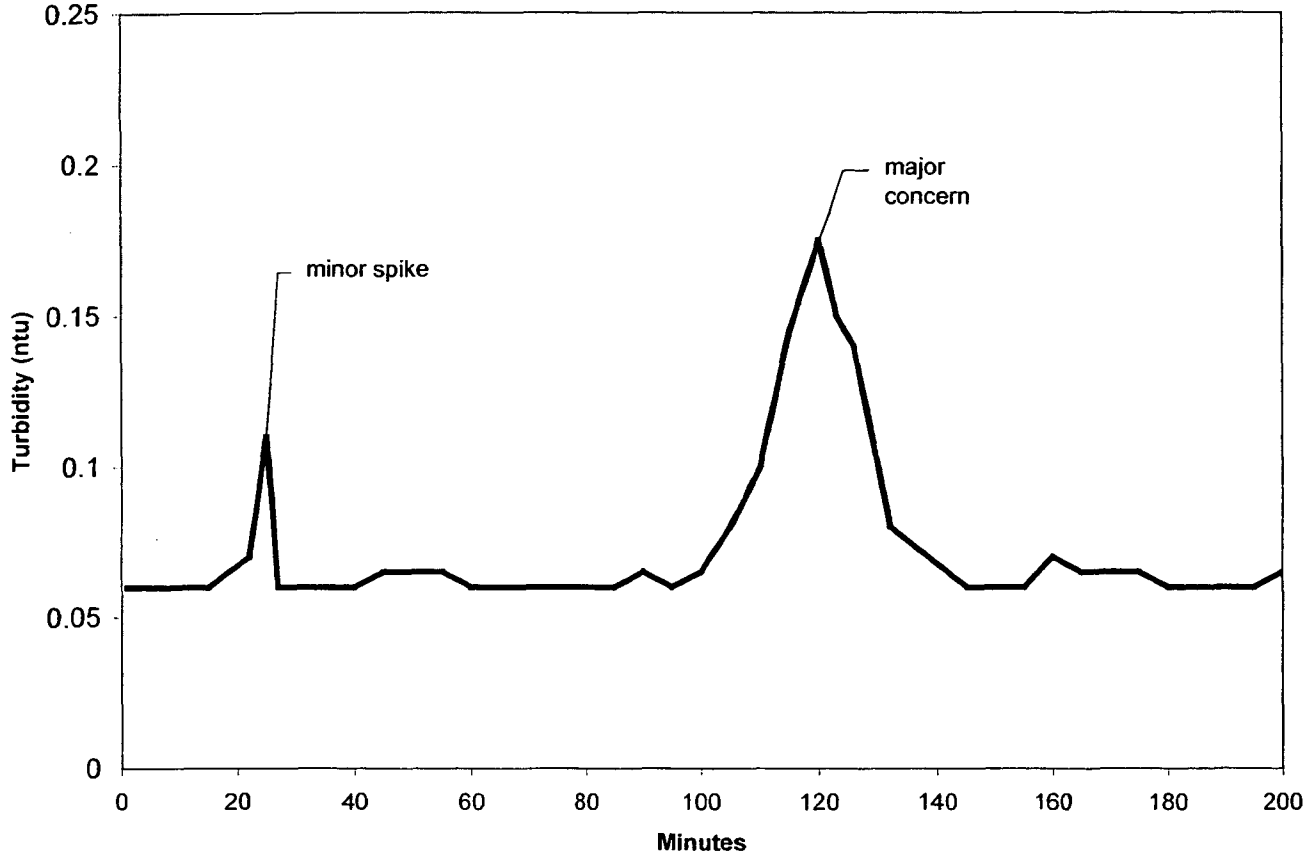

Figure 2.14 Spikes of poorer filtrate quality. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

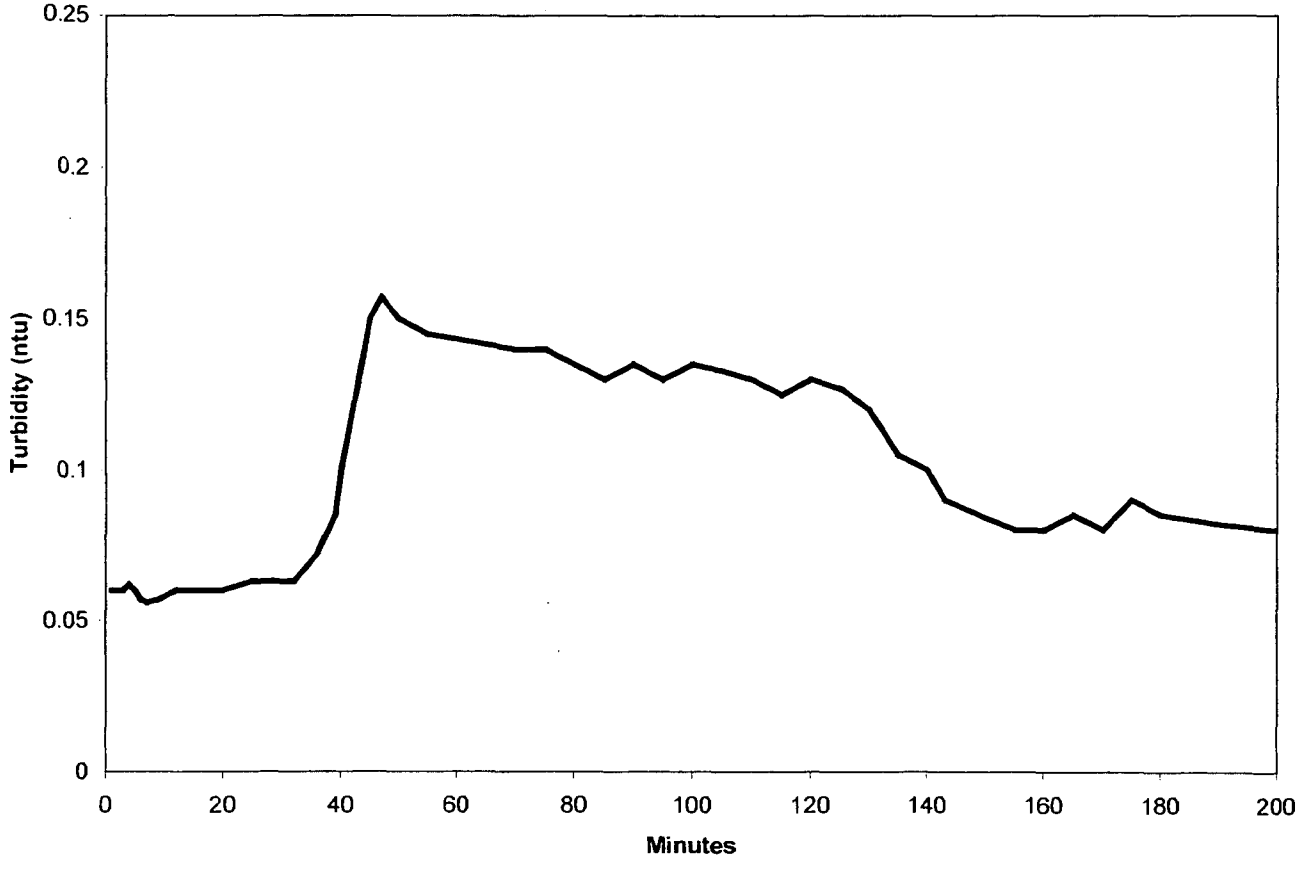

Figure 2.15 Step changes in filtrate quality. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

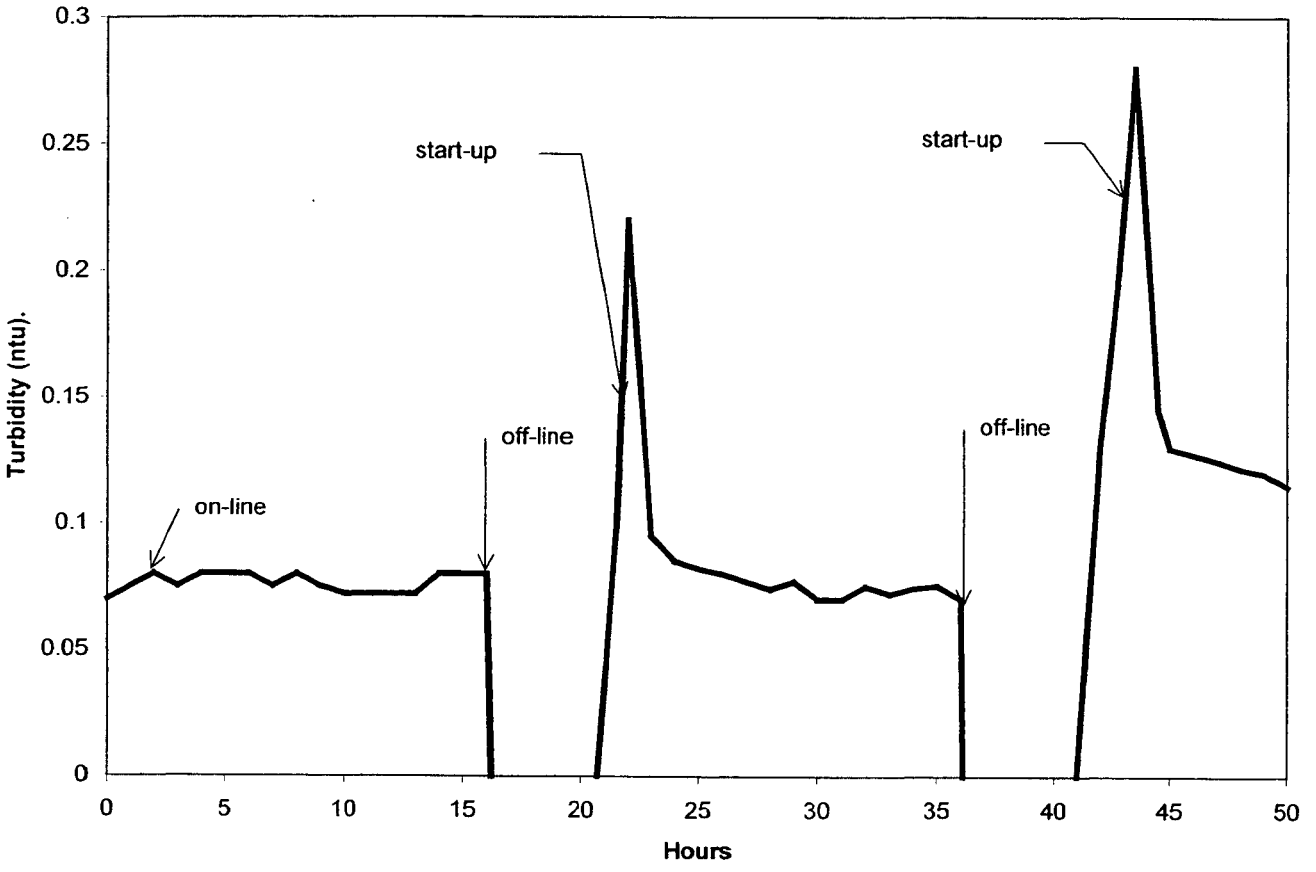

Figure 2.16 Filter start / stop showing spikes and step changes in filtrate quality. (*Source:* Excerpted from materials originally developed by the Pennsylvania Department of Environmental Protection, Chescattie 2001.)

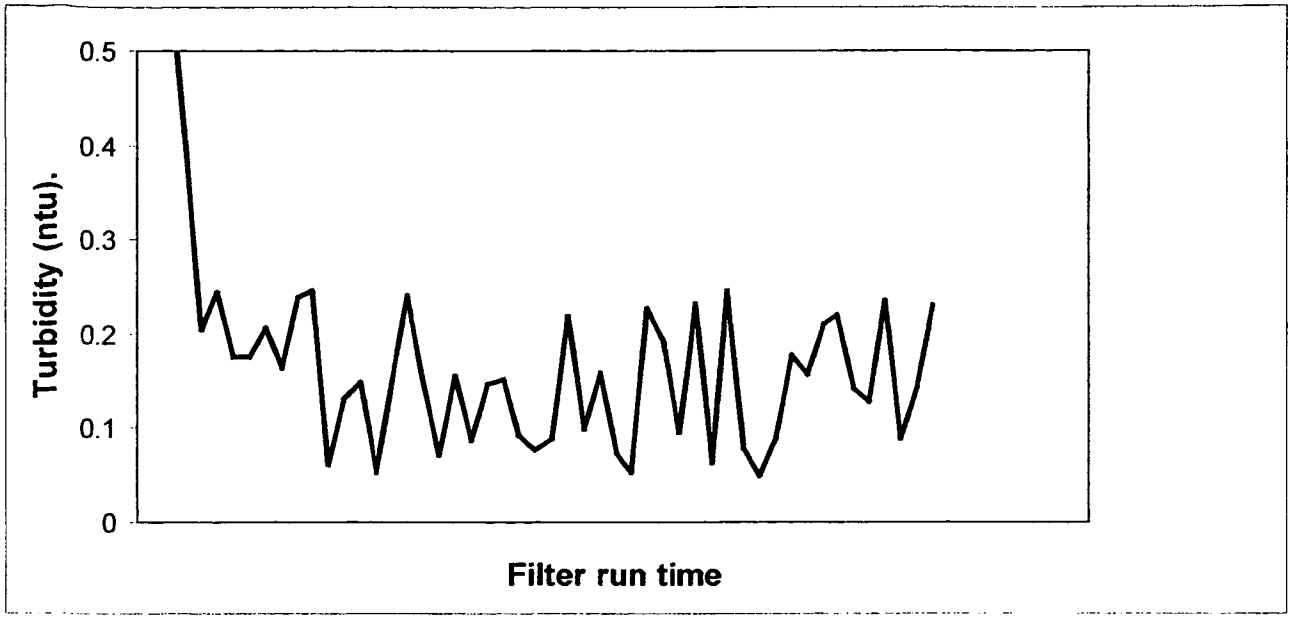

Figure 2.17 Highly unstable filter turbidity. (*Source:* Thames Water Utilities, 2000.)

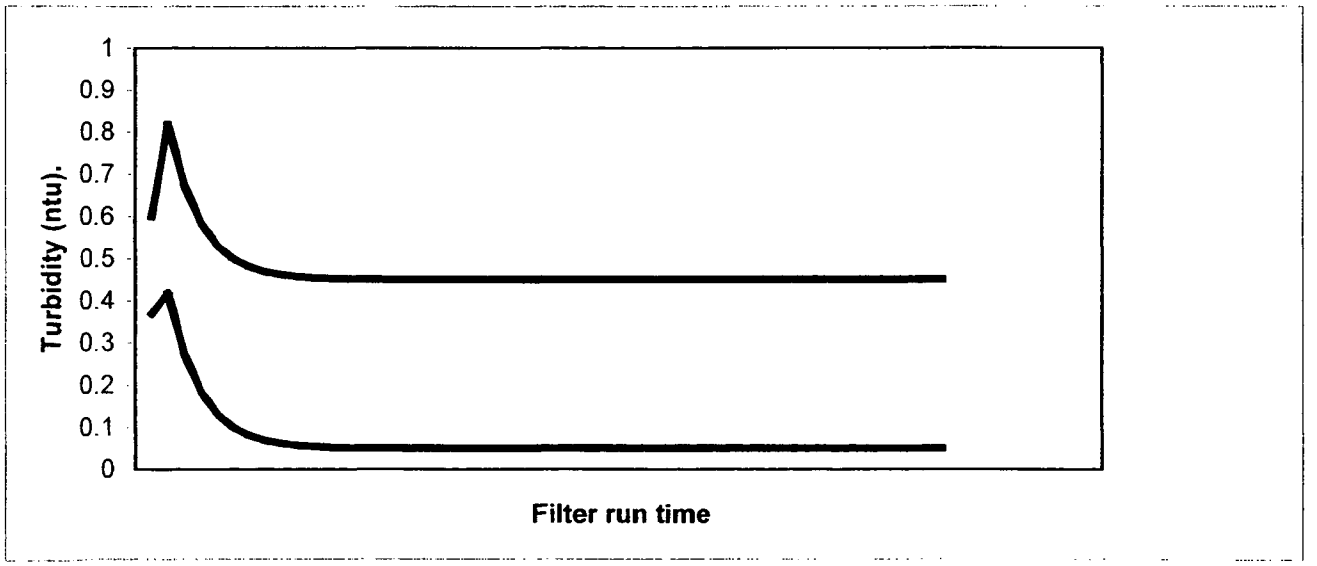

Figure 2.18 Stable turbidity but showing different steady state values. (*Source:* Thames Water Utilities, 2000.)

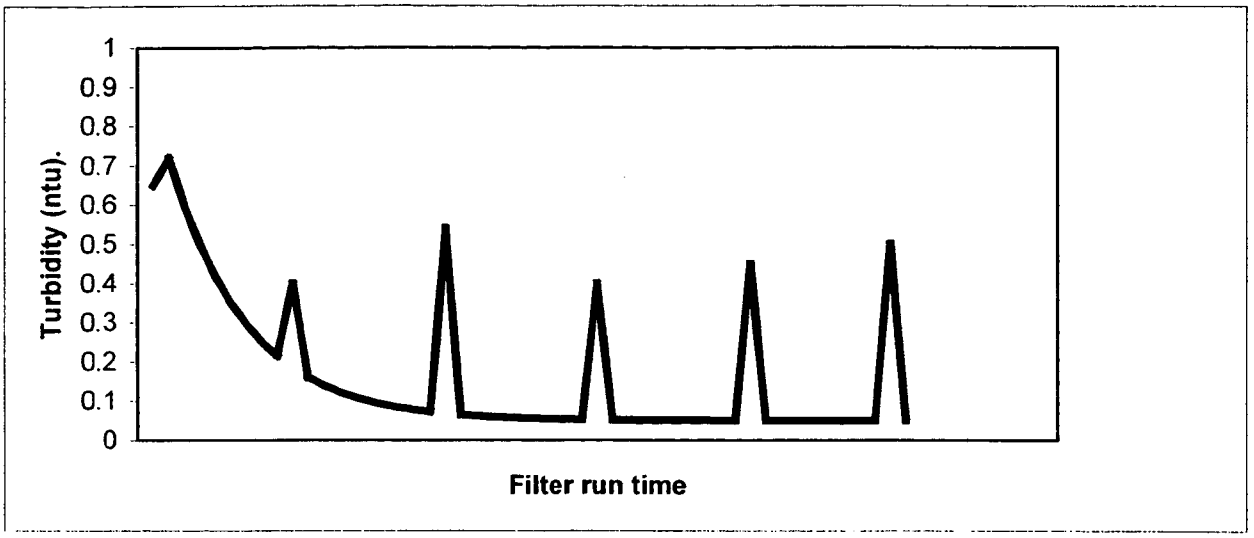

Figure 2.19 Effect of hydraulic surges due to other filters backwashing. (*Source:* Thames Water Utilities, 2000.)

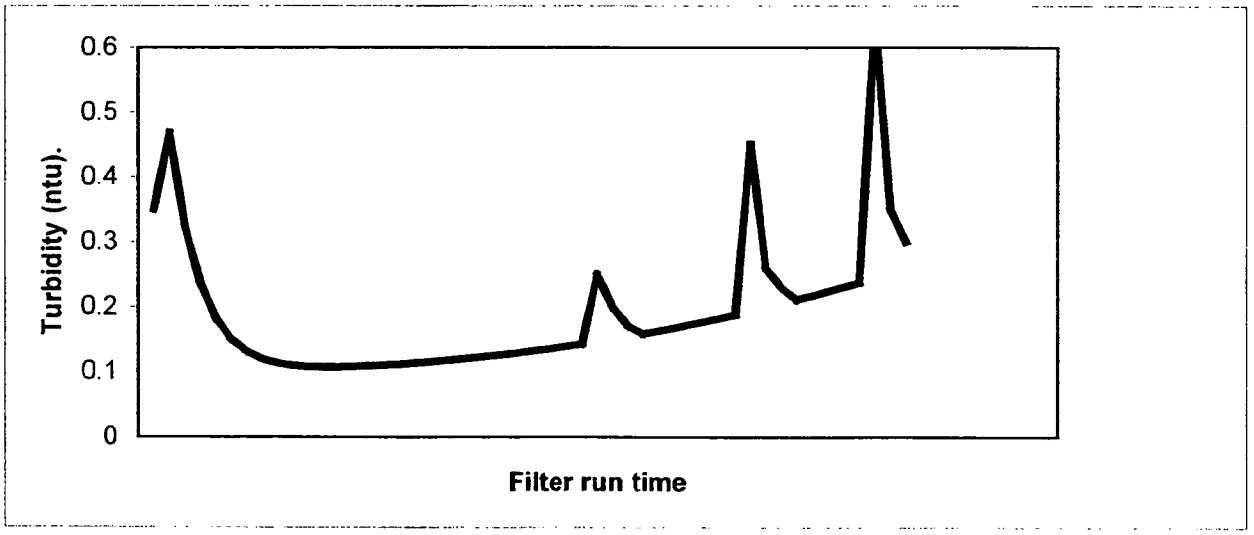

Figure 2.20 Spikes caused by flow rate changes during breakthrough. (*Source:* Thames Water Utilities, 2000.)

CHAPTER 3
THE REGULATORY ENVIRONMENT

INTRODUCTION

The Overall Regulatory Environment

Activities at water treatment plants may be governed by many kinds of regulations, including those related to labor rules, occupational safety, pollution control, and water quality. This chapter presents a review of drinking water regulations and guidelines that are closely related to water filtration and filter performance. Treatment plant operation will be influenced by regulations and guidelines, so operators need to be aware of the regulatory requirements or recommendations applicable to their circumstances. Information from the United States, Canada, the United Kingdom, Europe, Australia, and New Zealand is included so those who are interested water quality issues can learn about the approaches of various governmental bodies to water quality.

The emphasis in this manual is on operation and maintenance of water filtration plants with the objective of producing treated water having quality better than that required by regulations. When working to produce water, personnel at water treatment plants must be aware of other regulations, and must work within the constraints of those regulations while meeting water quality objectives. The scope of this manual is limited to water treatment and water quality. Other sources of information should be consulted for advice on regulations not dealing with drinking water quality.

Regulations Related to Water Quality

In recent years, the Partnership for Safe Water program has strongly advocated 0.1 nephelometric turbidity unit (ntu) as an important goal for filtered water. This program, carried out in cooperation with the EPA, the Association of Metropolitan Water Agencies, the AWWA Research Foundation, the Association of State Drinking Water Administrators, and the National Association of Water Companies, emphasizes the importance of optimizing filtration efficacy to attain filtered water quality superior to that required by regulations.

The concept of treating water to provide quality that is better than required by regulations or governmental guidance is not new. For over 70 years filtration engineers have supported attaining very low turbidity in filtered water. Seven decades ago, John Baylis (Baylis1924) wrote, "If we cannot tell

whether water has a turbidity of 1 or 0.1, how are we going to ascertain the proper amount of chemicals to use and when to wash filters? We are very careful to determine that the raw water turbidity is 35 and not 34 or 36, yet we are making very little effort to tell if the filtered water is 0.5 or 0.9. At the point where greatest accuracy is needed there is the least." It is interesting to note that at the beginning of the 21st century, the water industry again finds plant operators are setting filtered water quality goals that are at the edge of the capability for measurement by the conventional turbidimeters widely in use. Use of particle counters in the water industry is increasing, and at least one new concept of turbidity measurement has emerged.

At the conclusion of his 1924 paper, Baylis suggested that colloidal turbidity in filtered water should not at any time exceed 0.5, with the turbidity measurement being based on diluted suspensions of Fullers earth, in which the more concentrated turbidity suspension had been measured in a Jackson candle turbidimeters and found to have a turbidity of 25 or higher. In 1940 Baylis recommended attaining a turbidity of 0.2 turbidity unit as the standard for "A Grade" water (Baylis 1940). In 1960 Baylis indicated that Chicago's standard for turbidity in filtered water was 0.1 turbidity unit, in contrast to the US Public Health Service's recommended maximum of 10 turbidity units (Baylis 1960). Even though he lacked sensitive instruments, more than 70 years ago Baylis realized that attaining low filtered water turbidity was important, and he worked to attain that goal and advocated that others do the same. Over the years, others followed the lead of Baylis.

Thus for the Partnership for Safe Water to have a goal of treating water to attain quality that surpasses regulatory requirements is not a new concept. Rather, it represents a continuation of progressive water industry thought that has a long history. This manual endorses the concept of treating water so the quality is superior to that set by regulation. The concept of continuing to improve quality, as espoused by the Partnership for Safe Water, challenges water utilities to go beyond regulatory requirements to a higher level of quality.

Information on drinking water regulations, standards, and guidelines is presented in the following sections of this chapter, with a focus on regulations directly or very closely related to treatment plant performance at facilities employing coagulation and filtration or lime softening and filtration. A comprehensive review of drinking water regulations for inorganic and organic contaminants is beyond the scope of this manual.

UNITED STATES

The U.S. EPA promulgated the Interim Enhanced Surface Water Treatment Rule (IESWTR) on December 16, 1998 (U.S. EPA 1998a). This rule took effect on January 1, 2002. Essential features of the IESWTR were reviewed by Pontius (1999a). Water systems treating surface water or groundwater under the influence of surface water and serving 10,000 or more persons must comply with the IESWTR. The principal aspects of this rule that affect filter operation and maintenance are the tightening of the filtered water turbidity performance standard and the requirement for monitoring of turbidity of individual filters.

On April 10, 2000, the EPA published the proposed Long Term 1 Enhanced Surface Water Treatment and Filter Backwash Rule (LT1FBR) in the *Federal Register* (U.S. EPA 2000). The turbidity provisions for this rule, which applies to water systems serving fewer than 10,000 persons, are similar to those of the IESWTR, with slight modifications to reduce the burden on small systems (Hamele and Robichaud 2000).

When the IESWTR takes effect, conventional filtration plants and direct filtration plants (filtration plants in which chemical coagulation is employed) must produce filtered water that is 0.3 ntu or lower in 95 percent of samples taken each month. The proposed LT1ESWTR also has those provisions.

Under the IESWTR the turbidity of water produced by each filter must be measured with a continuous turbidimeter and the results recorded every 15 minutes. These records must be kept by the utility for three years. Turbidity excursions must be documented and reported, and depending on the severity of the turbidity excursion, the water utility would have to undertake different levels of action.

Turbidity events and consequences are:

- > 1.0 ntu in 2 measurements at 15 minute intervals; produce a filter turbidity profile (a graph of turbidity versus time)
- > 0.5 ntu in 2 measurements at 15 minute intervals after 4 hours of operation; produce a filter turbidity profile
- > 1.0 ntu in 2 measurements at 15 minute intervals in each of 3 consecutive months; prepare a filter profile and prepare a filter self-assessment report
- > 2.0 ntu in 2 measurements at 15 minute intervals in each of 2 consecutive months; arrange for a comprehensive performance evaluation.

The IESWTR includes other provisions, but these are the ones that will have the greatest impact on the filtration process, monitoring, and associated record keeping.

The proposed LT1ESWTR would require a water system serving under 10,000 persons to submit an exceptions report to its state primacy agency if two consecutive turbidity readings for a single filter exceed 1.0 ntu. If the system submits an exceptions report three months in a row for the same filter, the system must perform a filter self-assessment. If the same filter has two or more consecutive turbidity values of 2.0 ntu or greater during two consecutive months, then the system is obliged to arrange for a comprehensive performance evaluation. This evaluation may be made by the state or by a third party approved by the state (Hamele and Robichaud 2000).

When the IESWTR was promulgated, the EPA also promulgated Stage 1 of the Disinfectants and Disinfection Byproducts Rule. The purpose of this rule is "…. to reduce the levels of disinfectants and disinfection byproducts in drinking water supplies." (U.S. EPA 1998b). The amount of disinfection byproducts forming in water after disinfection can be related to the quantity of organic matter in water, expressed as total organic carbon (TOC). Therefore this rule contains operational requirements for removal of TOC at water filtration plants that practice coagulation or lime softening. Table 3.1 is based on, but not an exact representation of, the table on page 69474 of the EPA Rule. For details on this rule, users of this manual are referred to Pontius (1999b). The requirements of Table 3.1 do not apply if the source water TOC concentration averages less than 2.0 mg/L, if the treated water TOC concentration averages less than 2.0 mg/L, or if the concentration of total trihalomethanes (TTHM) average in the distribution system is less than 0.040 mg/L and the concentration of the sum of five haloacetic acids (HAA5) in the distribution system is less than 0.030 mg/L. Other factors also apply to avoiding TOC

removal requirements based on the concentration of disinfection byproducts in the distribution system. Consult Pontius (1999b) for details.

Negotiations among EPA and interested parties concerning the nature of the future Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) resulted in the development of a Stage 2 M-DBP Agreement in Principle, which includes disinfection byproducts, the LT2ESWTR, Ultraviolet Light for disinfection, and other issues. An electronic version of the September 12, 2000 signature copy, and a review of the agreement (Scharfenaker 2000) provide the basis for the discussion in this manual. In this agreement, conventional treatment plants in compliance with the IESWTR are presumed to attain an average of 3-log removal of *Cryptosporidium* oocysts. If source water monitoring demonstrates presence of *Cryptosporidium* oocysts at average concentrations of 0.075 oocyst/L or higher, additional treatment would be required. Refer to Scharfenaker (2000) for details. The Agreement in Principle does not address direct filtration plants nor does it address filtration plants that use dissolved air flotation for clarification. The Agreement appears to build on previous rulemaking, as it did not revisit the issue of TOC removal, which was covered in Stage 1 of the Disinfectants and Disinfection Byproducts Rule. Stage 2 rules are expected to be promulgated in mid-year, 2002. Final details will be available in sources such as *Journal American Water Works Association* after promulgation takes place.

Table 3.1

Required removal percentage of total organic carbon (TOC) as a function of source water TOC and alkalinity, Disinfectants and Disinfection Byproducts Rule, Stage 1

Source Water TOC (mg/L)	Source water alkalinity (mg/L as $CaCO_3$)		
	0 to 60 mg/L	>60 to 120 mg/L	>120 mg/L
>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%

In an effort to control contaminants that might be present in recycle streams, the Filter Backwash Recycling Rule was proposed as part of the Long Term 1 Enhanced Surface Water Treatment Rule in

April 2000. The Filter Backwash Recycling Rule (FBRR) was promulgated as a separate rule on June 8, 2001 (U.S. Environmental Protection Agency 2001).

The FBRR applies to any public water system, regardless of size, that uses a surface water or ground water under the direct influence of surface water, and treats using direct or conventional filtration. Systems using membranes, diatomaceous earth filtration, etc. will not be affected. Treatment processes that have been included as conventional treatment under previous rules, such as softening, are presumed to be included under the FBRR.

The recycle streams regulated by the FBRR are filter backwash water, sludge thickener supernatant, and liquids from dewatering processes. The recycle streams are to be returned to the treatment process prior to coagulation unless another location is approved by the State. If capital improvements are needed for return of recycle streams to an approved location, those are to be completed by June 8, 2006.

The rule includes requirements for providing information to state regulators and for keeping records related to plant operations. By December 8, 2003 each system must send the following information to the State:

- A treatment plant schematic showing unit processes, points of chemical addition, and the entry point of all recycle streams.
- Flow data (in gpm) including the typical recycle flow, maximum plant flow during the previous year, design flow, and State-approved operating capacity (if available).

Each public water system must maintain records on:

- Information submitted to the State;
- List of all recycle flows and the frequency of recycling;
- Average and maximum backwash flow rate through the filters;
- Average and maximum duration of the backwash process (minutes);
- Typical filter run length with written summary of how length is determined;
- Type of treatment, if any, provided for the recycle flow;
- Data on recycle treatment units such as physical dimensions, hydraulic loading rates, type and dose of chemicals used, and frequency of solids removal.

Although the text of the FBRR did not contain information specifying the length of time for which those records must be kept by water systems, EPA (Robichaud 2001) considers these records to be in the classification of data kept for sanitary surveys. Data for review by states during sanitary surveys must be held for 10 years, according to other provisions in the SDWA Regulations. Therefore water utilities should plan to keep the above-described records for 10 years.

In the United States, water utility employees who make decisions about water quality and treatment need to consider the problem of potentially conflicting results from the regulatory perspective, when a change is made in treatment. Lowering the pH to attain more effective coagulation could result in more corrosion in the water distribution system, and failure to meet provisions of the Lead and Copper Rule, unless corrosion control measures are taken before the water is distributed to the system. Adding lime to filtered water in a clearwell to help control corrosion might make the finished water more turbid than water from the filters. This would have the potential to bring about compliance problems unless an arrangement can be worked out with regulators to base turbidity compliance on filtered water instead of water leaving the plant. Abandonment of prechlorination, which also acts as a pre-oxidant, could provide an important benefit for compliance with DBP regulations, but lack of pre-oxidation might cause difficulties in attaining the very low level of turbidity desired to meet Partnership for Safe Water goals and in the inactivation of *Giardia* cysts. Sometimes very careful balancing of objectives and means used to attain them is required if all of the regulations and the utility's water quality goals are to be met at the same time.

Another potential conflict in regulatory compliance might occur when utilities practice enhanced coagulation to remove total organic carbon (TOC) for compliance with the Disinfectant/Disinfection Byproducts Rule. For some waters enhanced coagulation may not provide optimized particle and turbidity removal. Again a balancing act may be required to maintain effective treatment that complies with all applicable regulations.

A final word of caution relates to the manner in which drinking water regulations are enforced in the United States. Although the U.S. EPA promulgates regulations, in nearly all cases individual states adopt the regulations and are responsible for enforcement. States may adopt regulations that are more strict, but not less strict, than the EPA's regulations. In some instances, a state regulation may be more stringent than the federal regulation. Water system managers and operators need to be aware of the regulatory circumstances relevant to their utility.

Drinking water regulations continue to change and evolve in the United States. Regulatory affairs and related topics frequently are presented in the *Journal American Water Works Association.*

Users of this manual who are concerned about the status of the U.S. EPA's regulations are advised to seek information in the *Journal AWWA*.

CANADA

The Canadian approach to drinking water safety is different from the centralized regulatory approach used by the United States. Canadian drinking water quality protection involves a cooperative effort of the federal, provincial and territorial governments (Giddings 2000). In Canada a federal agency, Health Canada, develops *Guidelines for Canadian Drinking Water Quality* in consultation with provinces and territories (Health Canada 2000). Provinces and territories use the guidelines in developing their drinking water programs, but they are not obliged to set standards as rigid as those in the guidelines. Therefore, the drinking water standards applied may vary from province to province.

Both past and present reviews of Canadian drinking water programs reveal differences in approaches used by the provinces. Decker and Long (1992) reported that in the early 1990s only two provinces, Alberta and Quebec, had promulgated enforceable regulations based on the federal-provincial guidelines.

In March 2001, a review of provincial Internet sites showed that the differences among provinces continue, but more are moving toward enforceable regulations. Quebec had regulations on the quality of potable water, and Ontario announced new enforceable regulations in 2000. Affected in Ontario will be waterworks that supply water to six or more residences. These regulations will require all drinking water to be disinfected as of December 31, 2002, unless rigorous exemption conditions are met. As of December 31, 2002 all surface water must be treated by chemically assisted filtration and disinfection or by an equivalent treatment process. No provisions are made for exemptions for surface water treatment.

Nova Scotia has adopted enforceable regulations, using the health-based Guidelines for Canadian Drinking Water Quality. Routine monitoring will be required. Public drinking water systems serving 25 or more persons for at least 60 days per year, or having 15 or more connections are affected by these regulations.

Alberta has detailed regulations. Plants employing rapid rate granular media filters are required to meet specified turbidity reductions. If the source water turbidity equals or exceeds 2.5 ntu, filtered water turbidity must be less than 0.5 ntu in 95% of monthly samples. For source water less than 2.5 ntu, a monthly average turbidity reduction of 80% or attaining filtered water turbidity of equal to or less than

0.1 ntu is required. For this performance, conventional filtration plants are given 2.5-log removal credit for *Giardia* cysts and 2.0-log credit for virus removal.

In British Columbia, local determination is made regarding adequacy of water treatment, except that all surface waters must be disinfected, and all drinking water must meet enforceable limits for total coliform and fecal coliform bacteria.

Environmental Departments in individual provinces are responsible for issuing treatment plants with a "License to Operate." This license specifies how the plant should be operated, what chemicals can be used, how frequently samples must be taken through the plant and in the distribution system, as well as the water quality criteria that must be met. If the water quality criteria are not met, the infraction must be reported immediately to the Environment Department and the corrective action taken that is also specified in the License to Operate. Water quality criteria in Licenses to Operate water treatment plants may be more stringent than the Health Canada Guidelines.

The latest Canadian guidelines were issued in 1996, and include maximum allowable concentrations (MAC) for turbidity and coliforms. The MAC for turbidity of water entering the distribution system is 1 ntu, but turbidity may exceed 1 ntu if microbiological quality is acceptable and if the turbidity does not interfere with disinfection. The MAC for total coliform bacteria is stated in three parts:

- no sample should have more than 10 per 100 mL and none should be fecal coliform
- no consecutive samples from a site should show the presence of coliforms
- for community water systems, not more than one sample collected in a given set of samples should be positive for coliforms, and not more than 10% of samples should be positive for coliforms when 10 or more samples have been collected.

Recommendations are made for the extent of treatment, based on coliform sampling. For example if more than 10% of raw water samples in a 30-day period have a fecal coliform density > 100 per 100 mL or a total coliform density of > 1000 per 100 mL, then the source water should be treated by conventional treatment plus disinfection.

Canadian guidelines have an operational guidance for aluminum. Conventional treatment plants using aluminum-based coagulants should not exceed a total aluminum concentration of 100 μg/L based on a running annual average of monthly samples. For direct filtration plants and for lime softening plants, the operational guidance value is 200 μg/L.

Current issues for Canadian guidelines (Giddings 2000) include *Giardia* and *Cryptosporidium*, chlorinated disinfection by-products, uranium, cyanobacterial toxins, and aluminum. In addition, the significant waterborne disease outbreak at Walkerton, Ontario, in which a number of deaths were caused by drinking water in the summer of 2000 may have an influence on the future direction of the Canadian guidelines. If Canadians follow the pattern of drinking water regulation prevalent in the United States, where a major, newsworthy problem brings about more regulation, then the regulatory approach in Canada might become more stringent.

Information on regulatory developments and drinking water guidelines in Canada is seldom provided in the *Journal American Water Works Association.* For this information users of this manual may need to search internet sites of Canadian Provinces or the internet site of Health Canada.

WORLD HEALTH ORGANIZATION

The World Health Organization (WHO) is the United Nations agency that deals with public health issues. The primary aim of the WHO Guidelines for Drinking Water Quality is to provide a body of sound scientific knowledge to aid countries with the development of national standards and regulations. The guide values while not having any legal status tend to be regarded as the international standards. The World Health Organization emphasizes the importance of regional and national risk-benefit analysis to take account of local factors when setting standards and regulations. Readers of this manual are reminded that WHO Guidelines are prepared with the needs of developing countries in mind. The WHO Guidelines tend to be less stringent than EPA's Drinking Water Regulations, but this is not a reason for EPA to loosen its regulations. WHO Guidelines have been summarized by Twort, Ratnayaka, and Brandt (2000).

For turbidity WHO chose not to set a health based guideline value; however turbidity is recognized as an important parameter in two respects (1) as a measure of the acceptability of water to consumers and (2) as a disinfection efficacy criterion. WHO recommends that treated water turbidity is kept as low as possible with an upper limit of 5 ntu to avoid the indirect health consequences of consumers rejecting a water supply on aesthetic grounds. For effective, reliable terminal disinfection WHO recommends that the median turbidity of water immediately before disinfection does not exceed 1 ntu. Normal chlorination is defined - free chlorine residual of 0.5 mg/l, a contact time of 30 minutes, a pH of less than 8.0 and a turbidity of less than 1 ntu. In essence through this definition WHO established an international water treatment goal and the conditions chosen were those required to bring

about reductions greatly in excess of 99% for *E. coli,* Polio Type 1, Hepatitis A and Rotavirus but not the parasitic protozoa *Cryptosporidium parvum* and *Giardia lamblia.* WHO has yet to address parasites but by implication WHO has acknowledged that disinfection and a turbidity of 1 ntu is not an adequate safeguard.

EUROPE AND UNITED KINGDOM

The advent of standards and regulations in the U.K. can be traced back to the publication in 1980 of the first European Economic Community (EEC) Directive concerning the quality of water for human consumption, EEC/778 . This was implemented by all member states in 1985 and in the U.K. initially this was achieved administratively by the Department of the Environment issuing Information Circulars to public water suppliers. By 1989 the situation had evolved into substantive new legislation in England and Wales. Largely as a result of a serious water supply accident in 1988 where alum was delivered to a clearwell with alarming consequences for the consumers, a new criminal offence of supplying water unfit for human consumption was created (Water Act 1989). The European Union (EU) Directive standards were via this legislation in the form of the Water Supply (Water Quality) Regulations 1989. These regulations define sampling and analytical arrangements as well as specifying water quality parameters and standards for treated water at the point of consumption. The Water Supply (Water Quality) Regulations 1989 and subsequent amendments, most recent being made in 2000, are legally enforceable in England and Wales. In Scotland and Northern Ireland a different legal framework applies, but the quality standards are the same and it is only the mechanisms for the necessary investment and the timing for compliance that differ within the U.K. The standards, called Prescribed Concentrations or Values (PCV's) are mandatory and enforced by the Drinking Water Inspectorate (DWI). For turbidity at the point of consumption (i.e. the consumer's faucet) the PCV is 4 FTU (formazin turbidity units) which is identical to the Maximum Admissible Concentration set in the 1980 EEC Directive. During the 1990s the EU Directive has been reviewed and a revision published. Member states are required to implement the changes in 2003. In the U.K. this will be via amendments to the Water Supply (Water Quality) Regulations; however, neither the EU Directive nor the Drinking Water Inspectorate have proposed changes to the turbidity standard for treated water at the faucet.

The U.K. regulations also include health based standards for aluminum and aesthetic based standards for iron and manganese, again in line with the 1980 Directive. These have had a direct impact on water treatment and filtration management. The standard for aluminum and iron is 200 µg/l and for

manganese is 50 μg/l at the consumer's faucet. To meet these standards operators have had to achieve significantly lower concentrations leaving the plant, where coagulants are used in the process. The U.K. regulations also require operators to use only approved treatment chemicals and generally the regulations have led to restrictions on the range of coagulants used, especially iron-based coagulants that contain manganese as an impurity. In order to achieve these standards much closer attention has had to be paid during the 1990s to the management of coagulation/filtration and historic floc residues in the distribution system have had to be removed by cleaning of mains and service reservoirs. Where distribution systems contain significant amounts of older or unlined cast iron, rehabilitation has been required in addition to improvements in plant operation.

During the 1990s regulatory pressure to optimize water treatment plant operation gained momentum in the U.K. as a consequence of outbreaks of cryptosporidiosis attributed to public water supplies. The first of these large outbreaks occurred in Oxfordshire and Swindon in 1989 affecting water supplies from three conventional coagulation/filtration plants. Since plant operation was normal, i.e. the cause was not due to plant malfunction and furthermore, operator practice was the same as carried out throughout the whole country, the Government set up an expert advisory group under the chairmanship of Sir John Badenoch. The first Badenoch report in October 1990 addressed immediate issues and highlighted the importance of optimizing filtration, recommending the installation on individual rapid filters of turbidity monitors to detect conditions which might favor the breakthrough of oocysts into treated water (Badenoch 1990). Other recommendations were made regarding filter operation but no turbidity standards were proposed, only that operators should monitor and investigate any departures from the plant norm. A program of research was drawn up and commissioned by the government and the water industry.

In September 1995 the second Badenoch report was published. This reviewed the five years of research and recommended that operators developed specific strategies for each plant whereby the optimum use was made of either turbidity or particle monitors to minimize the passage of particles into supply at all stages of filtration (Badenoch 1995). Once again no specific turbidity standard or target was proposed. Regular monitoring for cryptosporidium in treated water was not recommended but the value of a risk based, raw water source monitoring program was confirmed. In association with district health authorities some water suppliers had developed raw water monitoring trigger (alerting) values for oocysts e.g. Oxfordshire Health/Thames Water adopted a trigger value 5 oocysts per liter based on 10 liter grab samples of raw water. In February 1995 Sir John Badenoch had held a workshop with the Drinking Water Inspectorate and water industry experts. The workshop proceedings (West and Smith

1995), together with the final Badenoch report recommendations, were taken as the basis for annual regulatory technical audits of water treatment operating practice. Through this annual inspection regime DWI enforced improvements in both monitoring and treatment at plants.

By November 1998 a third expert report under the Chairmanship of Professor Ian Bouchier concluded that knowledge had advanced such as to allow the Drinking Water Inspectorate to set a treatment standard of 1 oocyst in 10 liters based on continuous sampling of 1000 liters of treated water per day (Boucher 1998). Although this standard is not a health based standard it was based on general experience that no increase in cryptosporidiosis occurred in communities served by plants where oocyst concentrations were an order of magnitude lower than the proposed standard. The Bouchier report also stated that the use of particle count monitors provided additional information to turbidity measurements. Turbidity monitoring of filters was tightened by specifying that instruments should be capable of detecting changes in turbidity of less than 0.1 ntu and operator alarms were required to be set to be triggered when the final water turbidity increased by more than 50% of the normal average (or an equivalent standard) (U.K.WIR 1998).

In 1999 the Water Supply (Water Quality) (Amendment) Regulations were brought into effect to require water suppliers to carry out risk assessments for each plant and to install continuous *Cryptosporidium* monitors on all those assessed as high risk (Department of the Environment, Transport and the Regions 1999).

The onus of this new regulatory regime falls on plant operators who are expected to use the data coming from instruments in real time, and to note the behavior of the filter. In essence they must be able to distinguish between normal operation, and abnormal operation, and in the event of abnormal operation be able to take prompt corrective measures. Failure to "fly" the works in this way would be regarded as a lack of "Due Diligence" in the event of a failure to comply with the *Cryptosporidium* treatment standard.

To be able to comply with the new legislation operators must carry out risk assessment, sampling, monitoring, analysis and reporting in the manner prescribed in a "Standard Operating Protocol For The Monitoring Of Cryptosporidium Oocysts In Treated Water Supplies To Satisfy Water Supply (Water Quality) Amendment Regulations 1999, S|I No 1524."

This is found at the following web addresses: http://www.dwi.detr.gov.uk/reg/index.htm, http://www.dwi.detr.gov.uk/risk.pdf.

The following language is quoted directly from the U.K. regulation, with manual author comments in brackets [ ]:

"2 Risk Assessment

2.1 Water companies must carry out a risk assessment for each of their water treatment works taking into account the factors listed in Annex A of the Water Supply (Water Quality) (Amendment) Regulations 1999. However, for the purposes of the Regulations, the Secretary of State considers that the following water treatment works should in all cases (other than 2.2 below) be classified as constituting a significant risk.

i) Direct abstraction or with average storage of seven days or less from a river or stream.

ii) Evidence of rapid river or surface water connection to the aquifer demonstrated by the confirmed presence of fecal coliform bacteria in the raw water.

iii) Past history of an outbreak of cryptosporidiosis associated with the water supply where the reason is unexplained and no specific steps have been taken to prevent a recurrence.

2.2 Any treatment works, in which all water passes through sufficient treatment plant capable of continuously removing or retaining particles greater than one micron diameter and where this process is subject to continuous monitoring and shutdown on failure, will not require continuous monitoring irrespective of other factors, including 2.1 (i), (ii) and (iii) above. [Continuous monitoring for *Cryptosporidium* oocysts would be done by sampling a continuously flowing side stream of filtered water.] [N.B. Note 2.2 is intended to mean membranes.]

2.3 The Drinking Water Inspectorate on behalf of the Secretary of State will consider each risk assessment and will check that all water companies have satisfactorily carried out the risk assessment process in accordance with this Guidance and in a thorough, consistent and defensible basis, such that sources constituting a significant risk will not have been excluded from the requirements of the Regulations. The Secretary of State will notify each water company whether he is satisfied that it has carried out its risk assessment on this basis."

In order to comply with the regulations high risk plants must have installed an approved sampling apparatus (on the finished water). At the time of writing in Summer 2000 there were two approved types. The apparatus must sample a cumulative volume of at least I m^3 of water continuously over every 24-hour period. The apparatus installation, sample cartridge removal and replacement, transportation and analysis are all subject to strict forensic evidence type rules and failure to follow these is a criminal offence of itself. The DWI inspects each installation, the sampling arrangements and also the laboratory facilities. Furthermore the DWI must be notified by operators of any failure to sample or any tampering of the system, accidental or deliberate. There is no difference made in law between the detection of *Cryptosporidium* oocysts that are living or dead, active or inactivated, nor is the species, *C. parvum* (infective to humans) or otherwise significant.

Operators find themselves under intense pressure to operate treatment works in a way to minimize penetration of particles. No turbidity or particle standards have been set for this by the regulators, except the *Cryptosporidium* standard. Operators must seek to minimize finished water turbidity, and demonstrate that they do this by understanding what causes turbidity breakthrough, and reacting appropriately to signs of poor turbidity by recognizing events that are "abnormal" on their works. In the event of an outbreak being associated epidemiologically with a plant the Drinking Water Inspectors will look for signs that the plant was designed, operated and maintained in accordance with "best operating practice" and with "due diligence" and any deficiencies in terms of the guidance given in the Badenoch, Bouchier and UKWIR reports would be the basis on which water companies and/or individual operators would be prosecuted.

Early U.K. experience since the implementation of this regulation was reported by Rouse (2000), who expressed the viewpoint that the monitoring for *Cryptosporidium* oocysts had been beneficial as plant operators learned more about the subtle effects of plant operations on treated water quality.

AUSTRALIA

Australia was in the process of revising its drinking water guidelines in 1999. New Zealand has recently (2000) revised drinking water guidelines with new *Cryptosporidium* treatment requirements and disinfection byproduct goals. These changes, together with reports on the Sydney *Cryptosporidium* incident (McClellan 1998), have driven plans for advanced treatment in the region.

A joint committee of the National Health and Medical Research Council and the Agricultural and Resource Management Council of Australia and New Zealand (NHMRC/ARMCANZ) the prepared the

Australian Drinking Water Guidelines (NHMRC/ARMCANZ 1996). The latest issue in 1996 superseded the 1987 NHMRC/ARMCANZ Guidelines for Drinking Water Quality in Australia. These guidelines are not mandatory standards but represent a framework for identifying water quality through community consultation. The guidelines state that, "Drinking water should be safe to use and aesthetically pleasing." Ideally it should be clear, colorless and well aerated with no unpalatable taste or odor and it should contain no suspended matter, harmful chemical substances or pathogenic microorganisms.

Guideline values are based primarily on the latest WHO recommendations with some departures to move from the WHO aesthetically *acceptable* quality to the Australian goal of *good* quality drinking water.

Community consultation plays a key role in providing drinking water of safe and good quality where communities have the right to participate in policy-making decisions on how it is to be achieved. Agreed water quality and levels of service are based on estimates of risk and cost as well as local knowledge of the source water (including catchment protection), treatment processes employed, history of the distribution system and the quality assurance program exercised over its operation. Consumer needs and expectations influence the extent to which each community adopts the guidelines. For example, one community might choose to tolerate poorer aesthetic quality while another may choose to pay for treatment to bring water quality within normally acceptable limits. Currently, there is a community in South Australia that has raised a petition to have a water supply with "no added chemicals", including disinfectants.

Regulation of water quality in Australia varies State to State but generally the local health authority manages it, so variations can occur for municipal water quality guidelines within a State. State and Territory governments take a variety of approaches to dealing with water suppliers. Operating licenses, memoranda of understanding, charters, and performance agreements in some cases may be negotiated between the State or Territorial government agency and the water supplier. The regulation of water quality is not uniform across the nation because different approaches are taken by the various governmental bodies (Anon 2000).

Water treatment is hardly mentioned in the guideline document beyond saying that it can improve water quality. The guideline document comprises a loose-leaf manual that is regularly updated. Part 1 includes chapters on:

- Microbiological Quality of Drinking Water
- Physical and Chemical Quality
- Radiological Quality
- System Management
- System Performance
- Small Water Supplies
- Summary of Guidelines
- Guide to monitoring and Sampling Frequency

Part 2, comprising more than half of the document, is a very useful series of fact sheets for every conceivable contaminant likely to be encountered in source water. The fact sheets have a common structure;

- Guideline
- General Description
- Treatment
- Method of Identification and Detection
- Health Considerations
- Derivation of Guideline
- Reference List

Repercussions of the Sydney Water crisis in 1998 are still being felt throughout the region although no one was made sick as a result of the apparent detection of large numbers of protozoan parasites in the distribution system. Membranes are being considered for many new water treatment plants and operators of existing conventional plants are striving to meet tighter treated water turbidity goals.

NEW ZEALAND

The Ministry of Health published *Drinking Water Standards for New Zealand 2000* (Ministry of Health 2000) in August 2000. The standards list the maximum concentrations of chemical, radiological and microbiological contaminants acceptable for public health in drinking water. For community drinking water supplies the standards also specify the sampling protocols which must be met to demonstrate that the water complies with the Standards. Community water supplies are those that serve 25 people or more for at least 60 days per year.

Legally binding Standards and optional aesthetic Guidelines are based on MAVs (maximum acceptable value) that represent the concentrations of determinands that, on the basis of present knowledge, are not considered to cause any significant risk to the health of a consumer over a lifetime of consumption of the water. Nearly all of the MAVs in the Standards are based on the WHO publication *Guidelines for Drinking Water Quality 1998.*

There is also a grading system applied to treated water entering the distribution system based on raw water source quality and treatment processes in place and on water at the tap, based on an evaluation of the distribution system (Anon 2000). One letter grade is given for each, with an upper case letter representing water entering the system and a lower case letter representing tap water. Grades and their descriptions are:

A1 Completely satisfactory, negligible level of risk, demonstrably high quality
A Completely satisfactory, very low level of risk
B Satisfactory, low level of risk
C Marginal, moderate level of risk
D Unsatisfactory, high level of risk
E Completely unsatisfactory, very high level of risk

The New Zealand Standards were under major review and a new set of mandatory standards was issued during the latter part of the year 2000. Tables on inactivation of *Giardia* have been discontinued and replaced with CT tables for inactivation of *Cryptosporidium* by ozone and chlorine dioxide. Monitoring and compliance for bacteria in drinking water is now based on *E. coli*, with an MAV of less than 1 per 100 mL. A protozoa MAV of less than 1 cyst or oocyst per 100 liters is a guideline.

Compliance criteria for filtered water are related to particle counting (for cartridge, bag, diatomaceous earth, and slow sand filters serving more than 10,000 people) and turbidity measurement. Protozoa criteria for filtration plants employing chemical coagulation and filtration are:

- All water must be filtered
- Turbidity of water leaving each filter must be measured, and
- 95% of the turbidity measurements each day must not exceed 0.5 ntu when on-line turbidimeters are used (this will be reduced to 0.1 ntu on January 1, 2005)
- during the filter run (except for filter-to-waste) turbidity must not exceed 1.0 ntu (this will be reduced to 0.5 ntu on January 1, 2005)
- for continuous monitoring, no increases of more than 0.2 ntu shall occur in any 10-minute period, except that up to two turbidity records per day may exceed 1.0 ntu to allow for spurious peaks (this will be reduced to 0.5 ntu on January 1, 2005)

With regard to monitoring for protozoa, the regulations state, "Although reliable direct enumeration of *Giardia* and *Cryptosporidium* strains can now be made, this is not used as a compliance criterion because of the high degree of uncertainty as to the interpretation of the results."

The Minister of Health, through the Local Officer of Health can shut down a water treatment plant for transgression if he believes that there is a risk to consumer health. Local health officers police the system by taking samples at consumer's taps.

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CHAPTER 4
FILTER OPERATION AND OPTIMIZATION

INTRODUCTION

This chapter contains an introduction to some engineering concepts related to filtration. When the filtration process is understood, trouble-shooting and problem solving can be done on a sound basis. Careful management of filtration rates is a key aspect of producing excellent filtered water, and this aspect of filtration is covered in Chapter 4. Techniques are described for optimization of filtration to attain stringent water quality goals, because over the last several decades, the trend in water treatment has been to seek to meet lower and lower filtered water turbidity goals. Finally, a substantial portion of this chapter is devoted to describing treatment strategies that water utilities have employed for coping with regular water quality events that place their plants under stress or with unusual water quality events.

FILTRATION CONCEPTS

Filtration Mechanisms

Concepts of particle removal by filtration are explained in Chapter 8, "Granular Bed and Precoat Filtration" (Cleasby and Logsdon 1999) in *Water Quality & Treatment*, 5th Ed. The discussion of filtration mechanisms in this Guidance Manual is based on that chapter. The two mechanisms by which particles are removed in porous beds are particle attachment and physical straining. Straining occurs when the particle is too large to pass through the pores of the filter bed. Precoat filtration can remove a wide range of particles by straining, but a typical granular media bed, if composed of round media having an effective size of 0.5 mm, would not strain out round particles smaller than about 75 μm. For purposes of comparison, a *Cryptosporidium* oocyst is about 3 to 6 μm in size. For effective removal of very small particles by granular media filtration (the subject of this manual) a mechanism other than straining is needed.

Removal of particles within a granular media filter bed is referred to as depth filtration. Depth filtration occurs by the mechanism of particle attachment. By themselves, the very small particles such as clay, algae, and microorganisms are not readily removed by depth filtration because they have negative surface electrical charges and electrostatic forces work against their attachment to grains of

filtering material. Coagulation of raw water, properly done, changes the nature of the surface charges on the small particles, so they can stick to the surface of grains of filter material. Particle removal in depth filtration involves both transporting the particle to the grain surface so the particle can collide with the grain, and attachment so the particle "sticks" to the grain. Filtration researchers have shown that particles also can stick to previously attached particles. In *Water Quality & Treatment, 5th Ed.* Figure 8-10 (page 8.33) is a scanning electron micrograph that illustrates the relative size of the 1-mm sand grains, a pore space between grains, and the 5 to 10 μm particles attached to the sand grains and removed by depth filtration. This figure (Figure 4.1 at the end of this chapter) shows that attachment is much more important than straining, as the particles attached to the grains are very much smaller than the pore in the micrograph. Figures 4.2 and 4.3 are scanning electron micrographs of clean filter sand and dirty filter sand with attached particles.

Biological Activity in Filters

In the United States, past filtration practice involved the application of chlorinated water to granular media filters. The chlorine residual inhibited microbiological growth in filter beds and kept the beds "clean." Increasingly stringent regulations on disinfection by-products (DBPs) have brought about changes in chlorination practice, and at some plants the application of free chlorine is delayed until after filtration. Whether or not it is intended, the filter bed eventually becomes biologically active if water containing no disinfectant residual is filtered. The benefit of biologically active filters is that some natural organic matter can be removed in the filter bed, resulting in lower concentrations of DBPs being formed after disinfection. On the other hand, greater numbers of heterotrophic plate count (HPC) bacteria are discharged by biologically active filters, as compared to filters operating with a disinfectant residual. The numbers of HPC bacteria can be very substantially reduced by post-filtration disinfection, so HPC should not be a big concern at a plant using biologically active filters.

In biological filters living microorganisms (bacteria) are attached to and growing on the grains of filter material in the filter bed. The growth of microbes in filter beds can cause concern to filtration plant staff, as the potential for sloughing of microbes from the filter is a consequence of their growth. Biological filtration is often accomplished by pretreatment with ozone. Use of ozone as an oxidant is discussed in Chapter 8 of this manual. Yates et al. (1998) conducted pilot filtration tests in which preoxidation with free chlorine and with ozone was practiced. They found that use of ozone actually resulted in lower filtered water particle counts than use of chlorine. This happened even though

prechlorination would hold down growth of bacteria in the filter bed, but use of preozone would promote the growth of bacteria and would ultimately lead to some sloughing of bacteria.

At Thames Water Utilities roughing filters have been used prior to slow sand filtration. These are highly biological and contain fauna and flora similar to that in slow sand filters. No coagulants are used. When separate air scour and water back-washing steps are used for backwash, it takes only 12-15 weeks to accumulate 1.5 kg/m^2 of organic matter as carbon (after backwashing). With collapse pulse back-washing the attached carbon remains at less than 250 g/m^2 (usually less than 120 g/m^2. Based on the Thames Water Utilities experience, if a collapse pulse wash is used to backwash biological filters, mudball problems should not develop as a result of biological activity unless large masses of organic debris (fish, algae etc.) are captured and not washed out.

The Filter Cycle

Simply stated, a filter cycle can be described as starting a clean filter, operating the filter to remove particles from water, ending the run, and backwashing so a new run can be started. Head loss increases as particles are removed from the water and accumulate in the filter bed. Termination of the filter run may occur for a variety of reasons, including:

- accumulation of maximum head loss,
- an increase in filtered water turbidity to the maximum level accepted by the utility,
- operation for a maximum time allowed at the utility, or
- a decrease in demand for water that results in taking one or more filters out of service.

When a filter is operated with the primary emphasis on producing very low turbidity in the filtered water, maximizing the length of the filter run may not be an appropriate operational goal.

During the operation of the filter to produce water, the most complex portion of the filter run occurs during the initial period of time after start-up. Filter ripening, or the initial improvement in filtered water quality, happens then. The phenomenon of filter ripening, and ways to reduce or eliminate the initial turbidity spike, are the topics of Chapter 7. Most filter runs exhibit one or more turbidity spikes at the start, after which turbidity declines. The majority of the run produces stable water quality. In some instances, filtered water turbidity may increase later in the run.

Several studies have identified different phases in the filter cycle but have used slightly different terminology. Figure 4.4 shows an idealized representation of the filter cycle (Chipps, 1998) incorporating seven phases described in the literature. The filter cycle is started when the filter is returned to service at the end of a backwash, and is terminated with a backwash. Some plants may use filter-to-waste to prevent poor quality water produced during the ripening phase from passing into the clearwell.

Not all phases in the filter cycle have been observed in any one study, and their duration and filtrate quality may be variable. In Figure 4.4 the numbers in circles correspond to the following:

1) the lag phase (Amirtharajah and Wetstein 1980, Cranston and Amirtharajah 1987), where clean backwash water passes out of the filter from the filter underdrains (up to time T_u);

2 and 3) two deteriorating or pre-ripening phases, where effluent quality becomes poorer, exhibiting two peaks (Amirtharajah and Wetstein 1980, Cranston and Amirtharajah 1987), caused first by dirty backwash water remnants within the bed (up to T_m), then second by backwash water above the media because of the particles it contains, and the dilution effect of re-stabilizing the influent suspension (up to T_{a+i});

4) the ripening period, where filtrate quality improves (up to T_{r1} or T_{r2} [phase 4a], depending on the definition of ripening);

5) effective filtration by a ripened filter (Ginn *et al.* 1992), optimum filtration (Cranston and Amirtharajah 1987) or working (Janssens *et al.* 1982, Vigneswaran and Chang 1989) stage (from T_r to T_b);

6) a period of deteriorating filtrate quality, known as the breakthrough phase (recognized in all the references cited) (from T_b);

7) finally a period of no further deterioration where breakthrough has reached a maximum value (Vigneswaran and Chang 1989), and wormhole flow (Baumann and Ives 1987) may be occurring (after T_w).

The lag and deteriorating phases, given as 1-10 minutes by Amirtharajah and Wetstein (1980), are rarely mentioned in the literature. Where they are, measuring conditions, i.e. sampling intervals or instrument responsiveness, may mean these phases, or some of the details, are missed.

THE EFFECT OF INTERRUPTING A FILTER CYCLE

For granular media filters, the best operating practice is to run through the filtration cycle until the limit for head loss, operating hours, or filter effluent turbidity is reached and then backwash the filter after it is removed from service. If a filter is operated for a while, stopped, and then restarted without backwashing, the shear forces involved in restarting the filter can wash out the particles trapped within the filter bed. During a waterborne disease outbreak investigation at Carrollton, Georgia (Logsdon, Mason, and Stanley 1990) the effect of restarting dirty filters was evaluated. Filters that had been operated continuously since being put into service were producing water with turbidity in the range of 0.07 to 0.18 ntu. This was much lower than the turbidity from three filters that had been operated, stopped, and returned to service without backwashing. Those filters were producing water with turbidity ranging from 0.20 to 3.2 ntu, with the worst-performing filter ranging between 1.6 and 3.2 ntu for up to 3 hours after restart. The plant was not equipped with turbidimeters for individual filters, so filter performance was evaluated by taking grab samples. Blending the effluent of all filters into the clearwell masked the poor performance of individual filters during this event.

The effect of restarting filters without backwashing was evaluated during EPA-funded filtration demonstration studies at the Duluth Water Filtration Plant in 1977 and 1978 (Schleppenbach, 1984). This plant had been constructed to remove amphibole asbestos from Lake Superior water, so performance evaluation focused on the asbestos fiber content of filtered water. Full-scale dual media and mixed media filters were restarted, going from 0 to 3.25 or 4.87 gpm/sf (7.9 or 11.9 m/hr) in a period of 15 minutes. Alum was the coagulant, and a nonionic polymer was used to strengthen floc. Results were mixed. Generally restarting a filter did not cause filtered turbidity to exceed 0.10 ntu, a level not much above the typical filtered water turbidity of 0.03 to 0.05 ntu after filter ripening. The exception usually occurred when a filter was restarted with high head loss. In some restarts when a filter was returned to service after accumulating more than about two thirds of the usual terminal loss of 8 feet, asbestos fiber counts peaked at well over 0.1 million fibers/L (MFL), and sometimes the fiber count did not decline to less than 0.1 MFL during the 20 to 30 minutes in which samples were taken during restart. In two restarts at high head loss, fiber counts peaked at 3 to 4 MFL. Operation of a

ripened filter typically produced counts in the range of 0.02 to 0.05 MFL. High asbestos fiber peaks were unpredictable, and high turbidity peaks were not observed. The full-scale studies showed that sometimes filters could be restarted with little apparent deterioration of water quality when floc was strong, but performance was not easy to predict. Therefore the practice of restarting dirty filters should be avoided if at all possible.

Operators of filtration plants operated by small water systems may feel constrained to operate filters, remove them from service at the end of a shift, and later restart them without backwashing. The experience cited above indicates that this is a very risky practice. The first Group of Experts' report in the U.K. (Badenoch, 1990) said that "rapid filters should not be restarted after shutdown without backwashing". Authors of this manual strongly recommend that filters always should be backwashed before being restarted. If the treatment plant's configuration forces the restart of dirty filters, the system should develop and implement a plan to modify the plant so restart of dirty filters is not necessary. The California Surface Water Treatment Rule requires that a filter be backwashed after being shut down, prior to start-up.

If restarting dirty filters is absolutely unavoidable, some suggestions are provided in this section of the manual. The authors of this report, their employers, the Technical Review Group, members of the Project Advisory Committee, and the AWWA Research Foundation can not guarantee the universal success of these suggestions, and persons who engage in the practice of restarting dirty filters assume all liability for the consequences.

1) A dirty filter may not be restarted unless a continuous turbidimeter is used to monitor the turbidity of the water produced by that filter, with data recorded at intervals no longer than 60 seconds. Note, however, that neither a turbidimeter nor a particle counter is sufficiently specific or sufficiently sensitive to detect passage of pathogenic microorganisms at concentrations of public health concern.
2) A filter that is restarted without backwashing should be equipped with filter-to-waste, and if so equipped, filter-to-waste must be used until the filtered water turbidity meets regulatory requirements and the quality goals of the water utility.
3) If a filter is not equipped with filter-to-waste, the filter run must be terminated and the filter must be backwashed if appropriate quality goals are not met upon restart of a dirty filter. Using the Interim Enhanced Surface Water Treatment Rule as a guideline, if filtered water

turbidity exceeds 1.0 ntu, the filter must be stopped immediately and backwashed. [Exceeding 1.0 ntu for two readings that are 15 minutes apart triggers a special reporting provision of the IESWTR. Utilities that are routinely restarting dirty filters without backwashing probably need increased regulatory scrutiny and technical assistance. For a utility that is doing a competent job of water treatment, avoiding the special reporting would be preferable; hence the need to immediately terminate the filter run and backwash the filter.] If filtered water turbidity does not rapidly decline and go below 0.3 ntu in 15 minutes, the run should be stopped and the filter backwashed.

4) Head loss that had developed before a filter was shut down can be an indicator of the potential for problems when a filter is restarted. Compare the head loss at shutdown to the total head loss gain that is normally experienced in a single, uninterrupted filter run. A filter that had developed more than 50% of the total head loss before shutdown <u>should</u> be backwashed and then started up. A filter that had developed more than 75% of the total head loss <u>must</u> be backwashed and then started up as the risk of discharging accumulated floc during restart at high head loss is great. Clogged pores in the filter bed cause head loss. The higher the head loss, the worse the clogging, and the greater the shear forces upon restarting a dirty filter. As a filter bed becomes more clogged, a smaller proportion of the total run time is available. Starting a dirty filter well into a run, under conditions of high head loss, involves a smaller gain in terms of the number of hours potentially available for operating until terminal head loss is reached, but a very much greater risk, in terms of the potential for discharging pathogens stored in the filter bed into the filtered water.

5) If dirty filters have to be restarted, this must not be done when weak floc is stored in the filter bed. Use of filter aid polymer can help to strengthen floc and thus improve resistance to shear upon restart of the filter.

6) Some plants may be designed to permit recycling water from a suitable downstream point back to the filters so that they run continuously. At one plant in the U.K. chlorinated, filtered water is recycled overnight when demand is low back from the clearwell to the inlet of the rapid gravity filters using the backwash water pumps, and then through the downstream granular activated carbon (GAC) adsorbers. This avoids taking the filters out of service overnight. The GAC ensures that chlorine concentrations do not become excessive. Clarification is by dissolved air flotation (DAF). The DAF tanks are desludged before the

inlet is closed. As a process, DAF is reasonably amenable to stop-start operation like this. Before the plant is restarted the operator checks turbidity trends and chlorine residual to ensure that water quality is satisfactory.

FILTER FLOW RATE MANAGEMENT

Proper Management of Filtration Rates and Potential for Problems

When a granular media filter is operating, probably the riskiest operation to perform is to increase the filtration rate, yet this has to be done at many filtration plants. Careful management of filtration rates is essential for production of low-turbidity water. Filtration may be thought of as a delicate balance between the water flowing through the media and some of the particles in the water being deposited on the filter media grains while others may tend to become detached from the deposits. It is analogous to snow resting on the branches of a tree. If the wind starts up the snow may get blown off the branches. In the same way if the water flow rate increases, some of the material deposited on the filters may be brought back into the water flowing through the bed, and it might be more difficult for additional particles to be deposited.

The potential for quality deterioration caused by increases in filtration rate has been known for a long time (Cleasby, Williamson, and Baumann 1963). The original research on filtration rate increases demonstrated that the quality deterioration resulting from a rate increase was greater when the rate change was made rapidly rather than gradually. The peak effluent concentration of iron floc (the particulate matter being removed in the filter) was about 30 times higher for an instantaneous 25% rate increase as compared to the peak for a 25% rate increase carried out over 10 minutes. For a 25% rate increase over 5 minutes the peak was six times higher than for the same increase over a 10-minute period. Furthermore, filtered water quality deteriorated more when the filtration rate was increased by a larger percentage. Cleasby, Williamson, and Baumann reported that a 100% rate increase discharged 22.5 times more materials than a 25% rate increase.

Because rate increases can flush previously-deposited material out of a filter bed, imposing rate increases on filters with high head loss is particularly risky, as head loss in the filter is an indication of the extent to which the bed is clogged with floc and dirt. Thus a rate increase early in the filter run would be less risky than the same rate increase made late in the run when head loss is high. In this

project, one utility reported that particle counts in filtered water increase when a filtration rate increase is applied during the last 10 hours of the run.

Harms and Horsley (2001) showed a figure in which a rate increase of slightly less than 25 percent caused very little change in turbidity at 17 hours into a run, but a similar increase at 25 hours caused turbidity to spike from under 0.2 ntu to over 0.6 ntu. This is shown as Figure 4.5.

Floc strength influences the response of a filter to a rate increase. Logsdon et al. (1981) evaluated the effect of rate increases on the passage of *Giardia* cysts in a direct filtration pilot filter. They observed increased passage of cysts through a granular media filter when alum was used as the coagulant but no filter aid was used (Figure 4.6 at the end of this chapter). In a run with the same dosage of alum and a nonionic polymer filter aid, a filtration rate increase barely increased the filtered water turbidity, and cyst removal was not impaired (Figure 4.7 at the end of this chapter). This showed that weak floc is more susceptible than strong floc to turbidity breakthrough problems caused by increasing the filtration rate. The same conclusion can be reached by reviewing Figure 4.8 (Cleasby, Williamson, and Baumann 1963), which is a graph depicting the relationship of the rate of increase in filter flow of the effluent iron concentration caused by the rate increase. Two distinct data sets are presented in the figure. The higher concentrations caused by a rate increase are those associated with the weaker floc.

When a turbidity breakthrough event occurs, granular media filters can discharge contaminants along with floc that had been removed and stored in the pore spaces of the filter bed earlier in the run. In a filtration test carried out by Logsdon et al. (1981) cysts had been seeded (spiked) continuously for just over 31 hours before the supply was exhausted. Then two hours later, when more than three volumes of the flocculators and filter had been displaced, a rate increase caused a massive discharge of *Giardia* cysts, as demonstrated in Figure 4.9. Head loss was high at this time, causing the filter to be more vulnerable to breakthrough caused by a rate increase than it would have been early in the run. Due to operating circumstances, the cysts detected in the effluent at this time could not have been in the influent water. Therefore they had to be in the floc that had been stored in the filter for the first 31 hours of operation when cysts were seeded. This demonstrated the potential for a filter to discharge previously-removed microbiological contaminants into finished water during a rate increase.

Cleasby et al. (1992) recommended that filter rate increases be made gradually. They stated, "If effluent rate controllers are used, the modulating valve and valve controller should make the necessary changes in the valve position slowly and smoothly over several minutes to avoid sudden rate changes. The change in valve position should be proportional to the deviation of the measured variable (level or

rate) and the desired set point (level or rate). . . . Controls should be designed to slowly ramp up to the rate when a transition in rate is needed." Cleasby and Logsdon (1999) wrote, "Filtration rate increases on dirty filters should be avoided or made gradually (over 10 min)."

Because of the influence of floc strength on the water quality produced when a filter is subjected to a rate increase, it is not possible to prescribe a rate increase procedure that would in all cases avoid turbidity breakthrough. Operators need to be cautious about increasing the rate on filters, especially those that have accumulated a substantial amount of floc as indicated by high head loss. If turbidity breakthrough occurs when filtration rates are increased, remedies include increasing the rate more gradually over a longer time, and using a polymer to strengthen floc.

In the U.K. the recommendation of the Badenoch Expert Group (1990) was that flow rate step changes should not exceed 5 percent per minute, and that for weak flocs 1.5 percent per minute was likely to be the acceptable maximum increase. Ives (2001, pers. comm.) has suggested that as a rule of thumb flow rate changes should typically be no more than 3 percent change per minute. This should be reduced to 1 percent change per minute where floc is weak, and could be possibly as high as 5 percent per minute with strong floc (probably meaning strengthened with polymer). These recommendations were derived from the work of Cleasby, Williamson and Baumann (1963). Since it is difficult to measure floc strength on site, suitable tests should be carried out by water utilities to determine appropriate flow rate change strategies for each water plant. Yorkshire Water in the U.K adopted a standard rate change of not greater than 1.5 percent per minute for all their filters (Wilson 2001, pers. comm.). Operators need to understand how to manage the rate control system routinely used, as well as emergency procedures for manually operating controls or actually operating valves by hand, in the event of failure of the automatic control system.

Unpublished research on a pilot plant by one of the authors showed that in filtering water from conventional alum-dosed vertical clarifiers, a deep coarse media filter was more vulnerable to shedding deposits under flow step changes than a shallower bed of fine sand media. A dual media filter was found to shed particles from the anthracite layer, but these were retained by the finer sand underneath. This demonstrated the value of the sand layer in the dual media filter.

Strategies Used for Managing Rate Increases

Avoiding filtration rate increases is recommended as a means of minimizing turbidity breakthrough, but this mode of operation may not be practical at many plants. Rate increases can come

about when plant production has to be increased and idle filters are not available to be placed into service. At some plants, removing a filter for backwashing results in a rate increase for the filters remaining in service. Water utilities participating in this project for development of the filtration maintenance and operation manual reported a variety of approaches to avoiding filtration rate increases, or to minimizing the effect of increases on filtered water turbidity. Data were provided for 49 North American filtration plants ranging in size from 1.5 million gallons per day (mgd) to 540 mgd (6 to 2100 million liters/day). The number of filter beds in 48 of the plants ranged from 4 to 94. One plant of the 49 had two traveling bridge automatic backwash (ABW) filters, each with 132 cells. Treatment employed was the following:

- Conventional (coagulation, flocculation, sedimentation and filtration): 32 plants
- Direct or in-line filtration: 5 plants
- Conventional treatment or direct filtration possible: 3 plants
- Lime softening: 6 plants
- Oxidation and filtration for manganese removal: 1 plant
- Coagulation and sedimentation pretreatment followed by ABW filters: 1 plant
- Upflow clarification and multi-media filtration: 1 plant

Table 4.1 contains a tabulation of the North American treatment plants, processes employed, design capacities, number of filters at the plant, water source, and average and maximum turbidity for the sources. Table 4.2 provides information on treatment plants in Australia and the United Kingdom, including processes employed, design capacities, number of filters at the plant, water source, and average and maximum turbidity for the sources. Plant practices are reported in the following sections.

Managing Rate Increases Caused by Increasing Production

One group of questions in the filtration plant survey focused on how filtration plants managed rate increases caused by increasing water production. Table 4.3 summarizes answers to questions on this topic. Details are discussed in subsequent sections of this chapter.

Table 4.1

North American treatment plants providing data on design, water quality, and O&M procedures

Utility	Plant	Process	Capacity♦		No. of	Source Water	Turbidity, ntu
			MGD	ML/d	Filters		Avg.; Max.
Ann Arbor Utilities Dept.	Ann Arbor Water Plant	Lime softening	50	189	26	River and wells	3; 15
Brick Township MUA	Wm. Miller Central Water Plant	Conventional♣	16	61	8	River and wells	5; 23
Calgary Waterworks	Bearspaw Water Treat. Plant	Conventional	159	600	24	River	4; 50
City of Carrollton	Carrollton Water Works	Conventional	12	45	10	River	16; 400
Chester Water Auth.	Octoraro Treatment Plant	Conventional	106	227	12	Reservoir	11; 400
Chesterfield Cnty. Util. Dept.	Swift Creek WTP	Conventional	12	45	4	Reservoir	5; 22
Cincinnati Water Works	Richard Miller Treatment Plant	Conventional	220	830	47	River	50; 900
Clackamas River Water Dist.	C.R. Harrison Filtration Plant	Conv./Dir.Filt.*	30	113	6	River	3; 350
Cleveland Div. Of Water	Crown Water Treatment Plant	Conventional	115	435	12	Lake	17; 110
Colorado Springs Utilities	McCullough WTP	Conventional	50	189	4	Reservoir	1; 7
Colorado Springs Utilities	Mesa WTP	Conventional	42	159	8	Lake	1; 6
Colorado Springs Utilities	Pine Valley WTP	Conventional	84	318	8	Reservoir	1; 14
Connecticut Water Co.	MacKenzie WTP	Conventional	4	15	4	Reservoir	1; 11
Connecticut Water Co.	W.C. Stewart WTP	Conventional	6	23	4	Reservoir	1; 3
Dallas Water Utilities	Elm Fork WTP	Partial Lime Softening	330	1250	24	Reservoir, river	50; 1600
Detroit Water & Sewer Dept.	Water Works Park Plant	Conventional	240	910	75	River	7; 50
Detroit Water & Sewer Dept.	Lake Huron Water Plant	Conventional	300	1130	20	Lake	1; 8
Detroit Water & Sewer Dept.	Northeast WTP	Conventional	340	1290	48	River	6; 70
Detroit Water & Sewer Dept.	Southwest Water Plant	Conventional	240	910	20	River	11; 77
Detroit Water & Sewer Dept.	Springwells WTP	Conventional	540	2040	108	River	6; 67

(continued)

Table 4.1 (Continued)

Utility	Plant	Process	Capacity♦		No. of	Source Water	Turbidity, ntu
			MGD	ML/d	Filters		Avg.; Max.
Detroit Water & Sewer Dept.	Springwells WTP	Conventional	540	2040	108	River	6; 67
E2A/Systems	Evansville Water Filtration Plant	Conventional	60	227	34	River	47; 250
East Bay Municipal Util. Dist.	Sobrante WTP	Conventional	60	227	4	Reservoir	12; 70
East Bay Municipal Util. Dist.	Lafayette WTP	In-line	25	95	8	Aqueduct	1; 5
East Bay Municipal Util. Dist.	Orinda WTP	In-line	175	660	20	Aqueduct/Res.	1; 5
East Bay Municipal Util. Dist.	Upper San Leandro WTP	Conventional	60	227	10	Reservoir	3; 140
East Bay Municipal Util. Dist.	Walnut Creek WTP	In-line	80	302	4	Aqueduct	1; 5
City of Elgin	Riverside WTP	Lime softening	32	61	8	River, wells	21; 150
Elizabethtown Water Co.	Raritan-Millstone WTP	Conventional	165	625	36	River	9; 37
Eugene Water & Elect. Bd.	Hayden Bridge Filtration Plant	Conv./Dir. Filt.*	72	272	12	River	3; 70+
City of Fargo Public Works	Fargo Water Treatment Plant	Lime softening	30	114	6	River	74; 780
Fort Collins Utilities	Ft. Collins Water Treat. Facility	Conventional	74	280	23	River, reservoir	3; 7
Grand Rapids Water Syst.	Lake Michigan Filtration Plant	Conventional	142	537	18	Lake	3; 24
Wtr Dist. # 1, Johnson Cnty.	Hansen Treatment Plant	Lime softening	165	625	28	Rivers	240; 3300
Lincoln Water System	West Treatment Plant (for Mn)	Cl_2, Sed. Filt.	60	227	14	Wells	N/A**
Lincoln Water System	East Treatment Plant (for Mn)	O_3 In-line Filt.	50	189	8	Wells (GWUI)#	
City of Mesa	C.A.P. Water Treatment Plant	Conventional	48	182	12	River, CAP@	2; 15.
Milwaukee Water Works	Linwood WTP	Conventional	275	1040	32	Lake	3; 110
Milwaukee Water Works	Howard Avenue WTP	Conventional	100	378	8	Lake	3; 110
Modesto Irrigation Dist.	Modesto Regional WTP	Conv./Dir.Filt.*	30	114	6	Reservoir	12; 33
Northern KY Water Dist.	Fort Thomas Treatment Plant	Conventional	44	166	12	River	50; 900

(continued)

Table 4.1 (Continued)

Utility	Plant	Process	Capacity♦		No. of	Source Water	Turb., Avg.;
			MGD	ML/d	Filters		Max., ntu
Norwalk 2nd Taxing Dist.	Wilton Filtration Plant	Conv. W/ ABW trav. Bridge filter	10	38	2	Reservoir	2; 5
Philadelphia Water Dept.	Baxter Water Treatment Plant	Conventional	282	1070	94	River	8; 37
Southern Nev. Water Auth.	A. M. Smith Water Treat. Facility	Direct Filtration	600	2270	26	Reservoir	0.4; 0.6
City Utilities of Springfield	Blackman Water Treat. Plant	Conventional	33	114	8	River, Reservoir	3; 45
City of Troy	Troy Water Treatment Plant	Lime softening	16	61	8	Wells	N/A**
Tuolumne Utilities Dist.		Upflow adsorpt. Clarifier/filter and pressure filter	1.5	5.7	Not stated	Lakes, River	10; 200
Washington Suburb. San. Comm.	Potomac Water Filtration Plant	Conventional	285	1080	32	River	24: 510
Washington Suburb. San. Comm.	Patuxent Water Filtration Plant	Conventional	72	272	15	Reservoir	10: 20
Regional Municipality of Waterloo	Mannheim WTP	Conventional	19	72	4	River	7: 20

♦ MGD = U. S. gallons/d; ML/d = million liters/day

♣ conventional treatment = chemical coagulation and some type of sedimentation process followed by filtration

*can be operated as conventional plant or in direct filtration mode.

** turbidity measurements not required if ground water is not under influence of surface water

Ground Water Under Influence of Surface Water

@ Central Arizona Project

Table 4.2

Treatment Plants from United Kingdom and Australasia Providing Data on Design, Water Quality, and O&M Procedures

Utility	Plant	Process	Capacity♦		No. of	Source Water	Turb., Avg.;
			MGD	ML/d	Filters		Max., ntu
Thames Water	Farmoor AWTW	O_3♥DAF♠ Filtration	30	113	13	Reservoir	4; 12
Thames Water	Swinford AWTW	O_3 Conventional♣	15	57	16	Reservoir	4; 12
Thames Water	Grimsbury AWTW	O_3 DAF Filtration	4	15	6	Shallow Reservoir	5; 40
Thames Water	Shalford AWTW	Conventional	10	38	6	2 Rivers	5; 200
Thames Water	Worsham WTW	Conventional	3	11	8	River	12; 500
United Water	Myponga WTP	DAF Filtration	13	49	6	Reservoir	2; 7
United Water	Happy Valley WTP	Conventional.	225	850	16	Reservoir	24; 43
United Water	Hope Valley WTP	Conventional	72	270	12	Reservoir	5; 15
United Water	Anstey Hill WTP	Conventional	82	310	12	Reservoir / Pipeline	56; 134
United Water	Little Para WTP	Conventional	44	166	8	Reservoir	------
United Water	Barossa WTP	Conventional	42	159	8	Reservoir	1; 2

♦ MGD = U. S. gallons/d; ML/d = million liters/day

♥ozone is used in pretreatment

♠ DAF = dissolved air flotation

♣ conventional treatment = chemical coagulation and some type of sedimentation process followed by filtration

Of the 26 plants for which comments were provided on the effect on water quality caused by increasing filtration rates in response to an increase in production, about 2/3 responded that effects were minimal or negligible. At one softening plant, a sudden increase in production can cause increases in turbidity and particle counts. A manganese removal plant reported that rate increases increased turbidity, but for ground water treatment this is an aesthetic problem. Several plants with on-line particle counters and on-line turbidimeters noted slight increases in particle counts, and at three plants, particle counts sometimes increase but turbidity does not. The responses indicate that particle counters may be more sensitive than nephelometric turbidimeters for detecting water quality changes caused by filtration rate increases.

Gradually increase flow of filters in service. Gradually increasing the rate of flow through filters that are in service is a sound concept that has been advocated for many years by Cleasby, who studied the effects of rate increases in the early 1960's. A majority of the plants surveyed provided information on this question. Fourteen of the plants reported that the typical rate of increase in filtration was 1% per minute or less. Six plants reported that their filtration rate increases ranged from greater than 1% to 3% per minute. Rates of increase of 6% per minute and 10% per minute were reported, and one plant reported using instantaneous rate increases.

For increases in plant flow, gradual increases in filtration rate are most easily managed if variable speed raw water pumps are available. Provision of one or more variable speed pumps to give operational flexibility is a design decision that would be quite helpful to plant operators. At seven of the filtration plants for which information was obtained in this project, lack of flexibility in raw water pumping was listed as a cause for abrupt rate increases associated with increased water production.

Treated water storage acts as a buffer between system demand and plant production. As storage is provided for a larger fraction of a day's demand, treatment plant staff have more freedom to operate the plant with gradual changes in the rate of production. Plants with very little system storage have to vary production so it follows demand very closely, whereas plants with two days' or three days' storage in the system need to vary production only in response to overall trends in demand. Six plants reported that they experience filtration rate changes that occur because of a limitation of treated water storage volume. At plants having operational difficulties caused by frequently changing production to keep pace with system demand, building more storage facilities for filtered water is a wise investment, from the standpoint of both system reliability and filtered water quality.

Table 4.3

Filtration rate increases caused by increasing water production at 48 plants*

Is the Filtration Rate Increase Abrupt?**					
Yes, or sometimes yes depending on circumstances			10 plants		
No, it is slow or gradual			27 plants		
Typical Water Production Percentage Increase					
Up to 10%	11% to 20%		21% to 30%		Over 30%
10 plants	5 plants		5 plants		5 plants
Typical Filtration Rate Increase, Percentage per Minute					
< 1% per min	1% per min		>1% to 3% per min		> 3% per min
9 plants	5 plants		6 plants		2 plants plus 1 instantaneous
Typical Time Needed to Accomplish Water Production Increase					
Instantaneous	Up to 5 min.	Up to 10 min.	Up to 20 min.	Up to 30 min.	Up to 60 min.
1 plant	5 plants	6 plants	5 plants	4 plants	4 plants
Do the Filter Rate Control Valves Have Smooth Action?					
Yes – 34 plants			No – 1 plant		
What Causes an Abrupt Increase in Your Rate of Water Production?					
Can't change rate gradually	Limited volume of filtered water storage		Raw water pumping rates not flexible		Changes in water demand in system
3 plants	6 plants		7 plants		3 plants
Other reasons (1 plant each): operators; filter-to-waste changeover; power failure; putting lots of filters into service					
Abrupt Filtration Rate Increases Avoided by Putting Off-line Filter or Filters into Service					
4 plants					
*Some questions were not answered by some utilities, so totals in table differ for different aspects of plant operation. ** Some responses were incomplete or inconclusive.					

Other causes of abrupt filtration rate increases included changes in water demand in the system, and inability to change production rates gradually (which seems similar to lack of flexibility in raw water pumping and may be redundant).

Place idle filter or filters into service. Some water filtration plants have sufficient capacity that one or more filters can be kept out of service and ready for use when production has to be increased. Four plants reported using this practice to manage water production increases.

The possibility of placing more filters into service to manage production increases is plant-specific. Larger treatment plants located in regions of the country that are experiencing slow population growth are more likely to be able to use this strategy than plants where population and water demand are

growing rapidly. One plant reported that production increases are made only in conjunction with bringing one or more additional filters into production. Holding filters out of service, ready for future use, can be a good practice.

One note of caution is in order, as filters that are held out of service for excessive periods of time can develop water quality problems. If a filter is kept off-line for an excessive number of days, the chlorine residual in the bed can become depleted, leading to bacterial growth. The potential for problems of this type is discussed in Chapter 7. In this project, some utilities reported leaving filters off-line for periods of time ranging from two to five days. These time intervals may be excessive, especially if water is warm, as warm water causes bacteria to grow more rapidly. Growth of bacteria in a filter bed can cause depletion of the dissolved oxygen in the water in the bed.

Operators should routinely sample out-of-service filters before returning such filters to service to ensure that water quality within the bed is acceptable. If prechlorination is practiced, test for chlorine residual and heterotrophic plate count (HPC). This will help plant staff understand the relationship between chlorine residual and bacterial growth. Then before being returned to service, filters can be backwashed as needed based on depletion of chlorine residual to a concentration below the minimum acceptable value. At plants where prechlorination is not practiced, water within filter beds can be sampled for dissolved oxygen. If water in filter beds becomes anaerobic (essentially no dissolved oxygen present), oxidized iron or manganese captured in the filter bed could be redissolved. Discharging anaerobic water into the clearwell might cause iron or manganese problems, and taste and odor problems might also result from this practice. If granular activated carbon filters are left out of service for several days, nitrite may form, if nitrifying bacteria had become established in the bed during its operation.

Managing Rate Increases Caused by Removing Filter from Service for Backwashing

A second circumstance that can cause filtration rate increases is the removal of a filter from service for backwashing. At very large plants with two dozen filters, or more, this would not be a significant issue because the percentage increase resulting from taking one filter out of service would be quite small. At small plants with just two filters, backwashing one filter could cause the filtration rate to double on the filter still in service. At a plant with six filters, backwashing one would cause a 20% rate increase. This is an issue that is more important at small and medium-sized plants. The increase in flow imposed on the filters remaining in service would be even greater if the backwash water were

recycled directly to the plant influent, in the case of small treatment plants with very short process detention times, such as package plants.

Several approaches to avoiding or minimizing rate increases associated with backwashing were reported in this project. Some plants use only one of the techniques described below, but a few reported using two or three. One plant specifically reported using a combination of gradual rate increases, decreasing raw water flow, and allowing pretreated water to build up in the sedimentation basin. As with many other aspects of water treatment, plant operators shouldn't feel constrained to use only a single approach to managing treatment. Table 4.4 summarizes information on techniques used to manage or avoid filtration rate increases when a filter is removed from service for backwashing.

Table 4.4

How filtration rates are managed when a filter is removed from service for backwashing at 47 plants

Is the filtration rate increase abrupt?	
Yes, or sometimes yes depending on circumstances	9 plants, with a range in rate increase of 10% to 33%
No, increase is slow or gradual	38 plants
How is an abrupt filtration rate increase avoided?*	
A clean, standby filter is placed into service	26 plants
Rates on all filters increase, but gradually	17 plants, with typical rate increase of less than 1% per minute to 3% per minute
Raw water flow is decreased	9 plants
Excess pretreated water builds up gradually in basins and declines later on	8 plants

* Totals for plants using methods to avoid abrupt increase exceed the total plants reporting that they avoid abrupt increases because some plants use more than one approach to avoid an abrupt increase in filtration rate when a filter is taken out of service for backwashing.

Place idle filter into service. At plants where sufficient capacity is available, a filter is backwashed and then held out of service until the next filter needs to be backwashed. This enables operators to compensate for removing a filter for backwash by starting a filter that was recently backwashed. If an idle filter is placed in service when another is removed from service for backwashing, an operator will need to accomplish two tasks at the same time. At plants with on-line filtered water turbidimeters and automation for backwashing, this can be accomplished without excessive difficulty. At a manually operated plant simultaneous startup and backwashing may be very difficult or physically impossible.

When sufficient filtration capacity is available placing an idle filter into service is an excellent approach to avoiding a rate increase. Twenty-six plants reported doing this, although at some plants it may not be possible to hold a filter off line when peak production is needed. One would expect that large plants with many filters would use this practice, and this is the case. Nevertheless, one plant with a design capacity of 12 mgd (45 ML/d) and only four filters also reported using this practice when possible. When all filters are in use, the 12 mgd (45 ML/d) plant decreases raw water flow when a filter is backwashed.

Fifteen plants using this practice reported no effect or minimal effect on filtered water turbidity. One reported no effect on filtered turbidity, but a slight rise in particle count was observed. Two plants reported a slight increase in turbidity when an off-line filter was placed into service as a filter was taken out of service for backwashing.

Slowly increase rates on filters remaining in service. If filtration rates have to be increased because a filter was taken out of service, gradually increasing the rate of filtration on the filters remaining in service is a practice consistent with recommendations Cleasby has made on filtration rate increases for many years. When the percentage of the increase is not large, the gradual increase can enable operators to compensate for removal of one filter from service without an impairment of filtered water turbidity. Seventeen of the plants reporting on operating practices use this approach to minimizing the effects of rate increases caused by backwashing.

The percentage increase in flow caused by taking a filter out of service is related to the number of filters in service at the time. Plants with fewer filters experience larger percentage increases. Two plants with four filters reported increases as high as 33% and noted that although filtered water turbidity was not affected by these rate increases, the particle count did increase. At one plant where a gradual 10% rate increase is experienced, staff noted that a filtration rate increase imposed during the last 10

hours of a filter run could cause a particle count increase. In the 17 plants reporting on the use of this practice, the rate of increase of flow in filters typically ranged from less than 1% per minute to 3% per minute.

Decrease raw water flow while filter temporarily out of service. When plants have flexibility in raw water pumping, production can be decreased while a filter is backwashed. To do this effectively, however, flow-paced chemical feeders would be needed, as without this feature, plant operators would be busy making adjustments to chemical feed systems at the same time when they were performing and observing the filter backwash. Nine of the plants surveyed in this study reported that they could decrease raw water flow to avoid a rate increase during backwash. No plant using this practice reported an adverse effect on water quality. Adjusting chemical feed to keep pace with water flow is important, and the difficulties associated with making such adjustments at some plants may cause operators to use other approaches for dealing with rate increases during filter backwash.

Maintain or slowly increase filtration rate, allowing water levels in pretreatment basins to rise. Some filtration plants have pretreatment basins that are designed in such a way that the excess flow caused by removing a filter from service can be buffered by allowing the volume of water in sedimentation and flocculation basins to slowly increase during backwashing. Later when all filters are again in service, the excess water stored in pretreatment can be treated, allowing the water level to gradually decline to its normal value. This approach does not eliminate a rate change, but it eliminates the abrupt nature of the rate increase by temporarily using pretreatment basins as equalization basins. Eight of the treatment plants reported using this approach. At one plant the operator reported that breakthrough depends on circumstances.

Multiple approaches. Twelve of the plants employed more than one technique to avoid making an abrupt filtration rate increase when a filter is taken out of service for backwashing. At one plant employing coagulation and filtration, a combination of gradual filtration rate increases on all filters remaining in service, a reduction in raw water flow, and allowing some excess flow to build up in pretreatment was employed. Plant staff reported that when a filter is taken off-line for backwashing, they see an increase in particle count on the order of 0.2 particles/mL in the size range of 2 μm and larger.

RETURNING A FILTER TO SERVICE AFTER BACKWASH

At some plants, returning a filter to service after backwash will cause a decrease in the rate of flow in other filters and then a surge in rate. This effect is more pronounced if pretreated water flows rapidly into the newly washed filter, and it is a function of the type of rate control system used. If filter effluent valves are tied into the level of the filter influent channel, when the filter influent channel level drops slightly as the off-line filter is being refilled, the effluent control valves on the working filters will slightly reduce the flow rate to compensate for this. (This happens if the valves are trying to maintain the set point level in the influent channel.) Once the filter box is filled, the rate will again have to readjust upward so that all the filters are operating at the same rate, which will be a slightly lower rate than the rate experienced during the backwashing. Fluctuations in filtration rate as described in this paragraph are more likely to be detrimental in a plant with only a few filters than in a plant with a dozen or more filters, so small system operators need to be alert for the possibility of this problem. If backwashing a filter causes this kind of variation at a plant with a rate control system tied to the level of the influent channel, try slowly filling the filter box as a means of reducing the variations in filtration rate after a filter has been backwashed and it is being returned to service.

Slow Stops

In much the same way as described above, it may be possible in some plants to slowly close the inlet to a filter which is due to be backwashed, a so-called slow stop. This would be undertaken to allow the increase in flow rate to the remaining filters to be small enough to have no effect on filtrate quality. Once the inlet was fully closed the filter would continue with its normal drain down and backwash cycle.

SETTING GOALS AND ACHIEVING OPTIMIZED FILTRATION

Optimization of filtration is discussed in this portion of Chapter 4. Additional information on this topic may be found in this manual in the Chapter 13 case study, "Implementing Optimization at Filtration Plants."

Optimization as Used in This Manual

In general usage 'to optimize' may be understood as meaning to attain the most efficient or effective use of something. According to Renner and Hegg (1997), "Optimum performance of a treatment plant and its unit processes means achievement of high quality water on a continuous basis. Continuous performance is indicated by very consistent settled and filtered water quality despite variations in raw water quality, changes in plant flow rate, unit process operations such as backwashing a filter, or any other reasons." In the context of this manual, the meaning of optimization is consistent with the concept presented by Renner and Hegg.

In his discussion of coagulation, flocculation, settling and filtration, Conley (1965) stated, "In practice, it is important not to be too preoccupied with any one of the steps, but to look at the process as a whole." Robeck, Clarke, and Dostal (1962) also argued for a holistic view of water filtration, stating, "It is also apparent that coagulation and filtration are really one process and should not be studied separately." In optimized treatment as discussed by Conley and by Robeck, Clarke, and Dostal, the goal is not to squeeze the maximum performance out of any single process, but to have all processes in the treatment plant performing at levels that yield the best overall performance for the plant as a whole. If too much effort is devoted to attaining outstanding performance from a single treatment process, the performance of processes that follow may suffer.

Setting Water Quality Goals at a Filtration Plant

Water quality goals are essential if filtration is to be optimized. Setting goals provides operating staff with benchmarks against which they can measure plant performance. The filtration performance requirements set by EPA in the Surface Water Treatment Rule, Interim Enhanced Surface Water Treatment Rule, and future rules should not be considered goals, nor should regulatory requirements in other countries. The regulatory requirements are just that -- requirements. Public water systems in the United States have entered the era of the Consumer Confidence Report. In this era, goals ought to be more stringent than regulatory requirements so water utility customers will realize that their utility is doing its best to provide them with high quality water and not merely complying with regulatory requirements.

With respect to water quality goals, two tasks belong to the highest levels of water utility management. One task is to work with others in the water utility to select water quality goals that reflect

the attitude of providing water of excellent quality to the customers, and the second is to provide all necessary management support to ensure that the goals are met. Cleasby and his co-workers emphasized the importance of management support in two studies of water treatment plants they carried out for the AWWA Research Foundation (Cleasby et al. 1989 and Cleasby et al. 1992). In their 1992 report they wrote, "Management must adopt a low turbidity goal, convince the operators that this is a serious goal to be met, and budget adequate funds for whatever chemical dosages are required to achieve the goal. Chemical pretreatment prior to filtration is more critical to success than the physical facilities at the plant. However, good physical facilities may make achievement of the goal easier and more economical." These conclusions were based on observations made during visits to 21 successfully operated water filtration plants during the AWWARF study by Cleasby et al. (1989).

The authors of this manual strongly endorse the findings of Cleasby and his co-workers that effective pretreatment has more influence on filtered water quality than the physical facilities that are employed for pretreatment and filtration, i.e. the basins, piping, and filter box or vessel. (Cleasby and co-workers did observe that good physical facilities could enable operators to produce excellent filtered water more easily or more economically.) In addition to effective pretreatment, the condition of the filter media itself is a key factor in attaining effective filtration. Inadequate depth of media, dirty and clogged media, media full of mudballs, or media cemented together by calcium carbonate can not be as effective as clean, properly placed filter media.

A detailed evaluation of filtered water turbidity produced by 75 plants in Pennsylvania (Lusardi and Consonery 1999) revealed that the average values of maximum monthly filtered water turbidity were less than 0.3 ntu for a wide range of filtration plant sizes, ages, source waters treated, coagulants used, and ownership types. The authors suggested that intangible factors such as commitment to achieving low filtered water turbidity, the skill level of the operators, and operator attention to the treatment plant were more important than plant size, age, water source, and other technical factors.

Partnership for Safe Water Goals

The Partnership for Safe Water (referred to as the Partnership in this section of the manual) was created by the American Water Works Association, the American Water Works Association Research Foundation, the Association of Metropolitan Water Agencies, the Association of State Drinking Water Administrators, the National Association of Water Companies, and the U.S. Environmental Protection Agency in 1995. Its purpose is to encourage utilities treating surface water to employ "best practices" for

achieving the desired levels of consistent and reliable high quality water. The Partnership adopted stringent but attainable plant performance goals (USEPA et al. 1995) including:

- Consistently produce an effluent turbidity of less than 0.1 ntu from each individual filter.
- Consistently produce settled water of 2 to 3 ntu from sedimentation basins.
- Have no turbidity spike exceeding 0.3 ntu after backwash, at the start of a filter run.
- Produce filtered water turbidity of less than 0.1 ntu within 15 minutes after returning a filter to service following backwash. This goal is applicable for filters that are started at the full rate that is to be used for the run and for filters that are started at a slow rate with the intention of gradually increasing the filtration rate to the full rate as the run progresses.
- If filter-to-waste is practiced, produce filtered water turbidity less than 0.1 ntu before the filter is brought back on line.

- Maintain consistent excellent levels of performance regardless of changes in raw water turbidity.
- Seek to continue to improve plant performance, even when the above Partnership goals are attained.

The self-assessment procedures document (USEPA 1995) was reviewed, and that document was the basis for an AWWARF report, "Self-Assessment Guide for Surface Water Treatment Plant Optimization" (Renner and Hegg 1997). Water utility personnel planning to conduct a self-assessment at their treatment plant ought to consider this AWWARF report as a "must read" document. The original idea for the assessment concepts came from the Composite Correction Program developed for the USEPA by Renner et al. (1991), based on their experience and understanding of the performance capabilities of an optimized treatment plant. In one way the goals for optimized treatment have become more stringent as experience has been gained with assessment for optimization. In their 1997 report, Renner and Hegg recommended that turbidity should be less than 1 ntu from sedimentation basins, rather than 2 to 3 ntu. They recommended that filtered water should be less than 0.1 ntu, with possible exceptions for a short period of time just after a filter has been backwashed and placed into service.

Conducting a careful review of each process in the treatment plant is a good first step towards the goal of achieving the best performance from a treatment plant. The Partnership goals provide excellent benchmarks against which process performance in a plant can be measured. The systematic evaluation of water treatment plants using a carefully conceived set of guidelines has been carried out at numerous facilities throughout the 1990s. This is a field-tested and time-proven concept and its application at all filtration plants is recommended.

The Partnership for Safe Water program and some results were reviewed by Pizzi (1998). After presenting a comprehensive review of the Partnership program, Pizzi summarized the improvement in filtered water that had been attained by utilities taking part in the program. He presented a table based on 40 submissions of data to the program. His table indicated a substantial improvement in filtered water turbidity and is presented below as Table 4.5.

In a recent update on the Partnership for Safe Water Program, AWWA's *Mainstream* reported that at 78 plants in the program, 95 percent of the filtered water turbidity samples were 0.3 ntu or lower. After completion of Phase 3 of the Partnership program, 95 percent of the filtered water turbidity samples were 0.18 ntu or lower (Anon. 2000). This decrease in the 95th percentile filtered water turbidity represents an important improvement in water quality and filter operation and indicates that improvement can be attained when doing so is an operational goal.

Table 4.5

Summary of turbidity results reported by Pizzi, 1998

	Before optimization	After optimization
Composite 90% values	0.16 ntu	0.07 ntu
Composite maximum values	0.40 ntu	0.21 ntu
Composite minimum values	0.05 ntu	0.03 ntu
Largest turbidity spike	1.0 ntu	0.5 ntu

Roadblocks to Meeting Goals

Consonery et al. (1997) reported on evaluations at 290 surface water treatment plants in the state of Pennsylvania. They identified ten common problems encountered at the plants:

- Inadequate jar testing or lack of other coagulant control strategy
- Inadequate rapid mixing process
- Lack of individual filter effluent monitoring
- Inadequate or lack of a filter-to-waste capability
- Turbidimeters not calibrated
- Improper chemical dosages
- Inadequate operation and maintenance knowledge
- Starting up dirty filters, that is, returning a filter to service without backwash
- Inadequate process monitoring
- Using filter run time as the only criterion for initiating a filter backwash

Most of the problems in the list of Consonery et al. are related to operation and maintenance. Improper rapid mix and lack of filter-to-waste are clearly design problems, and the latter can be expensive to retrofit. Although on-line turbidity monitoring may have been omitted by a design engineer, this is not difficult to add later from a technical or construction perspective. On-line turbidimeters have been added to many plants that were built before those instruments were commercially available, and the original turbidimeters have been updated with more modern instruments at numerous plants. Thus, of the problems cited by Consonery et al., most are the type that can be resolved by application of sound operation and maintenance concepts. This is consistent with the purposes of the Partnership and the objective of the 1997 AWWARF report of Renner and Hegg, which is that improved treated water quality should be attained by changing how things are done at the treatment plant, rather than by making big capital investments for facilities.

A detailed evaluation of filtered water turbidity produced by 75 plants in Pennsylvania (Lusardi and Consonery 1999) indicated that filtered water turbidity was similar for a wide range of filtration plant sizes, ages, source waters treated, coagulants used, and ownership types. A few exceptions to this finding, however, were noted by the authors.

Filtration plants using no coagulant had very high turbidity, with an average maximum monthly value of 1.2 ntu and an average annual value of 0.8 ntu. In fact, treatment of surface water by rapid rate granular media filters without using coagulant is not an approved technology under the US EPA's Surface Water Treatment Rule, and rapid rate granular media filtration can not function effectively unless the water has been coagulated, so it is not surprising that the filtered water turbidities reported were not in compliance with the Surface Water Treatment Rule.

Filtration plants using polymer but no metallic coagulant (no alum or iron) had high turbidity, with an average maximum monthly value slightly over 0.6 ntu and an average annual value of about 0.3 ntu. During the investigation of an outbreak of waterborne cryptosporidiosis at a small community in Oregon, Leland et al. (1993) noted that the gravity filtration package plant providing water to the affected community had been using polymer coagulant but no alum when the outbreak began. After jar tests were performed, alum and polymer were used for coagulation, and filtered water turbidity was lowered. Although management of only one coagulant chemical (cationic polymer) may be simpler for small water systems, the filtered water turbidity attained with this pretreatment approach may not be as good as the turbidity that could be produced by using metallic coagulant and cationic polymer or filter aid polymer for pretreatment.

Another category of plants having substantially higher turbidity as compared to others was the group of plants serving populations less than 3,300 persons. The largest proportion (41 percent) of the 75 plants studied by Lusardi and Consonery were in this population category. The high turbidity produced by this group of plants may indicate that systems serving fewer than 3,300 persons have difficulty raising the revenues needed to pay adequate salaries to hire, train and keep operators who can effectively manage plants that use coagulation processes. Small systems tend to have part-time operators, and this may contribute to problems in achieving low filtered water turbidity, as part-time staff may have difficulty gaining access to training that others obtain more easily.

Feedback on attaining goals

After goals have been set by management and support toward meeting the goals is provided, the adequacy of current information provided to plant operators is a key factor that enables them to meet the goals. On-line instrumentation provides water quality and plant operating information to operators as frequently as they need it. Monitoring is described in Chapter 5. Reliance on data provided by on-line systems presumes that a quality control program is being carried out to ensure accurate information for

use in making decisions about plant operation. Without adequate quality control the plant staff have no assurance that they correctly understand what is happening in the plant. Quality control is discussed in Chapter 12.

U.K. experience

In the U.K. a maximum value of 0.2 mg/L of iron or aluminum is permissible in finished water. In order to achieve this most plants would set a goal well within this target and 0.05 mg/L is typical. Monitoring for iron or aluminum in finished water is appropriate when either of those metals is used as a coagulant. Excessive concentrations of either dissolved or particulate iron or aluminum could indicate problems with coagulation, as when coagulation is done properly, the residuals of the metal coagulants will be very low. High concentrations of dissolved coagulant could indicate coagulation is being done at the wrong pH, and some metal is failing to precipitate. This is more likely to happen with aluminum than with iron, as the latter coagulant has a wider pH range over which it is highly insoluble.

In one U.K. utility, cultural changes have resulted in operators seeking to optimize the performance of their plants. The finished water turbidity data from some 36 treatment plants are automatically sent to a central database for analysis by the filtration optimization engineers. When this system was first set up the engineer would telephone the plant operator to ask for explanation of any period of poor filtrate quality. As time has gone on the operators have taken to reporting their explanations of problems and solutions automatically. Each month a summary of the performance of each plant is calculated based on the value of turbidity and the duration for periods when water quality exceeded the goal. By ranking the works into a monthly league table a competitive culture has developed so that operators seek to outperform their colleagues. The league tables used by the water utility are similar to those printed in newspapers to show the rankings of sports teams,

The lessons from this are clear. Firstly the headquarters of the organization demonstrated it was interested in what was taking place out in the field. It is easy for operators in remote parts, working outside office hours, to feel remote from their organization. Secondly the message was made clear that quality matters and it is important to do something about it. Thirdly there was the competitive sense of achievement through the league tables.

The concept of competition for improved treatment and improved water quality might find application in the United States among private water utilities that own multiple treatment plants, or in large metropolitan publicly-owned systems where a number of treatment plants are employed.

Optimized Pretreatment

For the purposes of this manual, optimized pretreatment is defined as pretreatment that together with proper filter operation, results in optimized filtration. Principles for optimizing chemical pretreatment and attaining optimized pretreatment are discussed in Chapters 8 and 9. Optimized pretreatment does not necessarily mean the clarified water turbidity is the lowest that can be produced. Phase IV Partnership goals for settled water turbidity are equal to or less than 1 ntu if raw water turbidity is 10 ntu or less, and equal or less than 2 ntu if the raw water turbidity exceeds 10 ntu. Operators may need to apply caution in their efforts to produce low settled water turbidity. The overall goal of treatment is to produce the best quality of filtered water rather than the lowest turbidity for settled water. Attempts to minimize settled water turbidity might lead to difficulties with filtration. For example, adding more polymer during pretreatment might yield settled water turbidity below 0.5 ntu at a plant, but the extra polymer might also make the floc very tough. This could cause short filter runs caused by the accumulation of nearly all the head loss in the top few inches of the filter media. Attaining the lowest possible settled water turbidity might thus be counterproductive.

Effective Management of Filter Operation

Filters perform most effectively when they are managed properly. This requires attention to each filter, to all filters as a whole, and attention to the relationship between water demand and availability of finished water stored in the system and at the plant. Effective management means that filters are operated in a smooth and steady fashion, not off and on or raising and lowering the filtration rate many times each day.

Because of the potentially bad effects filter start-ups and filtration rate increases can have on filtered water quality, operators need to be very careful when bringing each filter on line after backwashing. Filtration rate increases are necessary from time to time at any filtration plant, but these increases are to be made with care, raising the rate as gently as possible. The head loss of each operating filter is an indicator of the degree of clogging in the filter bed, so it also must be monitored.

Making rate changes on filters that are near terminal head loss is a risky procedure and one to be avoided if possible. This means the timing of filter backwashing has to be watched closely, so removing one filter from service for backwash does not cause undue stress on the filters that continue operating, especially other filters with high head loss. When multiple filters are approaching terminal head loss, a

rate increase caused by removing one filter from service for backwashing might push the head loss in another filter up above terminal value. Such a situation could lead to a chain reaction of rate increases on filters in service, excessive head loss accumulation, and multiple filter washings in a short time. The best way to avoid this problem is to watch the accumulation of head loss in all of the filters while keeping alert to the balance of water system demand and water availability in storage. If an increase in production can be anticipated, filters can be backwashed and made ready for higher production before a crisis develops at the plant.

In an automated system two ways to avoid this chain reaction setting off multiple backwashes are a) to limit the number of filters that can enter the backwash queue at any one time, and b) to set the backwash head loss trigger to flow-normalized head loss. Flow-normalized head loss is the term used to describe head loss data that are adjusted to a common water temperature and rate of flow through the filter. A procedure for adjusting head loss data to common parameters is described briefly in Chapter 6. Safeguards should be put into place to ensure this trigger is not set off by normalizing (adjusting) under low flow rate conditions.

Implicit in effective management of filters is the need for effective backwashing, which is discussed in Chapter 6 in this manual. Other critical aspects of effective filter management, filter ripening and controlling the initial turbidity spike, are presented in Chapter 7.

Appropriate Monitoring for Optimization

Operators can optimize a treatment plant, and keep it optimized much more easily when they have current, up to date information on the status of processes and water quality at the plant. By knowing what is currently happening in their plant, operators can make decisions rapidly and not let a bad water quality situation get out of hand. If water quality monitoring is done manually once or twice per shift, or if a day's effort is expended in jar tests to get current information on chemical dosing requirements, water quality could deteriorate because of the delay in learning what is happening in the plant or the delay in finding the needed remedy. Monitoring for rate of flow in the plant, for coagulation dosage and its efficacy, and for clarified and filtered water turbidity can all be very helpful in plant optimization. Monitoring is the topic of Chapter 5 of this Manual.

TREATMENT STRATEGIES FOR WATER QUALITY EPISODES

Changes in source water quality can make treatment more difficult at plants employing coagulation or lime softening and granular media filtration, and heavy runoff may also increase the risk of a waterborne disease outbreak. In a study of the association between extreme precipitation and waterborne disease outbreaks from the period of 1948 through 1994, Curriero et al. (2001) found that 51 percent of waterborne disease outbreaks were preceded by precipitation events above the 90th percentile (i.e. the highest 10 percent of precipitation events) for the area where the outbreak happened, and 68 percent of the outbreaks were preceded by precipitation events above the 80th percentile. This study gives clear evidence that events involving precipitation that is substantially greater than normal, by increasing runoff, may lead to waterborne outbreaks. High runoff may have elevated turbidity; higher than normal concentrations of total organic carbon that might make coagulation more difficult, and elevated concentrations of pathogenic microorganisms including *Cryptosporidium* oocysts and *Giardia* cysts. Events with relatively high precipitation or events involving heavy runoff from rapid snowmelt should be times when treatment plant operators are especially alert to maintain the efficacy of treatment.

This section of the manual is based on the responses provided by the water utilities participating in the study, along with reviews of published literature. Most of the plants were conventional plants employing coagulation, flocculation, sedimentation, and filtration. If a process train other than conventional treatment is used at a plant discussed below, that treatment train is briefly described. Information on the capacity of these plants, the type of source water, and the turbidity range of the source water was presented earlier in this chapter in Tables 4.1 and 4.2. Additional strategies for dealing with various water quality episodes at 21 plants were reported in Cleasby et al. (1989).

The source water quality problems, and some solutions described in this portion of Chapter 4 are:

- Variable raw water turbidity
  - Change coagulant or polymer dosage using historical dosage charts, jar tests, pilot filter data, on-line filtered turbidity or particle data, zeta potential, streaming current, or observation of floc size
  - Change to different intake level
  - Fill treated water reservoirs to capacity when major storm is predicted
  - Blend different source waters

  - Monitor quality of water in presedimentation reservoir and plan ahead for treatment changes
- Variable raw water pH
  - Feed chemicals for adjusting pH
  - On-line monitoring for lime softening plants
  - Monitor alkalinity
- Taste & odor
  - Use PAC, $KMnO_4$, chlorine dioxide, or prechlorination
  - Use both PAC and $KMnO_4$
  - Slow filtration rate for water applied to GAC filter-adsorbers
- High color/high TOC
  - Increase coagulant dosage
  - Lower pH
  - Increase ozone dosage
  - Keep pH at 10.5 or higher in lime softening plants
  - Increase $KMnO_4$
  - Use PAC
  - Monitor coagulant demand
- Cold water
  - Blend ground water and surface water to raise source water temperature
  - Change from alum to iron coagulant or PACl
  - When using alum, coagulate at higher pH for cold water
  - Speed up flocculators
  - Do note overfeed alum
- Iron/manganese
  - Use more frequent monitoring when problems are expected
  - Use preoxidation
- Algae, other biological organisms, and amorphous matter
  - Change intake depth
  - Use copper sulfate to control algae in reservoirs

  - Use iron(III) salts to control algae in reservoirs
  - Change coagulant dosage at filtration plant
  - Consider lowering pH of coagulation
  - Work with watershed program to minimize algae in source water
  - Conduct reservoir monitoring and management programs
  - Circulate water in deep reservoirs to move algae out of photic zone where light is available to support growth
  - (for taste & odor problems, see taste & odor section above)
- Multiple source water quality changes
  - Develop matrix table for chemical dosages covering water quality ranges

Operational issues that can cause filtrate quality problems, and some responses are:

- Rapid flow rate changes
  - Avoid rapid changes in rate
  - Manage raw water flow to avoid rapid filter rate 77changes
  - Manage finished water pumping and storage so rapid filter rate changes not needed
- Air binding in filters
  - Keep filter off-line for ½ hour before backwashing to allow air to be released from filter before backwash
  - Do not use surface wash if a filter is air-bound

VARIABLE RAW WATER TURBIDITY

Variations in raw water turbidity necessitate changes in coagulant dosage. Decisions on these changes are guided by information from a number of sources, including performing jar tests, using historical records of source water quality and coagulant dosage, and determining zeta potential or streaming current. Other operational strategies include decreasing the rate of filtration that would decrease the production at the plant and changing to a different intake location in a reservoir or to a different water source. An increased frequency of water quality monitoring, performance of jar tests,

and adjustment of chemical dosages are common practices when raw water turbidity episodes are encountered. Some specific examples of treatment practice are given below.

The Clackamas River Water District (CRWD) treats water from the Clackamas River, a source that can undergo changes in turbidity from under 10 ntu to several hundred ntu when major storms come into the Cascade Mountains off the Pacific Ocean. Because the river can change rapidly, CRWD slightly overfeeds coagulant during rising turbidity and slightly underfeeds during falling turbidity. This plant can be operated in a direct filtration mode when turbidity is low or in a conventional treatment mode for high turbidity water. CRWD also has a continuous turbidimeter on each filter effluent, uses a pilot filter for primary coagulant determination, and uses jar tests during storms. In addition, a streaming current monitor is used to assess coagulation. Historical data charts are used for determining limits for chemical dosage.

Operators at the Colorado Springs Pine Valley Plant adjust alum and polymer using zeta potential and observation of floc size to control treatment during turbidity episodes. At this plant, streaming current data are used as an early warning of changing chemical conditions, and historical data charts are reviewed to compare current results with past treatment results. Data on particle count and particle size also are used as guides for assessing treatment efficacy and determining treatment strategy during turbidity episodes as well as during normal plant operation.

At the Detroit Water and Sewer Department's Lake Huron Water Plant, operators increase or decrease alum dosage, minimize plant production if possible and rely on real-time instrumentation during turbidity episodes. Streaming current data are used to document trends and to recognize alum feed failures, and turbidity is monitored continuously at each filter effluent.

Elizabethtown Water Company operators at the Raritan-Millstone Plant follow historical temperature-based alum dosage charts with pretreatment pH charts that are set up for temperature ranges such as 39 - 45 °F (4 - 7 °C) and 45 - 55 °F (7 -13 °C), etc. The charts have data for alum, coagulant aid and potassium permanganate dosages used for raw water turbidity in various ranges, both for rising turbidity and for decreasing turbidity. The plant also uses powdered activated carbon (PAC) dosage charts based solely on increasing and decreasing turbidity. This plant has continuous monitoring of turbidity for each filter effluent and nine particle counters at key process locations. Jar tests and streaming current instrument data are also used to gain information on coagulation. The possibility of coagulation problems or taste and odor problems resulting from runoff containing road salt or

ammonium compounds has led to use of a chloride probe from November through April, and continuous use of a conductivity meter.

The East Bay Municipal Utility District has several filtration plants and employs a number of techniques to cope with turbidity episodes. Operators at all treatment plants reassess coagulant dosage and filtration rates during turbidity episodes. At the Sobrante and Upper San Leandro Water Treatment Plants (conventional treatment with ozone after sedimentation operators may change to a different reservoir intake depth to obtain better quality raw water. Filtered water turbidity from individual filters is monitored continuously at all plants operated by the East Bay Municipal Utility District. At their Upper San Leandro and Sobranate Water Treatment Plants, strategies for coping with turbidity episodes include increasing alum, cationic polymer, and nonionic polymer dosage per historical records and use of streaming current data.

The Eugene Water and Electric Board fills finished water reservoirs to near capacity and slows the plant to minimum flow when a bad storm is predicted. This utility's facility can be operated as a conventional plant or in a direct filtration mode, depending on source water quality. Plant staff use a streaming current instrument, a pilot filter, and continuous particle counting and turbidity monitoring for each filter as ways to set coagulant doses and evaluate the efficacy of coagulation. Strategies used to cope with extraordinarly high turbidity encountered during a flood on the McKenzie River (the water source) were described in a *Journal AWWA* paper (Wise 1998). As a result of a program of cross-training for treatment plant staff, everyone was able to rise to the challenge of treating water during the largest flood in three decades, and satisfactory filtered water quality was maintained under very adverse conditions.

The Fort Collins Water Treatment Facility has access to a river water source and a reservoir water source. These can be blended to cope with turbidity increases. Jar tests and zeta potential are used for coagulant dosage determination.

Both filtration plants at Milwaukee monitor streaming current, filter influent turbidity, and filter effluent turbidity and particle counts to determine the appropriate alum and chemical dosages in response to changes in the turbidity of Lake Michigan, the source water. Pre-ozonation is used at each of these conventional plants.

Reservoir water is the source for the Modesto Irrigation District, where gross adjustments of coagulant dosages are made by evaluation of streaming current monitoring and historical data. Fine-

tuning of coagulation is based on filtered water particle counts and turbidity, and on filter run times. This plant employs ozone, and it can be operated in a direct filtration or conventional mode.

City Utilities at Springfield, Missouri uses jar tests and follows historical data charts for dosage correction. This utility, located in southwestern Missouri, subscribes to a weather information service provided by satellite so information can be obtained at any time on weather coming in from Kansas, Oklahoma, and northwestern Arkansas. This provides advanced warning for thunderstorms and extreme rainfall events that could cause turbidity episodes in the watershed. In the summer, when people are watering lawns, information from the weather forecasting service also helps the utility make estimates of short-term future demands as influenced by the potential for local rainfall.

At the Mannheim Water Treatment Plant of the Regional Municipality of Waterloo, Ontario the plant operators monitor river turbidity at the inlet and outlet of the presedimentation reservoir. This enables them to estimate the turbidity of the water that will be pumped from that reservoir to the treatment plant. Equipped with an estimate of the future trend of turbidity out of presedimentation reservoir, plant staff can plan in advance for changes in treatment. This conventional treatment plant employs ozone between clarification and filtration.

At Thames Water's Shalford works an automatic algorithm was programmed into a programmable logic controller (PLC) to set the coagulant dose according to the river water turbidity, essentially putting a lookup table into electronic form. This table was based on the practical experience of the works chemist over many years.

VARIABLE RAW WATER PH

Among the utilities participating in this study and having a strategy for dealing with variations in raw water pH, most reported that they respond by feeding caustic soda or lime. Other strategies include use of soda ash and carbon dioxide. Reasons for adjusting pH, and pH goals generally were not stated by participating utilities, but would be expected to be to ensure coagulation is optimum for the objective of the filter plant. Bell-Ajy et al. (2000) provide examples showing of how pH control is important for optimized or enhanced coagulation. This study focused on filtration and the pretreatment needed for effective filtration, so post-filtration pH or alkalinity adjustment practices for purposes of corrosion control or DBP control were not considered relevant to the project, even though they are important for maintaining good water quality in the distribution system. Three utilities reported that alkalinity is monitored and chemical dosage depends in part on the alkalinity data. Sodium aluminate is used by

some to help maintain a stable pH. Two utilities reported that they use historical data charts as a guide to adjustment. One utility has the capability to add either caustic soda or sulfuric acid as needed to keep pH in the proper range.

Control of pH is very important at lime softening plants. Three plants reported that settled water pH was monitored continuously. Three others used grab sampling of settled water, at frequencies of 6/day, 12/day, and an unspecified frequency. Use of on-line pH monitoring at lime softening plants is recommended as a means of maintaining precise control of treatment chemistry and reducing the analytical burden on operating staff.

TASTE & ODOR

Many species of algae and some actinomycetes are capable of producing unpleasant odors and tastes, often described as earthy / musty, sometimes fishy, or resembling vegetation such as grassy, geranium, cucumber, etc. A comprehensive compilation of papers on taste and odor was edited by Persson, Yurkowski and Marshall (1983). The degree of any problem depends not only on taxon (genus, species etc.) but also biomass and the condition of the algal cells. For oligotrophic waters in which algal is growth limited by the scarcity of nutrients, algae are unlikely to produce foul taste/odor from most taxa because of insufficient nutrients to support growth of large numbers of organisms. There are exceptions to this, the most notable being the genus *Cynura* which when present in densities as low as only a few cells per liter can impart an unpleasant taste. Whole cells and colonies may give rise to some taste/odor but the problem may increase markedly if the cells are lysed and the cell contents are released. Chlorination may increase the off-taste/odor as well or may change the taste/odor to something more unpleasant. Caution definitely is required if pre-chlorination is used on algae-laden waters. At taste panel sessions held weekly through the summers of 1984 and 1985 consisting of Thames Water employees, a taste and odor attributed to the compound geosmin was described by various panel members as earthy, musty and even chlorinous.

Taste and odor problems are encountered by many water utilities. For this AWWARF project, information on the strategy for coping with taste and odor was provided by 35 North American treatment plants. Nineteen of the plants feed powdered activated carbon (PAC) to cope with taste and odor. Ten can use potassium permanganate, and nine of the plants noted that they could feed both permanganate and PAC. Three coped with taste and odor by using prechlorination, while one employed chlorine dioxide. Nine of the plants participating in this study use ozone, and several commented positively about

the effects of ozone for controlling taste and odor problems. One plant that uses ozone also employs hydrogen peroxide as needed. A few plants used GAC filters. One of these noted that during taste and odor episodes the filtration rate could be slowed to increase the contact time for water in the GAC filter bed. Information on treatment plants and the strategies they use for dealing with taste and odor problems is presented in Table 4.6. Graham et al. (2000) produced an AWWARF report on the use of PAC for taste and odor control.

Thames Water Utilities staff have experience with one small shallow reservoir in which nitrate (all 10+ mg/L) was reduced to nitrogen gas. Another unpleasant experience with hypolimnetic water involved development of a pink-purple color due to "purple" sulfur bacteria. Unfortunately the water was also saturated with hydrogen sulfide so the smell was awful!

Thames Water and others (Hyde et al. 1987) successfully converted sand filters to GAC filters during the 1980s to deal with taste and odor episodes. It was necessary to ensure GAC media grain size was comparable to the sand media. Backwash rates had to be reduced to ensure media was not lost from the filter and the washwater weir freeboard was extended for the same reason. Air bubble entrainment in the wash water pumps caused problems with media loss at one site and must be avoided. Exposed metal surfaces in contact with the GAC were covered with a paint coating approved for use in contact with potable water.

When operators have to take filters out of service for prolonged periods of time for maintenance, or when filters are rested after backwashing, it is important to check that taste or odor is not generated by biological activity in conditions of little or no dissolved oxygen in the filter.

HIGH COLOR/HIGH TOC

The link between high concentrations of true color in water and high concentrations of dissolved organic carbon (DOC) is well known. When water has a high concentration of true color, the dose of coagulant chemical needed for effective treatment tends to be proportional to the concentration of color. Natural organic matter (NOM) can occur in forms other than color, and some NOM can be quite difficult to remove by coagulation. The ratio of UV absorbance at 254 nm to dissolved organic carbon concentration is referred to as specific UV absorbance, or SUVA, a concept introduced by Edzwald et al. (1985). SUVA is expressed in units of L/mg-m. White et al. (1997) reported that waters having a high humic content, as indicated by higher SUVA, could be treated by chemical coagulation to attain higher

Table 4.6

Strategies Used for Dealing with Taste and Odor Problems

Utility	Plant	Process	O_3	PAC	GAC	$KMnO_4$	Pre-Cl_2	Other
Ann Arbor Utilities Department	Ann Arbor Water Plant	LS	X		X			
Chester Water Authority	Octoraro Treatment Plant	Conv.		X				
Chesterfield County Utilities Dept.	Swift Creek WTP	Conv.		X				
Cincinnati Water Works	Richard Miller Treatment Plant	Conv.		X	X	X		
Clackamas River Water District	C.R. Harrison Filtration Plant	Conv/DF		X		X		
Cleveland Division of Water	Crown Water Treatment Plant	Conv		X		X		
Colorado Springs Utilities	McCullough WTP	Conv						Change source
Colorado Springs Utilities	Pine Valley WTP	Conv					increase	
Connecticut Water Company	MacKenzie WTP	Conv			X			
Connecticut Water Company	W.C. Stewart WTP	Conv			X			
Dallas Water Utilities	Elm Fork WTP	Partial LS	X	X				
Detroit Water & Sewer Dept.	Water Works Park Plant	Conv		X				
Detroit Water & Sewer Dept.	Northeast WTP	Conv		X				
Detroit Water & Sewer Dept.	Southwest Water Plant	Conv		X				
Detroit Water & Sewer Dept.	Springwells WTP	Conv		X				
E2A/Systems	Evansville Water Filtration Plant	Conv		X		X		
East Bay Municipal Utility District	Sobrante WTP	Conv	X			X		Monitor raw water reservoir

(continued)

Table 4.6 (Continued)

Utility	Plant	Process	O_3	PAC	GAC	$KMnO_4$	Pre-Cl_2	Other
East Bay Municipal Utility District	Upper San Leandro WTP	Conv.	X			X		Also use hydrogen peroxide and monitor raw water reservoir
City of Elgin	Riverside WTP	LS		X				
Elizabethtown Water Company	Raritan-Millstone WTP	Conv.		X		X		
Eugene Water & Electric Board	Hayden Bridge Filtration Plant	Conv/DF		X				
City of Fargo Public Works	Fargo Water Treatment Plant	LS	X	X		Can use		
Fort Collins Utilities	Ft. Collins Water Treatment Facility	Conv.		X		X		Chlorine dioxide
Grand Rapids Water System	Lake Michigan Filtration Plant	Conv.		X				
Water Dist. # 1 of Johnson County	Hansen Treatment Plant	LS		X				
Milwaukee Water Works	Linwood WTP	Conv.	X					
Milwaukee Water Works	Howard Avenue WTP	Conv.	X					
Modesto Irrigation District	Modesto Regional WTP	Conv/DF*	X					
Northern Kentucky Water District	Fort Thomas Treatment Plant	Conv		X		X		
Norwalk Second Taxing District Water Department	Wilton Filtration Plant	Conv./ ABW					X	Algae control in reservoir, change intake level
Philadelphia Water Department	Baxter Water Treatment Plant	Conv.		X		X		

(continued)

Table 4.6 (Continued)

Utility	Plant	Process	O_3	PAC	GAC	$KMnO_4$	Pre-Cl_2	Other
City Utilities of Springfield	Blackman Water Treatment Plant	Conv.		X		X		Test for Geosmin, MIB, etc.
Washington Suburban Sanitary Commission	Potomac Water Filtration Plant	Conv.		X		X		
Washington Suburban Sanitary Commission	Patuxent Water Filtration Plant	Conv.						Test for Geosmin, MIB
Regional Municipality of Waterloo	Mannheim Water Treatment Plant	Conv.	X		X			

LS = lime softening.

Conv. = Conventional treatment with coagulation

Conv./ABW = conventional pretreatment followed by Automatic Backwash (Traveling Bridge) Filter

*can be operated as conventional plant or in direct filtration mode.

levels of NOM removal than waters with low SUVA. They found that waters treatable to attain TOC removal consistent with EPA's proposed Stage 1 D/DBP Rule had an average SUVA of 3.9 L/mg-m, whereas waters not amenable to chemical coagulation for removal of TOC had an average SUVA of 2.6 L/mg-m.

Algae can serve as another source of DOC, in addition to causing problems with tastes and odor. Eutrophic waters, in which algal growth is not limited by nutrients, can be subject to large "blooms" of algae. Some algal taxa will proliferate under these conditions and out-compete many others for light so a few species dominate, usually at high biomass. If these produce bad taste/odor then really serious problems can arise. Sometimes such problems are not apparent in the raw water, but the algae become a nuisance only when the cells either lyse or start to rot. Many diatoms are like this, producing a very characteristic odor. This leads to a dilemma of choosing to use an oxidant to kill the cells and release the cell contents (DOC) or not use an oxidant and perhaps get poorer removal during treatment. The other dilemma is that if oxidants are used and they cause the release of cell contents, the oxidant demand is increased due to the higher DOC concentration in the water. Increasing the oxidant dose again can produce more oxidation or disinfection by-products, depending on which oxidant is being used. Possibly the best approach is to reduce the populations of algae in the source water. Some water utilities have to treat water during episodes of high concentrations of color or total organic carbon (TOC) or both. The most common response to such episodes involves increasing the coagulant dosage, or lowering pH. These are concepts related to enhanced coagulation, and in fact two utilities reported using enhanced coagulation during color/TOC episodes. One utility that uses enhanced coagulation also increases ozone dosage to treat water during these events. Two utilities reported using potassium permanganate and two used prechlorination. Staff at one treatment plant where lime softening is practiced noted that they optimized TOC removal by maintaining pH at 10.5 or higher in the primary softening unit.

The Elizabethtown Water Company provided its standard procedure for high color or TOC concentrations. It is:

- Use special high color alum dosage chart that exceeds normal dosage called for on standard turbidity/temperature charts.
- Increase permanganate; in winter can use ORP meter and in summer raise setting 0.1 ppm.
- Put PAC into service.

- Discontinue use of coagulant aid if in service.
- Watch for increased coagulant demand.
- Use pH 6.2 pretreatment.
- Above 70 °F (21° C) temperature use lower pretreatment pH.
- Have filter aid prepared for use if needed.

During the summer, when water temperature is in the range of 59 °F to 68° F (15 °C to 20 °C) the operators at the Mannheim Water Treatment Plant add sulfuric acid to bring pH down to about 6.8. This assists in 1) stabilizing ozone residual, 2) reducing aluminum residual, 3) lengthening filter runs, and 4) reducing dissolved organic carbon (DOC) concentrations. Although this was not referred to as enhanced coagulation, it is a treatment strategy appropriate for treating water to remove color and TOC.

COLD WEATHER / NEAR FREEZING WATER

Cold water can present problems to filter operators due to its impact on water chemistry, especially when alum is the coagulant. Cold water also results in higher head losses through filters as the water is more viscous when cold. This will cause starting head loss to be higher than with warmer water, and may cause the rate of head loss accumulation to be relatively higher. An opposite effect is that filtration may be less effective as the higher viscosity causes higher shear stresses within the filter which may make it harder to deposit particles on the media surface and easier to disturb the deposits and possibly re-entrain them in the flow. Careful control of changes to flow rates may be more critical in cold waters than in warmer waters.

Treatment of cold water has been subjected to research. Haarhoff and Cleasby (1988) compared in-line filtration results when aluminum sulfate and ferric chloride were used as coagulants. They reported that for water temperatures less than 37 °F (3 °C) the ferric chloride removed turbidity more effectively but alum gave a slower rate of head loss development. These comparisons were based on using equimolar concentrations of the metal coagulants (i.e., equal numbers of aluminum atoms and iron atoms used for coagulation). With each coagulant, the total filter clogging head loss was about 39 inches (1.0 meter) when turbidity breakthrough started to occur. This may have been an indication that the floc formed in cold water was weak

Hanson and Cleasby (1990) studied flocculation of cold water. Comparing tests at 68 °F (20 °C) and 41 °F (5 °C) they reported that under some conditions, flocculation efficiency can decrease in cold

water, and flocs of metal coagulants may not be as strong when formed in cold water. Hanson and Cleasby also presented chemistry theory explaining why increasing coagulation pH in cold water, as compared to the pH used for warm water, may be advisable. Manual users interested in the chemistry of cold water coagulation are encouraged to refer to the Hanson and Cleasby paper.

Operators at a number of water treatment plants located in northern latitudes or at high elevations have developed strategies for treating water when its temperature is near the freezing point. Some utilities have both ground water and surface water. They find that water treatment is easier when the warmer ground water is blended with surface water to raise its temperature. Warming water to room temperature is not necessary to attain better treatment. Changing the temperature from 34 °F up to 41 °F (1 °C up to 5 °C) or higher may be sufficient. Another benefit of treating somewhat warmer water is that the slow reaction rate for alum in very cold water can result in precipitation of aluminum after water has been filtered. Alum floc can be weak when formed in very cold water, so some utilities use polymer to strengthen floc.

The difficulties encountered with using alum to treat very cold water have led some utilities to switch to other coagulants. The Clackamas River Water District formerly used alum but now uses polyaluminum chloride (PACl) as a coagulant. To treat cold water, the Northern Kentucky Water District uses ferric sulfate in addition to the Clar$^+$Ion™ coagulant (a product of General Chemical) that is used throughout the year. This is done when the water temperature drops below 55 °F to 60 °F (13 °C to 16 °C) in the late fall or early winter because it helps to weight the floc and improve settling during this time of year. Use of the combination of coagulants continues through March, after the water has warmed up. Doses of both coagulants are adjusted on the basis of jar tests and settled water turbidity in the plant. The ferric sulfate dose typically is in the range of 20 percent to 25 percent of the Clar$^+$Ion dose when both coagulants are being fed. At the Washington Suburban Sanitary Commission's Patuxent Water Filtration Plant, ferric chloride is used in the winter. The change from alum to ferric in winter was based on jar test and full-scale results. At the Mannheim Water Treatment Plant of the Regional Municipality of Waterloo, operators switch from alum to polyaluminum chloride as the coagulant in winter when water temperature is less than 50 °F (10 °C). Alum is used when water is warmer than 50 °F (10 °C). Formerly the change was made at 59 °F (15 °C) but practice changed due to the higher cost of PACl. During the summers of 1998 and 1999 Waterloo used sulfuric acid in addition to aluminum sulfate. In the summer of 2000, a 7 percent blend of acidified alum was used. Jar test studies performed with a ferric coagulant look promising at Waterloo. Thames Water at their Farmoor Water Works used to

change from alum in the summer to polyaluminum chloride during the winter months as this assisted clarifier performance. More recently, for reasons including changing from clarifiers to dissolved air flotation (DAF), superior process performance, cost of changing over from one coagulant to another and reduced sludge production, PACl has been used all year round. United Water's Haworth Plant in New Jersey switches over from alum to PACl typically in October when the water temperature drops to about 50 °F (10 °C) and switches back to alum in April when temperature rises back up to 50 °F (10 °C).

The Elizabethtown Water Company provided the strategy used for cold water treatment. It is:

- Coagulate at higher pH, following temperature-turbidity chart for correct pretreatment pH
- Use alum dose chart for specific temperature range for applicable turbidity
- Speed up flocculators at temperature below 45 °F (7 °C).
- Operate at the lowest settled water turbidity that does not result in filter breakthrough
- Critical not to overfeed alum
- Critical to cut to prescribed chart minimum alum dose and hold there until raw water color decreases below 20 units
- Vary permanganate with ORP meter
- Don't use coagulant aid
- Put carbon into service at first sign of a storm increasing raw water turbidity. Use accelerated carbon dosage that is predetermined by supervisors depending on predicted weather, time interval from prior storm to present incoming storm, and condition of roadways (salt on roads).
- Check ammonia and chloride concentration of the raw water on a daily basis to determine the concentration of these contaminants in the raw water

IRON/MANGANESE

Iron and manganese can be present in source water as a result of low dissolved oxygen concentrations in the hypolimnion of unmixed, deep, eutrophic reservoirs. As organic matter is used by microbes, dissolved oxygen can be depleted, resulting in conversion of precipitated iron and manganese to soluble forms. In nutrient-rich waters subject to algae blooms, dissolved oxygen can cycle up and down in day and night due to photosynthesis in the daytime and continuous respiration by algae, both

day and night. At night oxygen concentration may fall to very low levels, and remaining oxygen may be removed. If this occurs in treatment plants, the consequence can be bad tastes/odors, or resolubilization of iron or manganese in sludge at the bottom of clarifiers. If oxygen concentrations vary markedly, large variations in pH may occur and this also could cause problems with iron and manganese.

Techniques for control of iron and manganese are well understood in the water industry. Oxidation is necessary to remove dissolved iron or dissolved manganese, so more complete information on removal of these contaminants is presented in Chapter 8, which discusses pre-oxidation as a step in pretreatment. When prechlorination is used for manganese removal, soluble manganese in the form on Mn(II) is sorbed onto filter media coated with manganese dioxide. In the presence of free chlorine, the manganese dioxide promotes the oxidation of Mn(II) to manganese dioxide. If filter media replacement is carried out at a plant that has been removing manganese by this process, manganese removal is likely to be poor until the new media develop a coating of manganese dioxide. No new techniques were reported by utilities in this study. One idea related to control of iron and manganese is to increase the frequency of monitoring for the metals when problems with iron or manganese are expected or are occurring. Use of greensand media for manganese removal is discussed in Chapter 11, Filter Media Characteristics, Selection, and Replacement.

When iron or manganese are removed by filtration, backwash the filters sufficiently to remove the iron or manganese particulate matter stored in the filter bed during the run, as discharge of iron- or manganese-laden water into the distribution system is likely to result in customer complaints.

ALGAE, OTHER BIOLOGICAL ORGANISMS, AND AMORPHOUS MATTER

Organisms in water can present severe problems to operators of water filtration plants. Among many problems the most common are likely to be:

- Taste and Odor problems due to algae or actinomycetes in the raw water.
- Taste and Odor problems due biological decomposition in low dissolved oxygen concentrations in raw water or treatment plant tanks.
- Filter clogging algae.
- Filter clogging invertebrates.
- Aesthetic problems arising from filter penetrating invertebrate larvae / eggs, causing animal growth in distribution systems.

- Major threats to public health from disinfection resistant organisms such as *Giardia* cysts and *Cryptosporidium* oocysts passing through poorly operated treatment plants.

A recommended source of information on the topic is AWWA Manual M7, *Problem Organisms in Water: Identification and Treatment, 2nd Ed.* (AWWA, 1995). This manual includes chapters on various kinds of bacteria, nematodes, Chironomid larvae, crustacea, rotifers, algae, protozoa, and some other organisms. Numerous color photomicrographs of organisms are presented in an appendix, and a troubleshooting guide for problem microorganisms is provided. AWWA Manual M7 is recommended as a helpful source of information on dealing with problem organisms in water.

Algae can cause severe problems for water utilities. Some types cause tastes and odors. Blooms of those algae and diatoms can result in extensive customer complaints. Other kinds of algae and diatoms can bloom and be present in such abundance that filters become clogged. Removal of algae by sedimentation is not particularly effective because these organisms prefer to float rather than sink. If algae are still living and are exposed to sunlight in a sedimentation basin, they can produce oxygen. The oxygen bubbles that form tend to float particles to which they are attached, compounding the difficulty of removing algae by sedimentation.

Filter clogging can be caused by debris in water, such as dead cells, leaf parts, amorphous matter, etc., and by a variety of algal types. Diatoms are an important group of filter-clogging algae. The rigid shell (furstule) surrounding the diatom cell causes diatoms to clog filters (Palmer 1959, 1962, 1980). These rigid inorganic shells contain silica and do not decompose. (The growth and death of enormous numbers of diatoms millions of years ago has resulted in deposits of diatomaceous earth, an inorganic filtering material, at some places in the United States. One should never expect diatom shells to decompose within a filter bed.) Diatoms may be killed by oxidants such as chlorine or ozone, or by algaecides such as copper sulfate, but the inert shells still would have the ability to clog the filter. Many dinoflagellates also have silica incorporated into their cell walls e.g. *Ceratium spp.* and have the potential to cause similar problems. Palmer listed the following genera as those of greatest concern: *Asterionella*, *Fragilaria*, *Tabellaria*, and *Synedra*. *Navicula*, *Cyclotella*, *Diatoma* and *Cymbella* may occasionally be troublesome.

Cellulose cell walls are unlikely to be degraded in conventional water treatment, so killing algae may not be helpful and may have the disadvantage of releasing organic cell contents. Dead algal cells/colonies may collapse and block or surface blind sand media. At Thames Water this has been

observed in the case of *Volvox aureus*. The colony collapses, the cellulose walls remain as a "bag" which then blocks the interstices in the media bed. This may be more of a problem with water that has been treated with ozone or other oxidants. Some algae can survive oxidation but are highly stressed as a result. Under these conditions they may produce palmelloid stages in which cells group in mucilage and form sticky aggregates.

Filter-clogging algae have caused problems at water treatment plants for decades. Effects of algae on plant operation were the subject of a joint discussion at the 1964 AWWA Annual Conference (Poston and Gamet 1964). In Lake Michigan, *Asterionella*, *Fragilaria*, *Melosira*, *Synedra*, and *Tabellaria* were present in the greatest concentrations. *Tabellaria* was thought to cause more short filter runs than all other species combined. *Cladophora*, a filamentous algae, was reported to have caused problems with clogging of screens at treatment plants. At Detroit, short filter runs were caused by *Asterionella* (Poston and Gamet 1964).

Some organisms can give plant operators a double dose of trouble by causing both tastes and odors and by clogging filters. Included in this group are *Anabaena*, *Anacystis* (referred to in some texts as *Microcystis*), *Asterionella*, *Dinobryon*, *Synedra*, and *Tabelleria*, according to the color plates of algae important to water treatment presented in Part 10000, BIOLOGICAL EXAMINATION, in *Standard Methods* (APHA, AWWA, and WEF 1995).

Some filamentous algae such as *Melosira, Tribonema* and *Aphanizomenon* can cause two operational problems. The first is that they clog filters rapidly and so cause problems with high frequency of backwashes and potentially limit the volume of water a plant is capable of producing. The second is they can necessitate serious changes to backwash operation. These filaments, or clumps of filaments clog the filter on the surface of the bed, rather than penetrating into the body of the media. If this happens head loss development is not the usual linear trend but appears as a curve which gets steeper as the filter run progresses (similar to an exponential increase). As a result it can be impossible to drain water down through the filters in the normal way before backwashing. Various methods have been devised in Thames Water to deal with this problem including: dumping the above bed water over the backwash water outlet weir before starting the backwash, dumping the water through purpose-designed penstocks in the backwash weir wall, or breaking up the mat by application of air scour, or a short burst of backwash water, and then draining to waste through the bed to reach the water level at which can be initiated. All of these techniques cause the backwash to require skillful operator intervention, and prolong the period the filter is not producing water.

Palmer (1980) listed 45 of the more important filter clogging algae. His list included blue-green algae (cyanobacteria); such as *Anabaena*, *Phormidium*, and *Oscillatoria*; and green and yellow-green algae; such as *Chlorella*, *Closterium*, *Mougeotia*, and *Tribonema*. The filamentous diatom, *Melosira* can cause great difficulty with filter clogging. Only small amounts are needed to surface bind a filter, perhaps less than 5 or 10 μg/L as chlorophyll-*a*. Certain combinations of algal taxa can surface bind filters, perhaps synergistically. In such a scenario one specie would accumulate on the media surface but only increase head loss marginally, and then another specie would fill the gaps and then cause surface blinding. Anecdotal references to this in the U.K. usually involve an open structured algal colony such as *Asterionella* in combination with a more compact cell (e.g. *Stephanodiscus*).

Hatches of small animals, if they pass through clarification, can also blind filters. One example of this is the microcrustacean, *Daphnia*, referred to as the water flea. Another crustacean capable of hatching and causing filter-clogging problems is *Cyclops*. At one Thames Water works many years ago an infestation of Chironomid (fly) larvae took place. These non-biting midges entered the plant via the river supply and via adult midges laying eggs on the surfaces of flat-bottomed clarifiers and rapid gravity filters. Rough concrete surfaces and filamentous algae growth provided shelters for the growing larvae which later emerged as adults to lay eggs again. The whole process only took two to three weeks. In summer the small larvae often were present in disconcerting numbers in the final, treated water. They passed through the dual media by burrowing. So many were present in the filter that an unsightly problem - "wriggly worms in tap water" – occurred if only a small proportion passed through the filter. This problem was reduced markedly by spraying the exposed water surfaces with water, 24 hours a day. The clarifier basins and filters are now covered and sealed against adult midges and no problems have resulted since. Inspection hatches were provided on these covers so filter and clarifier inspection could still be carried out. Chironomid larvae are discussed in AWWA Manual M7 (AWWA 1995).

In an era when rapid sand filters (typically with about 2 ft or 0.6 m of 0.5 mm sand) were used more commonly than in the 21st century, Palmer (1980) stated that most of the microscopic organisms found in flocculated, settled water were removed in the top 0.5 inch (1.3 cm) of sand. Palmer observed that some organisms penetrated deeper, while others disintegrated rapidly as a result of contacting filter media. Use of dual media filters or of filters with a coarse monomedium bed has become much more common since Palmer published his work, so deeper penetration of filter beds by microscopic organisms could occur with filters having media with an effective size of 1.0 mm or larger versus the 0.5 mm sand that Palmer may have encountered in earlier decades.

The motility of organisms influences their behavior in filters. Some of the pigmented flagellated algae such as *Dinobryon, Synura, and Mallomonas* may be able to penetrate deeper into filters than diatoms can penetrate if chlorine or some other oxidant does not kill them. These algae possess flagella that enable them to move within the granular media bed. Some microscopic zooplankton, such as *Daphnia*, and a group of invertebrates known as rotifers also have the ability to move themselves through water by moving their appendages. These organisms commonly graze on algae and can cause problems in filters unless they are killed in pretreatment. Bernhardt (1984, 1989) noted that some rotifers could cause filter clogging problems but stated that predisinfection would eliminate the possibility that the rotifers could penetrate all the way through the filter.

Algae growing in filters can become a real problem - particularly filamentous forms such as *Cladophora* (and perhaps *Enteromorpha*). *Cladophora* in particular attaches to surfaces and may grow prolifically. *Cladophora* can grow on launders and weirs and it seems responsible for some media loss. On nozzled floors even worse effects can take place, as nozzles have become totally blocked by entwined *Cladophora* that was transported down to the nozzles during back-washing.

Algae removal mechanisms are somewhat related to the size of the algal cells or colonies. The flocculation of large colonies such as those of *Asterionella* or *Fragillaria crotenensis* does not follow the mechanism of flocculation by charge neutralization (Bernhardt 1984, 1989). As a result of their large size these algae can be removed by filtration, even without flocculation. Metal coagulant used in a relatively low dosage can result in removal of a very high proportion of these algae. Bernhardt and Clasen (1994) studied the coagulation of the small blue-green alga *Synechocystis minuscula*, which has a simple geometric shape and a diameter of about 6 μm. They reported that the flocculation of these algal cells did follow the principle of adsorption coagulation with charge neutralization when cationic polymers or alum ($Al_2(SO_4)_3 \cdot 18H_2O$) were used. When the electronegative surface charges of the algal cells were brought to a near-neutral condition, the algal cells formed agglomerates. Bernhardt and Clasen noted that pH adjustment to pH 6 was needed to flocculate the small algal cells when alum was used for charge neutralization. Sweep flocculation became dominant as pH approached 7. The authors felt that algal cells needed to be enclosed in hydroxide flocs for removal by sweep flocculation.

Edzwald (1993) described research on flocculation of *Cyclotella*. This alga had a mean size of 6.1 μm and an electronegative surface charge. Alum dosages did not need to be large enough to completely neutralize the surface charge, for effective removal of algae-sized particles to be attained. In fact, substantial removal of algal-sized particles was achieved at an alum dosage that was one-fifth of the

dosage reported to achieve charge neutralization, when pH was 6.5 and *Cyclotella* was present at a concentration of 5 x 10^4 cells/mL.

Removal of algae by different unit processes in the University of Iowa's water treatment plant was studied by Speedy, Fisher, and McDonald (1969). They reported that algae removal by alum coagulation, flocculation, and sedimentation averaged 37 percent. Chlorination did not improve removal. Lime softening in solids contact units generally removed 80 percent to 90 percent or more. The more effective performance of lime softening was attributed to the heavy weight of the lime softening floc. They noted that most of the algae removal took place in the top 6 inches (15 cm) in a rapid sand filter, whereas the entire depth of an anthracite filter bed removed algae.

Direct filtration has been used to treat low-turbidity source waters, but the presence of algae can be a limiting factor for the application of this process. Hutchison and Foley (1974) reported that diatoms caused short filter run times at direct filtration plants treating Lake Huron water in Ontario. After pilot testing, 1.5 mm e.s. coal was placed in a full-scale dual media filter at the Grand Bend Plant. Runs from this filter were longer than runs from a dual media filter with 0.92 mm e.s. coal by about 50 percent to 100 percent. During the period of this comparison, algae counts (90 percent diatoms) exceeded 3000 asu/mL several times. Hutchison (1976) found that when algae levels were in the 1000 to 8000 asu/mL range, a filter with 1.5 to 1.6 mm e.s. coal could produce twice as much water as a filter with 1.0 mm e.s. coal. [Note: Palmer (1962) defined the areal standard unit as "An area of 400 square microns, used as a unit in designating the amount of plankton in water."]

Monscvitz et al. (1978) reported that an in-line filtration plant (the Alfred Merritt Smith Water Treatment Facility, or AMSWTF) employing coagulation and filtration was not effective for removing plankton from Lake Mead source water. Pilot plant testing showed that addition of a flocculation step in the treatment train improved plankton removal efficiencies by filtration to greater than 90 percent. When the AMSWTF was expanded from 200 mgd to 400 mgd, flocculation was included. The plant has been expanded again, to 600 mgd, and flocculation continues to be used. The plant in its present configuration is capable of routinely producing filtered water having a particle count of less than 20 particles per mL, in the size range of 2.5 μm and larger.

The AWWA Filtration Committee (Committee Report 1980) found that, "In general, waters with less than 40 units of color, turbidity consistently below five units, iron and manganese concentrations of less than 0.3 mg/L and 0.05 mg/L, respectively, and algae counts of up to 2000 ASU/mL appear to be perfect candidates for direct filtration." This report was based on direct filtration plants operating in the

1970's and does not reflect the capability of deep bed filters employing coarse filtering material, such as the 6-foot (1.8 m) deep, 1.5 mm e.s. anthracite filter beds used in plants such as those at Los Angeles and Modesto in California. Based on the findings of Hutchison and Foley (1974) and Hutchison (1976), deep bed, coarse monomedium filters should have a greater capability to cope with algae and diatom blooms than traditional dual media beds having 1.0 mm e.s. coal in the top layer of filtering material. Further assistance in selecting the correct process to treat various combinations of turbidity and algae (measured as chlorophyll *a* concentration) was provided in Chapter 6 of the book edited by McEwen (1998).

Although use of dissolved air flotation for clarification is not widespread in North America, this process has been used more commonly during the last two to three decades in Europe and the U.K. DAF is an excellent process for algae removal, because algae tend to float, and flotation for removal of flocculated particulate matter works to remove algae from water in the same direction in which they naturally tend to move. Edzwald and Walsh (1992) studied algae removal by DAF and gravity sedimentation. Using lake water spiked with 10,000 algae cells per mL, the total of algae-sized particles per mL after sedimentation ranged from 17,000 to 24,000 in four treatment conditions. After DAF clarification the total of algae-sized particles per mL ranged from 3,000 to 9,000 in three treatment conditions and was 24,000 in the fourth, ferric chloride at 43 °F (6 °C). In three of four conditions tested, DAF performed much better than gravity sedimentation.

Zabel (1985) compared algae removal in a DAF clarifier operated at an overflow rate of 5 gpm/sf (12m/hr) and a floc-blanket sedimentation plant operated at an overflow rate of 0.4 gpm/sf (1 m/h). Removal of *Aphanizomenon*, *Microcystis* (referred to in some texts as *Anacystis*), and *Chlorella* ranged from 90 percent to 98 percent by DAF and from 76 percent to 87 percent for sedimentation. Removal of *Stephanodiscus* was 83 percent for DAF and 59 percent for sedimentation. Zabel commented that at times the algae counts in water treated by DAF were lower than the algae counts in water treated by sedimentation AND filtration. He also noted that algae removal can be improved by lowering pH.

The effect of pH on flocculation and filtration of uncoagulated algal suspensions has been evaluated (Foess and Borchardt 1969). In jar tests carried out at pH 10 and lower, *Chlorella* did not flocculate, but above pH 10.5 the algal suspensions flocculated irreversibly. This suggests that high pH lime softening might be effective for removal of *Chlorella*. Foess and Borchardt presented data showing that the electrophoretic mobility (a function of the surface electrical charge) of a suspension of *Chlorella* in tap water decreased towards zero as pH decreased. In the absence of coagulant chemical, filtration of

suspensions of *Chlorella* and *Scenedesmus* was more effective at very low pH (less than pH 3.0) and less effective as pH increased. Filtration of *Scenedesmus* at pH 6.1 resulted in removals ranging from 60 to 80%. Lowering pH would decrease the surface electrical charge on algae cells, thus causing them to be more readily flocculated and removed by filtration, so the Foess and Borchardt work tends to support Zabel's comment that algae removal can be improved by lowering pH.

During pilot plant testing for treatment of North Saluda Reservoir water at Greenville, S.C., the floated floc exuded a fishy smell after it had been removed from the DAF clarifier, even though no fishy odor problems were reported by customers of the Greenville Water System. This was interpreted as resulting from removal of very dilute numbers of algae from the water into the floated floc, where sufficient numbers had been concentrated together to produce a detectable odor.

Organic compounds are released by algae during their growth, and these compounds, like other kinds of natural organic matter, can interfere with coagulation. Bernhardt reported that iron salts at concentrations of 4-10 mg/L, along with a cationic polymer, can be used successfully to treat algae-laden waters. Bernhardt (1985) discussed how organic matter released during algal growth interferes with flocculation and stated that concentrations of this organic matter as low as 0.1 mg/L (expressed as DOC) can seriously interfere with coagulation. This interference may help explain why algae-laden waters can be difficult to treat in direct filtration and conventional treatment.

When water is treated by direct filtration, amorphous matter (detritus) may cause treatment problems as serious as those caused by planktonic algae. Syrotynski (1971) evaluated filter performance at a diatomaceous earth filtration plant and concluded that amorphous matter is a source water constituent that needs to be considered because of its capacity to flocculate and plug those filters. He recommended a limit of 200 areal standard units (ASUs)/mL for filtered effluent. Amorphous matter would have a greater influence on performance of direct filtration, where all particulate matter is removed in the filter bed, than it would have on filtration when a clarification process such as gravity sedimentation or dissolved air flotation is employed in the process train.

Amorphous matter may cause filtration problems when the source water is a reservoir or lake subject to seasonal turnover events. One source of amorphous matter is organic debris from dead, disintegrated algae cells that sink in reservoirs. During summer stratification, the amorphous matter can settle to a depth in the lake or reservoir where the water density and the amorphous matter density are equal. Leaves of deciduous trees that fall or are blown into lakes and reservoirs are another source of amorphous matter. After the leaves sink to the bottom, they are subject to rotting and disintegration.

Combined concentrations of algae and amorphous matter have approached 3500 ASU/mL on occasion in surface samples in some reservoirs (Hoehn 2000).

The need to control algae in surface water sources, or to treat water to remove algae, is experienced by many utilities, especially those that treat lakes and reservoirs. Control of nutrient input to the catchment (watershed) has been done in Switzerland. Controlling nutrient releases is practical only in locations where the water would naturally be oligotrophic, i.e. where remediation is possible. Nutrient control costs a lot of money and requires phosphorus and nitrogen removal at sewage treatment plants, use of low-phosphate detergents, etc. In many lowland (downstream) situations the source water is naturally eutrophic so remediation is impractical. Where the human population is dense, such as in southeastern England, the nitrogen and phosphorus concentrations in surface waters are 100 to 1000 times more than required for maximal algal growth, so remediation is probably impossible.

Staff at twenty-seven plants reported on strategies they use for algae control. Avoidance of algae and diatom problems is a popular approach among utilities. At five plants using reservoir or lake water, depth of withdrawal of water is varied to obtain better quality water. Lakes or reservoirs serving as water sources for six plants are treated with copper sulfate ($CuSO_4 \cdot 5H_20$) or some other algicide to control algae, and one utility has an extensive watershed management program to prevent algae-related problems. Chemical dosage is changed at several treatment plants to attain more effective treatment, and at one plant diurnal changes of alum dosages are used. At this plant, pH increases begin late in the day and then pH decreases during the night, particularly when water temperature is in the range of 55 °F to 65 °F (13 °C to 18 °C). Oxidation by prechlorination or ozone or potassium permanganate or chlorine dioxide is employed at a number of plants. Ramadan (2000) described experience in Napa, California with $CuSO_4 \cdot 5H_2O$ and $KMnO_4$ for dealing with algal taste and odor problems, along with the odors attributed to different algae and their susceptibility to control with copper sulfate.

Thames Water Utility formerly used copper sulfate applied in massive amounts from a small boat directly into off-stream reservoirs used to store water extracted from the River Thames and River Lee. Large doses were needed because the source water had a relatively high pH and high carbonate hardness, causing most of the copper sulfate to end up as the insoluble basic carbonate on the reservoir floor. Use of copper sulfate for algae control gave some benefits in terms of taste/odor in the water and treatment costs, but TWU stopped dosing with copper for several reasons:

- The copper killed most of the cyanobacteria (blue-green algae), which then floated to the surface and rotted - releasing the entire cell contents (including toxins) and making the taste/odor problem much worse. The rotten algae also produced gaseous products, which resulted in complaints from people living near the reservoirs that were treated.
  - The copper also killed the zooplankton - so use of copper removed the grazing pressure on the algae.
  - The release of cell contents released micronutrients (amino acids, trace elements etc.) which together with the removal of grazing pressure meant that the next algal bloom occurred quickly and sometimes biomass was greater.
  - Treatment was expensive as most of the copper was converted to basic carbonate.
  - Manpower costs for treatment also were high.
  - Dust from the copper sulfate is both toxic and corrosive.
  - Dosing by boat was not very accurate anyway - very 'hit and miss'.
  - Better methods of controlling algae were found for the deeper reservoirs (via light limitation) and more modern biomanipulation.
  - Finally use of copper is not seen to be environmentally friendly these days.

For many years the main water source for City Utilities at Springfield, Missouri was a lake that experienced blue-green algae blooms, specifically in the form of *Oscillatoria* and *Raphidiopsis.* The algae-related problems were mainly related to taste and odor, typically starting in July and lasting until September. City Utilities has used different intake levels and increased dosages of potassium permanganate, PAC, and chlorine to combat the taste and odor problems during algal-bloom episodes. City Utilities conducts an extensive program of watershed monitoring and protection. This is viewed as a long-range tool for the utility to use to maintain or improve source water quality, but it does not directly effect day-to-day water treatment decision-making. Successes of the program include reduced phosphorus concentrations in the source waters. The presence of taste and odor compounds does directly affect operational decisions, as taste and odor events remain spontaneous and immune to prediction. These events have occurred both in the presence and in the absence of elevated algal populations.

The Cincinnati Water Works has employed potassium permanganate for pre-oxidation prior to rapid sand filtration if higher than normal algae concentrations exist. Filter run hours decrease, however, as a direct result of the addition of the manganese compounds being trapped on the filter media.

At the Philadelphia Water Department's Belmont Plant, the goal of the algae process control effort is to avoid impact of the algae on settling of floc and to avoid any filter effluent deterioration due to the algae. At this plant, algae blooms have been found to influence the pH of the Schuylkill River. When raw water pH rises, this is a good indication of presence of large numbers of algae, principally *Cyclotella*. If the river pH increases significantly over previous days, a permanganate demand test is performed on the raw water. Potassium permanganate dose is determined using Table 4.7, which allows for excess permanganate ion (MnO_4^-) in the raw water basin for high-count algae blooms.

In addition to potassium permanganate treatment, cationic polymer at a dosage of 0.5 to 1.0 mg/L is often applied at the rapid mix to help settle *Cyclotella* laden floc. This approach was used for a *Cyclotella* bloom in 1998 when pH in the river increased from 7.7 before, to a peak of 9.4 during, and down to 7.5 after the bloom. Potassium permanganate dose was fed to the raw water basin influent according to Table 4.7. Algae analyses on the first day showed *Cyclotella* counts of 86,500/mL and 23,800/mL in the river and raw water basin effluent, respectively. The raw water basin effluent count rose to 39,200/mL in the afternoon. On day 2, *Cyclotella* counts of 166,300/mL and 33,500/mL were found in the morning river and raw water basin effluent samples. The afternoon raw water basin effluent sample dropped to 17,700/mL. Ferric chloride dose was raised a number of times following jar tests. A dose of 0.5 mg/L of cationic polymer was added at the rapid mix and was effective in the jar tests. *Cyclotella* counts in the clarifier effluent were 2300/mL and <1000/mL on days 1 and 2, respectively. The clarifier effluent rose 0.1 ntu and the filter effluent rose only 0.01 ntu, indicating a successful treatment strategy.

Table 4.7

Philadelphia Water Department Belmont Plant Permanganate Dosing Table

River pH	$KMnO_4$ Dose
< 7.9	MnO_4 Demand
7.9 – 8.0	1.5 (MnO_4 Demand)
8.0 – 8.5	2.0 (MnO_4 Demand)
> 8.5	2.5 (MnO_4 Demand)

Thames Water Utilities and predecessor organizations have had decades of experience with problems caused by algae. Tastes and odors have been dealt with by the use of ozone and GAC adsorbers, which were principally installed to remove pesticides to European Standard levels of < 0.1 µg/L per pesticide, <0.5 µg/L total pesticides. Two sites had DAF installed and this has been found to be a much better means of clarifying low turbidity reservoir water subject to algal blooms. Ozone has been found to be essential to achieve effective flotation during times at one works when a shallow reservoir is the source of significant algal blooms. In London where several reservoirs are available, regular reservoir sampling has enabled a knowledge to be gained of the behavior of algal blooms in reservoirs and a strategy developed to manage which water sources are in use at any time. Some reservoirs are sufficiently deep that algal population sizes can be controlled by inducing a vertical circulation into the water body, taking small algae out of the photic zone and reducing photosynthetic activity (Toms 1987). This is achieved either by bubbling air through diffusers or pumping the water into the reservoir through angled inlet jets (Bayley et al. 2000, Toms 1987).

Another possible method involves use of iron(III) salts - notably the ferric sulfate and ferric chloride. These act by precipitating phosphorus and making it unavailable for algal growth. Use of iron salts to control algae in reservoirs is expensive as large quantities of iron salts are required and this is not the most environmentally friendly option either, but possible if no other option is available.

An unusual approach to control of algae in Derbyshire, U.K. was reported (Everall and Lees 1996) in which rotting barley straw controlled algal growth. The addition of rotting barley straw at a concentration of about 50 g/m^3 (50 mg/L) reduced dominance of cyanobacteria (blue-green algae) and brought about a general reduction in phytoplankton productivity. Prior to the application of the barley straw, the reservoir had experienced annual blue-green algae blooms.

If one has a eutrophic reservoir without the means to control algal blooms then other problems may manifest themselves. Some examples follow:

All algae require a carbon source. A very few species can live heterotrophically for a while, but the vast majority are obligate autotrophs and live by converting carbon dioxide to organic carbon through photosynthesis. As an algal community proliferates, the concentration of carbon dioxide will generally reduce leading to an increase in pH. Cyanobacteria in particular can go a bit further in waters containing bicarbonates, as they have the ability to remove carbon dioxide from the bicarbonate ion leaving the insoluble carbonate behind. This is very important as the pH can rise suddenly to over 10. Sometimes ponds or lakes turn milky greenish-white due to this phenomenon. One of Thames Water

Utilities' reservoirs (only used as a standing reserve) used to exhibit pH values in the summer months of 9.5 to greater than 10, due to blooms of cyanobacteria. This kind of situation can cause serious problems for coagulation control (high pH and removal of bicarbonate).

Recently concern has increased over cyanobacterial toxins. The hepatotoxins (e.g. microcystin LR, a cyclic heptapeptide, from *Microcystis spp.*) and neurotoxins (e.g. anatoxin A from *Anabaena spp.*) are all endotoxins - therefore exposure is only likely if algal cells are lysed or if the cells are ingested whole. The other toxins are via direct (usually skin) contact with the algae. The highest risk comes from ingesting the cells. Use of conventional treatment, slow sand or direct or contact filtration should prevent this problem as most - if not all - poisonings have occurred through ingestion or contact with raw or unfiltered water. Many treatments seem effective at removal - a high pH (above 7) may biodegradation or chemical removal. Ozone and other oxidants are effective, as is activated carbon (potentially adsorption and biodegradation).

Thames Water Utilities has had a number of problems with mucopolysaccharides from cyanobacteria. Some of these compounds are listed as toxic but the biggest visible problem occurs in alkaline waters. The mucopolysaccharides are secreted by the cyanobacteria (the genus *Microcystis* is the worst offender in the U.K.) and form a jelly-like mass surrounding a colony. These mucopolysaccharides dissolve in alkaline waters. In TWU's source waters with a pH above 7.5 these compounds pass through treatment and are unnoticed unless one adds some acid, such as when making tea. Under acidic conditions the mucopolysaccharides precipitate as a light highly voluminous floc causing cloudy tea. Ozone at a relatively high dose, GAC, and reverse osmosis can be effective in treating these compounds.

Zooplankton can cause problems with both clarification and filtration. At TWU zooplankton caused a serious problem with the return of settled wash-water back to the head of works. The zooplankton didn't settle well and were recycled en-masse in a really good example of a concentration loop.

Fish can get into basins in treatment plants, depending on the size of raw water screens. Generally fish are not much of a problem. Dead fish might impart a bad taste to the water and they can serve as nuclei for large mud-balls in rapid gravity filters. They also do not serve as a good advertisement for what a well operated potable water treatment plant should look like, so should be regularly removed using a fishing net.

On the basis of treatment plant practices and literature reported upon previously in this section of the manual, when preventive measures such as treatment of reservoirs or changing intake depths can not be used to avoid treatment of source water containing large numbers of algae or diatoms, lowering the pH in pretreatment may be an effective approach. This should be tried in jar tests before changes are made in the plant. Algae do not settle well, so visual observation of floc and the extent to which the algae can be flocculated may be a practical means of assessing pretreatment efficacy in jar tests.

Killing algae by pre-oxidation may appear to solve some treatment problems, but if the organic materials inside the cells are released upon death an disintegration of the cells, problems of taste and odor may result. Extra care is needed for treatment of algae, which can cause operational problems such as short filter runs and aesthetic problems such as unacceptable tastes and odors.

MULTIPLE SOURCE WATER QUALITY CHANGES

Some water utilities encounter raw water with variable turbidity and variable TOC concentration. Coagulation can be much more difficult if two significant raw water quality characteristics change. To cope with situations like this, plant operators who have encountered variation of turbidity and TOC concentration may choose to prepare a matrix chart for coagulant dosage. An example, with upper case letters indicating alum dosages entered in the blank boxes, is shown in the Table 4.8.

The challenge of removing both particles and TOC by coagulation and filtration will move to a new and higher level when the EPA Disinfectants and Disinfection Byproducts Rule takes effect on January 1, 2002. At some water filtration plants, requirements for removal of a percentage of TOC will be have to be met, along with the provisions of the Interim Enhanced Surface Water Treatment Rule.

For some waters, TOC removal can be increased by using a higher concentration of metal coagulant (alum or iron coagulant) and by coagulating at a lower pH, such as 5.5 or 6.0. Vrijenhoek et al. (1998) presented information on a pilot study that demonstrated that enhanced coagulation with higher alum doses and a pH of 5.5 could attain both particle removal and TOC removal. The chemistry of the water being treated does have an effect on the results attained by enhanced coagulation. Colorado River water is more highly mineralized than State Project Water in Vrijenhoek's study. The total particle count (2 μm and larger) was higher in filtered Colorado River water than in filtered State Project Water. Filtered water turbidity for both source waters was less than 0.10 ntu, and the TOC percentage removals that will be required in the future could be met. Effective alum dosages ranged from 20 mg/L to 60 mg/L, depending on the coagulation pH.

Table 4.8

Example of matrix table for coagulant dosages over a wide range of water quality

	Low TOC	Medium TOC	High TOC
Low turbidity	Alum, A mg/L	Alum, B mg/L	Alum, C mg/L
Medium turbidity	Alum, D mg/L	Alum, E mg/L	Alum, F mg/L
High turbidity	Alum, G mg/L	Alum, H mg/L	Alum, I mg/L

The work of Vrijenhoek et al. shows that water treatment can be adjusted to remove both particulate matter (turbidity and particles) and TOC, but high coagulant dosages may be needed. The chemistry of the water being treated will influence the pretreatment approach (see Chapter 8). Use of higher dosages of metal coagulant will result in production of greater amounts of sludge, which could influence the time interval for cleaning sedimentation basins manually. Some adjustment of the frequency of operation of sludge removal equipment might be needed if coagulant dosages are increased substantially. A discussion of clarification is presented in Chapter 9.

RAPID FLOW RATE CHANGES

The potential for filtered water quality to be deteriorated by rapid increases in filtration rate was demonstrated by Cleasby et al. (1963) nearly four decades ago. The water utilities participating in this AWWARF study have grasped the importance of this concept and operate their plants accordingly.

The most widely-used approach to avoiding water quality changes resulting from rapid flow rate changes is to avoid rapid changes. In some utilities this is done by coordinating the efforts of the water treatment staff with those responsible for water distribution. Management of raw water flow to the treatment plant, and management of finished water pumping and storage are important strategies. If filtration rates must be changed, adjustment of chemical dosages to control turbidity breakthrough is a commonly used technique. Many utilities reported using gradual rate changes.

An unexpected finding of research at Thames Water (see Chapter 13 case study, Improving Filtered Water Turbidity by Continuous Dosing of Supplementary Coagulant at Thames Water Utilities, and Bayely et al. 2001) was that the supplementary coagulant dose resulted in very little change in filtrate turbidity and particle counts, even when subjected to large step changes in flow rate.

AIR BINDING IN FILTERS

Air binding sometimes happens when filters are used to treat water that is near saturation, or perhaps supersaturated with atmospheric gases. Air binding problems may be encountered more often when the source water is cold, as the solubility of oxygen is greater in cold water than in warm water. If the head loss (pressure drop) within the filter bed results in pressure in the bed that is lower than atmospheric pressure, the dissolved gases may come out of solution and form air bubbles in the bed. Figure 4.10 (Sanks 1978) shows how development of head loss very near the top of a filter bed can eventually cause pressure within the filter bed to become less than 1 atmosphere, which leads to air binding. Water can not flow through the area occupied by a bubble, so formation of bubbles in the filter bed reduces the cross-sectional area available for filtration. This causes a more rapid increase in the rate of head loss gain and can lead to turbidity breakthrough if filter operation continues.

Air binding can be caused by operating a filter in a manner that causes nearly all of the head loss to build up in the top few inches of the media. When the head loss at a location in the filter bed is greater than the distance from that location to the water surface over the media, the pressure at that location is less than 1 atmosphere. For example if the depth of water over the media is 3 feet (0.9 m), and the head loss is 5 feet (1.6 m) at a depth of 1 foot (0.3 m) down into the bed, at that location the pressure is less than 1 atmosphere. Under standard conditions, 1 atmosphere of air pressure equals 34 feet (11.1 m) of water. The pressure at the location in this example is 1 atmosphere (34 feet or 11.1 m) + 4 feet (1.3 m) of water from the water surface to the point 1 foot (0.3 m) down in the bed – 5 feet (1.6 m) of water (head loss). Thus the pressure at the point in question in this example is 33 feet (10.8 m) of water, 1 foot (0.3 m) less than 1 atmosphere.

Algae can cause or contribute to air binding problems. Algae carry out photosynthesis during the daylight hours. High dissolved oxygen concentration can occur during the day when the water can become supersaturated with oxygen and this, in theory, could potentially cause gas binding of filtration media. Air binding may be more of a problem with contact filtration, particularly if filters are uncovered and algae are actively growing in the top water as well. If head loss is high in the upper portion of the filter bed this increases the likelihood of removing oxygen gas as bubbles in the media.

The typical approach to air binding is to limit head loss in filters during times when air binding might be a problem. A design solution for air binding is to provide deep filter boxes that allow for 6 feet (1.8 m) of water, or more, over the filter media, depending on the anticipated terminal head loss. An alternative approach is to design the outlet weir so the filtered water level is higher than the top level of

the filter media. This limits the total available head loss to the distance between the elevation of the water flowing into the filter and the elevation of the water as it flows over the outlet weir.

When the downward flow of water ceases at the end of a filter run, entrained air bubbles no longer have the velocity of water in the bed to prevent their rising up and out of the bed. To prevent media loss at termination of filtration, operators can shut off the influent water to the filter and allow the level of water in the filter box to drop down below the level of the washwater trough. Then any bubbling action that might occur could not wash media out of the bed. Some air bubbles may be not released after flow through the filter ends, and if backwashing is begun at the usual rate of flow, the upward water flow may cause a violent release of the remaining air. Again, if the water level in the filter box is below the washwater trough, media loss will not occur. Even so, starting the backwash by using a very gentle upward flow of water can help to minimize the disruption that might occur in the filter bed because of a violent release of lots of air. Caution is the watchword when dealing with air-bound filters.

At the Pine Valley Water Treatment Plant operated by Colorado Springs Utilities when air binding occurs the filter is taken off-line and remains out of operation for 30 minutes before it is backwashed. The backwash is carried out manually without surface wash. Backwash rate is increased very slowly. The objective of this procedure is to release the air from the filter bed in a way that does not cause media to be washed out and lost.

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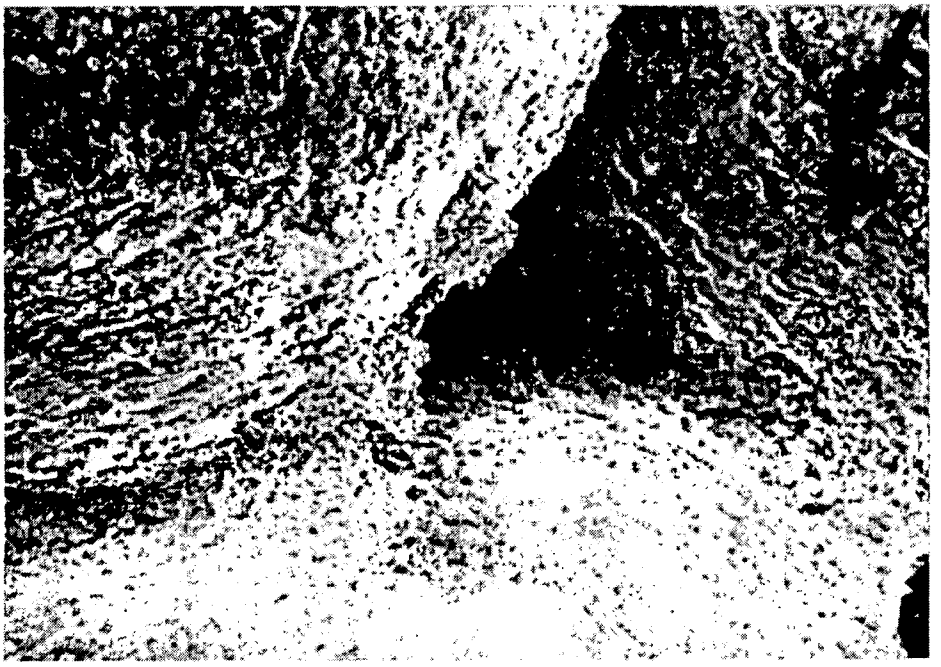

Figure 4.1 Scanning electron micrograph of sand grains with attached particles (*Source:* Robinson, Saatci, and Baumann; Iowa State University Engineering Research Institute Reprint 80106, 1980; reprinted from Cleasby, J.L. and G.S. Logsdon 1999. Chapter 8, Granular Bed and Precoat Filtration. In *Water Quality & Treatment, 5th Ed.* Edited by R.D. Letterman. New York: McGraw-Hill.)

Figure 4.2 Scanning electron micrograph of sand grains (*Source:* Thames Water Utilities 2000)

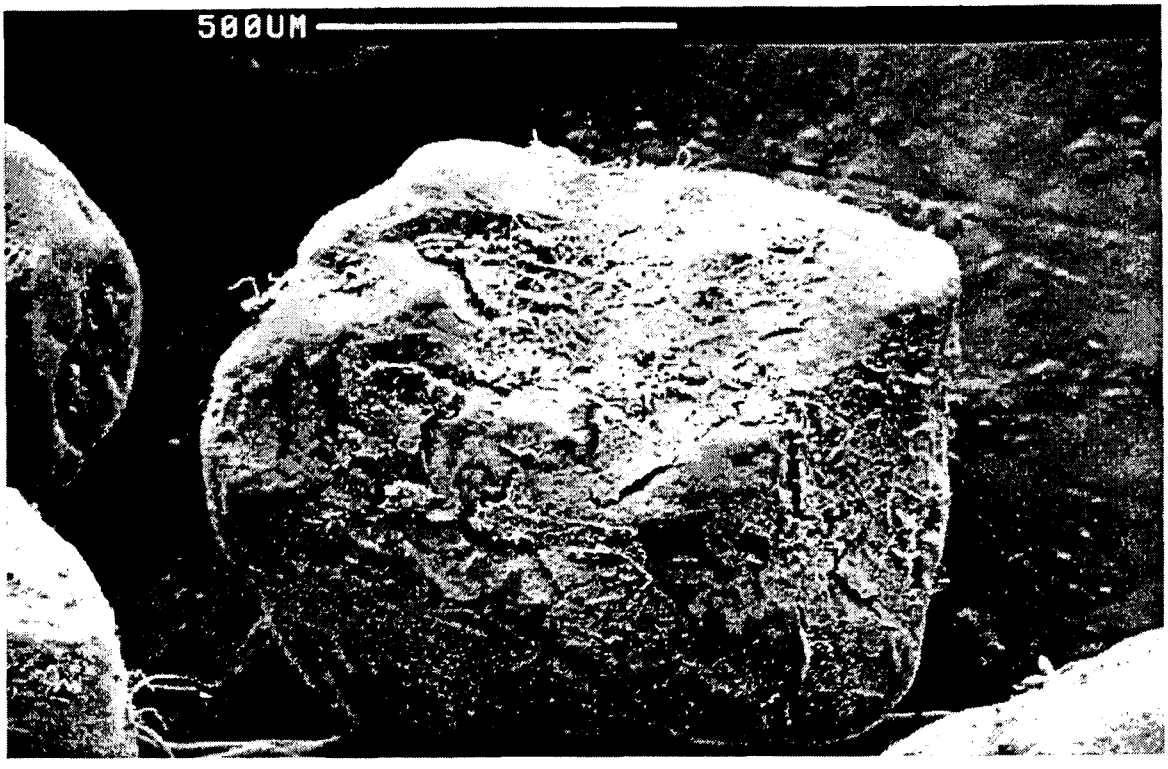

Figure 4.3 Scanning electron micrograph of dirty sand grains with attached particle (*Source:* Thames Water Utilities 2000)

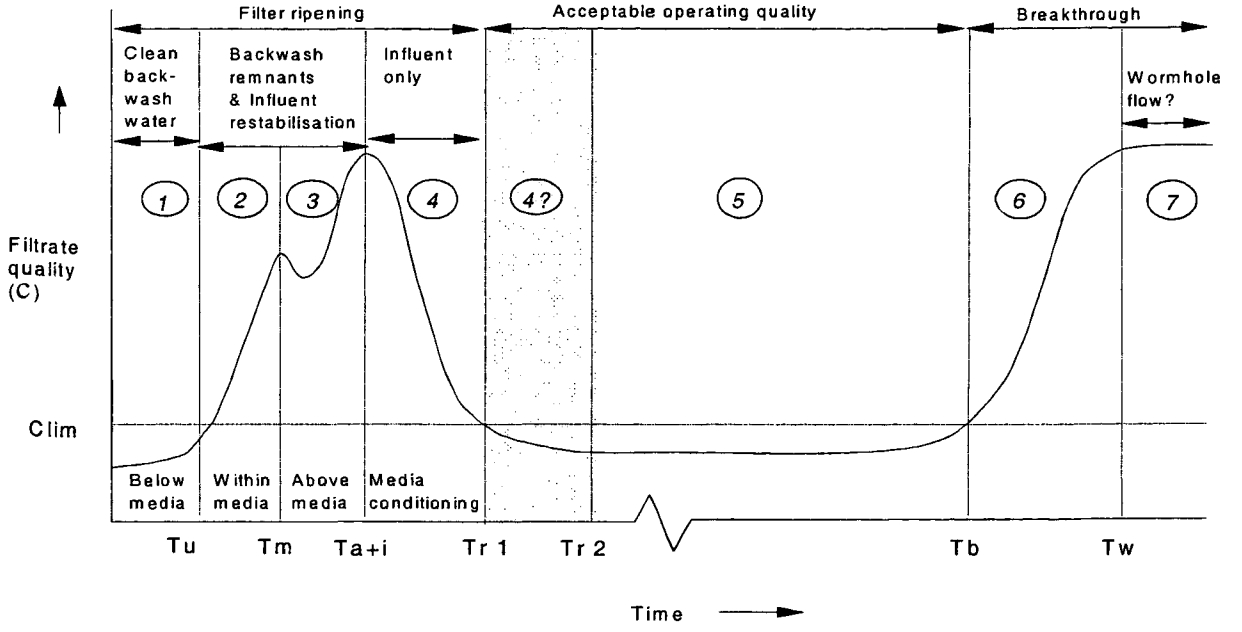

Figure 4.4 An illustration of a seven phase filter operating cycle showing the pre-ripening phase, the ripening period, a best operating stage and the breakthrough phase. (*Source:* Chipps 1998; based on Amirtharajah and Wetstein 1980, Janssens et al. 1982, Cranston and Amirtharajah 1987, Vigneswaran and Chang 1989, and Ginn et al. 1992. Reprinted with permission from Roder, Holmes and Chipps; 2000.)

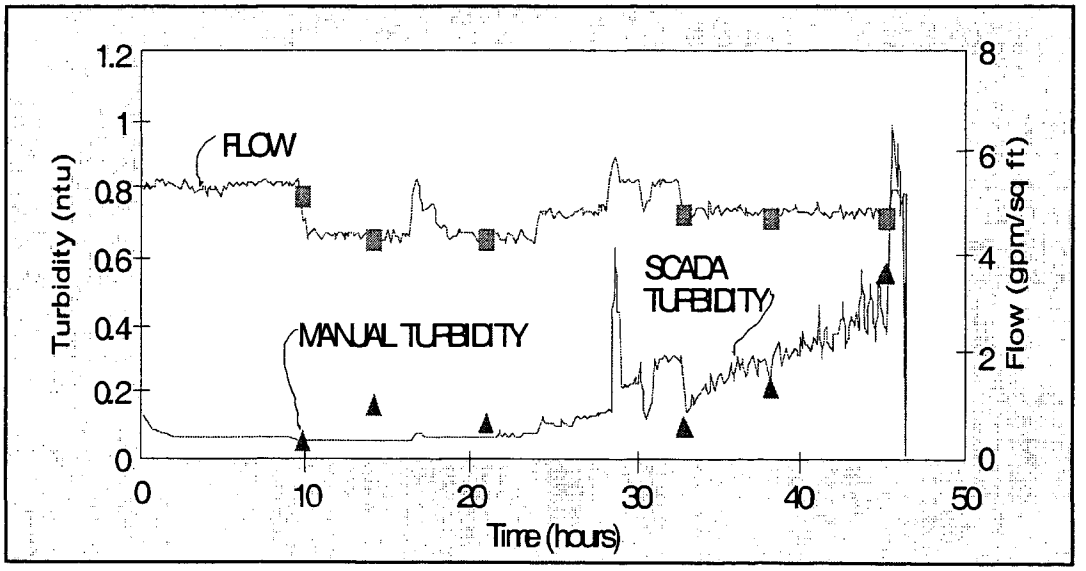

Figure 4.5 Effect of filtration rate increases on turbidity (*Source*: Harms and Horsley 2001)

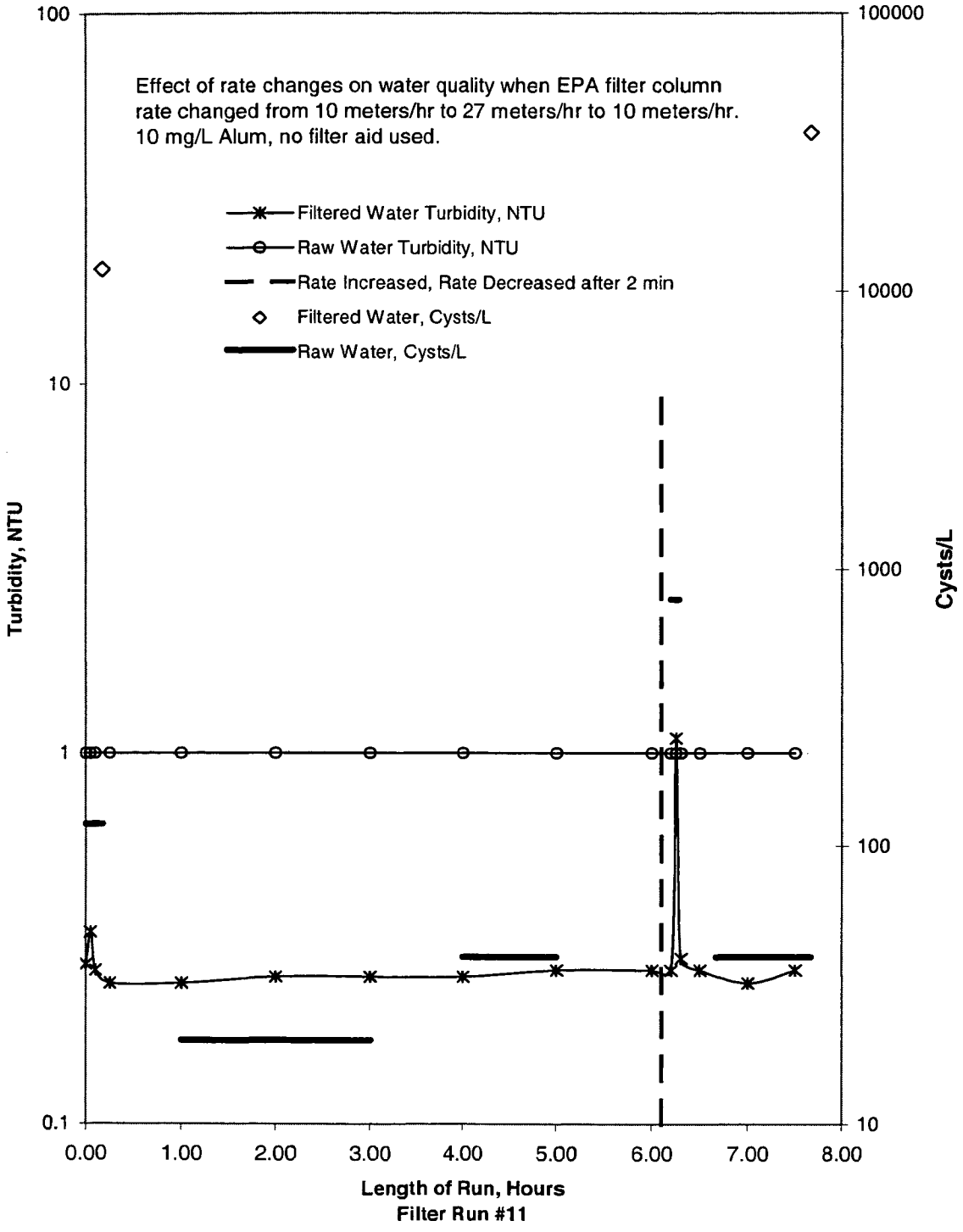

Figure 4.6 Weak floc turbidity breakthrough during rate increase (*Source:* Adapted from Logsdon et al. 1981)

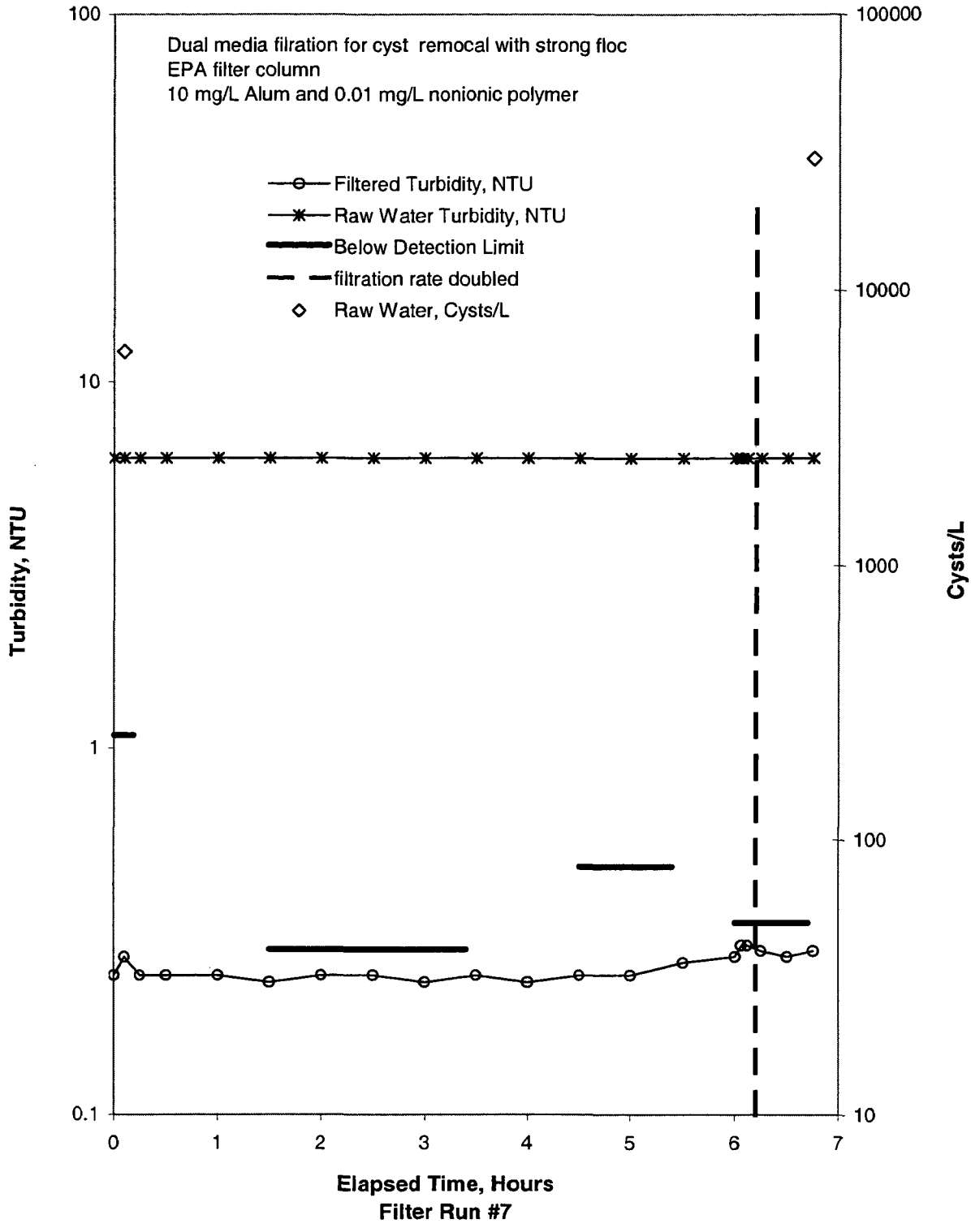

Figure 4.7 Floc strengthened by filter aid resists breakthrough at rate increase (*Source:* unpublished data of Logsdon et al.)

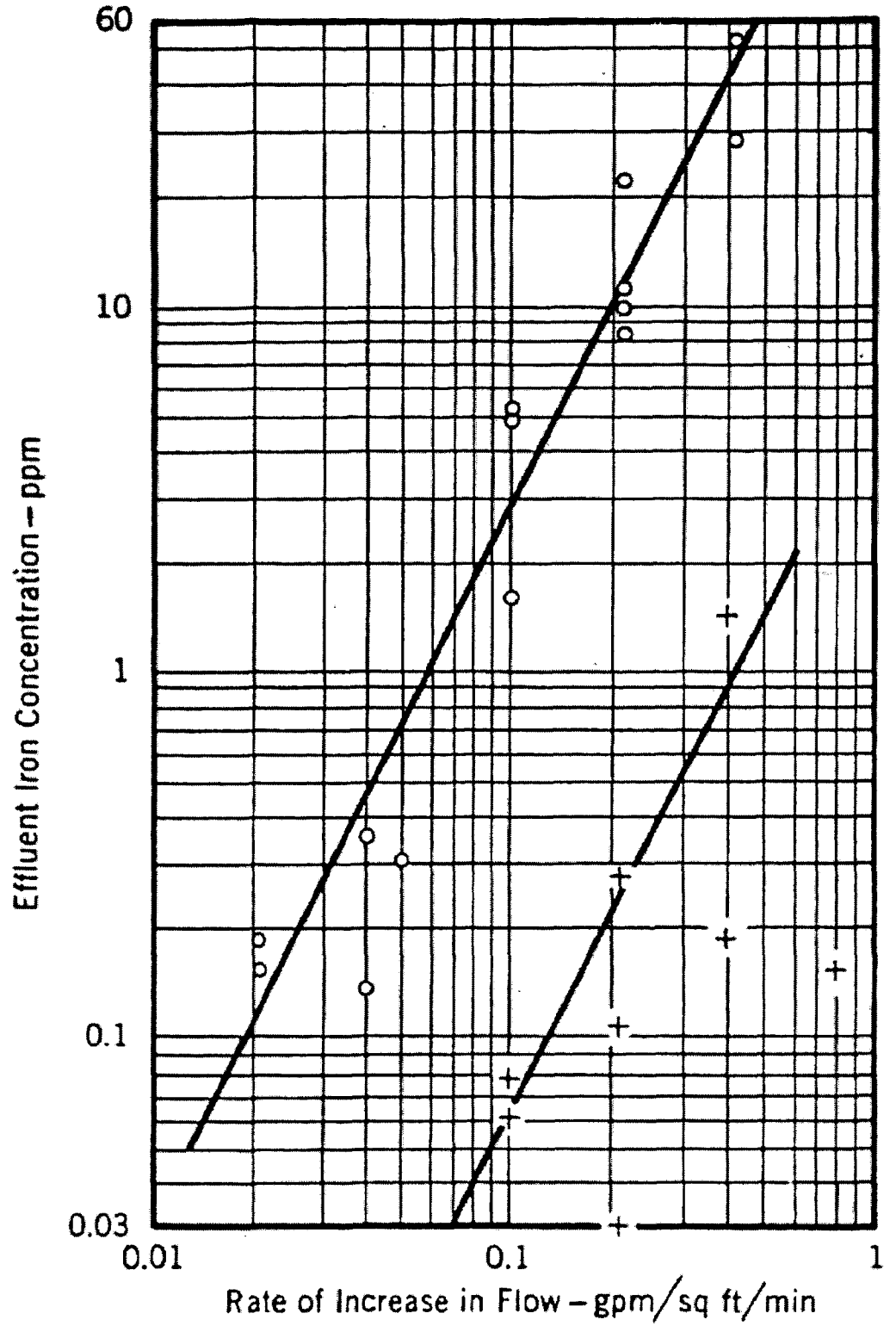

Figure 4.8 Breakthrough amplitude in filter flow of the effluent iron concentration caused by the rate increase in flow (*Source*: Cleasby, Williamson, and Baumann 1963)

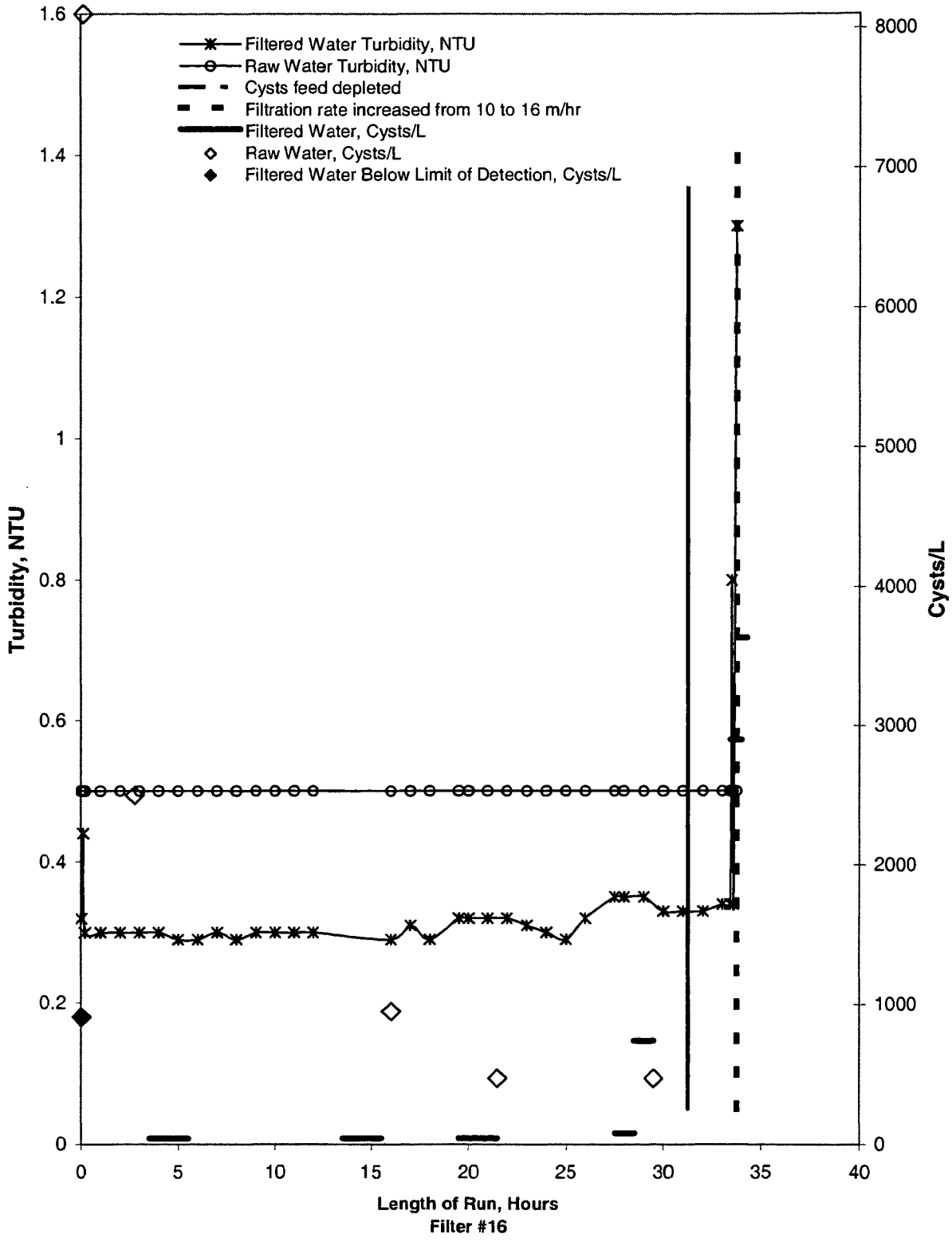

Figure 4.9 Turbidity breakthrough at end of run discharges cysts stored during run (*Source:* Adapted from Logsdon et al. 1981)

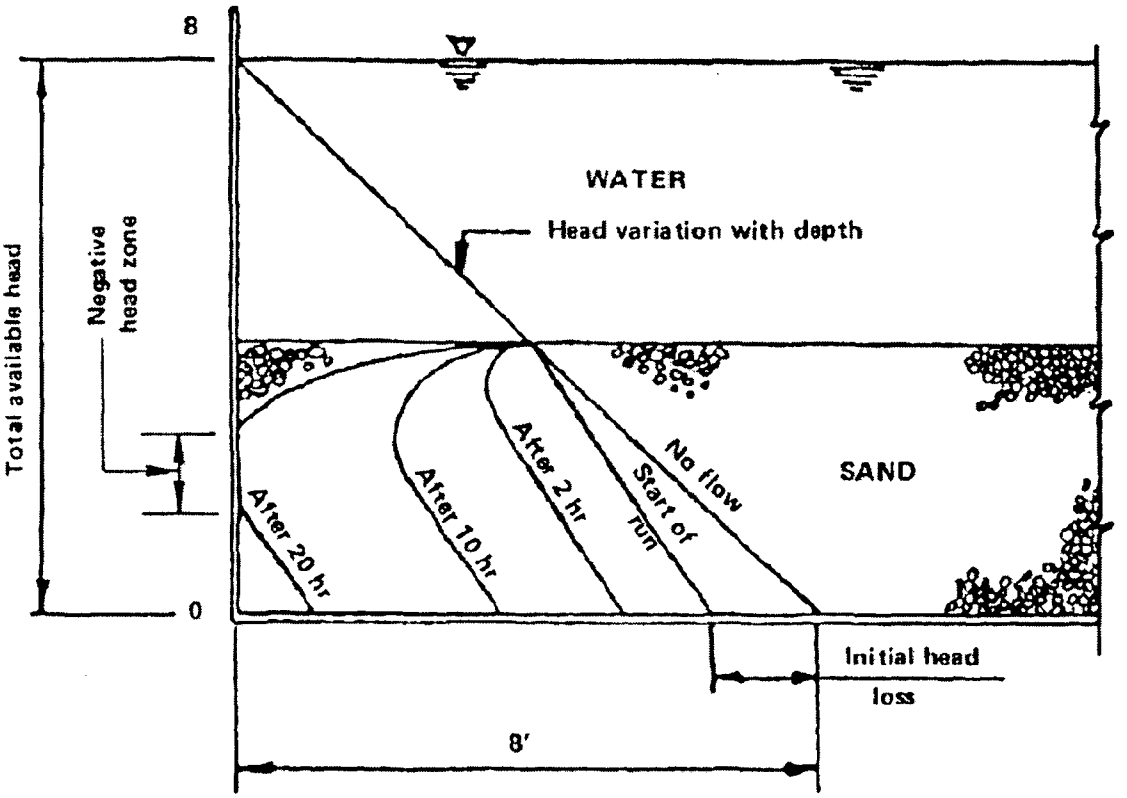

Figure 4.10 Head loss development at various stages of filter run (*Source:* Reprinted with permission from *Water Treatment Plant Design*, Edited by R.L. Sanks, 1978. Copyright CRC Press, Boca Raton, Florida.)

CHAPTER 5
FILTER PERFORMANCE MONITORING

INTRODUCTION

Filtration is a dynamic process. Throughout a filter run, from start to finish, conditions are changing. Some of the changes may occur so slowly that they are not apparent at any given time, but during an entire run, which may last from several hours to several days, changes will occur. Filter monitoring is the key to understanding what is happening within the filter. Unless data are obtained and recorded, a plant operator will not know what a filter has been doing. It is necessary for filter plant operators to have information on filter performance so intelligent decisions can be made with regard to filter operation. Chapter 5 presents information on aspects of filter operation and water quality that should be monitored and provides suggestions on how to manage and use monitoring information after it is collected.

WHAT TO MONITOR AND WHY

Filter performance can be evaluated in a number of ways. Measurement of turbidity from individual filters, combined effluent turbidity, and particle counts are some ways in which water quality can be monitored. Using turbidity and particle counting data, specific aspects of filter runs can be evaluated. Examples include turbidity spike magnitude and duration, particle count spike magnitude and duration, and total particles passed by the filter during a filter run. Other valuable measures of filter performance are effluent flow rate, head loss, the rate of head loss gain, and the unit filter run volume (gallons of water passed through one square foot of the filter during the entire run). As more ways of monitoring filter performance are used at a treatment plant, operators can gain additional insights into the condition of the filters and their performance. The most comprehensive understanding of filter condition can be gained by monitoring multiple filter performance characteristics.

SUMMARY OF FILTER PERFORMANCE MONITORING TECHNIQUES REPORTED BY UTILITIES

Techniques used for monitoring filter performance were reported by water utilities. Table 5.1 summarizes information from 37 plants practicing coagulation.

Filter performance monitoring by an on-line turbidimeter at each filter was very common at the plants participating in this study, as indicated in Table 5.1. This is expected, as many of the utilities that provided information on their plant practices were participants in the Partnership for Safe Water. On-line particle counting is increasingly being applied in water filtration plants. Use of particle counters is expected to increase in the future. Slightly over one fourth of the plants have on-line pH monitoring for settled water, and almost one half monitor the combined filter effluent pH. Settled water pH would in most plants give the best indication of the pH of coagulated water.

Five plants treating surface water by lime softening reported on their practices. Data from the lime softening plants are NOT included in Tables 5.1. Monitoring pH is quite important at lime softening plants. Three of the five measured settled pH on-line, one used 6 grab samples/day, and one used grab samples (no frequency given). Two plants measured combined filtered water pH on-line; one used 8 grab samples/day, and one used grab samples (no frequency given). Turbidity monitoring is required at surface water plants. Two monitored raw turbidity on-line, and four monitored the turbidity of each filter on-line. None of the five reported using on-line particle counters for raw water or for each filter.

Table 5.1

Performance monitoring techniques used by AwwaRF participating utilities at 37 filtration plants

Method	Number of plants using method
On-line turbidity monitoring, raw water	28
On-line turbidity monitoring, settled water	18
On-line turbidity monitoring, each filter	34
On-line particle counting, raw water	13
On-line particle counting, each filter	14
On-line pH monitoring, settled water	10
On-line pH monitoring, combined filter effluent	17

TURBIDITY

Measurement of Turbidity

Turbidity (cloudiness) of raw and filtered water has been measured for many years. A brief history of the practice of turbidity measurement and of the concepts on which the turbidity is based was prepared for the Hach Chemical Company by Sadar (1996). When compared to today's sophisticated instruments, the Jackson Candle Turbidimeters were very crude. They were calibrated by using suspensions of diatomaceous earth. The observer looked down through a flat-bottomed glass tube, and recorded the depth of turbid water in the tube that was sufficient to diffuse the image of a burning candle located below the tube. Although not very precise, and not capable of measuring low levels of filtered water turbidity, such instruments served a good purpose by enabling treatment plant staff to have an estimate of the turbidity of the water, especially the raw water.

Over the years, analysts tried to develop instruments that could measure lower levels of turbidity. Because light is scattered with it strikes particles in water, measurement of scattered light was adopted as a means of quantifying turbidity. The EPA method for turbidity (Method 180.1) and *Standard Methods* 2130B use the principle of measuring light scattered at a 90° angle. Details can be found in the EPA Methods Manual and in *Standard Methods* (APHA, AWWA, and WEF, 1995).

The concept of observing light scattered at a 90° angle is actually quite old. John Baylis, a water purification engineer and scientist who worked for the Chicago Department of Water for many years, published a paper having a diagram of a "floc detector" in 1930. In this paper he advocated using a "floc detector" on every filter to evaluate the clarity of filtered water and to detect passage of flocculated matter (Baylis 1930). Baylis' "floc detector," a device developed by and for a water utility, consisted of a round flask and an incandescent lamp mounted in a box, with a viewing port at a 90° angle to the incoming light. Thus, he foresaw both the concept of using 90° scattered light and of having a detector for each filter, concepts that became a regulatory requirement seven decades later.

Turbidimeters have a number of shortcomings. Because they rely on scattered light, turbidimeters are not effective for detecting passage of activated carbon fines, which are black and do not scatter light. Turbidimeters are not sensitive for detecting biological matter having an index of refraction similar to the index of refraction of water as only a small fraction of incident light would be scattered when refractive indices are similar. When the signal is strong and turbidity is measured, the identity and size of the particles causing the turbidity is unknown. Turbidity is a general physical

measurement, rather than a quantifiable measurement related to a specified number of particles of a certain size. Nephelometers (turbidimeters that measure 90° light scatter) can detect particles smaller than 1 μm. Vanous (1978) presented data showing that the peak instrument response for a Hach nephelometer (Hach 2100A) was obtained for particles about 0.2 μm in size. For particles 1 μm and larger in size, the instrument response is less. This is more pronounced for dilute suspensions. Turbidimeters that employ the nephelometric method as required by EPA are able to detect light scattered from particles that are one tenth of the minimum size of particles detected by particle counters commonly-used in the water industry.

A recent development in turbidity measurement is an on-line turbidimeter that employs a laser diode. According to Johnson, Carlson, and Banerjee (2000) this instrument is much more sensitive than nephelometers employing tungsten lamps or light-emitting-diode sources, and its sensitivity rivals particle counters. These authors compared the laser turbidimeter to a light blockage particle counter and to a nephelometer using a tungsten lamp (Hach 1720 D). They noted that because particle counters typically detect particles in the size range of 2 μm and larger, particles below that size are not detected by particle counters, but they can be detected by nephelometers. The highly sensitive laser turbidimeter detected some increases in sub-micron particles even though the particle counter did not show a change in water quality. The authors reported a change in filtered water quality from 0.025 ntu to 0.018 ntu in one filter run, as an indication of the sensitivity that can be attained. Johnson, Carlson, and Banerjee concluded that the laser turbidimeter was "... much more sensitive than a conventional turbidimeter when monitoring water with a turbidity lower than 0.1 ntu."

CONTINUOUS MONITORING OF TURBIDITY

In spite of its shortcomings, at the beginning of the 21st century, turbidity of filtered water is the best indicator of filter performance, taking into account both the cost of instrumentation and the kind of information provided. On-line turbidimeters are instruments that should be affordable even for small water systems, because they replace manual labor required for an analytical task that has to be performed any day when a filtration plant treats surface water. Their use at filtration plants treating surface water is expected to become universal in the near future. For compliance with the Interim Enhanced Surface Water Treatment Rule after January 1, 2002, continuous turbidity monitoring for each filter will be necessary for filtration plants serving 10,000 persons or more and treating surface water or ground water under the influence of surface water. For systems serving fewer than 10,000 persons this requirement is proposed to be effective 36 months after promulgation of the Long Term Stage 1 Enhanced Surface Water Treatment Rule. Continuous turbidity monitoring for each filter is recommended in this manual for all surface water filtration plants regardless of size, because this is the most affordable means for a plant operator to know how every filter is performing, during every minute of operation.

Operating a filtration plant without an on-line turbidimeter for every operating filter is like operating the plant while wearing a blindfold. Conditions in a single filter can change quickly, particularly during times when filters are vulnerable to quality problems. These times include starting a filter, making the transition from filter-to-waste over to production for consumption, increasing the rate of production in the plant, and increasing filtration rates to compensate for removing a filter from service for backwashing. Without a continuous stream of data from the filters, operators will not be able to detect quality changes rapidly and respond properly.

Turbidity data must be recorded for regulatory purposes, and alarms must be provided to alert operators to potential problems. The Interim Enhanced Surface Water Treatment Rule (IESWTR) requires the turbidity of each filter to be monitored continuously, and the data will have to be recorded and saved for at least three years (USEPA, 1998). In contrast to the requirement for continuous monitoring of turbidity for individual filters, the IESWTR does not require continuous monitoring of finished water discharged into the distribution system. For this, grab samples taken each four hours can satisfy the regulatory sampling requirement.

The Interim Enhanced Surface Water Treatment Rule requires utilities to measure the combined filter effluent turbidity and meet a regulatory requirement that the turbidity of the system's filtered water must be less than or equal to 0.3 ntu in at least 95 percent of the measurements taken each month. This

rule mandates measuring combined effluent turbidity and is the main reason utilities have for measuring turbidity of combined filter effluent. As discussed above, if operators had only combined filter effluent turbidity data, they would have no way to know the turbidity produced by a single filter.

The Partnership for Safe Water has a goal of producing filtered water having a turbidity of 0.1 ntu. Attaining such a stringent goal requires optimized pretreatment and careful filter operation, and continuous monitoring of filtered water turbidity from each filter is an essential part of an optimization program.

Recommendations on the installation of on-line turbidimeters are given in Chapter 12.

Special Applications of Turbidity Measurement

The Partnership for Safe Water has software for handling and analysis of large amounts of turbidity data collected at water filtration plants during a month or a year. Turbidity percentile data can be developed for the 50^{th}, 75^{th}, 90^{th}, 95^{th}, 96^{th}, 97^{th}, 98^{th}, and 99^{th} percentile turbidities. Typically turbidity data are plotted by month with turbidity values on the y-axis and the percentage of time turbidity is less than a specified value plotted on the x-axis. Both scales are in arithmetic scales rather than logarithmic or probability scales. The percentile indicates the percentage of turbidity values equal to or less than a particular turbidity value. For example, if the 98^{th} percentile turbidity in a data set is 0.12 ntu, then 98 percent of the turbidity values are equal to or less than 0.12 ntu. Percentile data can not show the time-versus-turbidity trend for a single filter run. Analysis of data for percentile values can, however, be used to analyze a data set containing results from multiple filter runs. This is a major advantage of percentile analysis, because very large amounts of data can be entered into a database for analysis.

When continuous turbidity measurement at each filter is employed, huge amounts of data can be generated in a month or a year. Using the percentile analysis technique is a way for operators to look back at a large number of past filter runs. For example, turbidity percentiles could be analyzed for all of the runs for each month for a year, so operators could review the results month by month and learn how consistent filtered water quality had been over the year.

At Thames Water Utilities, summary measures of turbidity are analyzed to track filter performance (Edwards et al. 2000). The data selected for analysis are the average weekly turbidity for a filter, the 97.5 percentile data, and the duration of the period when filtered water turbidity exceeds 0.2 ntu. Average weekly turbidity indicates how a filter behaved over the week's operation. Maximum

turbidity, expressed as a percentile value, indicates filter behavior during turbidity spike conditions. The duration of time exceeding 0.2 ntu indicates the amount of time when a filter was operated above the initial trigger value of 0.2 ntu. By examining this combination of summary data, water quality managers are able to gain an overall understanding of filter behavior. For long-term evaluations, summary bar charts depicting the performance of all filters in the plant are prepared, showing overall plant performance on a week-by-week basis. The summary bar charts are useful for identifying out-of-norm performance for an individual filter or for a period of time, depending on how the data are grouped and analyzed.

During some years prior to publication of this manual, the Modesto Irrigation District (MID) used a filter performance index calculation to evaluate filter behavior. This calculation included filtered water turbidity, water production, wash water usage, and other factors. More recently, MID has used turbidity removal percentile graphs as the tool for viewing overall plant performance. MID reported that ".... percentile turbidity removal graphs give the clearest view of plant performance."

Two interesting approaches to using turbidity measurement were reported in the survey of utility practices done for this project.

The Swift Creek Water Treatment Plant of the Chesterfield County Utilities Department has four filters with dual media. These filters were designed so a sample of filtered water can be withdrawn at the interface between the coal and sand. The purpose for measuring the turbidity of filtered water at the interface of the coal and sand in a dual media filter is to assess the removal of turbidity by the coal layer. When floc is strong enough, turbidity removal occurs in the coarse upper layer of coal, and the lower sand layer is present as a polishing layer that removes a small additional amount of turbidity. When floc is weak as a result of pretreatment conditions, it can penetrate the coal layer. In that situation, the burden of removal falls on the shallower layer of sand under the coal. If large numbers of particles pass through the sand layer, turbidity breakthrough would result. In dual media filters the sand layer generally is used as a polishing layer and it is not expected to remove substantial amounts of turbidity. Interface turbidity data provide operators with a tool for evaluating floc strength (a function of pretreatment) and filter performance and enable operators to anticipate and thus avoid turbidity breakthrough episodes.

The Modesto Regional Water Treatment Plant is equipped with six filters containing 6 feet (1.8 m) of 1.5 mm e.s. anthracite monomedium. One of these deep-bed monomedium filters is equipped with sample taps through the filter box at 1-foot (0.3-m) intervals. These taps supply water to continuous

turbidimeters and help the operators understand what is happening within the filter bed. The preferred arrangement for a series of sampling taps is to place them offset from a vertical line at various horizontal distances so all of the taps do not take water from a localized zone in the bed and cause higher filtration rates (water velocities) in the withdrawal zone. During times of higher total head loss caused by strong floc, usually only the top one or two feet (0.3 to 0.6 m) of media experience a rise in turbidity before the filter needs to be backwashed due to head loss. On the other hand, if floc is weaker and penetrates into the bed, a rise in turbidity can be tracked as it progresses down into the bed and turbidity breakthrough can be predicted before it reaches the filter effluent. This monitoring technique lets operators know if they need to adjust floc strength so the tendency for breakthrough can be reduced.

When water samples are withdrawn from within a filter bed, the rate of flow of water to the turbidimeter should be within the limits prescribed by the instrument manufacturer. The velocity of the water flowing through the area of the sampling probe (e.g. the area of slots on a fine filter nozzle) should be similar to the interstitial velocity of water flowing through the filter bed. Ideally, these velocities should be the same, but filtration rates change from time to time, and adjusting the sample flow rate every time the filtration rate changed could be burdensome to the operating staff. As a compromise, match the velocity in the sampling probe to the velocity within the filter bed at the average filtration rate. When designing an in-filter sampling method it is essential that the sampling device does not permit media to leave the filter. In addition, the sample should be taken from within the bed, and not at the filter wall.

Additional information about the within-bed filtered water quality monitoring at the Swift Creek Water Treatment Plant and at the Modesto Irrigation District is presented in the Chapter 13 case study, "Monitoring Water Quality within the Filter Bed."

Using Turbidity Data as a Guide to Filter Condition

After joining the Partnership for Safe Water program in 1996, during the following year the Philadelphia Water Department developed a systematic approach to classifying turbidity peaks for filter effluent upon restart after backwash (Guest and Jadczak 2001). This system has been used to determine the action to take in response to turbidity peaks. The Philadelphia Water Department's goals for turbidity peaks after backwash are for no peak to exceed 0.3 ntu and for the turbidity to be 0.10 ntu or lower after 15 minutes of operation following startup. According to Guest and Jadczak, filter status categories are:

- Class 1: Peak turbidity less than 0.30 ntu and does not exceed 0.10 ntu for more than 15 minutes.
- Class 2: Peak turbidity less than 0.30 ntu but the 0.10 ntu goal has not been attained after 15 minutes of operation.
- Class 3: Peak turbidity above 0.30 ntu but less than 0.50 ntu. A filter in this class is prioritized for investigation.
- Class 4: Peak turbidity above 0.50 ntu. A filter in this class is prioritized for investigation and action.
- Class 5: Peak turbidity 1 ntu for 15 minutes or above 0.50 ntu after four hours in service. A filter in this class is to be taken out of service immediately for investigation.

When a filter's status declines from Class 1, filter backwash reports and prior filter inspection reports are studied to learn the cause of the performance change. Semiannually, filters that do not meet Class 1 status are examined physically and are placed into condition categories 1, 2, or 3.

Category 1 filters are visibly dirty and exhibit evidence of ineffective backwash and a need for maintenance as indicated by:

- Mudballs on more than 5 percent of the filter surface.
- Mud in filter cores after backwash.
- Media pulls away from walls of a drained filter after backwash.
- Backwash expansion is less than 20 percent as measured by backwash expansion tool (of the type shown in Chapter 10 of this manual).
- Turbidity in backwash water exceeds 10 ntu at end of backwash.
- Visual observation of inadequate backwash flow distribution across filter.
- Surface wash rotation rate less than 5 rpm or leaking valves or clogged nozzles.
- Leaking washwater or effluent control valves.

Filters in Category 2 are deemed to be in worse condition than those in Category 1 but do not show signs of complete failure. Improved pretreatment or more effective backwash procedures may be needed.

Category 3 filters may need to be rebuilt. They show signs of physical failure, such as:

- Craters or depressions in media
- Significant amount of media in underdrain
- Severe structural problems
- Other evidence such as gravel disturbance or major media growth or shrinkage

By setting up a ranking system, the Philadelphia Water Department has developed a means of setting priorities for maintenance and filter rehabilitation activities at its three plants that have a total of 160 filters. Although water systems with smaller plants and fewer filters might not face the same degree of urgency for setting priorities on work, they would benefit from having guidelines for filter performance and for the level of effort needed when filter problems are apparent. The concepts applied in Philadelphia approach to filter evaluation could be adapted and applied to other filtration plants.

PARTICLE COUNTING

Concepts

Particle counting provides data that are more detailed than turbidity data. Turbidity is a gross measure of the cloudiness of water, whereas particle counting provides estimates of the number and size range of particles in filtered water. Particle counters have a high sensitivity to changes in filtered water quality, and often an increase in particle count is detected in filtered water before turbidity increases. Thus particle counters can provide an early warning for incipient turbidity problems. When a water utility can afford the cost, use of a particle counter to monitor each filter continuously is recommended for optimizing filter operation and filtered water quality.

Particle counters enumerate and size particles in a variety of ways. These include displacement of liquid volume by a particle passing through a counting cell, light blockage as a particle passing through the sensor casts a shadow on light detectors, and light scatter by a particle. Particle counters functioning on the light blockage principle are now used almost exclusively in drinking water treatment applications (Broadwell 2001), so other types of particle counters are not discussed in detail in this manual.There is no precise mathematical relationship between particle numbers and turbidity; however, it is often true that the numbers are associated, i.e. when turbidity increases, particle counts rise. The

increase in particle counts may be as large as 10-fold for a doubling in turbidity for example. When turbidity is caused by particles that are smaller than the size that can be detected by a particle counter, particle count increases may not track turbidity increases. On the other hand, if GAC fines or coal dust particles were in the water being analyzed, a turbidimeter might not detect the particles (black particles scatter little or no light) but if they were large enough to be counted by a light blockage particle counter, the black particles would cast a shadow on the sensors and would be counted.

Since some studies have revealed particle breakthrough at the end of a filter run while turbidity trends remained flat, it is an important question for utilites to ask whether they can afford *not* to have particle counters, whereas on the other hand due to cost of ownership (purchase price, installation, maintenance, calibration, data processing, and taking process action) the water supplier must determine whether they *can* afford to have counters.

Particle counting is probably most useful as a routine operational tool when a plant has attained its ultimate capability for controlling turbidity. If filtered water turbidity is greater than 0.1 ntu it is likely that further optimization work could be undertaken and its benefits judged by a turbidimeter. When turbidities are reliably less than 0.1 ntu a particle counter can be used to "fine-tune" a plant beyond the levels that can be attained by depending solely on a nephelometric turbidimeter.

Application of Particle Counting in Water Treatment Plants

Particle counters installed at water filtration plants typically have used sensors capable of counting particles in a size range of 2 μm and greater. These counters have an upper particle size limit for detection and for passage of particles through the sensor. Frequently light blockage counters are equipped with a sensor having a cross-sectional area of 0.75 mm x 0.75 mm (750 μm x 750 μm). A visible floc particle in settled water having a dimension greater than 0.75 mm either would block the sensor or would be broken up in passage through the sensor. The practical limit of the size of particle that can be counted is smaller than the size of the sensor. Very high numbers of particles per milliliter, perhaps 20,000 to 30,000 particles per mL, can approach or exceed the concentration limit for sensors, resulting in an undercounting of particles. Turbid source waters, such as muddy rivers, would have to be diluted to be counted, if one wanted to estimate the concentration of particles in raw water. These limitations, while serious for certain applications, would apply to filtered water only if its quality was much worse than acceptable filtered water quality. Recommendations on installation of particle counters are given in Chapter 12.

Particle counting has drawbacks for water utilities. Particle counters have been considerably more expensive than continuous turbidimeters. No standard method for counting particles in water samples exists, and results from one manufacturer's instrument are not necessarily comparable to results from a different manufacturer's instrument. Particle count data for a specific water utility and instrument generally can not be directly compared to particle count data from another utility, even if instrument brands are the same. McTigue et al. (1998) in a nationwide evaluation of particle removal by filtration, equipped a trailer with particle counters and others laboratory instruments, and transported it around the country to about 100 water treatment plants. This enabled them to collect particle count data that could be compared from plant to plant. They reported that the filtered water particle count for particles greater than 2 μm in size ranged from 1 particle per mL to more than 8000 particles per mL, with a median of 14 particles/mL. McTigue et al. used Met One particle counters in their study. Data obtained by water utilities using other brands of instruments may not be comparable.

Development of a practical guide for particle counting by water utilities was sponsored by the AwwaRF (Hargesheimer and Lewis 1995). In their report, the authors stated that plant influent and filter effluent are the most important sampling locations to use if particle counting is to be done for assessing plant performance. They recommended that settled water samples not be subjected to particle counting, and noted that analysis of blended water samples from the clearwell or finished water provides only general information. Speaking of clearwell and finished water samples, they wrote, ".... because these samples are blended from various processes and are slow to respond to changes, they are not good sources of operational information." Hargesheimer and Lewis found that water could be conveyed to particle counters using tubing in lengths of up to 10 feet without affecting particle counts over the short term. Copper, stainless steel, and PTFE tubing could be used for supplying water to particle counters over a period of months without a biofilm build-up that would influence particle counts.

In a discussion of statistical considerations in particle counting Hargesheimer and Lewis reported that at least 400 particles must be counted to achieve 10 percent precision (90 percent confidence) during a particle count analysis. If the filtered water has 100 particles/mL, only 4 mL needs to pass through the sensor to reach that number, but if the particle count is 1 particle/mL, then 400 mL needs to pass through the particle counting sensor. For a flow rate of 50 mL per minute, the counter would need to be on for 8 minutes to count 400 particles at a concentration of 1 particle/mL. Particle counting practice should be adapted to the expected quality of the water being analyzed. Plants that produce filtered water with very

low particle counts should set the particle counters to analyze water for a longer time before the data are archived for analysis.

Operators can develop confidence in particle counting data by experience as well as by using statistics. According to Hargesheimer, McTigue and Lewis (2000), "For practical drinking water applications, it is certainly true to say that the more particles that are counted during each count interval or the more counting intervals there are, the greater the confidence that can be associated with the data. In water treatment plants, operators build increasing confidence in low particle count data if the results are consistent with each subsequent count and if changes in process are immediately mirrored by changes in the particle count results."

Particle counters are very sensitive devices for monitoring filter performance. Their use can enable operators to improve filtered water quality by revealing quality differences that would not be apparent if turbidity data were the only monitoring data available. Hargesheimer et al. (1998) used particle counters to assess filtered water quality at the Bearspaw Water Treatment Plant in Calgary, Alberta. Whereas filtered water turbidity monitoring in the range of 0.03 to 0.10 ntu did not reveal the effects of small coagulant dosage changes, particle counting was more sensitive and did show changes in quality.

At treatment plants where the staff have optimized treatment to the point of diminishing returns through the use of turbidity data, installation of on-line particle counters to monitor filtered water quality is a means of continuing to optimize treatment and attain further improvement in quality. This was shown by the Calgary experience, and was also demonstrated at the Hayden Bridge Plant of the Eugene Water & Electric Board. In their report for this project, the staff reported that a filter aid is used at an average concentration of 0.02 mg/L and wrote, "Before we could 'see' the difference in results with particle counters, we used filter aid only when the water was below 50 ^{o}F. Now, the operators can see a benefit during the summer months and we use it year round." Previously, continuous turbidimeters had been used to monitor turbidity from each filter, and the effluent typically was less than 0.10 ntu.

The Milwaukee Water Works operators have diagnosed operating problems with the aid of particle counters (Carmichael, Lewis, and Aquino 1998). Filters at the Howard Avenue Water Treatment Plant have two independently operated effluent valves and headers. The flows from each portion of the filter are combined and conveyed to the clearwell. The sample stream for the particle counter is taken from the combined effluent. Operators investigated when one filter had slightly elevated particle counts (2 μm or larger) of 3 to 5 per mL as compared to 1 to 2 per mL for another filter.

They found that one of the two filter effluent valves had not opened, causing half of the filter to operate at a filtration rate that was twice the intended rate. A slight particle breakthrough was the clue the operators used to detect an operating problem with the filter. Turbidimeter readings from a properly functioning filter were 0.01 ntu versus 0.02 ntu for the filter with the valve problem. Turbidimeters are not precise at such low turbidity levels, so it is very unlikely that the operators would have investigated this problem based on turbidity readings of 0.01 and 0.02 ntu. Without particle counters and an alert and curious staff, this problem could have gone undetected.

In another instance of investigating plant performance based on particle counts (Carmichael, Lewis, and Aquino 1998), operators noticed that particle counts in the effluent of two filters increased from < 1 per mL to about 5-15 per mL and then decreased. These episodes occurred around midnight every other day. The influent to these two filters came mainly from one of the four parallel sedimentation basins. Operators realized the elevated particle counts were being observed about the time when the cross-collectors were scheduled to be operated to clean the sedimentation basin floor. The cross-collectors were inspected and were working properly. Operators found that the pump that removed accumulated sludge from the basin had failed, so sludge was building up. When the cross-collector passed through the built-up sludge, solids were resuspended into the settled water and then appeared in the filter influent. This caused the slight increase in filtered water particle counts. Without particle counting, this problem might have gone undetected for a longer period of time.

Additional information on the use of particle counters for evaluating filtration plant performance is presented in the Chapter 13 case study, "Monitoring and Review of Rapid Gravity Filter Performance Using On-line Particle Counters at Hope Valley Water Treatment Plant, Adelaide, South Australia."

Using Particle Count Data

When particle counters are used to monitor filtered water quality continuously, they should send data to a recording and archiving system. If particle counters are to be used as early warning devices for turbidity breakthrough, they need to be connected to an alarm system. After particle counting data have been measured and recorded, making use of the data can be a challenge. Particle counters can provide information on the numbers of particles in several specified size ranges, in addition to the total number of particles in filtered water. Fortunately, particle counters often are sold with computers for data storage, manipulation, and analysis.

Frequency of counting was addressed by Hargesheimer and Lewis (1995), who used 1-minute counting intervals. After ten particle counts had been performed, the mean, maximum, and minimum values of the ten counts were stored in computer memory. They noted that the maximum and minimum counts in a 10-minute interval were useful for indicating whether large changes in the particle concentration had occurred during that time interval. A 50-hour filter run would be 3000 minutes long and would have 300 data sets for each size range of particles counted during the run.

Hargesheimer et al. (1998) provided examples of ways to handle the massive amounts of data generated by particle counters. One approach is to show the total particle counts (for example, number of particles $\geq$ 2.0 µm/mL) as a function of the length of the filter run in hours as seen in Figure 5.8. An example of the trend of particle counts versus time during a filter run is presented later in this manual in Figure 13.7. Hargesheimer et al. (1998) also evaluated the cumulative results of filter performance by tabulating the particle counts during a filter run and determining values for the 10^{th}, 50^{th}, 90^{th}, 95^{th}, and 98^{th} percentiles as seen in Figure 5.9 The use of percentiles for particle count data was similar to the approach for turbidity data analysis in the Partnership for Safe Water, as discussed previously in this chapter. Some spreadsheet programs can be used to tabulate data in order of magnitude, from largest to smallest or from smallest to largest, and then percentiles can be calculated. Each means of data presentation provides a different perspective on filter performance, and when viewed together the time-trends graphs and the percentile data tables facilitate interpretation of the results of the filter runs.

Another approach for use of particle counting data for filter performance evaluation is to obtain data on raw water and filtered water particle counts and calculate log removals, which are percentage removals expressed in another way. For example, a 90 percent reduction = 1 $\log_{10}$ removal, a 99 percent reduction = 2 $\log_{10}$ removal, a 99.9 percent reduction = 3 $\log_{10}$ removal, etc. The percentage removal or log removal results are based on calculations made using the raw water count and filtered water count. At a filter plant that produces water having a consistent filtered water particle count, the log removal or percentage removal will be a function of the raw water particle count. A low value of log removal attained when the raw water particle count is low does not mean that plant performance is poor. This might be the case, or perhaps log removal and percentage removal just look poor because of the low raw water particle concentration. Hargesheimer et al. commented on this problem, stating, "Log removal is not a good indicator of plant performance because it is influenced more by particle counts in source water than by those in finished water." This conclusion applies at well-operated, optimized filtration

plants. It may not be valid at a plant that is poorly run, with highly variable filtered water particle counts.

When continuous particle counting is performed for water from each filter, the overall performance during a filter run can be determined by summing all of the particles that passed through the particle count sensor during the run. Used alone, these data would indicate that a longer filter run passed more particles. To adjust the data for filter run length, the time of the run should be accounted for by multiplying the minutes of the run by the flow rate through the particle counter. For a run that was monitored from start to finish at a constant particle counter flow, this calculation will yield the total milliliters of water that passed through the sensor. Then the total particles counted can be divided by this volume, giving the average particle count per mL for the entire run. This information would be a valuable supplement to the percentile data described earlier. This averaging technique, however, is appropriate only for runs in which the filtration rate is constant for the entire run. To estimate the total number of particles passing a filter when filtration rates change, the particle count for a discrete time interval would have to be adjusted to account for the rate of filtration during the time interval. For example a filter operating at 4 gpm/sf (10 m/h) would pass twice as many particles in one hour as when the filter was operating at 2 gpm/sf (5 m/h) and the particle count per mL was the same. Calculation of flow-weighted particle count information would be complex if done manually, but it could be managed with modern computer capabilities and SCADA systems.

Several serious issues need to be considered when particle counters are used. Particle counters cannot identify *Cryptosporidium* oocysts or *Giardia* cysts if they are present in water samples. Protozoa would simply be counted as particles, and the protozoa would be only a very small fraction of the total number of particles in water, as other kinds of particles in raw and treated water samples may be much more abundant than protozoa.

Particle counters only give an estimated size of a particle assuming that all particles are exactly spherical and are opaque. Particles in nature have different shapes, indices of refraction, and optical densities as compared to the latex spheres used in calibration. The shadow cast by a particle is converted to an equivalent spherical diameter by the counter. The equivalent diameter is a function of particle shape and index of refraction. The accuracy of the final value also depends on the optical design of the counter.

In water samples with high particle population densities the total number of particles may be underestimated. The numbers in individual size classes may be underestimated or even overestimated (a

large number of particles below the counting size threshold being counted as larger units within the threshold). Particle counters assume that only one particle passes the sensor at a time. When two small particles cast a shadow in the detector at the same time they are sized as one larger particle. This is called primary optical coincidence. This results in an artificial reduction in apparent numbers and an incorrect shift in the size distribution. Manufacturers state the probable counts per mL at which more than 'X'% error due to optical coincidence may be expected [a function of the optics, flow cell dimensions and flow rate].

A second reason why particle counters give misleading indications of particle numbers and sizes in water treatment is because water treatment processes employ chemical or biological mechanisms by which primary particles are deliberately aggregated to facilitate their removal. Coagulation can aggregate raw water particles that were too small to be counted, resulting in countable particles. Also, countable raw water particles may be aggregated into larger sizes by coagulation. These phenomena acting together could either increase or decrease the numbers of countable particles. In biological filters the particles output from the filter are likely to be completely different in composition to those input (e.g. digested in invertebrate guts). Sometimes sloughing of flocs or aggregates can occur. There is no mechanism for a particle counter to distinguish between primary particles or aggregates of primary particles. For this reason the widely quoted concept of "log removals" can be misleading.

WATER QUALITY AFTER FILTER START-UP

Filter performance at the start of a run can be appraised by assessing the turbidity spike magnitude and duration, or by evaluating particle count spike magnitude and duration. The goals of the Partnership for Safe Water having no turbidity spike exceeding 0.3 ntu after backwash and producing filtered water turbidity of less than 0.1 ntu within 15 minutes after returning to service. Techniques for minimizing the turbidity spike at startup are covered in Chapter 7 of this manual. The turbidity goals of the Partnership are a good benchmark against which to measure performance of a filter on start-up. Particle counting goals for water quality after filter start-up are best determined at each filtration plant because of the differences in the performance of various particle counters.

HEAD LOSS MONITORING AND RATE OF HEAD LOSS GAIN

Measuring Head Loss and Using the Data

As water flows through a granular media filter bed, pressure drop, generally referred to as head loss, occurs. The head loss in the bed is proportional to the depth of the bed, the filtration rate (velocity of water flowing through the bed), and the viscosity of the water. Head loss is also a function of the size and shape of the filter media, and the porosity of the bed. For a clean filter bed the head loss increases in proportion to the filtration rate and in proportion to the viscosity of the water for filtration rates up to about 8 gpm/sf (20 m/h) and for filter media having an e.s. of 1.0 mm or smaller. Water viscosity is a function of temperature. The viscosity of water at 86 °F (30 °C) is slightly less than one half of the viscosity of water at 37 °F (3 °C). Thus for a clean filter the head loss through the filter bed in the summer might be only half of the head loss through the bed during winter, for the same filtration rate.

Recognizing that the rate of filtration influences the rate of head loss gain, staff at the Louisville Water Company compare the performance of different filters by calculating head loss gain (feet/hour) divided by the filtration rate. This procedure enables the staff to assess filter performance after a correction has been made for the rate of filtration, and if other factors cause a filter to accumulate head loss at a rate faster than the norm, this becomes apparent. Another approach to comparing filter head loss gain is to divide the total head loss increase for a run (the difference between terminal head loss and clean bed head loss) by the Unit Filter Run Volume (UFRV), with the UFRV expressed as thousands of gallons per square foot (or hundreds of m^3/m^2). Thus for a head loss gain of 7 feet and a UFRV of 10,000 gallons per square foot, the head loss gain would be 0.7 foot per 1000 gallons per square foot. If the UFRV is calculated, as explained in the next section of this chapter, then calculating the gain in head loss per 1000 gallons per square foot would be quite easy. When using metric units, the head loss gain in meters could be divided by the UFRV expressed in hundreds of m^3/m^2.

When a filter is operated at a constant rate, head loss gradually increases throughout the run as flocculated particles are trapped within the filter bed during the run. Head loss monitoring data are used to inform the operator of the degree of clogging that has taken place within the filter. Trends of head loss development can reveal whether filtration is taking place in depth or whether surface blinding is occurring. When filtration takes place within the depth of the filter bed head loss tends to increase in a linear fashion over time if the filtration rate is constant, but with surface blinding head loss development becomes more rapid as the volume filtered increases. Typically operators backwash the filter that has

the highest head loss, when filter runs are terminated because of head loss instead of turbidity breakthrough.

Head loss must be monitored continuously and should be recorded continuously for each filter that is in operation, as it is an important factor to consider when making decisions about filter operation. If filters are operating at a low rate of filtration, and a rate increase is made, the head loss in each filter will increase roughly in proportion to the increase in filtration rate. If a filter were operating at 2 gpm/sf (5 m/h) and a head loss of 7 feet (2.1 m), with 8 feet (2.4 m) the maximum head loss attained before filter washing, increasing the filtration rate to 3 gpm/sf (7 m/h) would push the head loss over 8 feet (2.4 m). Furthermore, a filter that has nearly reached its maximum head loss has nearly reached its maximum degree of clogging that is acceptable. Increasing the filtration rate on a filter near its terminal head loss would be risky, as a massive turbidity breakthrough might be induced by the rate increase.

Granular media filters in pilot plants typically are equipped with multiple, regularly-spaced taps so head loss within the filter bed can be measured by visually inspecting water piezometers. These data are not monitored continuously, but are taken periodically. Changes in head loss within a filter bed can be studied to estimate where floc is being captured and stored within the bed. If too much filter aid polymer is used, floc strength can be so great that nearly all of the floc is captured and stored within the first few inches of the filter bed. This would cause nearly all of the added head loss to develop in the top of the bed, and measurements from head loss taps located at 6-inch (0.15-m) intervals in the bed would show where floc was stored and would indicate excessive floc strength. At plants where it is physically possible to insert head loss taps into filters at multiple locations within the filter bed, doing so would be a way to provide valuable operating information to operators. If they can be installed, piezometers are inexpensive but useful tools for evaluating filter behavior. Inside the filter bed, piezometers need to be fitted with a screen that can prevent clogging of the piezometer tube by filter media. If this is not done media can clog the tube and cause failure of this simple measuring device.

If a filter is operated for a long period of time (several hours or one operating shift) with no apparent increase in head loss, two possibilities merit consideration. At a plant employing alum or ferric coagulants, little or no particle removal is happening, which suggests ineffective filtration. For a plant where lime softening is practiced, if the particles carrying over to the filter are mainly calcium carbonate, these tiny granular particles may be accumulating to some extent in the filter bed without causing high head loss. Some lime softening plants report filter run times that could be attained in coagulation plants

only if a woefully inadequate coagulant dose were used. Being able to operate filters for extraordinarily long times before backwashing is not necessarily a sign of great operating skill or effective filtration.

Filter Head Loss Probe

Measurement and recording of bi-directional differential pressure within the filter bed is possible with the use of a filter head loss probe. This probe is used to measure water pressure at a point above the filter media, at points within the media bed and a point below the media. Measurement of head loss within individual layers of filtering material in a dual or mixed media bed is useful for evaluating where floc removal (filtration) is occurring. A large increase in head loss in the sand layer beneath the anthracite indicates that a large percentage of the floc is passing through coal and being captured in sand. This scenario would indicate modifications of the treatment process might be in order to allow for development of larger floc. A more typical scenario is a large increase in head loss in the anthracite layer but a small increase in head loss in the sand layer. This indicates removal of most of the floc in the top layer of the filter bed (surface loading). Surface loading a filter promotes short run times and inefficient filtration. Following backwash, the clean bed head loss for individual sand and anthracite layers is measured to determine if backwashing satisfactorily cleaned both layers of the dual media filter.

Figure 5.1 (provided by Roberts Filter Group) illustrates variations in head loss caused by an effluent modulating (or rate of flow control) valve that is "hunting." This behavior by a filter flow control valve can impair filtered water quality (Hudson 1981) so when it is detected and found to prevent attainment of the utility's filtered water quality goal, remedial measures are appropriate.

Figure 5.2 (provided by Roberts Filter Group) shows the data obtained at the end of a filter run, during backwashing, and upon start-up of a new run. After the filter was drained down, the backwash pump was turned on, head loss in the sand and anthracite layers increased with increasing water flow until the filter bed became fluidized. At the point of incipient fluidization, head loss becomes constant as flow continues to increase. The filter head loss probe could be used to detect fluidization of the entire media bed during backwash regardless of water temperature, filter condition or other variables.
Additionally, by keeping records of pressure within a filter bed from time to time, operators can develop a database on filter performance that may aid in detecting deterioration in filter performance with the passage of time. Such information could indicate that a filter inspection is needed.

OTHER DATA RELATED TO FILTER PERFORMANCE

Unit Filter Run Volume / Filter Productivity

The rate of head loss accumulation influences the length of a filter run. Data on filter run length merely indicate how long a filter operated before it had to be removed from service for backwashing. Long runs are not necessarily better than short runs, though. Many water utilities evaluate filter behavior on the basis of water produced during the run rather than on run length alone. If a plant has filters of different sizes (surface areas) the water produced per run has to be converted to water produced per square foot of filter per run, or Unit Filter Run Volume (UFRV) for purposes of comparing filter performance. Like the length of filter run data, the UFRV data taken alone may not be sufficient for evaluating performance. A UFRV of 4800 gallons per square foot (196 m^3/m^2) could be attained by a filter run at 10 gpm/sf (24.4 m/h) for just 8 hours (480 minutes) or by a filter run at 5 gpm/sf (12.2 m/h) for 16 hours (960 minutes). For a specified filter media design, filter run length is likely to be shorter if the filtration rate is increased. Run length in hours is a consideration when filter backwashing must be observed by an operator, as shorter runs mean more backwashes. UFRV, on the other hand, is focused on water production, and this is also quite important. Both numbers ought to be used to analyze filter performance.

The productivity of a filter may be determined by subtracting the volume of water used in the backwash sequence (top dump + backwash water passing to waste + filter-to-waste volume) from the total volume of water produced during the filter run. Evaluating the net water production of a filter accounts for backwashing and allows the operator to assess the influence of backwashing practice on water production.

By keeping records of unit filter run volume and net water production for each filter in the plant, operators will be able to look for and detect long-term, subtle changes in filter performance that might not be noticed simply by looking at day-to-day performance. For example, differences between performance in summer versus winter might become apparent. Substantial reductions in UFRV might be caused by an algae bloom or by air binding. Overdoses of filter aid polymer could cause excessively strong and tenacious floc to plug filters, and such floc could be quite difficult to wash out of the filter beds during backwashing. Washwater usage would also increase if filter-clogging algae caused short filter runs and long backwashes to remove floc and algae from the beds. Use of abnormally high backwash water volumes should alert operators to check pretreatment practice with regard to polymer

usage. Maintaining long-term records of filter performance is the key to effective use of data on water production and backwash water usage.

Rate of Flow in Filter

Regardless of the flow control system used in a treatment plant operators need to know the rate of flow of each filter. Operators at plants that use influent flow splitting on rapid gravity filters could calculate the rate of flow for each filter based on the rate of production for the plant, if it is known that the flow splitting to each filter is equal. All plants using effluent rate of flow control without equal influent flow splitting would need a flow meter for each filter. Some states set limits on filtration rates that depend on the type of water being filtered and the design of the filter media in the beds.

Some pressure filtration plants have been designed with two or more filters operating in parallel. When water flows through this kind of plant, the head loss will be the same for each operating filter. If the plant is not equipped with a flow meter on each filter, the distribution of flow in the filters and the rate of flow for each filter will not be known. In this situation, filters have become clogged, resulting in cleaner filters operating at a rate exceeding the design filtration rate. Operating filters at excessively high rates can cause water quality problems, so flow measurement is really needed for public health protection as well as for operational control.

Flow rate data are useful for operational reviews and may be needed for regulatory compliance, so such data must be recorded and saved in a format facilitating retrieval.

Flow rate should be monitored to detect hydraulic shocks from flow rate step changes which can dislodge retained deposits, to measure UFRV, to evaluate slow starts (most flow control valves do not have linear flow characteristics), and to detect if changing from filter-to-waste to filter to supply causes flow rate step changes.

Flow meters must be fitted in accordance with manufacturer's instructions with respect to both pipe geometry and provision of upstream and downstream straight pipe lengths to avoid unusual turbulent flow patterns in the measuring device. Where this is not possible it is advisable to check the error that will accrue using a test apparatus. Some flow meters require inserting equipment into existing pipe runs (e.g. magflo meters, pitot flow meters, orifice plates) but there are ultrasonic time-of-flight devices which can be clamped onto the outside of existing pipes.

Flow meters calibration can be roughly checked *in situ* by carrying out water level drop tests, as described in Chapter 12.

Temperature

Temperature influences water treatment in many ways, even entering into the regulatory compliance arena in terms of disinfection and attainment of required CT values (residual disinfectant concentration in mg/L, C; and contact time in minutes, T) used for evaluating the efficacy of disinfection in the United States. Temperature could be measured periodically at small plants using a graduated thermometer and manual recording of results, but at larger plants use of automated measuring and recording of temperature will save labor and time. Temperature data are useful in selecting the optimum pH for alum coagulation, for evaluating clean bed head loss in filters, for considering how to optimize flocculation, for adjusting backwash water flow on a seasonal basis, and for evaluating disinfection. For the latter reason, temperature data must be recorded and saved in a format that facilitates information retrieval.

Temperature data are required to determine water viscosity for calculating flow and temperature normalized filter starting head loss as a means of checking backwash effectiveness (see Chapter 6).

Changes in Chemical Quality through the Filter Bed

At lime softening plants, water quality changes occurring within a filter bed sometimes indicate the potential for changes to the filter media. If lime-softened water is not stable when it is filtered, but instead is supersaturated with calcium carbonate, some calcium carbonate may precipitate onto the filter media. When calcium carbonate solids form on filter media grains, the grain size gradually increases. Filtration effectiveness may be decreased if the media becomes too large in diameter. In extreme cases, the media can be cemented together in the filter bed, making the filter difficult or impossible to backwash.

At filtration plants where calcium carbonate encrustation of filter media is a concern, the filter influent and effluent can be sampled and analyzed for total alkalinity, carbonate alkalinity, or calcium hardness. The Ohio EPA (1999) recommends that the total alkalinity or carbonate alkalinity decrease across filters (expressed as mg/L) should be less than the quantity (5 divided by the filter loading rate in gpm/sf). This concept is not dimensionally consistent, that is, units are ignored. For a filter operated at 5 gpm/sf, the alkalinity drop should be less than 5/5, or less than 1 mg/L. For a filter operating at 2.5 gpm/sf, 5/2.5 = 2, so the alkalinity drop should be less than 2 mg/L. *Standard Methods* (APHA 1995) indicates that when alkalinity is in the range of 10 mg/L to 500 mg/L and is from carbonates and

bicarbonates, a standard deviation of the test measurements of 1 mg $CaCO_3$/L can be achieved. Thus to use the analysis of alkalinity drop as recommended by Ohio EPA, a water utility's laboratory analyst would have to be very careful and precise, and multiple analyses would be required to assess such a small change in alkalinity. The concept of measuring alkalinity drop through a filter bed might be more useful during a period of water quality upset, to determine whether the stability of the water applied to the filters was satisfactory. A large deviation from the Ohio EPA's recommendation could signal a serious potential for calcium carbonate encrustation that required quick attention to prevent media growth or cementation.

One water utility reported that a meta-phosphate product was used to avoid calcium carbonate precipitation on filter media.

Figures showing the effects of unwanted deposition of calcium carbonate precipitates are presented in Chapter 8.

Particulate Matter Passing Filter

Filtered water can be analyzed for particulate matter that passes the filter bed, with the goal of developing information on filter performance. About a half century ago, John Baylis at the South Filtration Plant in Chicago advocated doing this using cotton plug filters. Technology has advanced greatly since then, and a number of options are available today. Monitoring filters for passage of particulate matter now can be done with different levels of cost and with different kinds of data output. One technique used by some utilities is the Microscopic Particulate Analysis (MPA). Another is the direct total microbial count. Still another, used at one water utility, is the "daily patch."

Hancock et al. (1996) described a procedure for the MPA, and concluded that this procedure is an effective tool for assessing plant performance. Use of the MPA procedure provides data on the kinds of biological particles that are passing the filter and the kinds 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.

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 as a means of 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, 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 on line 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 a 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.

The procedure for direct total microbial count is found in *Standard Methods* (APHA 1995), Method 9216. An epifluorescence microscope with magnification capability of 1000X is used to examine a polycarbonate membrane filter after a water sample has been filtered and acridine orange stain has been applied. Details are given in *Standard Methods*. This procedure can be used to detect both viable and non-viable bacteria, so it is applicable even when disinfection is carried out before filtration. Methods of bacteria detection that require culture of organisms are applicable only if disinfectant has not been used or if the bacteria is resistant to disinfection. Comparison of direct total microbial count in raw water and filtered water can be used as a measure of filter performance. A single test can be done in 20 to 30 minutes, according to *Standard Methods*. As an operations monitoring test, this procedure may be applicable at utilities that are large enough to afford the epifluorescence microscope and a staff microbiologist or microbiological technician who would check some raw and filtered water samples on a daily basis.

Another microbiological assay appropriate for evaluating filtration performance involves aerobic spores and *Bacillus* spores. Use of indigenous aerobic spore-forming bacteria for evaluation of treatment plant performance was first suggested by Rice et al. (1996). Spore-forming bacteria consist mainly of species of *Bacillus* bacteria and are ubiquitous in soils, so they are found in surface waters. Rice et al. reported that aerobic spores were found in abundance (1000 or more per mL) in many source waters. Often these bacteria are present in source waters in sufficient numbers that 3-log removal of microorganisms (the spores) can be demonstrated at filtration plants where chlorine is not applied until

after filtration. Analytical procedures for aerobic spores were presented by Nieminski and Bellamy (2000), who reported that analysis of aerobic spores in source water and filtered water could be used as a measure of plant performance. When source waters have high concentrations of the spores, log removal calculations can be performed. According to Nieminski and Bellamy, the analytical procedure costs about $25 per sample.

The "daily patch" technique has been used for over two decades at the Chester Water Authority. A 0.45 μm membrane filter of the type used for coliform analysis (Gelman or Millipore) is placed with the plain (ungridded) side up on a vacuum filter apparatus. A 1-liter sample of filtered water from the treatment plant is filtered through the membrane, which is then allowed to air dry. When dry the membrane filter is taped on a piece of white paper, using clear tape, and examined for daily variations in color. Membranes need to be saved so long-term comparisons can be made, and to enable utility personnel to develop an understanding of a "normal" result and one that should raise a red flag. If the "patch" is anything but white, Chester Water Authority personnel follow up with other checks and tests. For example, a yellow tint on the membrane would cause follow-up activities such as analysis for aluminum, iron, or manganese in the filter effluent. The patch test is not a standardized method, but it is a very inexpensive procedure by which treatment plant personnel could build up a database over time. As indicated in the information provided for this project, the value of this procedure is to identify times when further testing and investigation may be appropriate. The only equipment needed for this procedure is the vacuum filter apparatus used for coliform analysis, and a supply of membrane filters. This low-budget performance monitoring test should be affordable for even very small water systems that treat surface water. For such systems it could supplement turbidity monitoring, which is a required activity.

Other utilities also reported using variations of a patch test. Ann Arbor uses a similar test to examine filtered water for the presence of carbon fines in the filter effluent, particularly after installation on new GAC in a filter bed. When feeding potassium permanganate, the Clackamas River Water District passed a small stream of finished water through a clean cotton diaper. The volume of water required to cause a manganese stain on the diaper in the "patch" test at the treatment plant would be the equivalent of the water exposure attained by a very large number of household launderings of the diaper, when permanganate was dosed properly.

MANAGEMENT OF MONITORING INFORMATION

The Appropriate Use of Alarms

Whether a plant has two filters or 100, an operator's job can not consist of just sitting and watching the output from the continuous turbidimeters, particle counters, head loss monitors, and flow meters. Data from these instruments need to be stored for a variety of purposes including regulatory compliance and operational review. Furthermore the system has to have built-in alarm mechanisms to alert operators to potential problems, especially those related to rising turbidity or particle count in filtered water.

Alarms can be used to alert operators to situations in which a treatment plant's internal water quality goals are not being met, as well as to alert operators to incipient regulatory compliance failure. If alarms are set to alert operators after a failure has occurred, they are less valuable than if they are set to warn of approaching problems. In the latter case, the operator may have time to take action and prevent the occurrence of compliance failure.

In the United States, set points or trigger values for alarms might be related to regulatory requirements. For example, to avoid exceeding 0.3 ntu in combined filter effluent, plant staff might set the alarm at 0.3 ntu for the turbidimeter installed on each filter. At plants where management has determined to meet the filtered water turbidity goal of the Partnership for Safe Water, turbidimeter alarms would be set below 0.1 ntu for each filter. The goals and trigger values are a matter for discussion at each water utility that treats surface water or ground water under the influence of surface water.

In the U.K., as a result of The Water Supply (Water Quality)(Amendment) Regulations 1999 SI No.1524: Cryptosporidium in Water Supplies, and accompanying advice from the Drinking Water Inspectorate, operators are required to operate filters with due diligence and regard to best operating practice, and are expected to minimize filtered water turbidity. In this way the regulator expects that a well designed and operated treatment plant will achieve the treatment standard of less than one *Cryptosporidium* oocyst in 10 liters based on continuously sampling 1000 liters of treated water per day. The Bouchier (1998) report stated "it is understood that the proposed treatment standard has been derived from experience of routine samples in which the concentrations found in water treated according to accepted good practice were at least an order of magnitude lower than 1 oocyst in 10 liters and there was no increase in cryptosporidiosis in the community. The Group further understands that the

information available on infectivity, although limited, indicates that an infective concentration is at least an order of magnitude greater than 1 oocyst in 10 liters".

Keeping alert to the detailed performance of a bank of filters represents a significant challenge to an operator, who is often working alone with a multitude of tasks to perform. It is important that process and control engineers give the operator suitable trending and alarm tools on supervisory control and data acquisition (SCADA) systems, based on realistically achievable targets, so that the operator is really in control of the process. A user requirement specification has been drawn up in Thames Water to develop modifications to SCADA packages to produce tools for the operator and investigator (see Appendix 1 at end of this chapter).

Statistical Process Control

A detailed report has been produced by UKWIR (1999) which runs to 63 pages, and covers developing a statistical basis for setting turbidity alarms, based on percentiles derived from real operational data.

The report also describes using Cusum charts to determine over a period of time whether an individual filter produces filtrate turbidity that differs from the mean turbidity of a bank of filters. This may enable preventative maintenance to be undertaken before water quality deteriorates to unacceptable values.

Another comparative tool described by UKWIR (1999) was the box and whisker plot where maximum, minimum, median or mean, and upper and lower percentile data are plotted side by side for all the filters. The time period for this display could range from the current filter run, the last complete filter run, to maybe a week or month's worth of data or even longer. This again provides a tool to check overall plant performance, and whether an individual filter or its turbidimeter requires more detailed examination.

Trigger Values

Use of trigger values for alerting operators when to take action involves consideration of a number of issues: the regulatory standard; the plant goal; current performance; and what constitutes an abnormal or trigger event.

A careful examination of historical plant operating data will enable a statistician or other person with access to standard spreadsheet packages with statistical tools to determine "normal" plant operation, and to check whether there are seasonal variations to take into account. For each month "warning" and "action" trigger values can be set, based for example on the 95th and 99th percentile values. These could be rounded to the nearest 1/10th of a turbidity unit for ease of use. It is also important to determine how long these values have to be exceeded continuously before the alarm is sounded.

The UKWIR (1999) advised that during the ripening phase the normal alarms are muted and a second set of "peak" triggers are used. Furthermore a "low" alarm was recommended to highlight turbidimeter failure.

Cusum

The cusum chart recommended by UKWIR (1999) is generated by calculating the mean daily turbidity from a bank of filters and the individual filter mean daily turbidities. The difference between the individual filtrate value and the bank value (or a fixed target value) is calculated. These values are calculated each day and summed. The cumulative sum is plotted over time. In normal operation a filter is likely to randomly better or exceed the mean bank performance and the cusum will be a value around zero. A poor filter will regularly perform worse than the mean and so its cusum will increase with time.

An example of the CUSUM is given in two graphs. Random daily mean filtrate turbidity values between 0 and 1 ntu were generated in MS Excel for 20 days. These random values were then fixed. On filter 4, after ten days this value had an extra 0.1 ntu added to it, increasing by 0.1 each day till by day 20 the random value was increased by 1.0. The mean for all four filters was calculated for each day. The raw data are shown in the Figure 5.3 below.

It is possible to see from this graph that perhaps there was something wrong with filter 4 around day 15. The next graph, Figure 5.4, shows the same results plotted as CUSUM data, i.e. the cumulative differences from the mean. The random nature of the data mean that by chance filter 4 had outperformed the mean value up till day 10. The change in gradient when the data started to be corrupted at day 10 is very marked. It is this change in gradient that would alert a statistician to prompt an investigation into what was going wrong. In this example the backwash could have been progressively failing or there might have been a drift in the instrument. The advantage of using these statistical charts is apparent in Figures 5.3 and 5.4.

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APPENDIX 1: USER REQUIREMENT SPECIFICATION FOR GETTING THE MAXIMUM BENEFIT OUT OF ON-LINE TURBIDITY DATA USING SCADA PACKAGES. (PREPARED BY THAMES WATER UTILITIES STAFF)

Introduction.

This document details a user requirement specification for additional trends, mimics, alarms, and statistical performance analysis for SCADA systems.

It is anticipated that these tools will be expanded and developed over time and therefore flexibility and expandability need to be considered during the design and implementation of this work.

Background

The Badenoch and Bouchier reports make clear the need to have on-line continuous monitoring of rapid gravity filter (RGF) effluent, when these filters are used following chemical dosing as the primary barrier to pathogen passage. This includes filtration after clarification by sedimentation or flotation, coagulation/filtration (in-line filtration) and coagulation/flocculation/filtration (direct filtration).

The burden is on plant operators to use the data coming from these instruments in real time, and to note the behavior of the filter. In essence they must be able to distinguish between normal operation, and abnormal operation, and in the event of abnormal operation be able to take prompt corrective measures. Failure to "fly" the works in this way may be seen as lack of "Due Diligence".

The DWI's stated belief is that the *Cryptosporidium* events in the U.K. were all related to occasions when treatment works were not being operated correctly and that turbidity data showed this to be the case. It follows that managing filtration with a careful eye on filtrate quality will help minimize the risk of a *Cryptosporidium* incident and would put the water utility in a stronger defensive position if one occurred.

This puts pressure onto the front line operations staff. Instantaneous spot turbidity data, such as can be displayed on one page of a SCADA screen, are of little meaning in themselves; only trends of the full filter cycle can reveal what is taking place. However, in a busy treatment plant, with current levels of manning, and current SCADA systems, it is impossible to find the time to monitor constantly page after page of SCADA trend data.

This package of work shall provide tools that can carry out plant monitoring automatically, on line, and the ability to download the stored and derived data for off-line analysis. The off-line analysis (by others) will provide the correct alarm levels for the new software. This document consists of a set of user requirements to make the most of on-line turbidity data.

User Requirements

1. Filtration should be considered a batch process. The unit filter run is the basic data block. Performance statistics are derived from analysis of individual filter runs. (This makes interpretation of operational data much easier than the continuous data coming out from a clarifier or chlorination plant for example).

2. Each filter run begins upon successful completion of a backwash. It lasts until the next backwash is initiated.

3. Each filter run should have a unique **identifier tag** so that the associated data can be processed together. The tag should include "Site: Filter Number: Year: Run number".

4. The run number will increase by 1 every time a backwash is successfully completed i.e. all steps and valve movements have taken place in the correct sequence, for correct duration, and water and air flow rates have been as required. The counter to increase when the inlet valve reopens. The counter to be reset to 1 after the successful completion of the first backwash after the start of every year. It is likely the number of runs per annum will fall in the range 200 - 1000, (based on run times varying from 8 to 48 hours).

5. There should be a **filter status flag** (integer) set for each filter for ease of interpreting data: this should show whether the filter is:

   Status 1) Filtering to waste or recycle (i.e. filtered water does not go to supply) NOTE: Filter-to-waste may be retrofitted on plants so this flag should be provided on systems even if filter-to-waste is not currently practiced;

Status 2) Operating to supply (including draining down prior to a backwash if this water goes to supply);

Status 3) Backwashing (including drained and waiting for a wash once filtered water valve is closed. Also includes refilling whilst outlet valve remains closed);

Status 4) Out of service (Filter not operating for any reason, including if a turbidity meter, head loss gauge or flow meter unit is off-line or being repaired.)

Note

Normally during calibration the turbidimeter will have a "hold last value" set on the instrument itself by the person performing the calibration. For this reason a calibration flag is not required.

If a turbidity meter is off-line or being repaired the filter should not be operational. This is for information - an interlock is not required.

6. The SCADA data for each filter run should be capable of being parceled up into discrete packages containing the following data, based on one minute sample frequency. Data files shall have unique identifiers (Site: Filter Number: Year: Run number.dat) and be capable of being downloaded via floppy disc (zipped if necessary) or WAN. There are two reasons for this a) so that data can be analyzed off-line by experts using packages such as EXCEL, and b) for the production, on-line, of process performance statistics (see 7 below): The filter status flag shall enable each filter run to be examined in detail, so that for example turbidity measurements recorded during backwashing and filter-to-waste are not incorporated into statistics of process performance for water quality going into public supply.

   Data to be Collected:

   a) Identifier tag (see 3 above);
   b) date

c) time

d) elapsed filter run time (hours)

e) filter status flag (see 5 above)

f) influent pH (after coagulant dose and pH correction)

g) coagulant dose (mg/L)

h) polymer dose or pump status

i) influent coagulant residual (mg/L)

j) pre-oxidant dose (mg/L)

k) common influent turbidity (ntu)

l) filtrate turbidity (ntu)

m) flow rate (ML/d); (of filter)

n) filtration rate (m/h)

o) actual head loss (m)

7. SCADA should be programmed to present the following statistics for each filter run, based on data sampled at one minute time intervals.

   a) Mean flow-and-temperature-normalized head loss measured across the period from 30 to 60 minutes (at 30 second intervals) after the filtrate outlet valve moves off its closed limit following the completion of a backwash : each filter run will produce one datum point by calculating the mean of these 60 values and these data will be used to produce a long term filter starting head loss trend for each filter to report on media condition and backwash efficiency.

There shall be a facility to store this information for a minimum of 2 years. Trends shall be set up to display this information using a default window of 6 months.

   b) Filter run turbidity statistics for when filter status flag shows the filter was operational (Filter status flag = 2):

      a) mean,

      b) maximum,

      c) minimum

      d) median (50%ile),

e) variance (s^2),

f) 95%ile (i.e. 95% of turbidity values lower than this during the filter run),

g) 90%ile,

h) 40%ile

i) ratio of 90%ile/40%ile. (This latter value shows the degree of spread across the data and is analogous to the Uniformity Coefficient used to describe filter media size).

j) %ile of values <= 0.30 ntu (turbidity value to be operator enterable with sufficient security access)

k) %ile of values <= 0.20 ntu (turbidity value to be operator enterable with sufficient security access)

l) %ile of values <= 0.10 ntu (turbidity value to be operator enterable with sufficient security access)

m) % of filter run time when turbidity > 0.20 ntu (turbidity value to be operator enterable with sufficient security access)

c) There is also the need to present one filtrate turbidity statistic from either filter-to-waste or operational period (Filter status flag = 1 or 2): this is the peak value of turbidity in the first two hours of filter operation, following the opening of the filter outlet valve at the end of the backwash (shows magnitude of initial ripening spike)

d) Productivity or unit filter run volume (UFRV m/run i.e. cumulative volume of water (m^3) produced per m^2 of filter area per run)

8.

a) The SCADA display shall be set up so that one overview page shows in summary the quality of the filtrate turbidity from each filter, from both the current runs and a brief summary of the previous run for each filter. Colour is the key indicator, details are written within each coloured box. Figure 5.3 gives an example of how the performance of each filter might be presented on a one page SCADA mimic summary table. This page then allows access to trends of the current run (i.e. the normal trend facility), and to a second page (see Figure 5.4) showing detailed statistics of the previous run, as detailed in sections 7a), b), c) and d) above, and access to long term trends of the performance statistics.

b) A coloured border shall surround each of the statistical tables for each filter. The operating statistics are compared with performance triggers. If the statistics are acceptable then the border shall be green; if the statistics are marginal, requiring the operator to look in detail at trend data the border shall be yellow; if the statistics show the filtrate quality to be unacceptable then the border shall be red.

c) The performance triggers shall be operator enterable. One set of triggers will apply to all the filters on a plant. There shall be a lowlow, low, high and highhigh trigger for each derived statistic (N.B. separate values for current mean turbidity and historical mean turbidity are required). If any of the parameters exceed the low or high limit the yellow border shall be displayed. If any of the parameters exceed the lowlow or highhigh limit the red border shall be displayed. These trigger values shall be recorded once every 24 hours.

d) Colour change on the current run filter boxes shall only be enabled during filter operating periods(status=2) thus avoiding false alarms during backwash, run to waste, etc. The current value will show actual turbidity as sent from the turbidimeter. The mean value will show the arithmetic mean of data from the current filter run. During a backwash / filter-to-waste period it will hold the mean from the immediately preceding filter run. A text line will show filter status.

e) If the box around the current data for any of the filters changes from green to yellow or from yellow to red then an audible alarm should be sounded and a reason written to the SCADA alarm system.

9.

a) There shall be trends and SPC (Statistical Process Control) charts of the statistics generated in 7a), b), c) and d). These data will be used as tools to monitor long term performance and condition of each filter. There shall be a facility to store this information for a minimum of 2 years. Trends and SPC charts shall be set up to display this information using a default window of 6 months. An example of a long term trend would be the normalized starting head loss described in 7a) above

b) The Statistical Process Control charts of the statistics generated should include the X bar chart , Range chart and the Cusum chart. The Operator would be able to enter the group size, action and warning limits.

c) There is currently no requirement to calculate or display turbidity removal data (log or %), or specific analysis of ripening statistics. The system shall not preclude the addition of these parameters at a later date.

10. SCADA process trends and SPC charts should be shown on computer screens as coloured lines on a dark background. It is preferable that the computers be configured so that graphs can be printed as coloured lines on a clear/white background without having to re-draw screen trends. Units shall be displayed and printed for all parameters on trend graphs.
11. A historical interrogation function shall be provided. The example in figure 5.5 shows that the operator shall be able to enter a date and time and the system will display the statistics for the filter runs that were taking place at the time specified.
12. Example screens are presented below in figures 5.3, 5.4, and 5.5 showing the current overview page, the immediate preceding filter run page and the historical page for a 4-filter works. The overview page must be limited to one screen. There may need to be more than one preceding run and historical run page where there are many filters and more screen space is required. The SCADA should allow clicking on the poke point to take the operator to the appropriate trend graph, showing influent and effluent turbidity, head loss, flow rate, pH, coagulant dose and pre-oxidant dose data for the relevant run. The reader should imagine that the boxes in Figure 5.5 -5.7 are shown with colored borders where green is OK, yellow is ALERT and red is ALARM, similar to traffic lights.

These are examples only to help illustrate the points made in the text. The Contractor shall develop the layout of the mimics making good use of color and visual components available on the SCADA system in agreement with the Client. These example pages should be viewed in color.

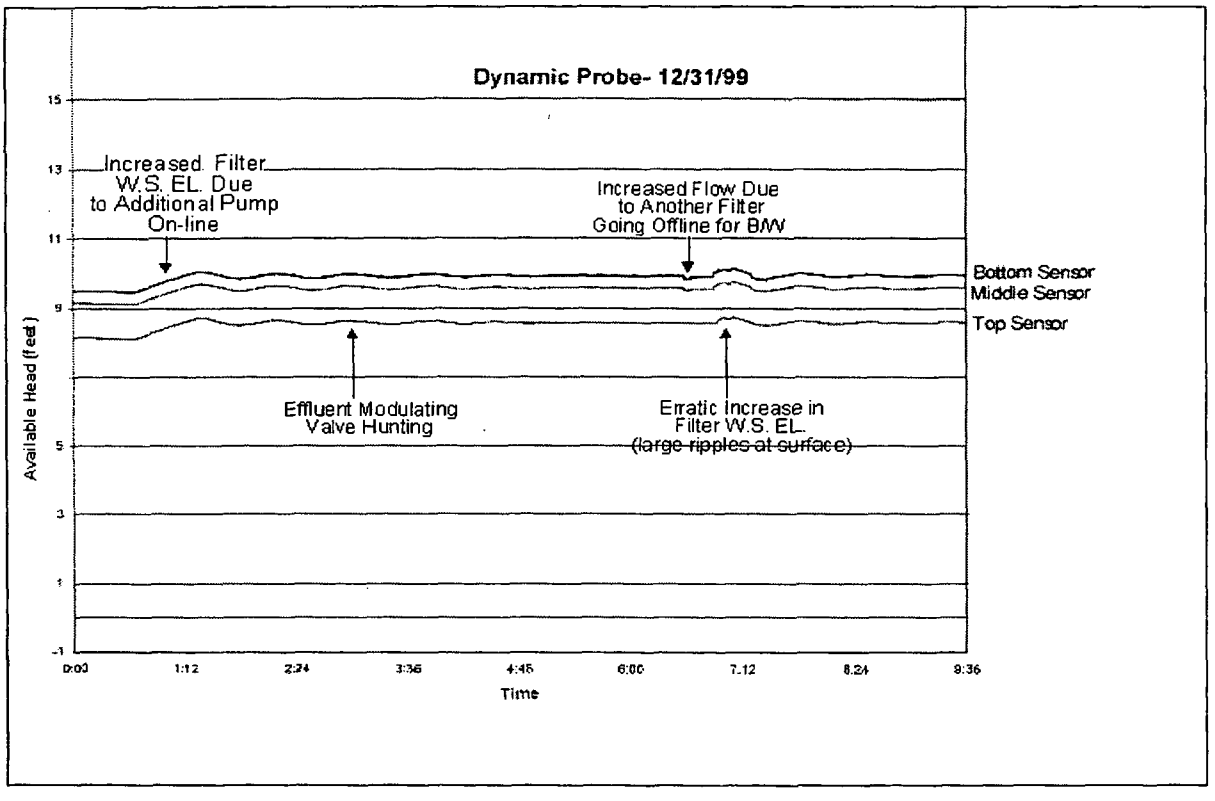

Figure 5.1 Data from head loss probe showing variations caused by filter effluent valve hunting (*Source:* Robert Filter Group June 2000)

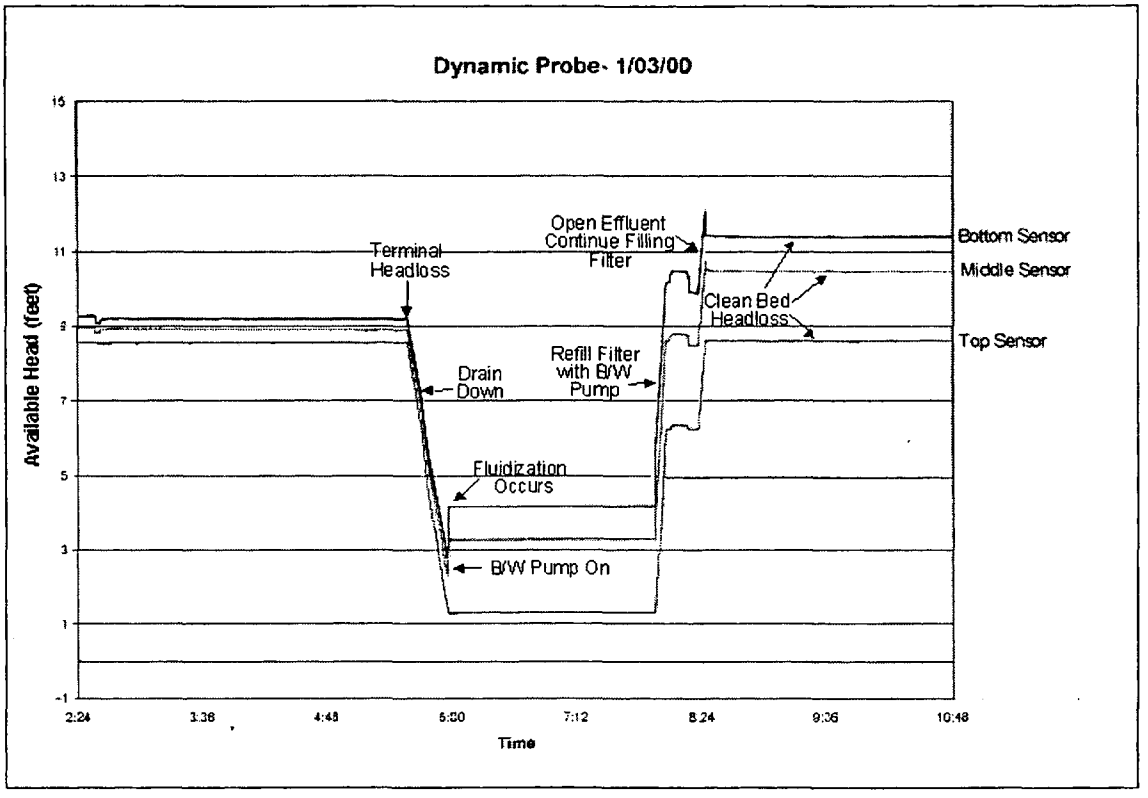

Figure 5.2 Data from head loss probe showing changes during backwash cycle *(Source*: Robert Filter Group June 2000)

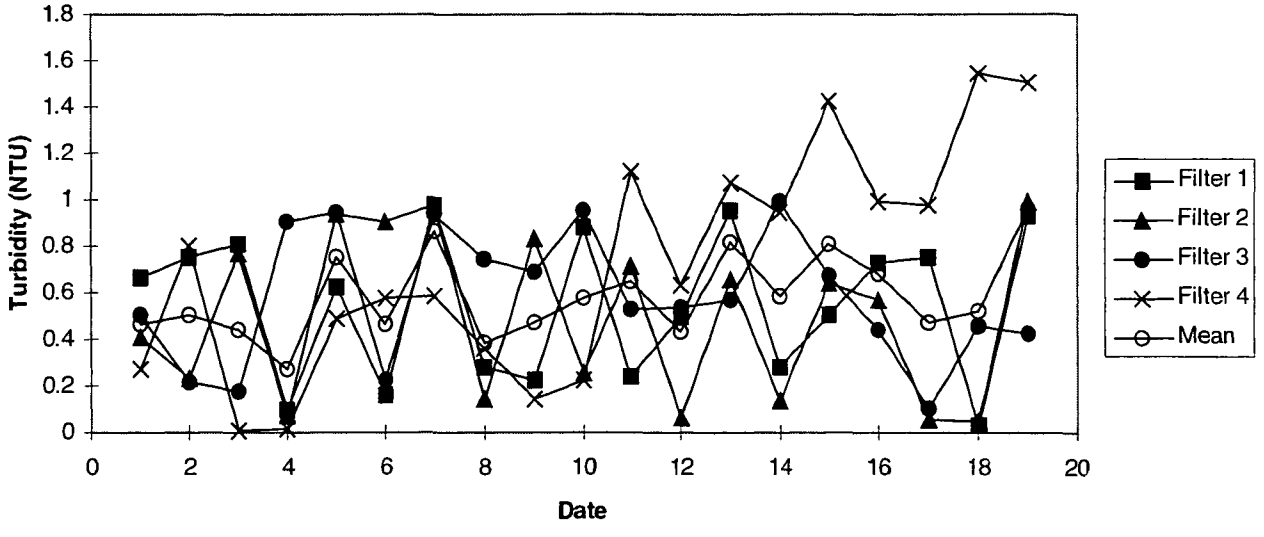

Figure 5.3 Simulated daily mean filtrate turbidity

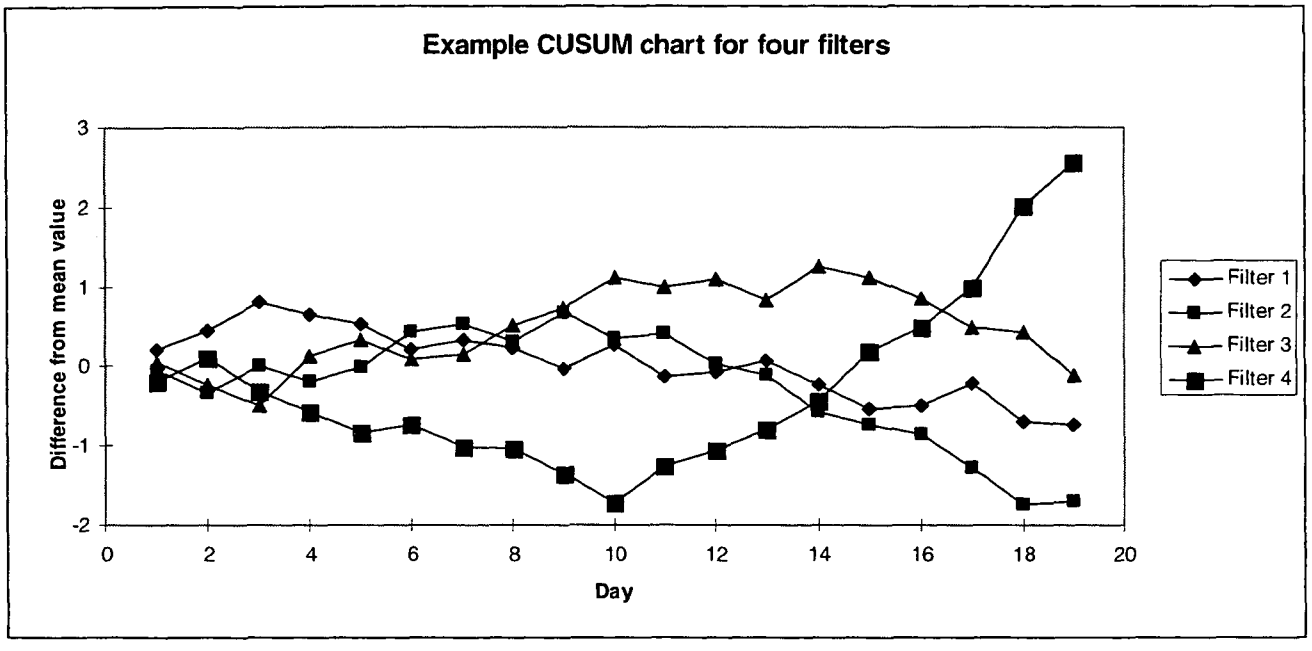

Figure 5.4 Example CUSUM chart for four filters

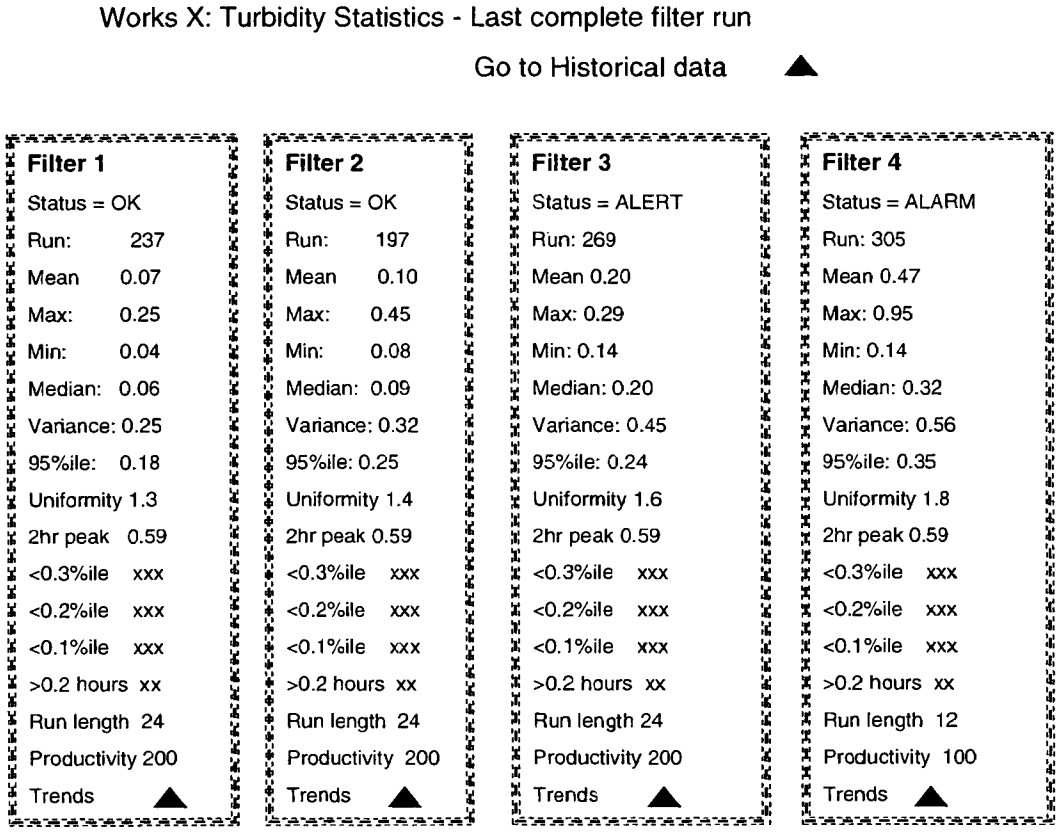

Figure 5.5 Example of overview data page.

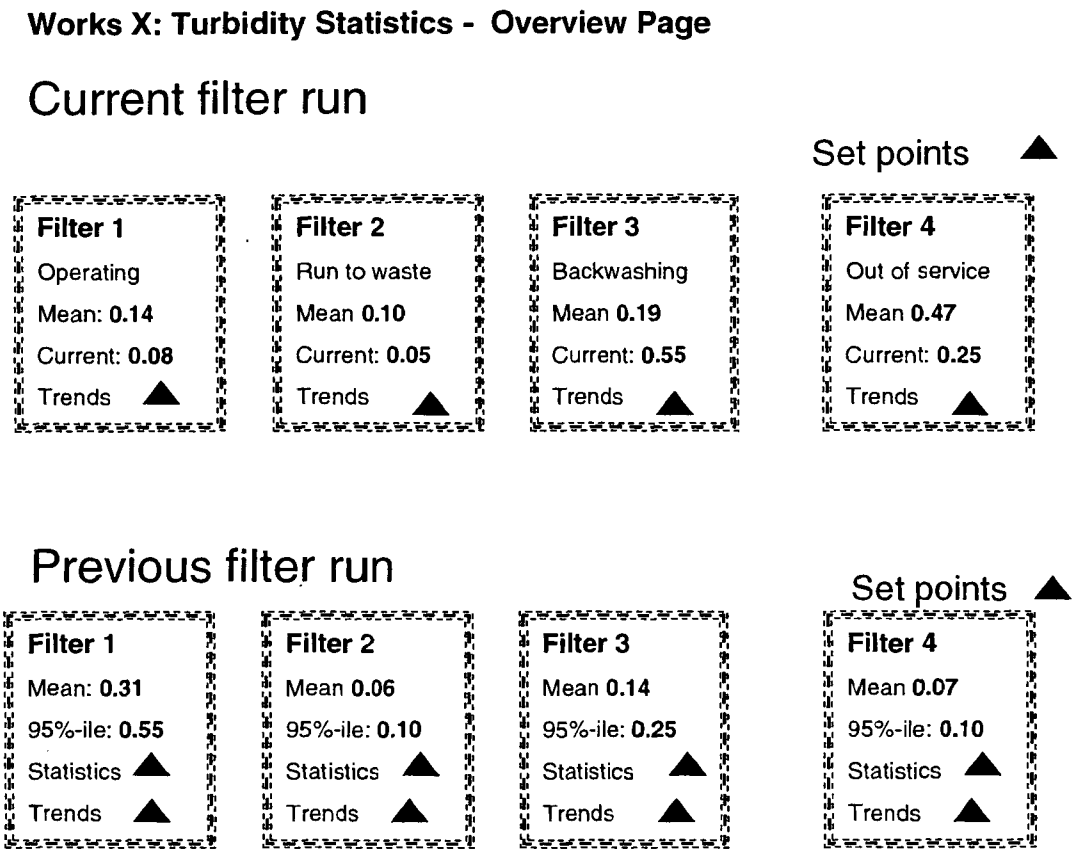

Figure 5.6 Example of last complete filter run data screen

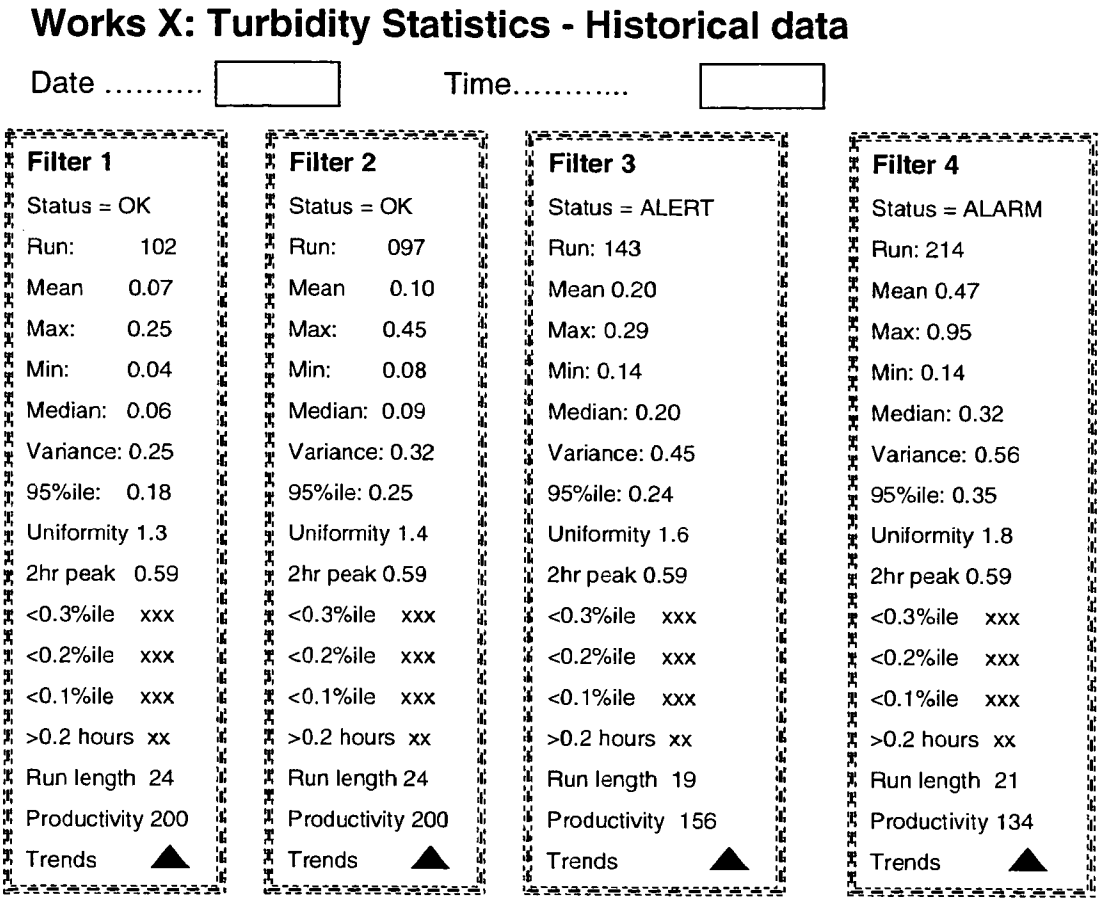

Figure 5.7 Example of historical data screen.

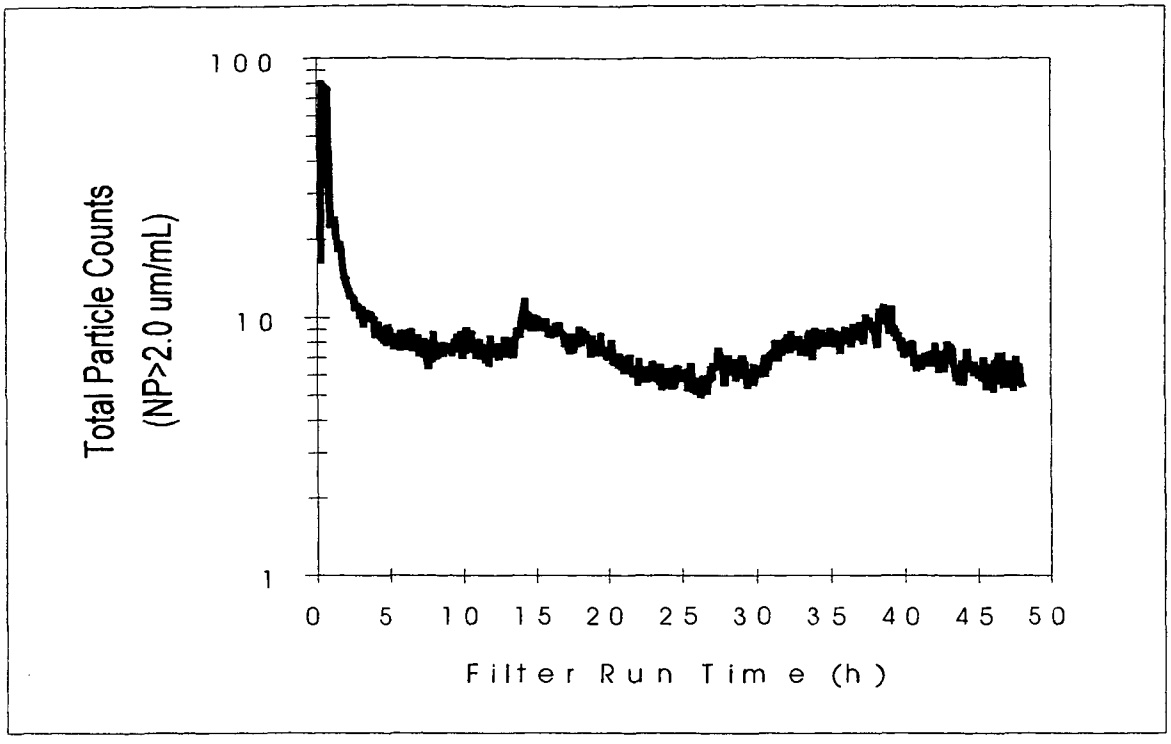

Figure 5.8 Total particle counts during a filter run (*Source*: Calgary Waterworks 2001)

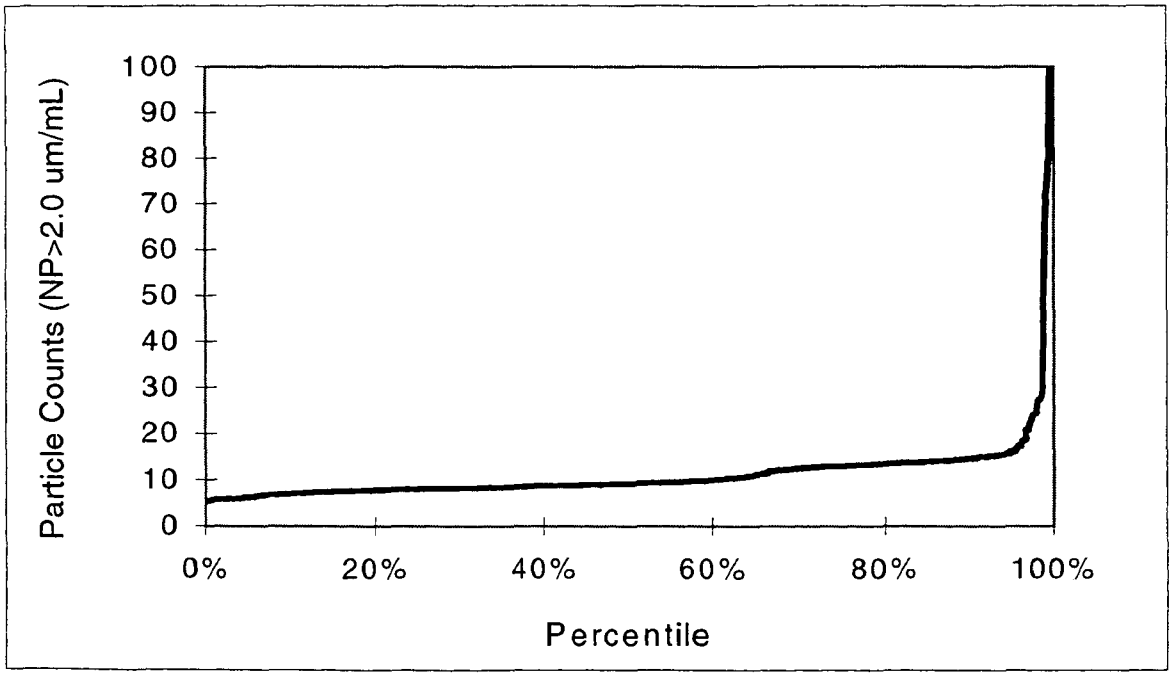

Figure 5.9 Particle counts during determined percentile of a filter run (*Source*: Calgary Waterworks 2001)

CHAPTER 6
BACKWASH MANAGEMENT AND OPTIMIZATION

INTRODUCTION

This chapter describes the filter backwashing process. The importance of observing filter backwashing as a means of detecting problems with the filter is emphasized in the first part of this chapter. Concepts of backwashing are discussed, including fluidization of granular media beds, the importance of auxiliary scour, and the relative efficacy of surface wash and air scour. The effect of temperature on fluidization is explained to demonstrate the importance of adjusting the rise rate in backwash in accordance with water temperature. Procedures for filter washing with surface wash and filter washing with air scour are recommended, and concepts related to scheduling filter washing are presented. Techniques for evaluating the effectiveness of filter washing are reviewed. A brief discussion of recycling or treatment of backwash water may be found at the conclusion of the chapter.

The objectives of backwashing are:

- to remove deposits from the surface of the filter material grains and to transport these out of the filter so as to recover the available voids for particle deposition and obtain a satisfactory back-to-service ("starting") head loss;
- to remove or prevent the growth of "permanent" undesirable biological or chemical deposits on the filter media, while allowing some degree of biological or chemical "maturation";
- to prepare the filter for the subsequent filter run; this can mean restoring media stratification in multi-layer filters, and might involve dosing extra chemicals to prepare the media or the influent water (Cranston and Amirtharajah 1987).

ROUTINE BACKWASH OBSERVATION

The most complex and equipment-intensive aspect of filter operation is backwashing. From the termination of a filter run, through washing, to the initiation of a new filter run, in a typical filter several valves must be actuated, pumps may be used to provide backwash water, and air compressors may be operated to provide air for air scour.

Although filter backwashing can be automated, the complexity of the process increases the possibility for problems, so some operator attention should be given, even if the complete backwash cycle can be handled by pushing one button or by clicking on a single computer command.

When downward flow out of the filter stops at the end of the filter run, operators need to be alert for release of bubbles that result when air is trapped within a filter bed during the run. When water is cold, or when source water is supersaturated with oxygen as a result of an algal bloom, air binding can take place within the filter bed. At the end of a run, when the downward flow of water ceases, air might be released and bubble up. Figure 6.1 shows an operator raking the bed of a package plant to release air before backwash. If a filter has become air-bound, delay starting the flow of wash water until the bubbling ceases, as the combination of backwash water flow and air release could disrupt media or wash it out of the bed. Additional air probably will be released at the onset of backwash if air binding had occurred in the prior run.

In some plants, if air can get into backwash piping, it can be released at the start of a backwash. The abrupt influx of excess air can damage filter media and supporting gravel, and this could even be damaging to the filter bottom. Again, this is a reason for the operator to carefully watch the beginning of a filter wash.

Observation of the initial stages of backwashing is important for any open, gravity filter that can be observed by the operator. Most filters employ some type of auxiliary scour, either surface wash with water, or air scour. When rotary sweeps are employed for surface wash, they should be briefly observed to be sure that they are turning properly, at the intended number of revolutions per minute. Rotation that is slower than normal could be caused by clogged nozzles or by a leak in washwater piping or in a valve. If air scour is used, it should be observed for uniformity of bubbling action all across the bed. Air scour may be observed to start from specific areas of a filter bed depending on the engineering detail of air distribution systems. However once the full bed area is being air scoured, the operator should note any unusual patterns of air distribution, including areas of low activity or no air bubbles or areas of violent boiling.

At the initiation of water wash, operators may be able to detect filter problems by watching for uneven upflow of water, either "boils" where the flow is excessive, or dead zones that would indicate no upflow or minimal upflow. Once the auxiliary scour has ended, the backwash water has been brought to its full flow, the operator should take time to observe the filter and check for possible problems. Even distribution of flow over backwash troughs is important to even upflow of the backwash water and optimal backwashing. A dislodged or unlevel trough can be found through visual observation of flow

over the troughs after the backwash rate has stabilized. Observation of peak washwater flow, wash time, and overall flow pattern should be performed to ensure consistency between washes. In some plants, underwater lights are used to evaluate the clarity of the water at the end of the wash. Visual observation of the washwater in the trough just as the flow begins to decrease at the end of the wash can also be used to subjectively determine backwash effectiveness. Figure 6.2 shows a uniform and acceptable backwash. In contrast, Figure 6.3 shows a backwash in which a filter "boil" is apparent. Figure 6.4 shows surface rotary sweeps in operation, but one of the nozzles is clogged, as indicated by the absence of the streak of bubbles behind the clogged nozzle.

Checking the condition of the bed before and after backwash is very important. If the filter bed can not be seen clearly when water has been drawn down to the top of the troughs, a periodic drawdown to the media surface is recommended. Figure 6.5 shows a filter with cracks in the bed. Figure 6.6 shows cracks in the filter bed and a crack where the media has pulled away from the wall of the filter box. Water can flow through these cracks much more readily than through porous media, so high-turbidity water could be produced by a filter like this. If a filter was not checked before backwashing, such cracks would not be discovered.

Looking at the filter bed after backwashing is also useful. The bed should be clean and level, with no foreign debris on the surface. In Figure 6.7, the surface of black anthracite filter material has been covered in some places by brown mudballs. Figure 6.8 shows mudballs and some anthracite removed from the surface of the filter depicted in Figure 6.7.

After the backwash has concluded, check the washwater troughs for presence of filter media. If a backwash was too vigorous or if bed expansion was excessive and media loss occurred during backwashing, some filter media may remain in the trough at the end of the wash. Presence of media in the trough after backwashing is a good indication of the need to review backwashing procedures. GAC and anthracite filter materials may be easy to see in a backwash trough because they are black and will contrast with the color of the trough. Sand may be difficult to see when it is washed into a concrete trough because of the similar color of sand and concrete.

If problems are observed at any time during the filter washing procedure, a thorough filter inspection may be appropriate. Chapter 10 is devoted to detailed filter inspection and maintenance procedures.

BACKWASH CONCEPTS

The Purpose of Backwashing

Cleaning the Filter Media

Filter backwashing is an integral part of the operation of a rapid gravity filter, as it defines the start and end of each filter run. The principal purpose of a backwash is to remove accumulated floc and particulate contaminants trapped in the filter media during the run. In essence a backwash involves sending a flow of water upward through the filter with sufficient force to separate the accumulated deposits from the filter media and wash them to waste or a washwater processing plant. In downflow filters this water is in the reverse direction to normal operation. Backwashing has an important influence on the performance of the filter during the ripening period (Amirtharajah and Wetstein 1980). Inadequate backwash can lead to longer-term problems such as mudballs and filter media upsets. Cleasby and Logsdon (1999) stated that the "backwashing system is the most frequent cause of filter failure." The filter design and backwash sequence must facilitate removal of accumulated material and dirty backwash water but prevent media loss.

In the short term, the deposits that are not removed by the backwash may add extra load to the filter. While this extra load might help ripen the filter there have been no reported studies investigating this. Amirtharajah and Wetstein (1980) have shown that particles remaining after the backwash can pass through the filter.

In the long term, chemical (Galvin 1992) and biological (Bayley, pers. comm. 1993) deposits can accumulate on the media surface if not removed by the backwash. It is important that the backwash efficiently removes deposits to avoid the development of "mudballs" which are aggregates of dirt, media and coagulant. An excessive film of biological material and/or inorganic matter must not be allowed to develop on the media. This can bind the grains together causing the washed bed to return to service with higher head losses at the beginning of the filter run. It may ultimately lead to the development of cracks through the bed, or dead spots in the bed leading to higher localized filtration rates in portions of the bed that are not clogged (Cleasby and Logsdon 1999). Kawamura (1975a) illustrated how cracks up to 0.4 inch (10 mm) wide appeared in a filter containing "many" mud balls. Jetting (i.e., localized areas of high water upflow) may disrupt the bed structure as gravel is pushed up into the sand (Cleasby and Logsdon 1999). Depending on the filter floor arrangement, sand can then pass into the under drains or block filter nozzles. Fulton (1988) discussed problems with caking of media grains due to inadequate backwashing.

Backwashing to Restratify Multi-Media Bed versus Backwashing to Clean Filter Media

As described above, the main purpose of backwashing is to clean the filter media and remove dirt from the filter bed. When dual media filters or multi-media filters are employed, a second purpose of backwashing is to restratify the filter bed after cleaning. Restratification restores the lower-density, larger medium (such as anthracite) to the top of the bed and the smaller, denser medium (e.g., sand) to a position underneath the larger media. For example, in a dual media bed consisting of sand and anthracite, both materials will be intermixed during a vigorous fluidized backwash, especially if air scour or surface wash is also used. When the cleaning portion of the backwash cycle is completed, an upward flow of water is employed to restratify the bed, moving the anthracite to the top, over the sand. During backwashing for restratification, neither surface wash nor air scour may be operated, as auxiliary scour interferes with restratification. When a filter is backwashed to accomplish restratification, this effect is maximized if the rise rate is gradually decreased to zero at the end of the backwash cycle. Slowly decreasing the rise rate causes the maximum amount of the smallest grains of each type of filter material to be located at the top of that layer of material when the backwash has been concluded.
For effective filtration by dual media or multi-media filters, this restratification step is necessary. Restratification is attained by full fluidization, typically with a 15 to 30 percent bed expansion (Cleasby and Logsdon 1999.) Restratification is NOT necessary for filter beds of coarse monomedium sand or anthracite, so full fluidization is not needed. Cleasby and Logsdon (1999) note that bed expansion for monomedium filters may be nil. Note however, that the rise rate used for backwashing monomedium filters must be high enough to wash the dirt out of the filter box, even though fluidization is not needed.

Backwashing Methods

In an introduction to filter backwashing Cleasby and Logsdon (1999) described four methods: i) upwash with full fluidization, on its own and ii) supplemented by surface washing; and backwashing assisted by air scour, with the air either iii) preceding a water wash or iv) combined with it.

Water alone was the least effective cleaning method and combined air scour and sub-fluidizing water washing was the most effective. Methods ii) and iii) were of similar, intermediate, effectiveness (Cleasby and Logsdon 1999). The assistance provided by surface washing was demonstrated by Kawamura (1975b). Cleasby et al. (1975) showed the benefit of preliminary air scour over water-only washing, but said that this method could not prevent long-term accumulation of material coating the sand grains.

For dual media filters Cleasby et al. (1975) suggested that further auxiliary washing should be provided at the media interface.

Use of air scour increases the danger of media loss during backwashing. Some equipment manufacturers, to minimize the loss of media when air scour is used in conjunction with filter washing, produce specially designed baffled washwater troughs. Three ways to manage filter washing in order to avoid media loss were discussed by Cleasby and Logsdon (1999):

1. For filters cleaned with air scour followed by water wash, lower the water level to about 6 inches (15 cm) below the top of the washwater trough and use air scour for 1 or 2 minutes. Turn off the air and then use a low rate of water wash to remove air from the filter before using the full flow of backwash to restratify the bed. Wash until the filter is clean, with backwash water having a turbidity of about 10 ntu (Cleasby and Logsdon 1999)
2. For simultaneous air scour and water wash of fine sand, dual media, mixed media, and coarse anthracite filter beds, lower the water level to just above the level of the medium. Use air scour for 1 to 2 minutes, and then apply a gentle water wash at less than one half of the minimum fluidization velocity (explained in more detail in this chapter and in Chapter 14) while the water level is rising toward the trough. Shut off the air scour when the water level reaches about 6 inches (15 cm) from the top of the trough. This provides time for most of the air to be removed from the bed before wash water overflows the trough. When water is flowing over the trough, increase the backwash flow to fluidize the bed and finish the cleaning action.
3. For simultaneous air scour and water wash of coarse monomedium sand or anthracite having an ES of 1.0 mm or larger, turn on air scour and apply a water wash at less than one half of the fluidization velocity. Wash with simultaneous application of air and water for about 10 minutes. The washwater will overflow during a portion of this phase of backwash. After the 10 minutes of combined washing, turn off the air and continue to use water wash until the filter is clean. The water wash rate may be increased, but for coarse monomedium beds, fluidization is not needed so the wash rate generally is kept below the fluidization velocity for the medium. If this method is applied to anthracite, special baffled troughs are essential to prevent the loss of anthracite during the simultaneous air/water wash during overflow. Simultaneous air/water wash works because one effect of air scour is to break up large flocs and lowers water rates (Adin and Hatukai 1991). Wash until the bed is clean.

The utility survey indicated that 70 percent of the plants were using surface wash assisted backwash, with 80 percent of these being rotary and 20 percent being fixed nozzle systems. About 27 percent of the plants were using air scour systems, with 3 of these plants also reporting use of surface wash systems. Only one plant with conventionally built filters and the plant that employed traveling bridge automatic backwash filters did not use either system to assist the backwash.

Filter Media Expansion and the Effect of Water Temperature

All filter backwashing techniques involve the upward flow of backwash water. The upward force that causes filter media to fluidize is related to the viscosity of the wash water. Cold water has higher viscosity so the wash water rise rate for a specified percentage of bed expansion is lower when water is cold. Warm water has a lower viscosity, so the required wash water rise rate for a specified percentage of bed expansion is higher for warm water. It is advisable to change wash rate with changes in water temperature, to compensate for these changes in water viscosity. If the bed expansion is too high, media may be carried over washwater troughs and lost. If the bed expansion is too low, the filter will not be effectively cleaned. According to Baumann (1978) a temperature correction factor of 0.68 is needed when adjusting the fluidization velocity necessary to attain a 10 percent bed expansion at 77 °F (25 °C) to an appropriate value for 41 °F (5 °C). Thus if a backwash water rise rate is set for a warm water condition of 77 °F (25 °C), that rise rate would be nearly 50 percent higher than needed for cold water at 41 °F (5 °C). Failure to adjust backwash rise rates according to water temperature on a seasonal basis or in response to a 18 °F (10 °C) change in average temperature could result in media loss as temperature decreases and could cause inadequate backwash as temperature increases.

The survey of participating utilities indicated a wide divergence in practices with regard to this factor. Only about 39 percent of these utilities indicated that they adjust their backwash rate seasonally, and these utilities reported maintaining their backwash expansion within +/- 2.5 percent annually. Expansion was measured a number of ways, from visual observation against markings on the filter wall to custom made expansion measuring tools to use of Secchi Disks. For utilities that measured backwash expansion, the frequency reported was occasionally to annually.

For the other 61 percent of utilities who reported that they did not adjust their backwash rate, most reported that the media expansion was unknown or never measured, some reported they used "manufacturers specifications" and "facility design", while another group reported that they used expansion tools but reported variation in media expansion from 0 to 50 percent. Operating backwash

without checking bed expansion and adjusting rise rate as appropriate for season (water temperature) is a potential source of media loss or a possible cause of inadequate backwash. The procedure for measuring bed expansion is described in Chapter 10, and this should be done seasonally or when a significant change in water temperature has occurred.

The Philadelphia Water Department is a water utility that adjusts backwash rate to compensate for water temperature. At the Baxter Water Treatment Plant a chart is used to indicate the appropriate rate of backwash for water temperatures at intervals of 5 °F from near-freezing up to a maximum of 85 °F. Appropriate rates are presented for both the dual media used in some filters and for the sand medium used in others. The goal of backwashing at this plant is to attain a 25 percent expansion of the filter bed, and backwash expansion is measured with surface wash turned off, using the backwash expansion tool described in Chapter 10 of this manual.

Cleasby (1990) and Cleasby and Logsdon (1999) recommended that backwashing with full bed fluidization should be calculated based on the V_{mf} (velocity of minimum fluidization), the point at which the pressure drop measured as water flows up through a bed of filter media stops increasing, being equal to the buoyant weight of the media, and the bed starts to expand. They recommended that the d_{90} size should be used for this calculation. The d_{90} size can be calculated (Cleasby and Logsdon, 1999) by the formula:

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

in which d_{10} is the effective size (ES) of a filter medium (the size for which 10 percent by weight would be smaller)

d_{60} is the size for which 60 percent by weight would be smaller and

d_{90} is the size for which 90 percent by weight would be smaller.

The uniformity coefficient (uc) is defined as the d_{60} size divided by the d_{10} size.

An example of calculation of the d_{90} size is given in Chapter 14.

Backwashing should be achieved with a water rate of 1.1 to 1.3 V_{mf}, based on a V_{mf} calculated using the d_{90} sieve size, therefore allowing the coarsest media grains to be mobile (Cleasby and Logsdon 1999). A value of 1.1 V_{mf} is preferred if gravel is present because of concerns with gravel migration. When no gravel is present 1.3 V_{mf} is acceptable. They discuss the importance of calculating this value for each plant to determine the minimum backwash flow rate requirements. For a bed containing

different types and sizes of media the minimum fluidization velocity will not be the same for all particles. They also emphasize the need to obtain a velocity higher than the V_{mf} using the d_{90} size for the coarser media to ensure that the entire bed is fluidized and free movement of the media is provided. An equation for calculation of minimum fluidization velocity and examples of such calculations are presented in Chapter 14.

Table 6.1 is a compilation of calculated 1.1 times V_{mf} values (Cleasby 2001). In the region of interest for typical filter media, the values listed in Table 6.1 compare favorably with backwash rates used successfully for years for typical filter media (2.0 mm d_{90} anthracite and 1.0 mm d_{90} sand), e.g. 15 gpm/sf (37 m/h) for sand and 20 gpm/sf (49 m/h) for anthracite. Table 6.1 also has correction factors to be applied for temperatures other than 25°C, for typical sand and anthracite d_{90} sizes.

Figure 6.9 presents an example of the experimental determination of V_{mf}. A filter column containing the medium is backwashed at increasingly high rise rates, and the head loss and bed depth are measured. At the minimum fluidization velocity, head loss no longer increases as rise rate increases, and the depth of the filter bed begins to increase. The top graph in Fig. 6.9 shows that head loss for the sand medium increased until a rise rate of about 18 m/h (7 to 8 gpm/sf) was attained. Bed expansion began at a rise rate of about 22 m/h (9 gpm/sf). For the anthracite medium, head loss leveled off and bed expansion began about 16 m/h (between 6 and 7 gpm/sf). Figure 6.10 shows the percentage of bed expansion for a dual media bed consisting of 18 inches (46 cm) of 1.0 mm e.s. anthracite coal over 12 inches (30 cm) of 0.47 mm e.s. sand at four different water temperatures (Berkebile 2001). This figure dramatically illustrates the need to increase backwash rise rates when water is warm, as compared to the rates used for very cold water.

Backwashing With Water Alone

In the US backwashing has traditionally used a fluidizing upwash, with bed expansion of 15-30 percent (Cleasby and Logsdon 1999), often assisted by a surface water scour. Hudson (1935) and Baylis (1937, 1959) reported that surface washing was needed in addition to fluidized upwash to eliminate mud-ball formation. Amirtharajah (1978) and Quaye (1976) said maximum hydrodynamic shear was needed to attain optimized removal of deposits. These conditions were met at expanded bed porosities of 0.65-0.70 (Amirtharajah 1978) or 0.75 and 0.78 for U.K. anthracite and sand respectively (Quaye 1976). Amirtharajah (1978) said that his porosity values in the upper finer media of the bed resulted in overall bed expansions of 40 to 50 percent, close to early rules of thumb for bed expansion.

Table 6.1

Fluidization velocity during backwashing

	Calculated 1.1* Vmf values calculated with Wen & Yu equation for mean sizes in Sanks Table V, pg 273 at 25°C, gpm/sf		
Mean size Mm	Anthracite SG = 1.7	Sand SG = 2.65	Garnet SG = 4.3
2.59	28.7		
2.18	23.5		
1.84	18.8	35.9	
1.54	14.5	28.8	
1.30	11.1	23.0	39.3
1.09	8.3	17.6	31.2
0.92	6.1	13.3	24.4
0.78	4.4	10.0	18.8
0.65	3.1	7.2	13.8
0.55		5.2	10.1
0.46		3.7	7.3
0.38		2.5	5.1
0.27			2.5

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 Degrees 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

(From 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.

Backwashing with Air Assistance

Amirtharajah (1978) noted that European tradition had been to utilize air scour, either followed by a water velocity sufficient to fluidize the media marginally (British practice), or simultaneously with water (mainland Europe). He concluded that the most effective way of washing a filter might involve a simultaneous air scour and sub-fluidizing water wash.

Cleasby and Logsdon (1999) summarized typical backwash air and water flow rates (see Table 6.2). For dual media with 0.5 mm ES sand, air rates of 3 to 4 cfm/sf (55 to 73 m/h) and fluidizing water rates of 15 to 20 gpm/sf (37 to 49 m/h) were typical. For combined air and water wash with 1.5 mm ES anthracite monomedium they reported air rates of 3 to 5 cfm/sf (55 to 91 m/h) along with water wash at a rate of 8 to 10 gpm/sf (20 to 24 m/h), followed by water alone at the same rate or up to 16 to 20 gpm/sf (40 to 48 m/h). Backwashing practices employed in the United States and the United Kingdom may differ as a result of the differences in anthracite filter material. In the USA, the specific gravity of anthracite mined in Pennsylvania is 1.7, whereas the specific gravity of anthracite mined in the U.K. is 1.4. The latter material is fluidized more readily, and this influences the backwash rise rates used.
The development of theory and practice of combined air and water backwashing have been described by Amirtharajah (1978, 1984, 1993), Fitzpatrick (1990) and Amirtharajah et al. (1991). Combining air scour with sub-fluidizing rates of upflowing backwash water produced the conditions, descriptively termed "collapse-pulsing", which resulted in the optimum removal of deposits from filter media. Amirtharajah (1984, 1993), Regan and Amirtharajah (1984), Amirtharajah et al. (1991), Addicks (1991) and Fitzpatrick (1990, 1993) have demonstrated the efficacy of collapse-pulsing backwashing.

Linear regressions of water flow rate as a percentage of V_{mf} against air flow rate under conditions of collapse-pulsing with sand and sand/anthracite filters were produced by Amirtharajah et al. (1991). Lower water rates required higher air rates and visa versa. It was recommended that air rates should fall in the range of 1.6 to 7.4 cfm/sf (30 to 135 m/h). At the lower end of the airflow range water rates should be 40 to 60 percent of V_{mf} where V_{mf} calculations are based on the d_{90} grain size. At higher airflow rates water flows should be in the region of 25 to 45 percent of V_{mf}. Amirtharajah (1984) presented a general equation for predicting collapse-pulsing conditions. Visual observations, at laboratory scale, by Fitzpatrick (1990, 1993) showed optimum cleaning of filters dosed with kaolin suspensions occurred under conditions of collapse-pulsing. Practical confirmation of the effectiveness ofbackwashing using collapse-pulsing has been reported by Amirtharajah et al. (1991),

Amirtharajah (1993), Chipps et al. (1995) and Logsdon et al. (1999) at pilot plant scale and full scale where collapse-pulsing conditions produced optimum cleaning in sand, dual media and GAC filters.

Design of facilities for air scour must be done with care. Chapter 13 includes a case study, "Case Study of Modifications to Air Scour System," which relates how operational difficulties led to improvements in filters equipped with air scour.

Influence of Trough Design on Media Loss during Backwash

Information on the hydraulics of backwashing and design of dirty backwash water outlet troughs has been presented by Kawamura (1975c). Further design information was presented by Norman and Gould (1984) and Cleasby et al. (1975, 1977).

Table 6.2

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

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

Source: Cleasby, J.L. and G.S. Logsdon. 1999. Granular Bed and Precoat Filtration. In *Water Quality and Treatment*, 5th Ed. Edited by R.D. Letterman. New York: McGraw-Hill.

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

Some media trough designs can reduce the extent of media loss that takes place during backwashing. Media loss during backwash can be a problem when existing filters with sand monomedium or anthracite/sand dual media are retrofitted with granular activated carbon (GAC) as GAC is more likely to be washed from a filter than anthracite under similar backwash conditions. Media loss also can occur when air scour is used during backwashing. Kawamura, Najm, and Gramith (1997) conducted backwash studies with a filter having a media surface of 6 ft^2 (0.56 m^2). They reported that simple baffles on the sidewall of the backwash trough could reduce GAC media loss as much as 70 percent. Commercially produced washwater troughs fitted with baffles are available.

Mechanisms That Clean Media During Backwashing

In the 1970s many workers sought to understand the conditions for optimum backwashing with water alone. Amirtharajah (1971) led the way to recognize the weakness of the scouring action when using fluidized backwash without auxiliary scour. Following his research other investigators also studied the problem and concluded that fluid shear was a poor mechanism, but inter-particle collisions caused removal of deposits: this is why surface washing or air scour were effective. Kawamura (1975a) examined the particle size of sand encapsulated in mudballs and found that most of the sand in the mudballs was much smaller than the effective size of the sand in the bed. He commented that small mudballs can grow rapidly into large mudballs or lumps if an effective auxiliary scour is not provided. Kawamura (1975b) presented an extensive discussion of the hydraulics of backwashing. Cleasby et al.(1975) and Valencia and Cleasby, (1979) accepted Amirtharajah's conclusion that was developed in his thesis. They used the weakness of water fluidization alone to support the need for auxiliary scour.

Amirtharajah (1978) said that particle collisions were of negligible importance in cleaning media grains during fluidized bed backwash because the energy in the water was used to fluidize the media and this kept the grains apart. Since an optimum porosity, between 0.6 and 0.8, was required for effective cleaning of media with fluidizing water, corresponding to bed expansions in excess of 50 percent (Amirtharajah 1978, Quaye 1976, 1987, Valencia and Cleasby 1979) Amirtharajah (1978) and Fitzpatrick (1993) attributed the majority of filter media cleaning to hydrodynamic shear forces (the hydraulic effect of the turbulence occurring during washing). As backwashing is practiced today, bed expansions of 50 percent are not used, but effective cleaning is attained by use of surface wash, which is moderately effective for cleaning media, or by air scour, which is very effective.

Using an endoscope and high-speed video recording Fitzpatrick (1993) observed media grain collisions during collapse pulsing.

Empirical evidence suggests that filter material grains do not collide with sufficient energy to entirely displace the thin film of water that exists between the grains on a very close approach (Ives, 2000). Pilot plant filter columns made of plastic (plexiglas, lucite, or perspex) do not become scratched on the interior surface after years of use even though the hardness of plastic used in filter columns typically is less than that of filter sand.

MANAGEMENT OF FILTER WASHING

The Initiation of a Filter Backwash

When a filter is in service, backwashing may be initiated for a number of reasons, including:

- filter effluent turbidity (or other measure of quality such as particle count) has reached maximum value allowed,
- head loss has reached maximum value allowed,
- time in service has reached maximum allowed, and
- plant operating considerations related to water production and distribution system demands.

Filters that are removed from service need to be backwashed before they are returned to service. Thus if a filter is shut down because its water production is not needed, that filter should be washed before it is restarted. Starting up dirty filters was identified by Consonery et al (1997) as one the top ten performance limiting factors at water treatment plants. They found that this problem was most prevalent at plants that do not operate 24 hours a day. The practice of operating a filtration plant intermittently for portions of a day rather than on a 24-hour-per-day basis can lead to passage of turbidity spikes, possibly containing protozoa, through the filter, especially when dirty filters are restarted without backwashing.

In some cases filters should be backwashed before being restarted, even if they were backwashed when taken out of service. Wierenga (1985) studied full-scale filters and found that bacteria could grow in filters that had been removed from service. Depletion of the chlorine residual in the water in the filter bed is a key to this growth. He observed growth of heterotrophic plate count bacteria after a filter had been held out of service for 64 hours, but saw little growth in a filter out of service for 40 hours.

The rate of growth of bacteria is related to temperature, with warm summer temperatures promoting more rapid growth. A fixed number of hours for which a filter could be left out of service and returned to service without backwashing can not be specified. If prechlorination is practiced, and the chlorine residual in water in the filter bed has been depleted, this would be a good indication that the filter should be backwashed before being returned to service, even if it had been backwashed after being taken out of service.

Filters operated in a constant rate mode require backwashing when the head loss limits the flow rate. In declining rate filtration, washing is initiated on low flow rate or high water level in the filter (Cleasby 1993). Ideally head loss and filtrate quality limits should be reached simultaneously to attain optimum water production from the filter (Montgomery Engineers 1985; Tien and Payatakes 1979). In the real world, however, reaching terminal head loss and turbidity breakthrough simultaneously is an unlikely event. For public health protection, a filter should not be on the verge of turbidity breakthrough when it reaches terminal head loss, and taking a filter out of service due to terminal head loss is preferable to removing it from service because of breakthrough.

Washing filters on the basis of run time may be necessary if backwashing is not optimal, resulting in excessive long-term dirt deposition. In this case some improvement in media cleanliness can be gained by washing filters more frequently than head loss would dictate (Bayley pers. comm. 1993). Consonery et al. (1997) also identified using filter run time as the only criterion for initiating a filter backwash as a top ten performance limiting factor. They found that this practice is most prevalent in plants without head loss or in-line turbidity monitoring capability. At plants lacking head loss and turbidity monitoring capability, operators lack the complete picture of filter performance and water quality that they need for making wise decisions on filter backwashing.

Evaluating Effectiveness of Backwash

Kawamura (2000) discussed three methods to evaluate the effectiveness of the filter washing procedure: (1) visually inspecting the filter bed before and after filter washing, (2) measuring the turbidity of the backwash water at 1 minute intervals after initiating backwash, and (3) core sampling of the filter bed both before and after filter washing and performing a floc retention analysis (discussed in Chapter 10 of this manual). He recommended the second method as an easy method for the operator to evaluate the effectiveness of the filter washing procedure in removing floc from the filter bed. Grab or continuous turbidity samples are collected and plotted to develop a turbidity profile of the backwash. A

low profile with a low peak curve is indicative of ineffective washing, while a high profile curve with a high peak is characteristic of effective washing. He also states that many plants wash their filters for an excessively long period of time, until the operator can see the surface of the bed. He says that this practice is actually detrimental to the filtration process, contributing to post-backwash turbidity breakthrough and requiring a longer ripening period.

With regard to a spent washwater turbidity goal for termination of filter backwash, variations in plant practice and in recommended procedure have been reported. Kawamura (2000) recommended terminating the backwash when the backwash wastewater turbidity reaches 10-15 ntu. Cleasby and Logsdon (1999) suggested that a filter has been sufficiently cleaned when the turbidity of the backwash water is 10 ntu. One utility participating in the project to develop this manual and successfully operating filters to meet the Partnership for Safe Water goal of producing filtered water turbidity less than 0.10 ntu reported that usually their filters are backwashed until the turbidity of the spent washwater is at or below 5 ntu. Another participating utility does a very good job of producing low turbidity filtered water but ceases backwashing before spent washwater turbidity reaches 15 ntu, so practice varies. If filters are not routinely washed until spent washwater turbidity is below 15 ntu, monitoring normalized clean bed (starting) head loss over a period of three months is recommended to confirm that backwash is adequate to maintain media in good condition. Conversely, overwashing a filter may extend the length of time needed for the filter to ripen when it is returned to service. Until more data are developed on this topic, the authors of this manual recommend that 10 ntu is a suitable goal for spent washwater, unless documented on-site practice indicates that some other value is appropriate.

The criteria used by the survey utilities to determine when to terminate a backwash were mainly based on past experience and visual determination by the operator of the clarity of the backwash waste water. A few plants used a preset backwash time, one plant used a backwash wastewater turbidimeter, and one indicated that it was determined by (management) policy.

Coordination of Filter Washing with Plant Operation

Backwash Schedules

Filter washing schedules may be influenced by plant operating circumstances, in addition to the filter performance aspects (filtered water quality, head loss, and filter run time). Among the factors that influence filter operation are:

- water system demand, volume of finished water in storage, and plant production rate,
- availability of wash water,
- capacity for storage, treatment or disposal of spent backwash water,
- number of filters at a plant and the effect of removing a filter from service for washing
- head loss status of other filters at the plant, and
- impact on post filter disinfection

The interplay of water system demand, availability of stored finished water, and plant production capacity can come into effect when demand is close to production capacity and storage is limited. If demand is excessive, availability of wash water might become limited. This would be a serious situation, and before a water utility gets in the position of not having sufficient water for washing filters, appeals should be made to the community served to conserve water.

The utility survey indicated that most plants use a combination of factors to determine when to backwash their filters, including hours in service, effluent turbidity, and head loss. Filter run hours ranged from 24 to 150 hours and averaged 80 hours at the plants reporting this information, with the exception of one plant. That facility had traveling bridge automatic backwash (ABW) filters. Filter operation is semi-continuous in this type of plant, and the plant is not taken out of service when one segment of the filter is backwashed by the traveling bridge apparatus. At the ABW plant, the average filter run length was 3 hours. Table 6.3 summarizes information on filter run lengths and values of filtered water turbidity and filter head loss that trigger backwash. Filter effluent turbidity was a criterion used at 85 percent of the plants, with an average of 0.21 ntu (range of 0.08 to 0.5 ntu) being used. At plants that now have a filtered water turbidity limit of 0.3 ntu or higher as a trigger for filter backwashing, that limit ought to be reconsidered and lowered before the Interim Enhanced Surface Water Treatment Rule goes into effect. By setting turbidity goals that are more stringent than the levels required by regulations, utilities will have time to adjust treatment and to develop filter management practices in ways that facilitate consistently attaining improved filtered water quality.

Head loss was used by 80 percent of the plants as a backwashing criterion, with and average of 7 feet with a range of 2.45 to 10 feet (2.1 m with a range of 0.75 to 3.0 m), with the ABW backwashing at 0.5 feet (0.15 m) of head loss. When filters are operated at high head loss, the risk of discharging contaminants trapped in the filter bed during the run is increased. Continuous effluent monitoring using on-line turbidimeters and particle counters can help operators minimize the risk of operating at high

head loss, but at many plants operators may simply find it easier to limit maximum head loss as a means of reducing the risk of breakthrough near the end of a run.

Other reasons stated for backwashing a filter, other than for maintenance purposes, were: change in plant flow rate; particle counts exceeding quality goal; and plant tours, when a filter might be backwashed to show visitors how filters are cleaned.

Very short filter runs can result in shortages of wash water, even in situations not involving maximum demand and production. For example, if an algae bloom on the source water has caused large numbers of filter-clogging algae to be present, these may cause very high rates of head loss increase and short runs, so that filter washing occurs often. This scenario could result in exhaustion of the supply of elevated backwash water storage, or the capacity of backwash pumps might be exceeded by the need for washing multiple filters at the same time. If such a problem were caused by filter clogging algae, application of auxiliary surface spray (for example, filter hosing, as described in Chapter 10) may be needed to break up the algae mat and shorten the backwash time. When algae are causing short filter runs pretreatment practices to reduce the concentration of algae in filter influent should be implemented. Additionally, to reduce or minimize problems in the future a watershed plan to reduce nutrient loading to the source water, or treatment of reservoir water for algae control could be considered.

Washwater Treatment or Recycle

In recent years, more filtration plants have been returning wash water to the raw water at the head of the plant or treating dirty washwater followed by return to the head of the plant. In either situation the capacity of dirty washwater storage and pumping facilities may be a limiting factor on the number of filters that can be washed at the same time (in large plants) or the number of filters that can be washed in a period of a few hours at other plants.

Table 6.3

Utility information on filter run length and criteria for run termination

	Average	Range
Run length	80 hours	24 to 150 hours
turbidity value that triggers run termination.	0.21 ntu	0.08 to 0.5 ntu
Head loss that triggers run termination.	6.9 feet (2.1 m)	2.45 to 10 feet (0.75 to 3.0 m)

Dirty wash water handling capacity also can be a limiting factor in some plants, if frequent washing exceeds the wash water treatment capacity. At plants where changes are being made in how dirty wash water is handled and disposed, plant operators should become involved so the changes do not have adverse effects on filter washing capability and flexibility.

An example of the interrelationships of plant production capabilities and filter washing practice is a plant with four filters and two rates of production. If the water demand was less than the lower production rate for a long period of time, it eventually became necessary to shut down the plant. Two filters could be washed at shutdown, and then the washwater holding basin would fill. Washing the other two filters before the plant was restarted had to be deferred until the spent washwater from the first two washes was treated.

Plant Size and Number of Filters

The number of filters at a plant has an important influence on scheduling of backwashing. At large plants, scheduling may be required in filter blocks containing many units to even out plant output and wash water demand or to equalize flow to a dirty wash water treatment facility. In such a situation washing may take place on a pre-set time interval. At a very small plant with only two or three filters, taking a filter out of service for backwashing can cause a substantial rate increase on the filter or filters remaining in service, as discussed in Chapter 4. When very few filters are available, operators must be careful to stagger filter washing so only one at a time needs to be washed, and so the accumulated head loss on the filters remaining in service at that time is moderate.

At a plant with very few filters and a constant rate of production, imposing a 50 percent or 33 percent increase in flow on a filter that is within 10 to 20 percent of its terminal head loss could cause that filter to experience a turbidity breakthrough or to very quickly reach terminal head loss. This would necessitate the immediate washing of a second filter after the first wash had been finished. Such a situation can result in a "chain reaction" of multiple filter washings when a plant has a limited number of filters, all filters are operating, and head losses have built up to a similar extent in all filters.

When rapid increases in head loss are noted, or when a number of filters seem to be gaining head loss in a way that is will require multiple filter washings in a very short period of time, operators need to sacrifice a bit of water production and deliberately remove filters from service for backwash at selected time intervals that will enable them to avoid having to wash too many filters in too little time. If filters are washed based on run time even though turbidity or head loss triggers have not been reached, the

problems caused by having to wash multiple filters in a short time can be avoided. This requires advanced planning and may also require using filter operating procedures that deliberately stagger the backwash and restarting times of filters. One advantage of this approach is that it enables operators to wash filters when head loss is more favorable (lower) and the filters remaining in service can better handle the increase in flow, if increases occur during filter washing. At one unmanned plant with large diurnal flow variations, the backwash program calculates the anticipated filter head losses when the flow rate will increase in the morning, and begins to backwash the filters so that they are all available to treat the required flow when the plant demand increases. A seasonal review of backwashing schedule is recommended to optimize water production and minimize backwashing costs without jeopardizing finished water quality.

Declining Rate Filters and Automatic Backwashing Filters

At declining rate plants it is very important to plan filter washes for declining rate filters so not all wash in a short time period. Also, it may be difficult for operators to manage washing times for filters that automatically backwash upon reaching specified head loss, especially if the plant is subject to wide diurnal flow variations. Both types of plants require careful planning and management of filter washing, and plants that automatically backwash filters based on head loss must have close observation of head loss in all filters to avoid "chain reactions" in backwashing.

Backwash Water Supply

Filter backwash water should be clean, filtered water. Sometimes it is drawn from a tank specifically built to hold backwash water. At some plants a portion of clearwell storage is used for backwashing, while at others system storage is the source of wash water. Backwash water may be chlorinated or unchlorinated. While some systems may have backwash water supplied under gravity from an elevated tank that was filled by pumps dedicated for that purpose or by the high service pumps, others have the backwash water pumped directly to the filters. The source of the backwash supply can vary significantly from plant to plant, and the impact on the treatment process is becoming a greater concern as more rigid water quality objectives are being set. Backwash supply source can vary from the filter effluent conduit, the plant clearwell or filtered water reservoir, finished water pump discharge or distribution system storage tanks. These sources can have a variety of chemicals present which may interfere with the filtration process, and the intermittent withdrawal of a large quantity of water for

backwashing can impact post filter chemical treatment addition and contact time.

The utility survey showed that 64 percent of the plants use backwash storage tanks as a source of backwash water; however, the source of supply to fill these tanks was not indicated in most cases. Another 24 percent of the plants use the clearwell or filtered water reservoir as their source, while 10 percent use the filter effluent conduit and one plant uses a distribution system reservoir. Several plants indicated the ability to use alternate sources as a backup or emergency supply. The backwash water in all but two plants out of a total of 45 plants contained a chlorine residual, with 77 percent having an average free chlorine residual of 1.05 mg/L (range of 0.03 to 2.0 mg/L) and 23 percent having an average combined chlorine residual of 2.1 mg/L (range of 1.0 to 3.0 mg/L). These results, presented in Table 6.4, indicate that as of 1999 the use of some type of chlorine residual in washwater was common, whereas washing filters without a chlorine residual was not typical practice.

Table 6.4

Treatment plant information on backwash water

Source of Backwash Water		Percentage
Backwash storage tank		64%
Clearwell or filtered water reservoir		24%
Filter effluent conduit		10%
Distribution system reservoir		2%
Information on use of chlorinated backwash water (reported by 43 of 45 plants)		
Type of residual	Average and (Range)	
Free chlorine	1.05 mg/L; (0.03 to 2.0 mg/L)	77 %
Combined chlorine	2.1 mg/L; (1.0 to 3.0)	23%
NOTE: 2 plants out of 45 had no chlorine residual in their backwash water.		

Accurate control of the wash water flow rate, which should be metered, is important for achieving the desired backwash effectiveness. Even on the smallest plants, a means of controlling backwash flow is necessary, so the rise rate can be varied during the washing procedure, and so the rise rate can be varied seasonally when the source water is cold in winter and warm in summer.

The participating utility survey indicated that all but one older plant (currently undergoing a major upgrade) and an ABW filter plant had flow measurement of the backwash water, and that for essentially all of these plants the flow rate could be controlled either automatically by the backwash control system and/or the operator.

One water treatment plant engineer reported problems with the backwash water tank built above ground. The variable level of water in this tank meant that the flow rate was hard to control. When the tank water level was high the pumped water rate was increased by gravity flow.

When designing backwash systems adequate provision must be made to measure and control rate of water flow and to change flow rate according to water temperature. Absence of effective rate of flow control, or failure to properly use rate of flow control for backwashing, can lead to media loss if bed expansion is excessive. For filters where fluidized wash and surface wash are employed, mudball development can result from inadequate bed expansion. If backwash water flow into a filter begins suddenly at a high rate, serious damage to the support gravel (if used) and to the underdrain is possible. Backwash flow rates must be measured and carefully controlled to protect the filter.

As a last resort, if a backwash flow meter is not available, the rise rate can be observed and used to guide adjustment of the flow control valve. This technique can be used at small filtration plants where the operator is close to both the filter and the backwash flow control during backwashing. A rise rate indicator could be fabricated using a float block made of rigid plastic foam insulation board, one or more yard sticks or meter sticks on a light-weight vertical shaft attached to the float, a marker for indicating the reading on the measuring stick and eye bolts fastened to the filter box wall to guide the shaft as the float rises and falls. Figure 6.11 is a diagram of this concept.

Backwash Water Flow Rate

The backwash water flow rate must be controlled carefully to avoid damage to filters or media loss. Backwash should begin gradually, over at least 30 seconds (Cleasby and Logsdon 1999) to avoid upsetting the support gravel (if this is present) or damaging the underdrain. Starting filter backwash rapidly can be a very serious mistake that causes damage in the thousands or ten thousands of dollars. Often a high rate of flow and a low rate are necessary so ability to control backwash flow rates over a wide range is required.

After backwash is initiated, if the wash water rate is too high, media may be carried over the washwater troughs and lost. If it is too low larger solids may not be washed out of the filter. Wash water

rise rate must be controlled, and it is desirable to ramp the flow rate down at termination of wash, especially for dual or multi-media filters. Ramp down is not important for monomedium filters. Because of the essential function performed by the backwash, both primary and standby pumps are required. Where there is the possibility of converting filters from sand to GAC media, allowance should be made for the different fluidizing velocities of the different density media.

Staff at one of thewater treatment plants participating in this project reported that an operator who had worked at the plant for about 30 days was asked to backwash a filter manually, rather than use the automatic controls through the PLC. This was done to train the operator on how to manually backwash a filter in case the PLC was inoperable.

The new operator opened the wash valve on the filter. Then, instead of opening the washwater valve on the washwater storage tank partially (only about 10 percent), the operator immediately opened the valve 100 percent. This resulted in a large volume of water surging into the filter, disrupting only the anthracite (as determined later). Before the operator could close the washwater valve, anthracite was lost from the filter. Based on the volume of anthracite recovered from a washwater holding tank and from the troughs, the utility estimated that 2 cubic yards of anthracite was lost from the filter bed.

A filter inspection revealed that no sand or gravel had been displaced during this event. The estimated 2 cubic yards of anthracite lost was only about 0.11 feet (1.32 inches) of depth if it was measured across the filter area, but because the water rushed into the filter and chose the shortest route, much of the anthracite that was lost was close to the front of the filter (where the washwater enters the underdrain system first). Thus, there was a definite sloped area where more anthracite was lost close to the front of the filter, and almost none to the rear of the filter.

On the day when the problem occurred, plant staff put the recovered anthracite into buckets and carefully placed it in the filter. They then air scoured the filter to help level the anthracite and measured an unaffected filter to determine how much additional anthracite needed to be put into the filter. Anthracite left in a bag in storage was used to top off the filter.

Backwash Water Pressure

As a means of assessing the condition of the filter floor or underdrains it is important to measure the water pressure in the backwash feed pipe downstream of the flow control valve. This should be done at the maximum water flow rate for each filter every time there is a backwash. These figures can be captured and trended on a chart or SCADA screen to give early warning of filter floor maintenance

problems. It is also of value to determine pump condition by measuring and recording water pressure at a given flow rate between the pump and the flow control valve.

Backwash Water Usage

Backwash water usage varies with several factors, including the depth of the filter box from the bottom of the filter medium to the top of the washwater troughs, the type of auxiliary scour used, the type and size of filter medium, and the difficulty encountered in cleaning the bed as influenced by the quality of the water applied to the filter, and the design practice of engineers in various countries.

Ives (1981) stated that backwash water volumes used were normally 1 percent of filter production, 3 percent was high, and 5 percent was considered excessive. This was based on U.K. experience with low backwash water rates of 36 m/h (15 gpm/sf), a rate sufficient to fluidize fine media, supplemented by air scour. Montgomery Engineers (1985) regarded 200 gal/sf (8 m^3/m^2) as a typical volume of water for a filter backwash. They suggested that a production efficiency of over 95 percent was desirable, so that less than 5 percent of the water produced should be used for backwashing, and stated a target productivity, of 5000 gal/sf (200 m^3/m^2)per run. They also said that as much as 50 percent of a plant's capital cost might be spent in the provision of backwashing and washwater treatment facilities.

Carns and Parker (1985) reported savings in backwash water by switching from direct filtration with alum to direct filtration with clay plus polymer for a low turbidity (<3.5 ntu) water. Wash water usage fell from 4.3 - 6.3 percent to 2.4 - 3.0 percent across three plants. The wash method was not described, but the reason for the wash water saving was that the change in coagulant allowed longer filter runs and higher filtration rates.

Because of the shorter runs caused by the higher filtration rates generally employed in direct filtration, Janssens et al. (1989) stated that this treatment method used up to 6 - 8 percent of production in backwash water, compared with 2 - 4 percent for conventional filters. This must be offset against the extra water volumes lost in conventional treatment due to removal of sludge from sedimentation basins or removal of floated scum from DAF clarifiers.

The utility survey reported using an average of 2.4 percent of the total plant production as backwash water, with a low value of 0.7 percent at the automatic backwash filtration plant, and a range of 1.06 - 7 percent at the other plants, with 71 percent of the plants using less than or equal to 3.0 percent. As more rigorous post backwash practices such as filter-to-waste are implemented to reduce

filtered water turbidity and particle spikes, and a lower fraction is processed for production, these backwash percentage values will probably increase at all plants.

BACKWASH TECHNIQUES - KEY POINTS

This portion of Chapter 6 summarizes key points for water washing, for auxiliary scour by surface wash, for air scour, and for combined air scour and water wash. These are provided as a quick guide on backwashing.

Water Washing

- Necessary to remove floc and dirt from filter.
- Usually requires fluidizing water velocity to expand filter bed.
- Extent of bed expansion at a given water temperature related to wash water upward velocity, water temperature, and filter medium size, shape, and density.
- Can be non-fluidizing wash for monomedium filter beds if combined with air scour when washing over a suitably designed weir.
- Needs to be a fluidizing wash to ensure correct stratification of dual-media and multi-media filter beds.
- If water wash rate is too high, media may be carried over washwater troughs and lost.
- Unwanted air in backwash water lines can cause filter underdrain failures or disruption of filter support gravel or washing away media over a weir.
- Important to provide over-pressure protection to prevent filter floor damage if back-pressure is too high e.g. due to blocked nozzles.
- A constant rate of fluidizing water expands the bed to a predictable height.

Surface Washing for Auxiliary Scour

- Commonly used in plants in North America designed in 1980's and earlier.
- Can be done with fixed grid of nozzles or with rotary sweeps.
- Requires a separate water supply with separate flow measurement.
- Sometimes difficult for rotary sweeps, which provide a circular wash pattern, to effectively reach corners of filter boxes.

- Clogging of nozzles in surface wash systems is a common problem, and cleaning or replacement on a periodic basis is needed.
- If surface wash is continued during maximum rise rate for backwash water, the combined rise rate above surface wash may be sufficient to wash media out of the filter bed.

Air Scour

- Common in Europe and United Kingdom for decades, now increasingly being installed in filtration plants in North America.
- Requires large air blowers and motors, and air supply piping.
- It is important to provide over-pressure protection and air release valves.
- Only filter laterals, plenums or block floor underdrains that have been designed for air flows and pressures may have air introduced into them.
- Separate air lateral systems can be installed within the filter media (e.g. at the top of the support gravel layer) to facilitate air scour as a retro-fit.
- Must be used with care to avoid disrupting support gravel if air and water pass through the gravel.
- Effect of air scour with no wash water flow is limited as it forms a few paths of least resistance ("veins") through the media - it can look very impressive from the surface however.
- Effect of air scour with sub-fluidizing wash water flow has been determined to produce the best known cleaning system (see below).
- When designed and operated properly, air is most effective auxiliary scour method.
- Air bubbles cause media to "burst" from the surface into the water above. If this happens when water is passing over the washwater troughs some media will likely be lost. It is not possible to predict where media grains will be as every encounter with an air bubble will move grains around the body of water. Some proprietary designs of wash water troughs and trough baffle systems are reported by manufacturers to reduce media loss in this situation.
- Air-induced media loss can be reduced if the weir has a properly designed continuous baffle running parallel to it which keeps air out and allows media to fall back to the bed.
- Air should be completely out of the bed before the full washwater rise rate is applied.
- Air blowers must not introduce oil or particles into the filter.

- Air pressure and flow rate should be monitored for optimum plant and equipment maintenance.
- Careful observations should be made regularly to assure that an even air scour distribution across the bed is being achieved, and that no dead spots or excessively vigorous areas are occurring.

Combined Air and Water Washing

- This method has proven more effective than air scour followed by water washing - the "veins" form, but the bed is sufficiently mobile to close them again. Pockets or lenses of air form and rise through the media, but as they rise the media closes in again - an effect that has been termed by Amirtharajah in several papers as "collapse-pulsing" backwash.
- The backwash rate should be very low during the air scour phase - Amirtharajah et al. (1991) published design criteria showing water flow rates of 30-50 percent of the minimum fluidization velocity (V_{mf}) based on d_{90} were required depending on air scour rate employed.
- For fine monomedium or dual-media or multi-media beds, it is essential to turn off air flow well before washwater rises up to the top of the washwater trough, to avoid media loss - there is serious risk of media loss from air remaining in the filter underdrains and filter media. It can take about a minute using high rate water to clear all this air.
- With coarse sand media, combined air scour and sub-fluidizing water backwashing (combined air and water backwash) can take place during overflow over a suitably designed weir followed by water only washing to clear air from the system.
- With dual–media and multi-media beds a fluidizing rinse is required to clear liberated solids from the filter and restratify the media layers.
- If a high rate water wash is used to remove air from under and within the filter the rate change from low to high rate should be started immediately after the air scour ends. Take care to increase the backwash rate in a gradual manner that will not damage the underdrain or support gravel. Air does not get adequately displaced by having a delay between the low rate and high rate backwash, or by continuing the low rate after the air stops - all that happens is that the water level approaches the washout level and there is more chance of media being lost when the high rate backwash starts running and the air bubbles are driven out.

- Air should be out of the bed before washwater overflows the trough at the full washwater rise rate.
- Combined air and water backwashing should be delivered only through underdrain systems that are designed for it, or air should be introduced simultaneously through a separate pipe network in the bed.
- Gravel layers must be designed to remain in place during simultaneous air and water backwash. See comments on experience with double reverse graded gravel system in Chapter 11.

FACTORS RELATED TO BACKWASH EFFECTIVENESS

Problems with Filter Drain Down

When filters are overloaded with filamentous algae a surface "mat" can rapidly build up on the surface which causes most of the head loss in this surface layer. As a result it is very difficult to drain the filter through the bed before washing. In this situation it may be necessary to dump the top water above the bed and weir through the wash water waste drain. This may still leave water above the media, risking media loss if air scour starts. Several alternatives are possible depending on the plant design:

- The head available might not be enough to drain the filter to the clearwell but there may be sufficient head to drain through the filter-to-waste or other filter emptying valve
- A short period of gentle backwash water flow might break up this algae mat sufficiently to filter this water to waste (NOT supply).
- A short application of air scour may also break up the mat, but this runs the risk of media loss. Again use filter-to-waste afterwards.
- A special top-dump valve can be designed into the filter weir wall or side wall - a valve is preferable mechanically to a penstock which can get jammed by media when sitting unused, as the expanded bed will reach some way up the penstock during fluidizing wash. An alternative is to use a siphon dump pipe from above the filter media into the wash water gullet.

Measuring Filter Bed Percentage Expansion

The measurement of filter bed percentage expansion during the water wash portion of backwash cycle is highly desirable but not always easy. This assists with optimizing washing conditions and minimizing media loss and helps with determining variations in backwash rate as water viscosity changes. Measurement of bed expansion is described in Chapter 10. Excessive upward flow velocities and the resulting excessive bed expansion can be a significant cause of media loss. To determine the adequacy of expansion for cleaning dirt out of the filter bed or the potential for media loss caused by excessive bed expansion, the water-only portion of the backwash should be evaluated.

Relationship of Filter Media Design, Backwash Auxiliary Scour Method, and Percentage of Bed Expansion Needed

A complicated interrelationship exists between the design of the filter media and the design of the filter box, the auxiliary scour method used, and the percentage of bed expansion needed. Some general concepts are important for understanding the relationships. For a single filter medium, the wash water rise rate required for fluidization increases as the diameter of the particles increases. For media particles of the same size and shape, the particles of greater density will require a higher rise rate for fluidization, as compared to the particles of lower density. For dual media and mixed media beds to be backwashed and restratified, the fluidization velocities of the different types of media need to be similar. This results in using smaller diameters of denser media such as sand, and larger diameters of less dense media such as anthracite or GAC. Densities of commonly-used filtering materials are given in Table 6.5.

When fluidization is needed in backwashing, such as to restratify dual or mixed media, the vertical distance or amount of bed expansion will be related to the bed depth. Deeper beds, if expanded to a fixed expansion percentage such as 15 percent to 30percent, would require a deeper filter box and more distance between the top of the medium and the bottom of the washwater trough. Media expansion typically is held to some point below the bottom of the wash water trough. When the wash water upflow velocity is sufficient to carry filter material grains up to the bottom of the wash water trough, the decreased cross-sectional area caused by the presence of the trough will increase the upward velocity in the region between the bottom of the trough and the overflow level.

Table 6.5

Grain densities of commonly-used filtering materials

Material	Density (g/cm^3)	Density (kg/m^3)
Virgin GAC with wetted pores	1.3 to 1.5	1300 to 1500
Pennsylvania anthracite	1.7	1730
United Kingdom anthracite	1.4	1450
Silica sand	2.65	2650
Garnet	3.6 to 4.2	3600 to 4200
Ilmenite	4.2 to 4.6	4200 to 4600

Adapted from Source: Cleasby, J.L. and G.S. Logsdon. 1999. Granular Bed and Precoat Filtration. In *Water Quality and Treatment*, 5th Ed. Edited by R.D. Letterman. New York: McGraw-Hill.

The increased velocity in the region between troughs can carry media that has passed the trough bottom on up and over the trough. Excessive expansion of filter media can cause media losses, particularly when deep filter boxes are not employed, so use of the media expansion tool described in Chapter 10 is strongly recommended as a periodic task to be sure that media expansion is in the proper range.

Another aspect of filter materials that relates to backwash rate and bed expansion is the range of sizes of a particular filter medium. The larger the range of sizes, the higher the required expansion to achieve full bed fluidization. The d_{90} size is the size recommended for use when fluidization velocity is calculated. The d_{90} size is closer to the d_{10} size when the uc is lower. Uniform coefficient (uc) values of 1.4 can be attained reasonably, but as the uc decreases, more and more filtering material has to be processed to get the size fraction desired. This increases the cost of the medium. As the d_{90} size increases, the wash water rise rate needed to attain fluidization increases. These values can normally be obtained from the plant design specifications or tests performed when the media was purchased or placed in the filter. However, since these values can change over time due to a number of factors, it is recommended that they be recalculated on a periodic basis from core samples as discussed in Chapter 10.

Filter media design, type of auxiliary scour used, and filter designs are related by the need to restratify multi-media filter beds. Whether air or water auxiliary scour is used, restratification would be needed for dual media or mixed media filters, so backwash rates would need to be adequate to attain

fluidization. On the other hand monomedium beds of anthracite or coarse sand do not need to be restratified so air scour is used with these beds and fluidization is not normally provided. Therefore wash water rise rates do not need to be as high for monomedium beds, expansion is less than for a comparable bed that would be fluidized, and wash water flow rates are reduced.

Filter box design, media design, and backwashing technique become very important when GAC medium is substituted for anthracite medium in dual media filters. The density of anthracite is greater than that of GAC so for similar media sizes the wash water rise rate for GAC should be lower. When a sand layer is present under the GAC, however, the rise rate has to be adequate to fluidize and clean both the sand and the GAC. Unless a filter conversion is thought through carefully, GAC loss during backwashing may become a problem. If GAC is used as a filter medium, it is important to be especially careful with backwashing. GAC is an expensive filtering material, and it is the most likely material to be carried up and out of the filters during backwashing.

Filter Launder Position and Shape

United States practice for location of launders is to provide for a horizontal travel distance of 3 feet (0.9 m) or less, whereas European practice with air and water during overflow generally does not use troughs and allows up to 4 m (13 ft) of horizontal travel. Some filters designs provide only a single side overflow weir for the whole filter box. This may be located along the long or short side of a rectangular filter box, which can result in a lengthy paths for the waste wash water to leave the filter box. It is more satisfactory to reduce the path length to about 5 ft (1.5m) by spacing launders across from the far wall to the weir at 10 ft (3 m) centers, as longer path lengths may lead to short circuiting of backwash flow and solids, and potentially may cause a less satisfactory filter wash.

In many filters it is common for the washwater outlet channel to be common with the influent water channel. However some filters have separate inlet channels or boxes and these may be designed to provide a "surface flush" where some of the new filter influent flow is used to displace the washwater remnants over the weir on the other side of the box, after the backwash pumps have stopped. The weakness of this system is that washwater remnants may start to settle down into the filter instead of being rinsed away.

Wash out weir walls often have a slanted top on the side of the wall that faces the filter. If media falls on the top of the walls, it may be able to slide or roll back into the filter box, because of the slope on the top of the wall. Cross launders may be a multitude of designs from Square section, "U"-shaped,

diamond or circular, depending on material of construction. Some troughs have been designed with surrounding but separate baffles to minimize loss of media during backwash. Alternatively wings may be attached to the outside of the troughs to provide a still area where air bubbles cannot enter, permitting settling of media grains before they are lost to the overflow. The height of the weir or launder above the filter media determines the amount of room for filter media expansion during backwash and the time available for air to be eliminated after termination of air scour so that the bed can settle to its expanded height.

The utility survey demonstrated a wide variation in this aspect of filter design. Some plants reported having as little as 6 inches (0.15 m) between the top of the media and the bottom of the wash water trough, while other plants reported having over 5 feet (1.5 m). Some plants reported several values for this measurement, indicating the use of different filter designs within the same plant from several plant expansions over the years. Alternatively, some plants reported a range of distances, which could indicate different media levels in the filters, possibly the result of media loss over time. Table 6.6 summarizes the reported survey information.

Table 6.6

Distance provided between media and backwash trough, as reported in survey of treatment plants.

Distance between top of media and bottom of backwash trough	Number of plants
6" – 11in. (0.15 – 0.28 m)	7
12" – 17 in. (0.30 – 0.43 m)	10
18" – 23 in. (0.46 – 0.58 m)	4
24" – 29in. (0.61 – 0.74 m)	5
30" – 35 in. (0.76 – 0.89 m)	1
>= 36 in. (0.91 m)	6

Providing a distance of 36 inches (0.91 m) or more between the top of the filter media and the bottom of the washwater trough is a departure from past practice in North America. Some reasons for this can be proposed based on the information provided by the utilities having these filters.

Two plants having 36 and 39 inches (0.91 and 1.00 m) between the top of the filter media and the bottom of the washwater trough had only 26 inches and 29 inches (0.66 and 0.75 m) of dual media, respectively. These plants were located in a region of North America where winters are long and cold. Providing filter boxes that are deeper than usual would be a good approach to minimization of air binding problems that might otherwise occur when very cold water is treated. At one of these plants, deep filter boxes were provided so filters could be converted to GAC filter-adsorbers in the future if the water utility chose to do so.

One plant was designed with monomedium anthracite filters containing 6 feet (1.8 m) of medium. This plant has a distance of 4.8 feet (1.4 m) between the anthracite medium and the bottom of the trough, which provides for 3 to 4 minutes of co-current air and water backwash before the rising washwater reaches the bottom of the trough. Deep filter boxes here also allow for a greater depth of water over the top of the media, helping to minimize air binding problems that might otherwise occur because of the use of pre-ozonation and a filtration rate of 6 gpm/sf (15 m/h).

Another plant was designed for use of 54 inches (1.37 m) of GAC over 11 inches (0.28 m) of sand. Clearance between the GAC and the trough bottom is 63 inches (1.60 m), which will help to minimize the loss of GAC when the beds are backwashed.

Manual Control of Backwash

Visual inspection of backwashing should be a routine part of filter operation. It is useful if operators can follow the progress of valve stops and starts while watching the filter by having a local terminal connected back to the SCADA system adjacent to each filter. A local controller is also valuable to perform valve maintenance activities periodically, or to perform manual backwashes.

One of the authors was impressed by the concept used to aid operators at one site where backwashing was fully manual and skilled labor was unavailable. Each valve handle and pillar was color coded according to function to help the operators implement the proper backwash sequencing (e.g. all inlet valves green, all outlet valves yellow etc. - be careful to check operators for color-blindness).

Influence of Backwashing Procedure on Filtered Water Quality

The procedures used in washing filters influence the cleanliness of the filter media after washing and the quality of the water remaining in the filter box after termination of backwash, both of which can affect the quality of filtered water when the filter is returned to service. At the Philadelphia Water

Department's Baxter Water Treatment Plant, a change in backwash procedure was followed by an improvement in filter performance. The backwash procedure formerly used was a surface wash and single rate of backwash. This was changed to surface wash and a step backwash. Details of the backwash procedure for water at 50 °F (10 °C) are given in Table 6.7. Backwash rise rates are varied depending on source water temperature at Philadelphia, so the rise rates would be different for other temperatures. Filter performance results are depicted in Figure 6.12 which shows the percentage of filter runs meeting the criteria of initial turbidity spike less than 0.30 ntu and filtered water turbidity exceeds 0.10 ntu for less than 15 minutes. The percentage of filters meeting these criteria dramatically increased in November 2000 when the step backwash procedure was initiated. Note that both before and after step backwash, a 2-hour resting period was used, and filters were not returned to service until 2 hours after backwash ended.

Clean Bed Head Loss as a Long-Term Means of Assessing Backwash

One measurement of head loss that has specific use for long-term evaluation of filter media condition is clean bed head loss. This is the head loss recorded at the beginning of a filter run, after a filter has been backwashed and returned to service. Head loss data can be adjusted, or normalized, to account for changes in water temperature and changes in filtration rate. Adjusting head loss data to a standard filtration rate and a standard temperature enables plant operators to make long-term comparisons of head loss in filters. Either a difference in temperature of about 49 °F (27 °C) or a doubling of filtration rate can cause a difference in head loss by a factor of 2, so adjusting to standard conditions is very helpful when head loss data for different operating conditions are being compared for a single filter. This is particularly useful for evaluating the amount of head loss that is observed after a filter has been backwashed and is placed into service. This procedure done as follows:

The ratio of actual filtration rate/design filtration rate is calculated and this is multiplied by the head loss to adjust for rate. Next the rate-adjusted head loss is adjusted for temperature by multiplying by the ratio of the viscosity of water at a standard temperature / viscosity of water at actual temperature. A temperature of 68 °F (20 °C) is recommended as the standard temperature.

Table 6.7

Procedures used in filter washing at Baxter Water Treatment Plant

Time, minutes	Backwash rate before step BW (gpm/sf (m/h))	Backwash rate for step BW (gpm/sf (m/h))
0	0 (0)	0 (0)
1	0 (0)	0 (0)
2	0(0)	0 (0)
3	17.2 (42)	4.8 (11.7)
4	17.2 (42)	4.8 (11.7)
5	17.2 (42)	4.8 (11.7)
6	17.2 (42)	17.2 (42)
7	17.2 (42)	17.2 (42)
8	17.2 (42)	17.2 (42)
9	17.2 (42)	17.2 (42)
10	17.2 (42)	4.8 (11.7)
11	0 (0)	4.8 (11.7)
12		4.8 (11.7)
13		0 (0)

NOTES: Surface wash began at minute 1 and ended at minute 7 for backwash procedure prior to step backwash. Surface wash also began at minute 1 and ended at minute 7 for step backwash. The backwash rates in this table are for 50 °F (10 °C). Different backwash rates apply at other temperatures.

The calculation for adjusting clean bed head loss to a standard rate of filtration and a standard temperature is: $H_n = H_{act}(Q_n/Q_{act})(\mu_n/\mu_{act})$ where

H_n = normalized head loss

H_{act} = actual head loss measured

Q_n = normalized rate of flow in the filter or normalized rate of filtration

Q_{act} = actual rate of flow in the filter or actual rate of filtration

μ_n = viscosity of water at the temperature selected for normalized calculations

μ_{act} = viscosity of water at the temperature for which the data were collected

When head loss in clean filter beds is corrected for both temperature (viscosity) and filtration rate, long term increases of clean bed head loss may be indicative of a gradual accumulation of deposits in the filter as a result of inadequate backwashing This is a non-invasive alternative to sampling and analyzing filter media for accumulated suspended solids.

Calculating the filtration-rate-and-temperature-standardized clean bed head loss and looking for changes in this value over time can be done to check filter media condition. At plants employing slow filter starts and gradual increases to full rate, operators should collect filtration rate, temperature, and head loss data only after the full filtration rate has been attained. The filtration rate and temperature selected as standard conditions must be used for all standardization calculations. For Figure 6.13, a standardized filtration rate of 4 gpm/sf (10 m/h) and temperature of 59 °F (15 °C) (for viscosity calculations) were selected by Thames Water Utilities Ltd. as those were mid point values for the range of filtration rates and water temperatures tested.

Some of the results of flow and temperature standardized starting head loss are plotted in Figure 6.13. The week numbers on the x-axis relate to the start of each year, i.e. weeks numbered 0, 52, 104, 156 and 208 started 1st January. The trials started in week 6, and data logging commenced in week 9. For improved clarity in plotting results (i.e. fewer data points), the standardized starting head loss data were averaged on a weekly basis.

The data from the trials with separate air scour and fluidizing water rinse were collected up to week 54. These data reveal that the mean weekly normalized starting head loss increased rapidly over the first 3 to 4 months of operation to a value some 2 to 3 times that of new media. After 3 to 6 months the values appeared to reach a plateau, although there was considerable scatter. The increase in normalized clean bed head loss indicated that the nature of the filter bed was changing over time.

After the first year the backwash method was changed to a combined air scour and water wash followed by water wash at a higher rate, and the media was replaced in each filter. A thick vertical line denotes media replacement. After the change in backwashing method the normalized head loss results produced trend lines with little scatter, little seasonal fluctuation and little gradient change. This indicated minimal long term changes to the filter media. The general tendency was that the starting head loss showed a small initial increase and then maintained a value slightly higher than that of new media, but not a rising trend. The effectiveness of the combined air and water wash is demonstrated by the

level, non-rising trend of the data for the normalized clean bed head loss data.

The filters were sampled for particulate organic carbon and suspended solids on the media after backwashing, and the results showed that the accumulated material was much greater on the filter sand at the end of the first year when the normalized starting head loss had been increasing, as compared to the next three years, when the normalized starting head loss showed little overall change. These data were presented by Chipps et al. (1995).

Although some inconsistencies in the data were noted, normalized clean bed head loss data showed the inadequate nature of the separate air and water wash and the greatly improved results with the combined air and water wash. The benefit of this filter monitoring method was that it did not require shutting down a filter or manual sampling of media. The standardized head loss data can be processed manually by an operator, or preferably automatically by a SCADA system. From the results it can be concluded that monitoring clean bed head loss, and normalizing the data for temperature and filtration rate, can be a practical and useful tool for detecting the gradual clogging of a filter bed due to inadequate backwash. Measuring head loss was much simpler than the particulate organic carbon and suspended solids measurement, which was disruptive and labor-intensive. This makes it a better tool for operators to judge backwash effectiveness.

CONTROL OF MUDBALLS

Effective Filter Washing

Control of mudball formation begins with effective filter washing practices. If excessive dirt is left on filter media, mudball growth can begin and then continue. A procedure for examining media for cleanliness (floc retention procedure) is presented in Chapter 10.

Avoiding Overdosing of Polymers

Experience of one of the Thames Water Utilities authors working in New Zealand has shown that the use of polymers on filters where the backwash system was not designed to clean polymer-dosed floc off the media has resulted in cases of badly cracked filter beds. Another author of this manual has seen a filtration plant operated in an in-line filtration mode (coagulation/filtration) at which cationic polymer dosage was used as the primary coagulant. An apparent overdose of polymer resulted in polymer "blobs" that resembled small jellyfish in appearance. Air scour and water wash did not break

up these "blobs," and filter hosing was recommended as a remedy. Routine dosing of polymers can also lead to some jelling or mudballs in the filter media. Some utilities clean the media periodically to break down the polymer. Disinfection with chlorine or treatment with sodium hydroxide has been used at some utilities. The polymer manufacturer should be consulted about the choice of chemical to be used for breaking up mudballs or polymer gel in a filter bed.

Management of Partially Dirty Media (Media Maturation)

In systems where pre-chlorination is not used, filter media can become colonized by biological growths, principally bacteria and fungi. This effect takes place over 3 to 4 months in London, and is termed maturation. The biofilm's effect on the surface morphology of the media can be beneficial to filtration. This has been noticed in roughing filters using 0.7 mm ES sand without coagulant treatment ahead of slow sand filters. It is not clear whether the same effect is of benefit in conventional treatment plants. Since many plants have abandoned or reduced pre-chlorination in an attempt to reduce trihalomethane concentrations it is possible that biological growths are more prevalent on filter media now than in previous decades. Too much biological material can cause problems of media clogging, high head loss and eventually cracked media. The simultaneous air and water wash is the best way of maintaining biologically active filters in an acceptable state.

Reduction in ammonia or dissolved oxygen concentration across filters in the absence of chlorine is one indicator of biological activity. Scanning electron microscopy can reveal whether biological growths are present, but the analysis technique is too destructive to give details of the biofilm's impacts on the filtration process. If media is biological, any media replacement program should be targeted at warm water periods rather than during winter months so that media matures more rapidly.

RECYCLE OF BACKWASH WATER AND OTHER RESIDUALS

Dirty Backwash Water

Potential Effects of Backwash Recycle

Dirty filter backwash water historically has been returned to the head of a WTP to be processed again. An equalization basin is usually used so that the spent backwash can be returned to the head of the WTP at a rate less than 10 percent of the raw water flow into the WTP. At conventional plants, filter backwash solids generally consist of the solids that failed to settle in the sedimentation basins as a result

of having a lower density (or specific gravity) or smaller particle size (Wolfe et al. 1996). Furthermore, the suspended solids concentration of dirty backwash water may be $1/10^{th}$ to $1/100^{th}$ (or less) of the concentration of sedimentation basin sludge. Concerns over the recycling of microorganisms, aggravation of taste and odor problems, and other issues have drastically reduced the number of WTPs that directly recycle spent filter backwash. Thus, in recent years interest has been generated in better understanding the characteristics of backwash wastes, since these must be processed along with other WTP residual streams.

Recovery of dirty backwash water has been very common for a number of reasons. It represents a rather large volume of water with a low solids content. Typically, in conventional treatment plants the volume is 1 to 5 percent of the total plant production, containing 10 to 20 percent of the total solids production and having suspended solids concentrations of 30 to 300 mg/L, depending upon the applied turbidity to the filters and the ratio of the backwash water to production (Cornwell 1999). Therefore, its recovery represents a savings in water resources and in the chemicals that were used to treat it initially. Most regulatory agencies require proper handling of wastes, and discharge to surface waters and recycle within the treatment plant are regulated to varying degrees. Usually new or rehabilitated plants are required to upgrade the waste stream treatment and recycle systems.

Cornwell and Lee (1993) reported on the quality and characteristics of waste streams that are recycled to water treatment plants, including filter backwash waste water with and without solids removal treatment, at eight full scale plants. They determined that the recycled waste streams have the potential to upset the treatment process itself or to affect the quality of the finished water. The impacts could be caused by the solids themselves, by constituents in the recycle streams, or by contaminants released by the sludge. The principal contaminants included: *Giardia* cysts and *Cryptosporidium* oocysts, particles, manganese, assimilable organic carbon, total organic carbon, total trihalomethanes and their precursors, turbidity, and aluminum.

These researchers reported that while the waste streams could cause water quality problems, none of the plants evaluated experienced finished water quality problems due to the recycle. They concluded that equalized, continuous recycle; proper waste stream treatment prior to recycle; and characterization of waste stream quality through proper monitoring should be used in conjunction with recycle operations. Renner and Hegg (1997) included recommendations for the self-assessment of recycle facilities in their AWWARF Self-Assessment Guide for Surface Water Treatment Plant Optimization report. They stated that recycle of inadequately treated spent backwash water can concentrate cysts to a level that can be many times the levels in the raw water, and that this

concentration can challenge the plant to the extent that numerous cysts pass through plant unit processes. They recommend an assessment of all waste streams recycled and their treatment facilities, evaluation of the percentage of recycle waste streams in the total plant flow, evaluation of their impact on water quality and the treatment processes, and consideration of options to avoid recycling any of these streams. They also recommend that recycle streams should be at a continuous flow of less than 5 percent of the plant flow rate.

Backwash Handling and Recycle Practices Reported in This Project

The AWWARF utility survey obtained information on the spent filter backwash water handling systems and recycle practices at 43 water treatment plants. Most of these plants had concrete basins for storage prior to pumping, three plants indicated that they practice plain settling and two plants have treatment facilities for the spent filter backwash water. A few plants use earthen lagoons or ponds for this purpose. Eight plants indicated that they did not have separate basins for this waste stream, and return the flow back to the head of the plant. A total of 15 plants indicated that they disposed of the spent filter backwash water, with about half of these having storage basins prior to disposal. Disposal was to sewers, rivers, lakes and "unnamed locations". Of the plants practicing recycle of this wastewater, the average percent recycle was 3.6 percent (range of <1 to 10 percent), with the maximum percent recycle reported as ranging from about 2.5 – 10 percent, although some plants reported maximum recycle percentages as high as 40, 50 and 80 percent. Kawamura (2000) recommended semi-annual monitoring of the waste washwater tanks for filter media accumulation. If an excessive amount of media is observed it is an indication that the filters are losing media during backwashing and that the backwash operation needs to be adjusted or the height of the wash troughs raised. He notes that this material is very abrasive and will erode the impeller of the waste washwater transfer pumps if not removed.

Very few of the plants in the AWWARF utility survey indicated that they monitored the water quality of the recycled flow, with a few systems collecting monthly or occasional grab samples, and three plants monitoring turbidity. Two stated that they use a streaming current instrument; however, this may have been part of the main plant monitoring system downstream of where the recycle stream was introduced. Most of the systems that practice recycle do not experience any water quality or treatment problems associated with the recycled stream, although a few plants noticing a slight increase in turbidity. One plant had increased tastes and odors and disinfection by-products associated with their

recycle, whereas three plants indicated that they saw an improvement with coagulation as a result of the recycle. Only two plants indicated that they adjusted their pretreatment flow or dosage to adjust for the recycled flow, with one of these doing this automatically based on a continuous streaming current instrument.

Filter-to-waste

Another form of waste from filters that is increasing the volume of filter wastewater is filter-to-waste, as an increasing number of plants use this practice of wasting filtered water during the ripening stage when a clean filter is being put back into service. The filter-to-waste rate varies from one WTP to another. While many plants use the normal filtration rate, many others use a much lower rate, normally as a result of having too small piping provided for this purpose, or where it is only done as a token measure to satisfy a regulatory authority. The water quality of this waste stream is very good, and has not been shown to adversely impact the treatment process if the equalization basin and waste water treatment and recycling facilities can accommodate this increased hydraulic loading.

Among the water utilities participating in the AWWARF survey, 21 plants indicated that they have filter-to-waste capability, although only 15 used it on a regular basis. One plant indicated that they had this capability originally, but the state made them remove it as a potential cross-connection. Inspection of filter effluent piping configuration from a cross-connection viewpoint might put many other plants in a similar situation, although there has been no reported incident of cross-connection contamination of filter effluent from this source. Several of the plants that indicate that they use filter-to-waste routinely have manual valves, and all of the plants that indicated that they have filter-to-waste capability but do not practice it have manual valves that would require the operator to go to the pipe gallery after each backwash to start and stop this practice.

Many of the plants in the AWWARF Survey that do practice filter-to-waste reported have a smaller pipe for this flow than that provided for the filter effluent line, thereby limiting the rate at which they can filter-to-waste, while the other plants use a rate up to the normal production filtration rate. Ideally filter-to-waste should be operated at the filtration rate that will be employed at the end of the filter-to-waste period. If a utility practices filter-to-waste at a low rate and then raises the filtration rate after filter-to-waste ends, this imposes a rate increase on the filter just as it begins producing filtered water for the clearwell and could result in a turbidity spike at a crucial time. Most of the plants that use filter-to-waste have a definite turbidity or particle count target value that they use to determine how long

to do this, while a few plants use a fixed time period. Only one plant indicated that they were limited in how long they could filter-to-waste by the capacity of the reclamation facility. Most of the plants implement this practice immediately following the backwash, while a few wait until after a filter has "rested" a while (been filled with pretreated water and kept off-line; see Chapter 7) or immediately prior to putting the filter back into production. The filter-to-waste flows to sludge lagoons, washwater recovery tanks, waste settling ponds, or reclamation facilities, and usually ends up being recycled to the head of the plant. Handling of the filter-to-waste water can be an obstacle to implementation of this procedure if piping and pumps for recycle are not available.

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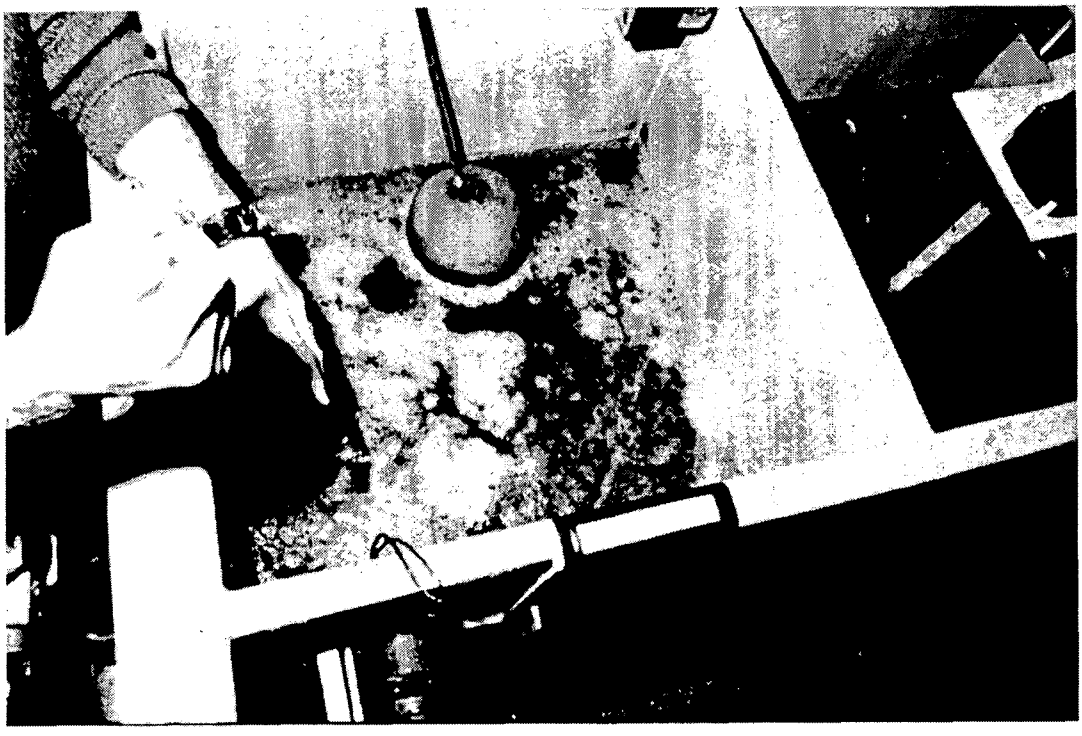

Figure 6.1 Air released from filter bed in package plant before backwash, caused by air binding. (*Source*: Kirmeyer 1979).

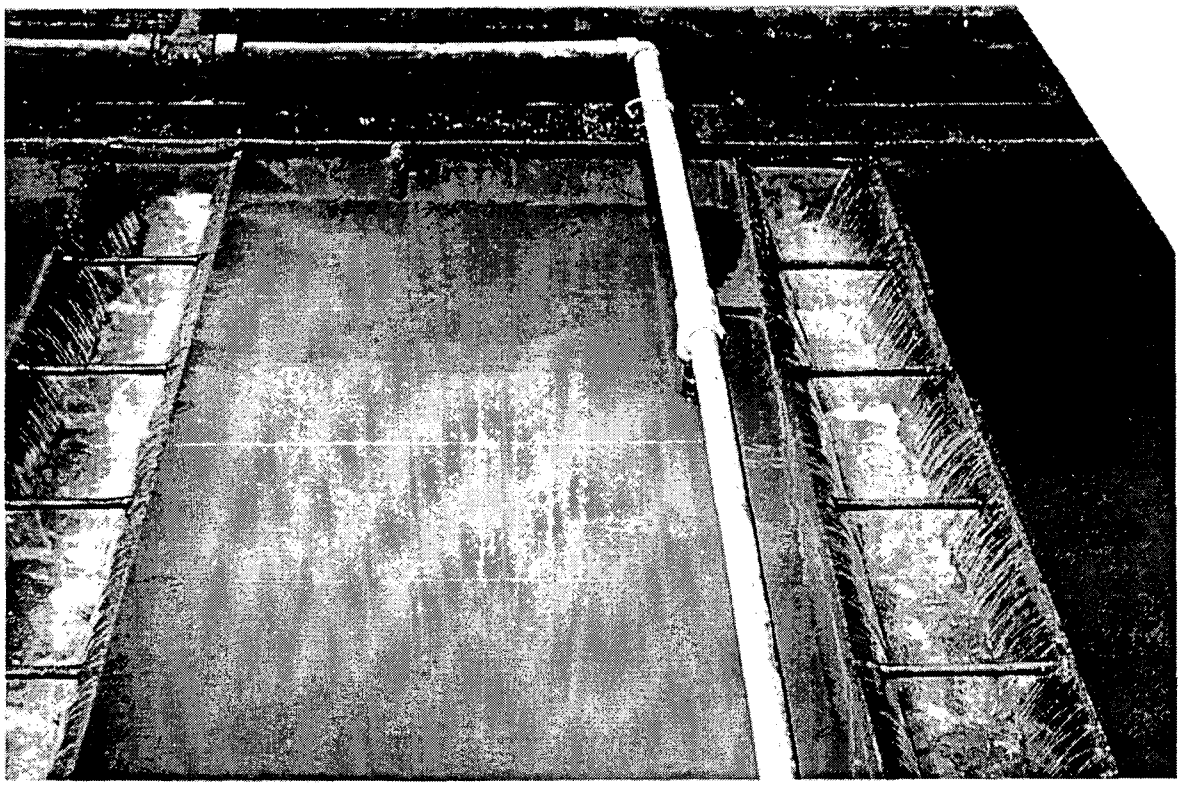

Figure 6.2 Routine filter backwash (*Source*: Black & Veatch 2001)

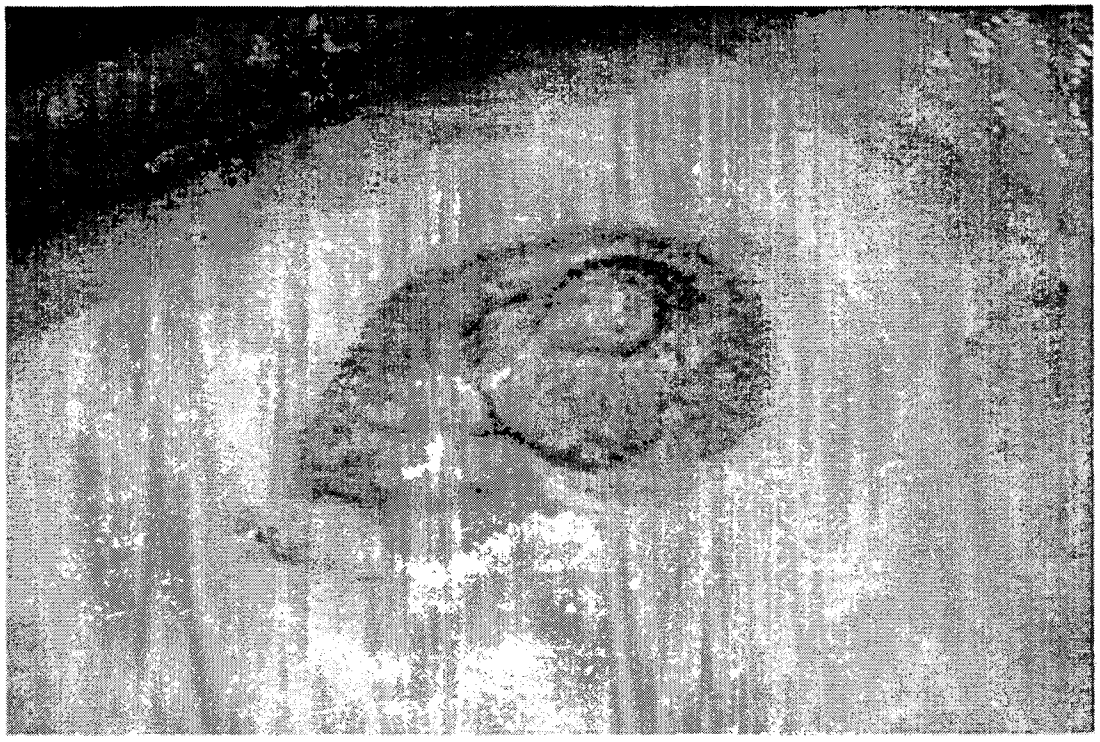

Figure 6.3 Filter boil shown in AWWA filter surveillance video. (*Source*: AWWA 2000)

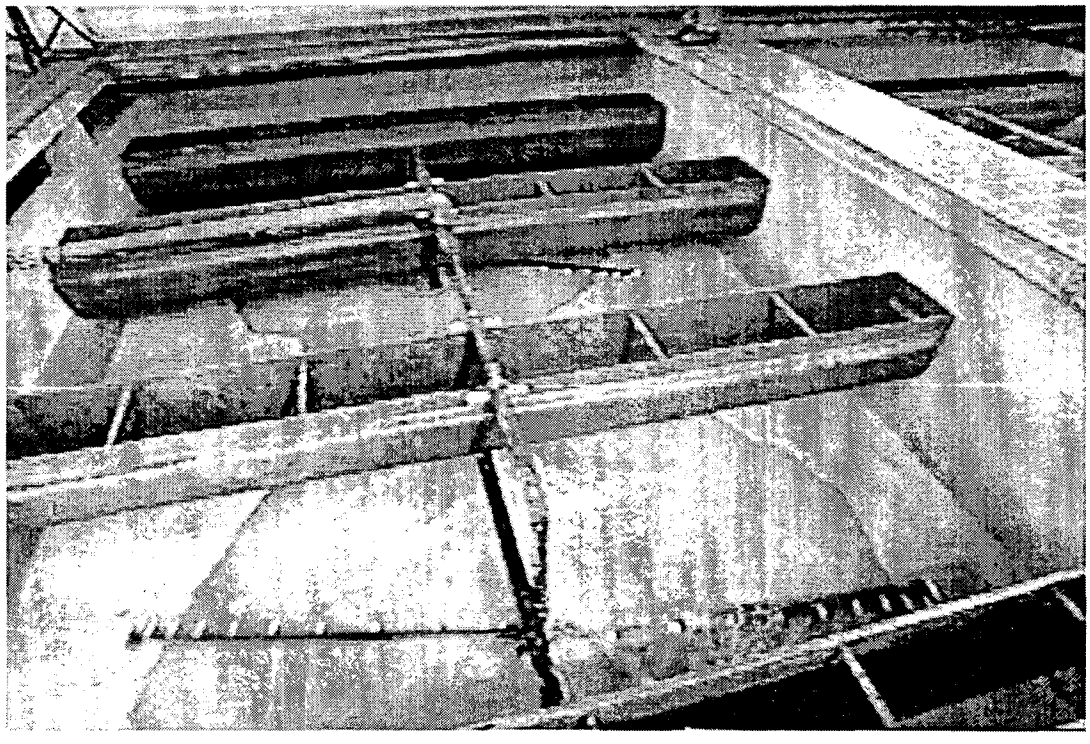

Figure 6.4 Surface sweeps in AWWA filter surveillance video; nozzle in bottom left-hand corner appears to be clogged (*Source*: AWWA 2000)

Figure 6.5 Cracks in filter bed. (*Source*: Thames Water Utilities 2000)

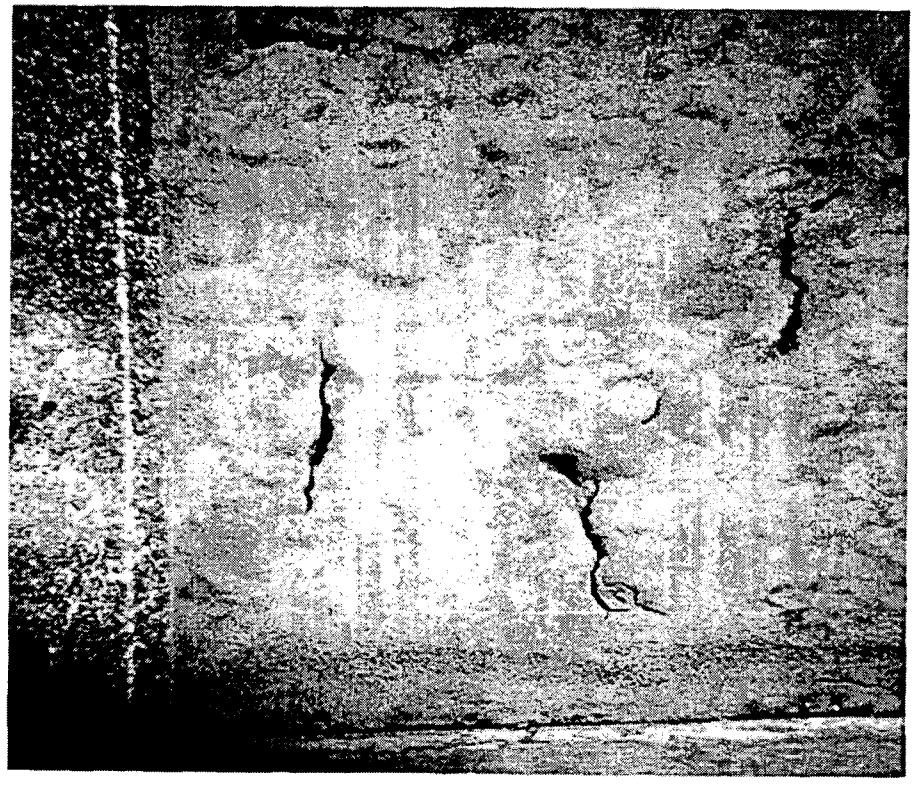

Figure 6.6 Cracks in filter bed and cracks near wall (*Source*: Thames Water Utilities 2000)

Figure 6.7 Newly backwashed filter with mudball "swirls" on black anthracite media (*Source*: Cleasby 2000)

Figure 6.8 Mudballs and anthracite removed from filter shown in Figure 6.7 (*Source*: Cleasby 2000)

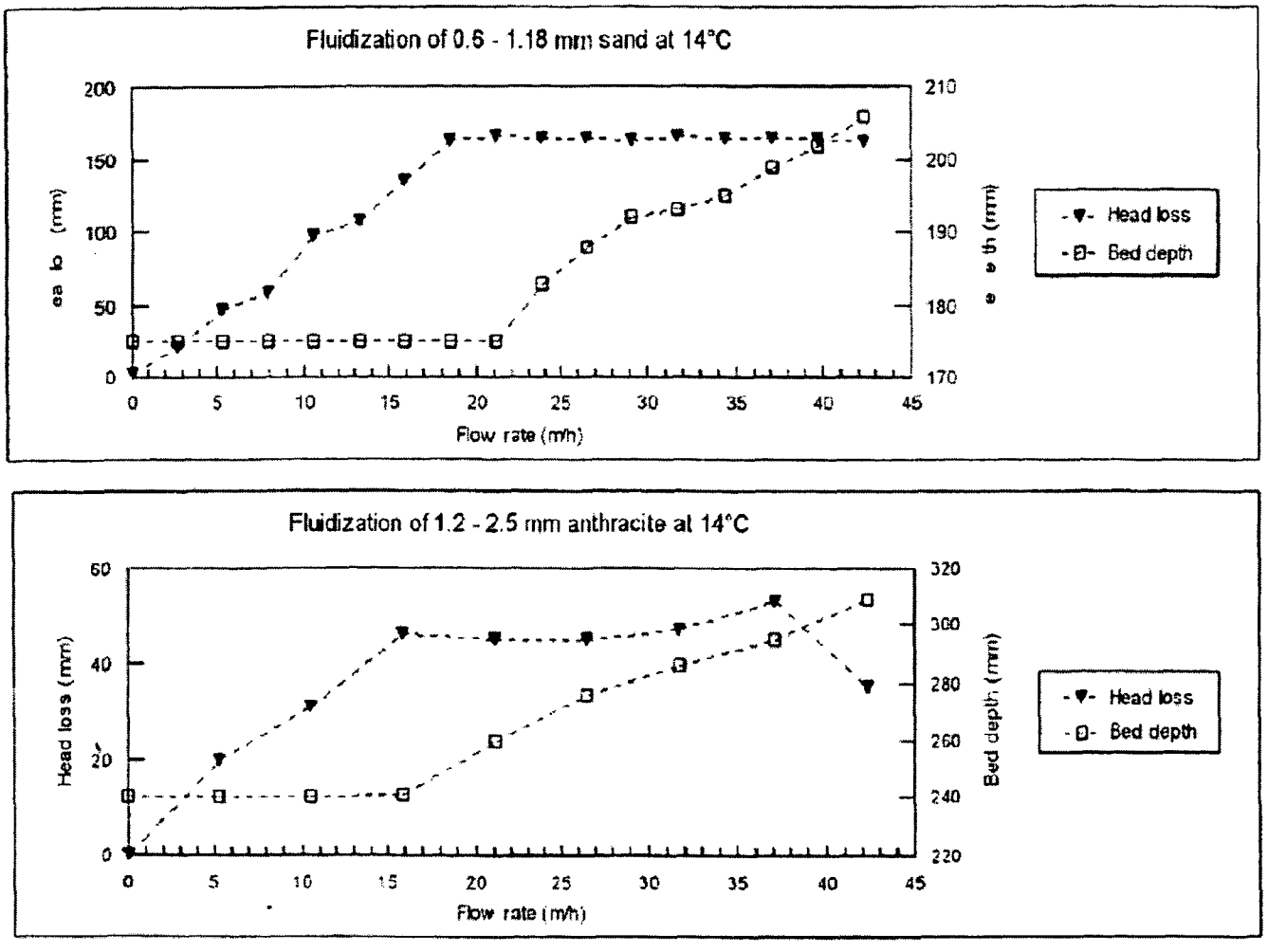

Figure 6.9 Filter backwashing to determine minimum fluidization velocity (*Source*: M.J. Chipps, PhD Thesis 1998.)

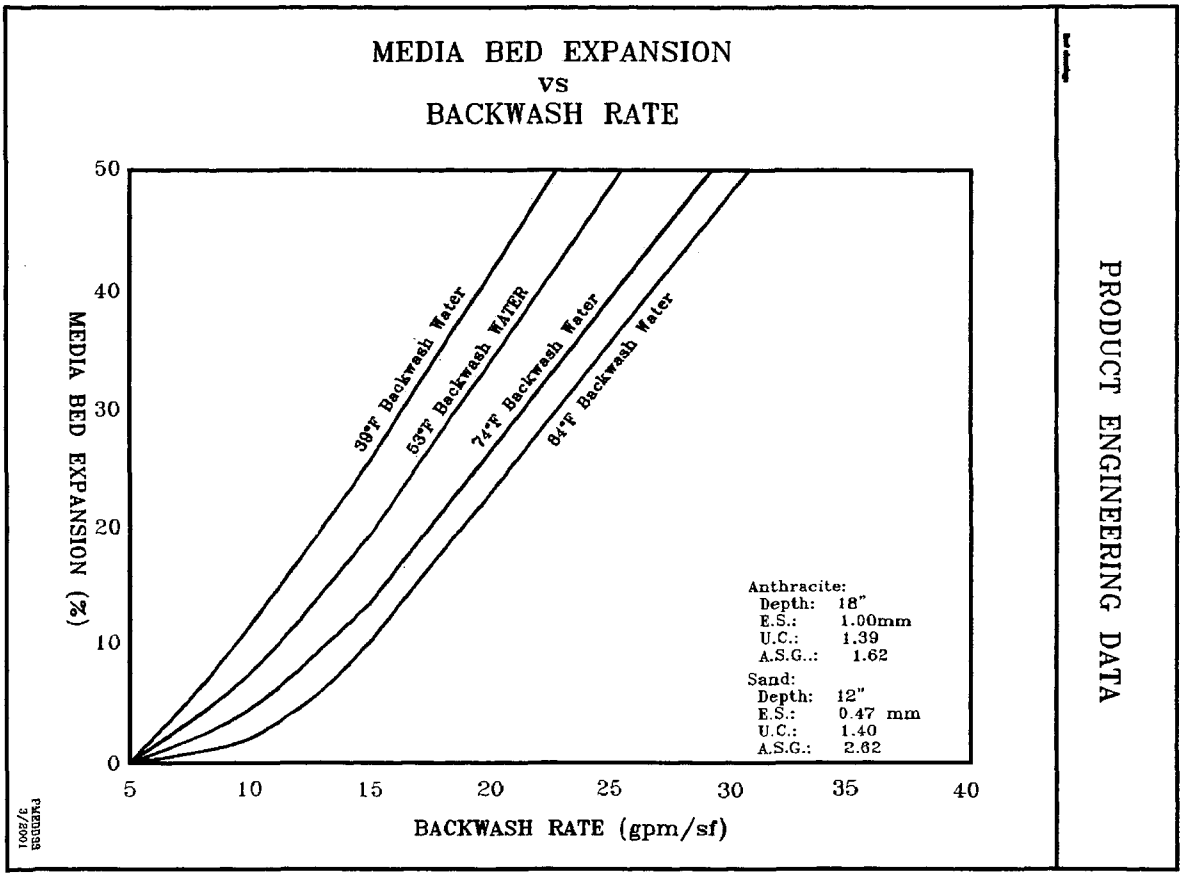

Figure 6.10 Media bed expansion versus backwash rate (*Source*: The F.B. Leopold Company, Inc. 2000)

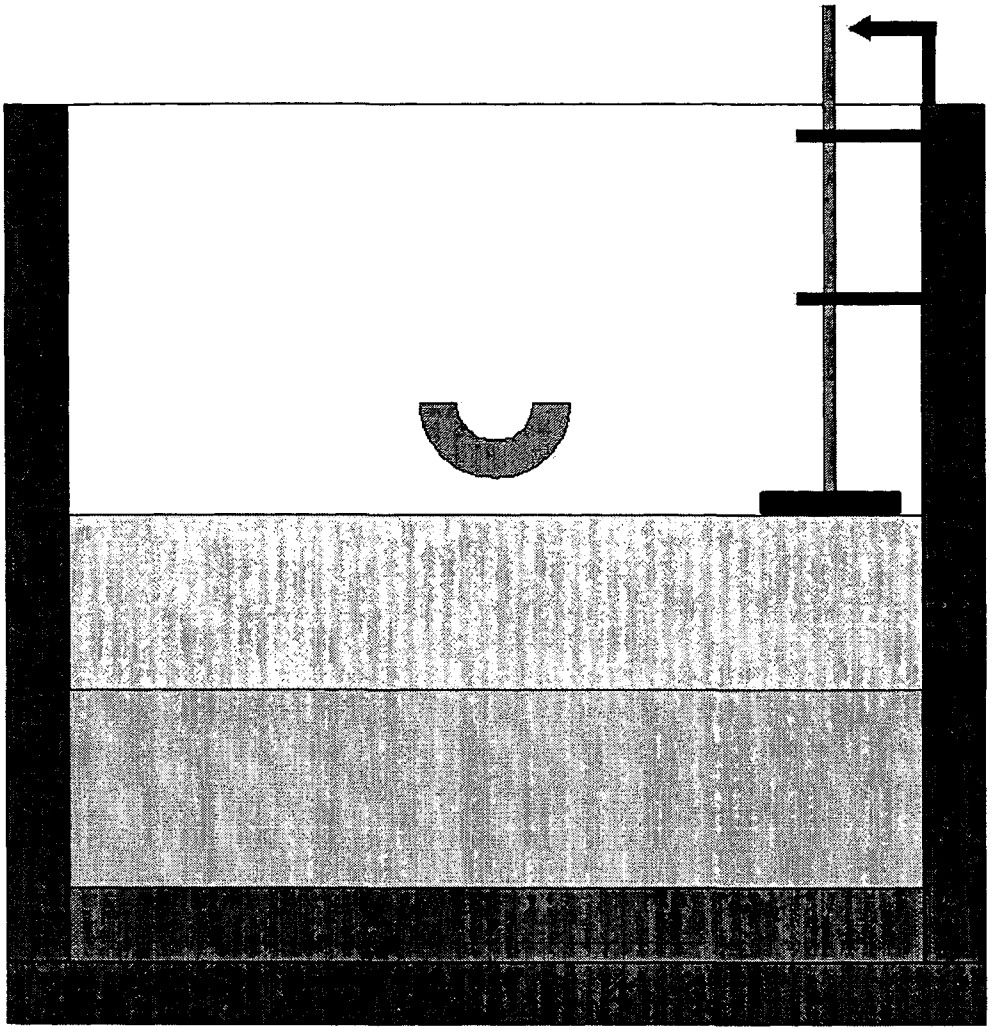

Figure 6.11 Schematic diagram of rise rate gauge for use with small gravity filter to measure backwash flow rate (*Source*: Black & Veatch 2000)

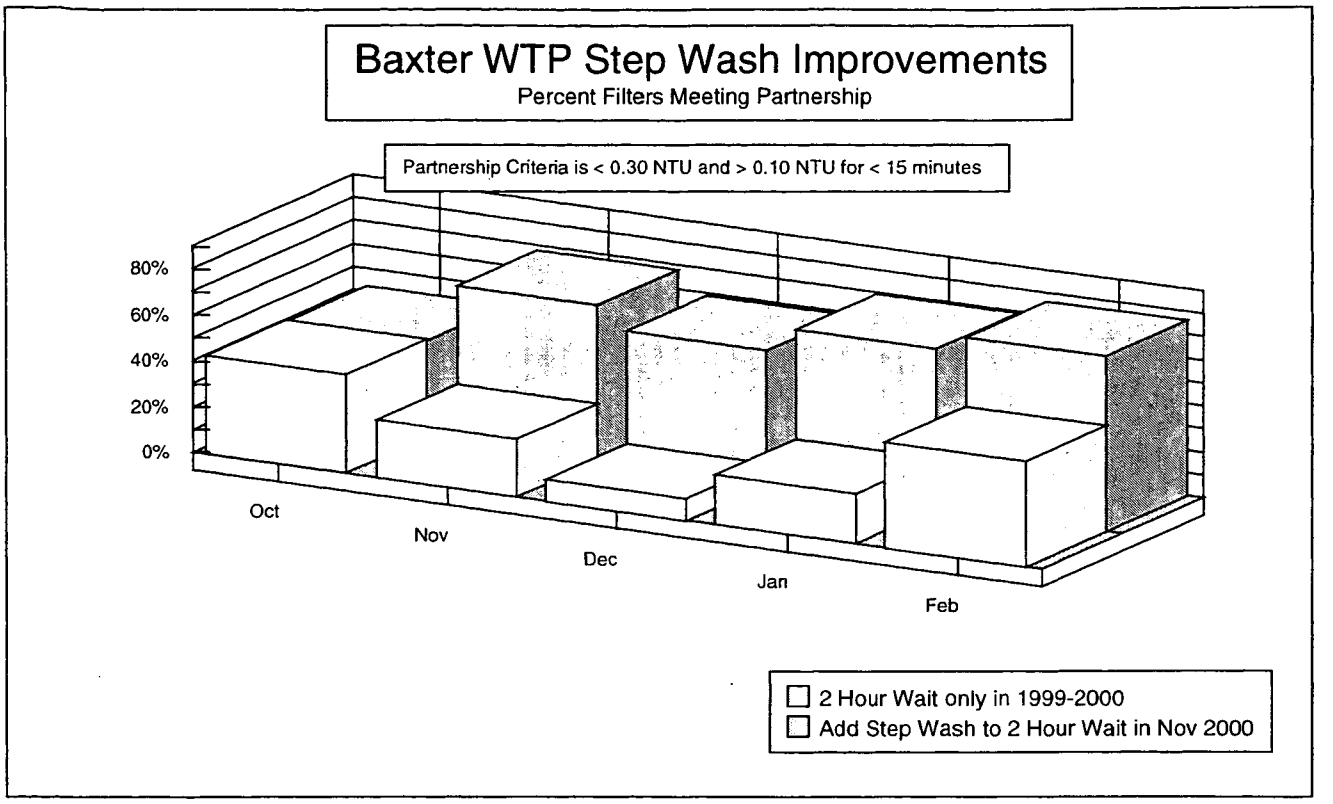

Figure 6.12 Percentage of filter runs meeting the criteria of initial turbidity spike less than 0.30 ntu (*Source*: Philadelphia Water Department 2000)

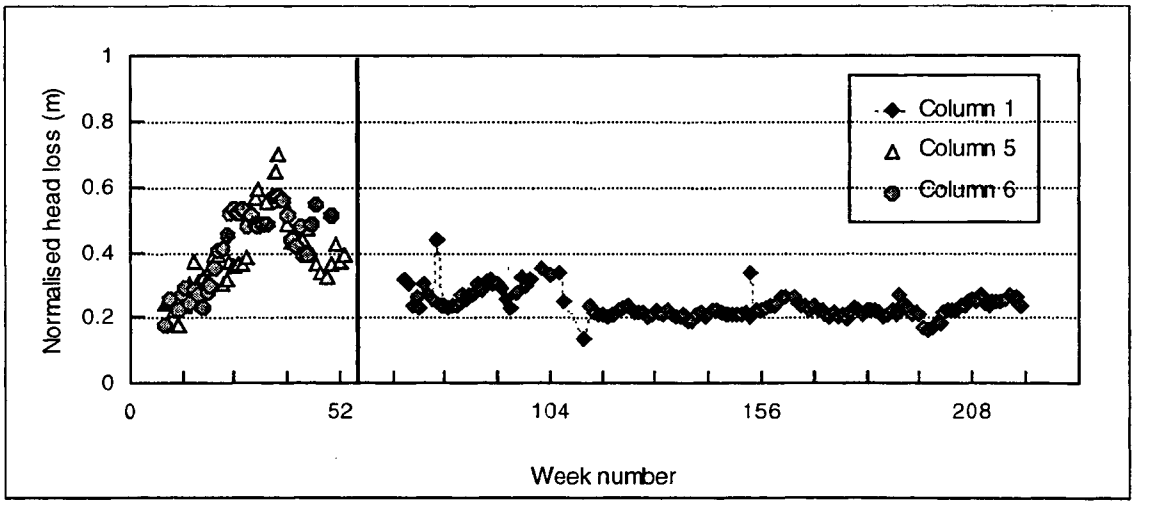

Figure 6.13 Standardized head loss data for two dual media filters comprising 1.1 ft (0.34 m) sand under 2.2 ft (0.66 m) anthracite. Columns 5 and 6 used 1.2-2.5 mm anthracite and 0.5-1.0 mm sand, column 1 used 1.7-2.5 mm anthracite over 0.6-1.18 mm sand (Source: Thames Water Utilities 2000)

CHAPTER 7

FILTER RIPENING AND CONTROLLING THE INITIAL TURBIDITY SPIKE

INTRODUCTION

Generally the quality of filtered water produced by a filter is poorer just after a new filter run starts, and quality then improves as the run progresses. This has been referred to as the initial improvement period, or filter ripening. Chapter 7 presents background information on the filter ripening concept, and summarizes the findings of this project on techniques used by water utilities to minimize the initial turbidity spike that is observed when a filter is placed into service after being backwashed. Generally water utilities providing information on their techniques used to minimize the initial turbidity spike reported that they used more than one approach for doing this.

FILTER RIPENING

The initial improvement in filtered water quality that occurs at the start of a filter run was included in a mathematical model by Stein (1940), and later on Ives (1960) evolved physical, experimental, and mathematical models. The initial improvement period was studied and reported upon in the 1960's (Cleasby and Baumann 1962; and Robeck, Dostal, and Woodward 1964) and was studied in detail by Amirtharajah and Wetstein (1980). Elevated concentrations of *Giardia* cysts were reported to occur during the initial improvement period (Logsdon et al. 1981). Because of the increased risk of passage of pathogens during the initial improvement period, the turbidity spike that occurs at the start of a filter run should be minimized.

Figure 7.1 is a graph prepared from data published by Allen Hazen in a report of filtration testing in Pittsburgh (Filtration Commission 1899). Hazen's data on the efficacy of coagulation and rapid sand filtration were collected at the end of filter runs, and at the beginning of subsequent runs after backwashing. His results were obtained when turbidity measurement was very crude and ineffective for filtered water, but plate count bacteria enumeration could be done. (Turbidity was measured by inserting a platinum wire mounted on a graduated stick into the water sample. The reciprocal of the depth in inches at which the platinum wire was just ready to disappear from sight was recorded as the turbidity. If the wire disappeared at 1 inch the turbidity was 1. If the wire disappeared at 10 inches the turbidity was 0.10, and at 33 inches, the turbidity was 0.03.) The Hazen data showed a pattern of higher bacteria

counts in filtered water after backwashing, with improvement as the filter continued to operate in each run. Note that Hazen's work was done before water chlorination was practiced, so the data he collected are a good indication of the extent to which bacterial cells can pass through a filter when a new run is started.

Data from a pilot plant filter run (Figure 7.2 at the end of the chapter) illustrate filter performance in which the initial turbidity spike was less than 0.3 ntu. Within one hour filtered water turbidity improved to less than 0.1 ntu. A gradual breakthrough started after 18 hours of operation. The focus of this chapter is on techniques for reducing the magnitude and duration of the initial turbidity spike shown in Figure 7.2.

TECHNIQUES TO MINIMIZE THE IMPACT OF FILTER RIPENING

Techniques for minimizing the time needed to attain routine or normal low-turbidity water after starting a filter run are described in this chapter. They include:

- filter-to-waste,
- the delayed start,
- the slow start,
- adding polymer or coagulant to backwash water, and
- adding coagulant chemical or cationic polymer to the settled water as it fills the filter box after backwash is terminated.

A common and fundamental operational aspect for all filter starting procedures is that the rate of filtration was zero while the filter was out of service, and to place the filter into service the filtration rate has to be increased. Floc particles that were dislodged from filter media grains during backwashing but not removed from the filter bed before the end of backwashing may not be firmly attached to filter media grains at the start of a run. These particles may be forced through the bed when the filter effluent valve is opened and the filter begins to produce water again. Worse yet, if a filter was taken out of service and not backwashed, and then at a later time returned to service, the previously trapped floc would be subjected to a major change in shear forces within the filter bed as the rate of flow changed from zero to the intended filtration rate. Typically the magnitude of filtration rate increase from zero (filter out of

service) to the normally used filtration rate is greater than the magnitude of rate increases that are encountered when the filter is operating. Also, some filter control systems overshoot the intended filtration rate when a filter comes on line due to inadequate design, a faulty or delayed sensing system, or inadequate maintenance or improper calibration. This problem accentuates the detriment of restarting a dirty filter.

Some procedures intended to help control the initial turbidity spike, such as filter-to-waste, and slow start, can impose rate changes on an operating filter. This must happen with the gradual or slow start, and rate changes are likely to occur during the transition from filter-to-waste to filtering to the clearwell.

Filter rate changes can cause deterioration of filtered water quality, as shown in research by Cleasby, Williamson, and Baumann (1963). They concluded that filtration rate increases can result in greater shear forces acting on material previously lodged in the filter bed and cause the discharge of that material. They also concluded that the amount of material discharged becomes greater as the filtration rate increase is performed more abruptly, and for rate increases of larger magnitude.

During any portion of a filter run, whether it is the start after backwash, the long part of the run with stable water quality, or the latter stage of a filter run when head loss is high, effective pretreatment with coagulant chemical (and perhaps with polymer) is essential when a goal of treatment is to produce low-turbidity water. One utility participating in this project noted that the key to controlling the initial turbidity spike is the primary coagulation, and another attained successful filter starts by using filter-to-waste and careful control of coagulant and polymer dosages.

During the course of the project to develop this maintenance and operations manual, water utilities were asked about techniques used to minimize the degradation of filtered water quality at the start of a filter run. Utilities reported about operations at 37 filtration plants where the initial turbidity spike nearly always was held to 0.3 ntu or lower, a goal of the Partnership for Safe Water. Information was presented for 7 plants that did not consistently hold down the initial turbidity spike to 0.3 ntu. Techniques used for controlling initial filtered water quality included conditioning the backwash water or influent settled water after backwash with a polymer or with a coagulant chemical, holding the filter out of service for a period of time after backwashing it, increasing the filtration rate gradually when the filter is put in service, and using filter-to-waste. Some plants used none of the above techniques, and some used more than one.

Data are summarized in Table 7.1. This table indicates that the majority of plants that successfully control the initial turbidity spike employ more than one method of doing this. Only three plants placed all of their reliance on filter-to-waste, while at 15 plants, filter-to-waste was used in combination with one or more other methods for lowering turbidity when the filter run began. Three plants employ filter-to-waste followed by a gradual start. Based on information on the filter-to-waste flow rates and the operating flow rates, these plants generally perform filter-to-waste at less than the full filtration rate, so they gradually increase flows to reach their operating rates. At the 12 plants that use filter-to-waste plus filter resting or chemical conditioning of backwash water (and perhaps a gradual start) the filter resting and chemical conditioning of backwash water probably aid in attaining the filtered water quality turbidity goal sooner, thus reducing time needed for filter-to-waste. Nearly all of the 18 plants using filter-to-waste reported that they monitor filtered water turbidity or particle counts as a guide to deciding when filter-to-waste should be ended. A single approach to controlling the initial spike was used at 9 plants, whereas multiple approaches were used in 26 plants.

Note that although the survey form for this project asked if utilities could generally control their initial turbidity spike to 0.3 ntu (the Partnership for Safe Water goal) numerous utilities actually did much better. Some reported that they did not cease filter-to-waste until the filtered water turbidity was less than 0.1 ntu or even less than 0.10 ntu. Eight plants reported that their filtered water turbidity declined to 0.14 ntu or lower in ten minutes or less. Another five reported reaching this turbidity in 20 minutes or less.

Of the plants that did not generally control the initial turbidity spike to 0.3 ntu or lower, four reported using no special technique when starting a filter. Three of the plants in this group of seven were lime softening plants. Controlling the initial turbidity spike may be more difficult when calcium carbonate crystals are present as compared to controlling turbidity caused by alum or iron floc. Two lime softening plants, however, did control the initial turbidity spike, so it can be done at softening plants.

Turbidity spikes during startup can be controlled when water system management makes a conscious determination to do so. The East Bay Municipal Utility District (EBMUD) instituted a program to monitor filtered water turbidity spikes in 1998 (Pontius, 2001. According to the Pontius article, EBMUD Superintendent of Water Treatment, Jim Smith, stated that, "The goal was to have no spikes above 0.10 ntu for more than 15 minutes, or no spikes greater than 0.30 ntu at any time."

Table 7.1

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

(Results from water utilities supplying information for this AWWARF project)

At the beginning of the program about 4 percent of the filter runs did not meet that goal, but in August and September, 2000, only a single filter run out of 853 did not meet the startup goal (Pontius 2001). Changes included retrofitting filter-to-waste where plants did not have it, and carefully adjusting coagulant and polymer dosages.

The techniques presented in Table 7.1 for controlling the turbidity spike at the start of a filter run have yielded mixed results. A procedure listed in the table may be unsuccessful at some filtration plants. For example, one participating utility stated, "And finally slower rate increases are always better, the time spent putting a filter in service is well worth it." However, another utility wrote, "Research thus far shows that the slow start procedure alone will not provide sufficient reduction of a poor quality filter ripening period. However, it may be used in conjunction with other methods to attain desired effluent quality." Selecting effective methods for controlling the initial turbidity spike at a filtration plant may involve an element of trial and error until the best combination of techniques is discovered.

Water utilities may choose to evaluate one or more procedures for controlling the initial turbidity spike on-site, as the efficacy of the various techniques was not consistent at all plants surveyed. As an aid to those planning a study of filter start-up procedures, an example of appropriate data to collect and evaluate for a study of addition of conditioning chemical to backwash water is provided. This list was developed in a study carried out by the Modesto Irrigation District. The following data were collected:

- Filter number
- Time the filter turbidity went greater than 0.1 ntu
- Time the filter turbidity went back less than 0.1 ntu
- Duration of time greater than 0.1 ntu
- Maximum turbidity of the spike
- Length of time that the particle counts were greater than 5 counts/mL for particles > 2 μm (Note: this does not correspond with turbidities greater than 0.1 ntu, but is an operating parameter set by MID staff. This value will be plant-specific, related to the water quality goal for particle counting, if applicable.)
- Time to ramp up to normal flow
- Length of the backwash
- Time during backwash that the backwash conditioning agent was added

- Backwash conditioning chemical
- Conditioning chemical dose
- Primary coagulant doses
- Filter aid and dose
- Raw turbidity
- Settled turbidity
- Raw water pH
- Raw water temperature
- Streaming current detector reading (if used)
- Raw water TOC

For all start-up studies, most of the data included in the MID list would be collected, except for the items that are specific to backwash conditioning. If start-up studies involve filter resting, the length of time the filter was out of service before restart is an important parameter. For studies of gradual filter starts, initial filtration rate, the timing, magnitude and duration of each rate increase, the length of time the filter operates at the increased rate before another increase is imposed, and the maximum filtration rate attained are important data. If coagulant or polymer are added to influent water when the filter box is filled, the volume and strength of chemical added, the time when added, and the duration of the time when the addition occurred are important.

Filter-to-waste

Filter-to-waste, sometimes called rewash, involves wasting the water from the first portion of a filter run rather than putting it into the clearwell. Water from filter-to-waste can be recycled back to the raw water. Generally this would improve the quality of the raw water. Some plants carry out the filter-to-waste process for a fixed period of time, but this practice may not achieve the goals for filter-to-waste. Filter-to-waste is done to prevent the discharge into the clearwell of the initial high-turbidity water that is produced by the filter.

One of the authors has been asked whether this water is suitable to return to an adjacent filter or into the main inlet channel feeding several filters. The answer is NO! Water from filter-to-waste should

be returned to the head of the plant where it can be blended with raw water and coagulated again. There are several reasons for this. For a start this water contains particles that were for various reasons unable to be filtered out of water. If an adjacent filter is not sufficiently ripened there is no guarantee that these particles will be removed when filtered again. If there is a fundamental problem with the charge chemistry on these particles, as Cranston and Amirtharajah (1987) suggested, then filtration of these particles is never likely to be fully satisfactory. Furthermore this practice could be said to by-pass part of the treatment process, a practice that was strenuously disapproved of by the Group of Experts reported by Badenoch (1990).

Filter-to-waste can be considered in the context of industrial waste treatment concepts including classification and segregation of industrial wastes, and conservation of wastewater. Discharging filter-to-waste to a basin receiving water treatment plant residuals such as spent backwash water and settling basin sludge would only serve to dilute the concentration of suspended solids in the backwash water or sludge, and probably would be detrimental to treatment of those residuals. Water from filter-to-waste is very high quality water that is not really "waste" in the same sense as sludge or spent backwash water. Mixing it with the residuals that may not be recycled can result in waste of water very suitable for recycle to the head of the treatment plant.

Bucklin, Amirtharajah, and Cranston (1988) studied filter-to-waste and stated, "In summary, a filter-to-waste procedure is only of value if (1) the post backwash characteristics for a particular system are understood, and (2) there are clear objectives for the use of the filter-to-waste period in terms of what exactly is to be accomplished." They did, however, conclude that because alternatives to filter-to-waste are available, other approaches to controlling the initial filtered water quality may be attractive to water utilities.

One basis for managing filter-to-waste is to monitor the filtered water turbidity, and waste it until the filtrate meets the turbidity goal of the utility. At that time, the filtered water quality is acceptable for discharge into the clearwell. At filtration plants where particle counting is done routinely, particle counts in filtered water could be used as the quality criterion for termination of filter-to-waste. Goldgrabe et al (1993) discussed use of particle counts and particle size distributions as a means to optimize filter-to-waste time when a purpose for using filter-to-waste was to control passage of cyst-sized particles into finished water. In their studies, large-sized particles (those > 10μm) were passed within the first 20 minutes of the filter run.

Whether particle counting or turbidity measurement is used, the important concept is that filter-to-waste is managed on the basis of the filtered water quality (the real reason for using filter-to-waste) instead of being managed only on the basis of a fixed time period for wasting filtered water. The length of time for filter-to-waste is site-specific and may vary with source water quality or pretreatment approach. For this reason, recommendations are not made in this manual for carrying out filter-to-waste for a specified time.

At some filtration plants the filter-to-waste piping may not be adequate to carry away the wasted filtrate when the filter is operated at the full filtration rate. In this circumstance, filter-to-waste would have to be conducted with the filter operating at a reduced rate, and after filter-to-waste ended the filtration rate would need to be increased. Increasing the filtration rate after filter-to-waste is ended could cause a spike or increase in turbidity, so the rate change would need to be managed with care. Unless turbidity of the filter-to-waste stream is measured continuously, and the turbidity of the filtered water is measured continuously, operators will not know if increasing the filtration rate at the end of filter-to-waste has had an adverse effect on water quality. At plants with undersized filter-to-waste piping that can not carry the full flow from a filter, renovating filter-to-waste and providing piping with capacity to handle water produced by a filter at its design flow is a plant upgrading project worthy of serious consideration.

At the end of filter-to-waste, a brief deterioration of filtered water quality may occur even if filter-to-waste is done at the full filtration rate, because of the need to change from diversion of filtered water to waste to directing the filtered water to the clearwell. Closing the filter-to-waste valve and opening the valve to the clearwell piping might cause a filter disturbance and temporarily impair water quality. Again the existence of a turbidity spike, its duration, and its magnitude would be very difficult to detect without having continuous monitoring of the turbidity of filtered water, both in the wasting mode and the production mode. If the sampling point for the continuous turbidimeter is located before the filter-to-waste diversion, the same instrument can serve both functions. Bucklin, Amirtharajah, and Cranston (1988) observed that at the Bozeman Water Treatment Plant, where filter-to-waste was practiced, the turbidity spike was related to the closing of the filter-to-waste valve, the opening of the clearwell valve, and the filtration rate. They explained that the closing and opening of the valves produced sudden rate changes in the filter.

A well-designed system should ensure that the opening of the filter outlet valve and the closure of the filter-to-waste valve was achieved smoothly and with no overall rate change to water coming out

of the filter. Sometimes questions are asked about the filter-to-waste rate. In seeking to minimize water loss a slow filter-to-waste rate may be proposed. This simply delays ripening and leads to the risk of a hydraulic shock when the filter comes back into service, potentially causing turbidity or particle breakthrough. Therefore, filter-to-waste should be conducted at the same filtration rate as intended for the subsequent filter run.

Delayed Start

Allowing filter media to "settle in" after backwashing, for a time of 1/4 hour to 24 or 48 hours has been done at some plants, and some operators believe this helps minimize the initial turbidity spike when the filter is started. In this strategy for controlling the initial turbidity spike, after backwashing is completed settled water is introduced to the filter box and held for a period of time before filtration begins. A delayed start could improve initial filtered water quality by allowing the filter media to consolidate slightly after backwashing, tightening the pore structure. Also during the delay time, floc particles that were not washed out of the filter box during backwash would have the opportunity to settle to the top of the filter media, and floc not removed from the expanded filter bed during backwash could attach to the filter media.

Using the delayed start method does not require special equipment or filter-to-waste piping. This procedure is applicable, however, only when plants have sufficient filtration capacity so it is not necessary to have all filters in service at the same time. During times of maximum water production in plants that need all filters in service as much as possible, employing a delayed start much longer than 1/2 hour may be impractical.

Delayed filter starts have been evaluated at three full scale plants and found to improve initial filtered water quality (Baird and Hillis 1998). To evaluate the degree of quality improvement attained, they depended on particle counting. The total number of particles in the 2 to 5 μm range were compared for the ripening period for control filters (no delayed start) and test filters operated with a delayed start. In the three plants, the reduction of particles during the ripening period ranged from 35 percent to slightly over 42 percent. Figures depicting particle counts versus time showed reductions in the peak particle count of over 50 percent for the delayed start filters as compared to the control filters with regular start.

A similar positive benefit of filter resting was reported by Pizzi (1996), who presented data from a study of two filters at a plant in Ohio. One filter was started immediately, whereas the other was rested for 4 hours. The turbidity peak from the rested filter was about half that of the peak for the filter placed into service immediately after backwashing, and the ripening period for the rested filter was 45 percent shorter (34 minutes versus 62 minutes).

Studies of resting filters were carried out by Thames Water Utilities for this project. Filters with delayed starts ranging from 46 minutes to 144 minutes produced lower turbidity than a filter with no delay upon start-up. Particle counts for the filter with the 144 minute delay were lower than for the filter with no delay. Figures 7.3 and 7.4 showing these data may be found at the end of this chapter. The notation RGF in the legend for these figures indicates that the filters are rapid gravity filters.

Resting filters before starting a new run is not a cure-all, as two plants participating in this AWWARF project reported using delayed starts but did not consistently control their initial turbidity spike. Nor can filters be rested for an unlimited length of time. This also applies to water filtration plants that have excess capacity, where the practice of keeping backwashed filters on "standby" for future service might be common.

Microbiological problems can develop if filters are out of service for an excessive time and then returned to service without being backwashed again. Wierenga (1985) observed that bacteria grew in out-of-service filters after the chlorine residual was depleted. Filters need to be backwashed after being held out of service for a long period of time. Unpublished studies of off-line filters carried out at Grand Rapids and provided for this manual development project indicate that in the summer, with water temperature in the filter bed approaching a temperature of 68 °F (20 °C) during an extended filter shut-down, the free chlorine residual could be depleted in the filter bed. This is conducive to growth of heterotrophic plate count (HPC) bacteria and total coliform bacteria. Chlorine residual depletion plus HPC growth was noted after a filter remained out of service for 64 hours, but residual depletion with little bacterial growth was observed when a filter had been out of service for 40 hours. Current practice at Grand Rapids is that a filter should not remain out of service for more than 24 hours. When a filter has been out of service for an excessive period of time, backwashing the filter before returning it to service is the surest way to avoid water quality problems that can be associated with chlorine depletion and bacterial growth.

Slow Start

At some filtration plants, the initial turbidity spike is managed by starting the filter at low filtration rate and gradually increasing the rate over a period of time, such as 15 minutes. For this procedure to be used, the filters must have rate control valves that can be increased gradually. This approach would not be applicable at declining rate filtration plants unless the filters were equipped with rate control valves that were used at the beginning of the filter run to limit the filtration rate. Use of slow start is not new. Hudson mentioned British experience with "slow start modules" in his discussion of a paper on filter rate changes (Cleasby, Williamson, and Baumann 1963). From this we can infer that the concept of starting a filter slowly has been in existence for at least four decades.

Results for using a slow or gradual start to attain better quality during filter startup are mixed. A number of investigators have not found this to be beneficial (Borrill and McKean 1993; Hillis and Colton 1995; and Keay 1995) but others have seen a benefit. On the basis of particle counting at full-scale filters, Borrill and McKean concluded that the slow start procedure was delaying the passage of particles but not decreasing the total number passed during ripening.

Hillis and Colton (1995) showed that nearly 50 percent of the 2-5 μm particles penetrating the filter during a 48 hour run did so during the ripening period. The effect of the slow start was to prolong the ripening period from about 25 minutes to 45 minutes. The slow start showed a two peak ripening period in contrast to the single peak when no slow start was used. Measuring 2-5 μm diameter particles, the single peak reached 30,000 particles/mL, whereas the two peaks were each around 22,000 particles/mL. The filtrate contained around 50 particles/mL after ripening. The cumulative number of particles passed in a given filtered water volume showed a clear benefit of the slow start, as it reduced treated water particle counts by about 30 percent. However the authors were aware that the counts during ripening were still high. Hall and Pressdee (1995) reported a similar reduction (average 30%) in particle counts comparing a slow start with a full rate start but the ripening period was not totally eliminated. The filtrate during the remainder of the filter run contained much lower particle numbers than the counts observed during the initial improvement period.

It must be concluded that, although the slow start makes some impact, removing 30 percent of a large number of particles still leaves a large number of particles! However trimming the height of a peak may enable a utility to meet its goals, albeit not necessarily the spirit of those goals.

In the utility survey done forthis project, one utility reported that a gradual filter start was tried but found to have no benefit at their plant where lime-softened water was filtered. Another AWWARF study found that the practice was beneficial. Some of these results are described below.

In their AWWARF-sponsored study of the characteristics of initial filter effluent quality, Bucklin, Amirtharajah, and Cranston (1988) reported that at the Helena Water Treatment Plant a direct relationship was found between the magnitude of the initial turbidity peak and the rate of flow when the filter was placed into service. They wrote, "The flowrate at which a filter is started immediately following backwash is proportional to the turbidity peak. This is a good argument for the incremental startup of a filter after a backwash." They concluded that the incremental, or gradual, filter starting procedure reduced the length of time needed for the initial improvement period. The standard procedure for placing a filter in service at Helena during the AWWARF study was ".... to slowly put the filter back on line in incremental flow rate steps ..." This procedure was compared to an instantaneous startup mode during the study. Table 7.2 in this report summarizes the data for filter runs listed in the AWWARF report (Bucklin, Amirtharajah, and Cranston 1988) for which the ultimate rate attained was either 2.6 or 2.8 gpm/sf (6.3 or 6.8 m/h), based on Tables 11 and 12 of their report. Using an incremental startup did not lower the peak turbidity observed on startup, but this procedure substantially decreased the duration of the turbidity peak (1 hour average for incremental startup versus 3 hours average for instantaneous start.)

An example of the schedule for an incremental startup is presented in Table 7.3. This table was based on Figure 15 of the AWWARF report of Bucklin, Amirtharajah, and Cranston. Those authors did not specify the rate of change for moving the valve (the number of seconds required for the valve to change its position) during the incremental changes. These data represent the practice employed for the shortest time period of incremental change in the filter runs studied in the AWWARF project. During the filter run for which startup rate data are given in Table 7.3, the peak turbidity reached during startup was approximately 0.27 ntu, according to Figure 15 in the AWWARF report.

The benefit to be gained from using the slow start approach for limiting turbidity spikes at the start of a filter run may be a function of the valve control mechanisms at the filter plant. Bearing in mind that Cleasby, Williamson, and Baumann (1963) reported that slow and gradual rate changes were less disruptive than abrupt changes, it can be inferred that the very slow and gradual opening of a valve would be preferable to intermittent but jerky operations. Thus if the six valve position changes

illustrated in Table 7.3 were each made gradually over 30-second intervals rather than abruptly in 1 or 2 seconds, the effect of changing the valve position about every two minutes should be minimized.

Operating the rate control valve slowly, in steps; instead of quickly or abruptly, in steps, is recommended. Furthermore, because Cleasby, Williamson, and Baumann found that the magnitude of the rate change influenced water quality (smaller changes caused less deterioration) operating the valve in multiple, smaller steps is preferred over using only a few, larger rate changes to go from a filter at rest to operation at the full rate.

At the Modesto Irrigation District, filter flow is ramped up by the SCADA system, using flow increases of about 0.2 mgd (0.8 ML/d) every 2 minutes beginning at a rate of 2.0 mgd (7.6 ML/d) per filter. This sequence of step increases and time intervals equates to a rate increase of 1.0 mgd (3.8 ML/d) in 10 minutes. The time needed to attain the total flow increase up to maximum set points ranging from 5.0 to 5.8 mgd (19 to 22 ML/d) per filter therefore would be 30 to 38 minutes. Often the initial turbidity does not exceed 0.1 ntu, and the worst case reported may be 0.16 ntu for a peak, with an hour needed to go below 0.1 ntu in filtered water. This plant also adds polymer to backwash water.

Three filter plants that use gradual rate increases at the start of filter runs reported that the initial turbidity spike was not controlled consistently to 0.3 ntu or lower. Furthermore one plant tried this approach and it did not work at that installation. This approach does not come with a guarantee of success. As described above, a filter rate start up that is slower, and more gradual, done with a larger number of smaller rate steps would have a better likelihood of success.

Coagulant or Polymer in Backwash Water

Addition of coagulant chemical or polymer to backwash during a portion of the filter backwash has been practiced for about three decades, beginning with Harris (1970) at the Contra Costa County Water District in California. Harris reported that filter media was conditioned to improve particle adsorption by adding nonionic polymer in the filter backwash water at a dosage of about 0.10 mg/L. [Harris gave no details on adding polymer but said the procedure was patented; US Patent 3478880. The patent should have expired by 1987. Unfortunately, the patent did not provide details on the timing for adding polymer, but was written in rather general language.] Harris reported that conditioning the filter media by adding the polymer during backwash was not a substitute for coagulating with an adequate

Table 7.2

Filter startup strategy comparison

	Instantaneous startup*	Incremental startup
Number of Runs	16	10
Ultimate Filtration Rate, gpm/sf		
Average	2.6	2.7
Maximum	2.8	2.8
Minimum	2.6	2.6
Turbidity Peak, ntu		
Average	0.28	0.26
Maximum	0.42	0.43
Minimum	0.19	0.17
Turbidity Peak Duration, hours		
Average	3.0	1.0
Maximum	4.0	1.0
Minimum	0.8	0.8

(Adapted from Bucklin, Amirtharajah, and Cranston 1988)

*Data are for second turbidity peak observed with instantaneous startup. Only one turbidity peak was reported for incremental startup.

dosage of alum. He noted that at his plant, filters could be started at a rate of 10 gpm/sf (24 m/h) and immediately produce effluent turbidity of 0.10 ntu or lower.

The plant was equipped with filters having anthracite and sand media, and air scour was used, rather than surface wash, to provide auxiliary scour. Harris' results were attained at a plant that was operated very carefully and are not indicative of results that may be attained by others. Do not operate filters at rates higher than the design rate or higher than the rate that has been approved by a regulatory agency.

Pilot plant studies (Yapijakis 1982) showed benefits of adding polymer to backwash water for direct filtration of surface waters in the New York-New Jersey area. In one case, using a nonionic polymer dosage of 0.10 mg/L to 0.15 mg/L reduced the duration of the initial improvement period by

about 50 percent but did not decrease the turbidity peak. In the other water studied, using nonionic polymer dosages of 0.05 mg/L to 0.15 mg/L reduced the turbidity peak and decreased the filter operation time required to attain a filtered water turbidity of 0.3 ntu. Details of the polymer addition procedures were not provided.

Table 7.3

Example of incremental filtration rate increases employed at Helena, Montana

Time since filter started (minutes)	Filtration rate (gpm/sf (m/h))
0 to 3	0.5 (1.2)
3 to 5	1.0 (2.4)
5 to 7	1.5 (3.7)
7 to 9	2.0 (4.9)
9 to 11	2.5 (6.1)
11 and on	2.8 (6.8)

(From Bucklin, Amirtharajah, and Cranston 1988; Figure 15)

These data are for a filter run started on June, 1986. Peak turbidity was 0.27 ntu

Bucklin, Amirtharajah, and Cranston (1988) studied the addition of coagulant chemicals to backwash water as a means of controlling the initial turbidity spike. They reported that coagulants can be a very effective means of controlling turbidity at the start of the filter run. They suggested that one way this worked was that the extra coagulant added during backwash could accelerate the filter ripening process. They stated, "As expected, the optimum injection time from the end of backwash is essentially the same as the minimum time necessary for the water in the filter unit to be completely displaced by the backwash water." This is interpreted as meaning that coagulant chemical should be injected into the backwash water until backwash water containing coagulant is flowing into washwater troughs and out of the filter box.

Cranston and Amirtharajah (1987) presented turbidity data for filter starts in which addition of alum to backwash water was tested in the full-scale filtration plant at Bozeman, Montana. The highest turbidity peak occurred when no alum was added to the backwash water. The most effective strategy was to add alum for the final 2.5 minutes or for the full 5 minutes of backwash, at a concentration of 17

to 18 mg/L in the backwash water. (See Figure 21 of the Cranston and Amirtharajah *Journal AWWA* paper cited above.)

Cleasby et al (1992) evaluated a direct filtration plant in Bozeman, Montana as part of an AWWARF project. They reported that the turbidity spike during the ripening period was completely eliminated by use of nonionic polymer to condition filter media during backwashing, a practice similar to that of Harris (1970). At Bozeman, a nonionic polymer dosage of 1.3 mg/L was fed into the backwash water during the last 3 minutes of the filter backwash.

Addition of coagulant or polymer to backwash water helps to condition the remaining suspended solids that were not washed out of the filter media during backwashing and the suspended solids that remained in the water over the filter media before the end of the backwashing.

At the end of a filter backwash, low turbidity, unused backwash water (typically, finished water) remains in the filter underdrain, under the media. If coagulant chemical or polymer addition is not stopped for a short time interval before the end of backwashing, some chemically conditioned backwash water will remain in the piping and underdrain cavity below the filter support material and filter media. At the start of the next filter run, the small volume of finished water containing polymer or coagulant will be discharged to the clearwell. The length of time between stopping the coagulant or polymer feed and ending the backwash will depend on the rate of flow of backwash water and the volume of water that would be in the piping and underdrain. Plant staff should be able to calculate this from plans of the filters and data on the backwash flow rate. If backwash water is treated by adding polymer or coagulant, stop the addition of the chemical for a short time before the backwash ends, as described above.

No clear consensus on ways to determine coagulant or polymer type and dosage and the duration of dosing was found in the literature or in the survey of utilities done in this study. Pilot plant testing and evaluation of a single full-scale filter equipped with filter-to-waste are preferred ways to evaluate addition of coagulant or polymer. In either of these situations, the filtered water could be wasted instead of flowing into the clearwell. If a full-scale evaluation is performed at a filter plant lacking filter-to-waste, operators will need to use caution and keep state regulatory engineers fully informed of plans, procedures, and testing results. At plants where coagulant or polymer is added to backwash water, mixing can be accomplished by the turbulent flow in the backwash piping that leads to the filters. Additional mixing will be accomplished as water with chemical passes through the underdrain and up through the filter media.

Extra Coagulant or Polymer Added to Settled Water Entering Filter Box

Some water utilities control or mitigate the initial turbidity spike at the start of a filter run by adding primary coagulant chemical or cationic polymer to the settled water entering the filter box as it is refilled following the termination of backwashing. Janssens et al. (1982) showed that an overdose of coagulant at the beginning of a filter run could improve initial filter effluent quality. Research on filter ripening by Francois and Van Haute (1985) led those authors to suggest that the initial improvement in filtered water quality occurred simultaneously with a change in the pore structure of the filter bed. Francois and Van Haute concluded that by overdosing inorganic coagulant at the start of a filter run, the filter-ripening peak could be reduced. This work provides a possible theoretical basis for the practice of adding coagulant to filter influent at the start of a filter run. There is no compelling theoretical evidence to back up this hypothesis however. An alternative case can be made that overdosing exposes the negatively charged media grains to positively charged flocs. This produces superior filtration until the media grains become positively charged. Continuing the overdose then leads to repulsion forces dominating and thus the deteriorating water quality noted by these researchers. Turning the coagulant dose down to that which achieves charge neutralization avoids repulsion effects.

In addition to the change in porosity that might be brought about by the addition of coagulant, adding coagulant to settled water flowing into the filter box could help to destabilize floc fragments left in the filter at the end of the backwash.

At the Lake Michigan Filtration Plant, operated by Grand Rapids, undiluted liquid alum has been added manually to influent settled water in a slug dose and this has effectively controlled turbidity spikes. The amount of coagulant added is approximately 1/3 gallon (1.3 L) per 8000 cubic feet (230 cubic meters) of water over the filter media. This calculation is based on the volume of water from the top of the media to the water surface, and ignores the volume occupied by wash water troughs. The dosage, calculated on the basis of commercial grade powdered or granular alum (filter alum, $Al_2(SO_4)_3 \cdot 14H_2O$), is about 3.7 mg/L. The typical alum dosage at this plant is about 13 mg/L. The peak turbidity at this plant typically does not exceed 0.1 ntu upon startup, which was described as "fairly prompt." Alum is added manually by the operator who backwashes the filter, using a plastic jug marked so the liquid alum can be measured easily. The alum is poured onto the surface of the inrushing settled water, and no mixing occurs other than the mixing that naturally happens when water enters the filter

box. Resting a filter after backwash is commonly done at this plant also, so both procedures may be influencing the initial water quality.

Using a similar dosage of liquid alum (3.3 mg/L when expressed as commercial grade dry alum) into settled water as it fills the filter box at the end of a filter backwash, the Greenville Water System has decreased the duration and magnitude of the initial turbidity spike at its Adkins Plant. This plant treats water from Lake Keowee, a large impoundment containing source water of stable, very high quality. In filter runs made with the same filter, started on two consecutive days, the peak particle count (2.2 to 15 μm) was about 500/mL when alum was not added to the influent settled water, contrasted to about 50/mL when the alum was added. Without alum addition the peak turbidity was about 0.15 ntu, whereas it was about 0.10 ntu with alum addition. Again, the coagulant is added by pouring a measured amount of liquid alum onto the surface of the water coming into the filter and no additional mixing is provided beyond that which occurs as the water comes into the filter box. More information on work done at Greenville is presented as a case study in Chapter 13, "Addition of Alum to Settled Water Flowing into Filter Box." Another case study on this topic in Chapter 13 is "Shortening Filter Ripening Time by Short Term Additional Coagulant Dosing."

At the Milwaukee Water Works a comparison was made between backwash with no polymer addition, backwash with cationic polymer (Cat-Floc T) added to the backwash water, and adding cationic polymer to the influent settled water for the last hour of a filter run and then adding it again during the first hour of the following run (Carmichael, Lewis, and Aquino 1998). The strategy of adding polymer to the influent settled water both before and after backwash in a dosage of 0.4 mg/L controlled the initial spike better than adding polymer to backwash water, as determined by particle counting. Both the peak height and duration of the spike were reduced by this technique.

Full-scale practice at Milwaukee was modified later to include addition of a slug dose of (undiluted) cationic polymer in the filter box in front of the influent valve. That slug dose is mixed as the settled water flows into the filter box after the influent valve is opened. The volume of polymer added in the slug dose is based on filter size and is calculated to deliver a dosage of 0.4 mg/L based on the amount of water needed to fill the filter. Then during the first hour of the filter run, polymer is feed is fed at a dosage of 0.4 mg/L. Polymer is no longer fed during the last hour of a filter run before backwash, as this did not prove to be beneficial.

Based on information provided by water utilities for this project, determination of coagulant or polymer type and dosage to use, and duration of dosing all are done by trial and error. A common

mistake that has to be avoided is the assumption that "if a little bit is good, a lot is much better." Overdosing either an inorganic coagulant or a polymer when settled water flows into the filter box or before and after backwash could have very bad consequences. Francois and Van Haute (1985) noted that applying the chemical overdose for too long at the beginning of a run caused filtered water turbidity to rise at the end of the dosing. In addition, if excessive alum is added to the influent settled water, mudballs might develop in the filter. This has been observed at Grand Rapids and is a factor in the alum dosage used there. The ability of excess polymer dosages to cause problems of short filter runs and mudball formation is well known.

Operators who try the slug dosing method or the short-term continuous feed method are advised to start at low dosages of coagulant or polymer and gradually increase the dosage if no positive effect is seen in the filter effluent quality. Furthermore, to develop solid evidence that the procedure is effective, they should perform alternate filter runs with added coagulant or polymer and filter runs having no added coagulant or polymer. In this way it can be established that the lowered turbidity spike at the start of the run was a result of adding the chemical to the filter influent water and not a consequence of source water quality and treatability changes that occurred over time as the testing program was under way.

Information is very limited on procedures for adding a continuous supplemental dose of coagulant for a period of time. The 1-hour time period used successfully at Milwaukee may not be the best time interval at other plants. Use of a cautious approach to application of a continuous supplemental dose of coagulant or polymer, starting with a dosing period of 15 minutes and increasing to 30 minutes and 45 minutes before trying a 1-hour interval is recommended. Note that effluent quality sampling has to be done very frequently, and the 15-minute interval for turbidity data collection that is required in the Interim Enhanced Surface Water Treatment Rule will not be adequate to describe the profile of the time vs. turbidity curve. Sampling at 5-minute intervals or using a continuous turbidimeter would give data that are more descriptive of the rapid changes in quality that occur at the start of a filter run.

Some water utilities treat source water for which alum is somewhat ineffective in very cold water. If this condition exists, the period of time between addition of alum to the filter box and the start of the run may be too short for the alum to react. This could cause dissolved alum to pass through the filter bed and into finished water. Where alum reaction time has been a problem in winter, this technique for controlling the initial quality of water produced at the start of a filter run may not be helpful. If the procedure is tried, monitoring the filter effluent for dissolved aluminum for the first hour

is strongly recommended, with samples collected every 10 minutes, or more frequently. For comparison purposes, two or three dissolved aluminum samples would be required during the stable portion of the filter run, after the end of the initial improvement period.

The chemical addition technique described above has been done with liquid alum and with cationic polymer. Water utilities using primary coagulants other than alum ought to be able to use their primary coagulant for controlling the turbidity spike, in the manner described above. If a full-scale evaluation is performed at a filter plant lacking filter-to-waste, operators will need to use caution and keep state regulatory engineers fully informed of plans, procedures, and testing results.

RETROFITTING FILTER RIPENING CONTROL METHODS

The ease and cost of retrofitting filter ripening control methods varies considerably, depending on the method chosen. Discussions of retrofitting or adapting plants for controlling filter ripening are presented in this section.

Filter-to-waste

Major reconstruction often is needed to retrofit a plant with filter-to-waste piping and valves. This can be the most expensive option for existing filtration plants.

Delayed Start

No construction is needed if extra water production capacity exists. Care is required to ensure plant output is not affected, either in terms of volume or quality with extra flow going through remaining filters.

Slow Start

No construction is needed if operators can manipulate filter rate control valves slowly, gradually, and easily.

Coagulant or Polymer Addition to Backwash Water

Adding coagulant chemical or polymer to backwash water does not require as much construction and equipment as adding filter-to-waste piping and controls, but the equipment needs are significant. To condition backwash water with chemicals, it is necessary to provide a chemical supply tank, a chemical pump, piping, valves, and controls.

Coagulant or Polymer Addition to Filter Influent (Settled Water)

Equipment needs for adding coagulant chemical or polymer to filter influent water range from very simple to something similar to that required for adding chemicals to backwash water. No construction is needed if the chemical is added manually. To provide for a continuous chemical feed into the filter box for a sustained period of time such as one hour, a chemical supply tank, chemical pump, piping, and controls would be needed.

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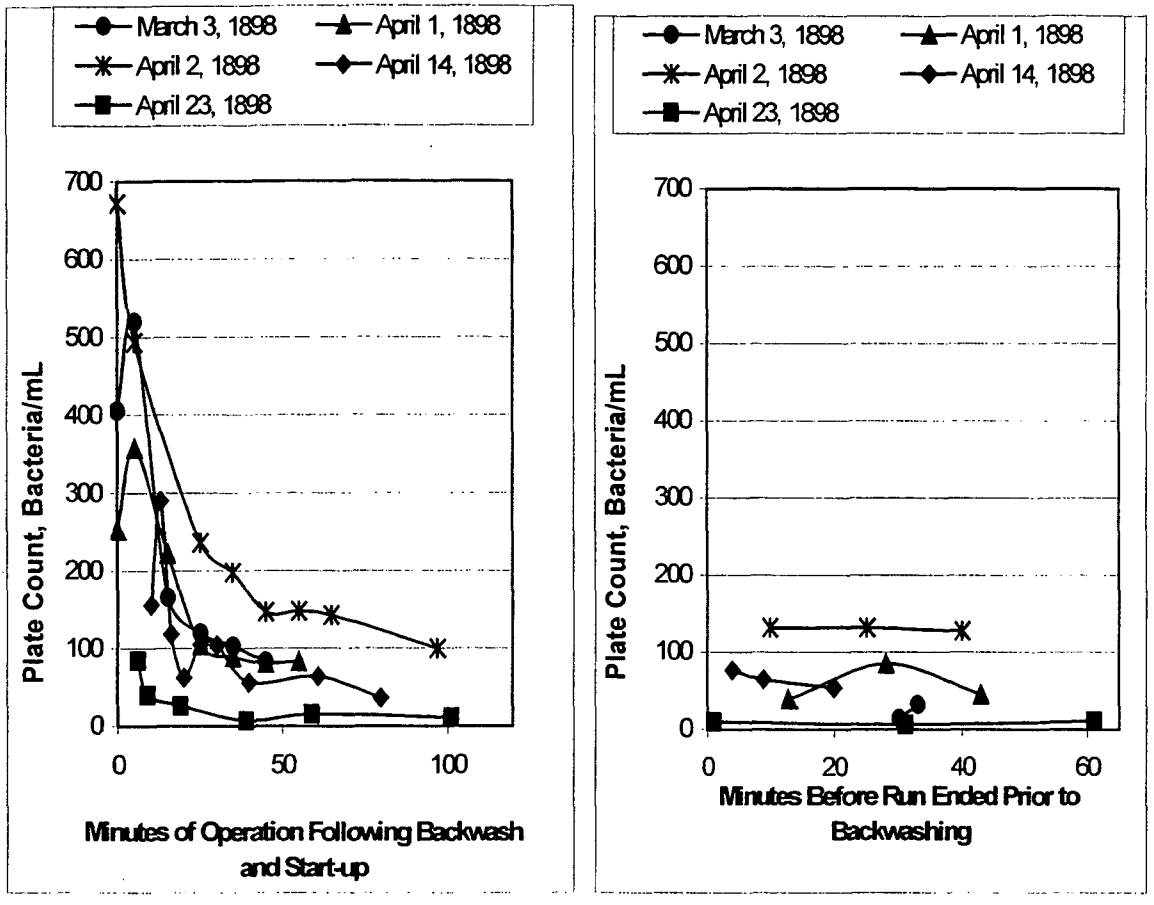

Figure 7.1 Passage of bacteria during filter ripening after backwash (*Source*: Data from Filtration Commission of the City of Pittsburgh 1899)

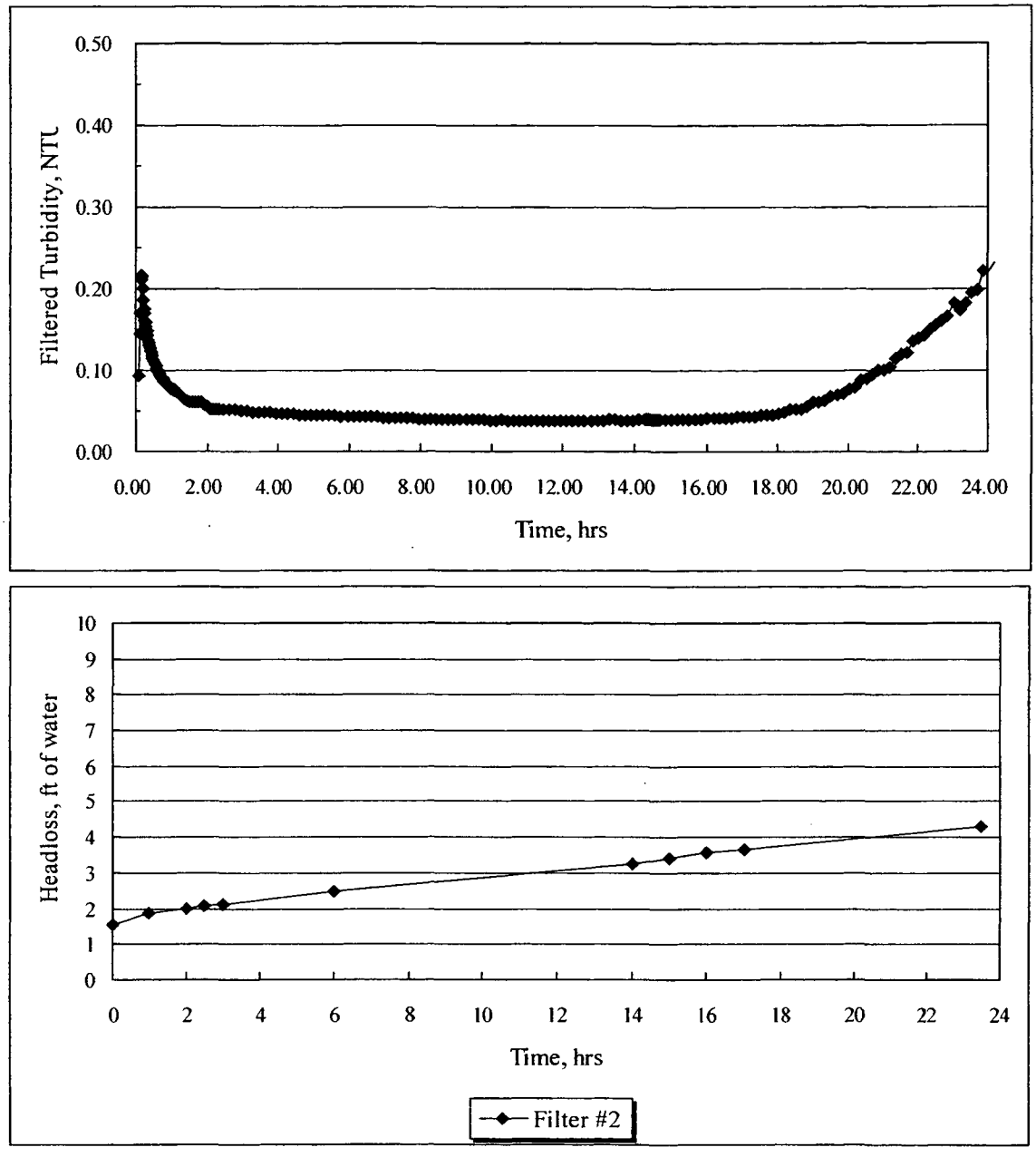

Figure 7.2. Initial improvement, stable operation, and turbidity breakthrough

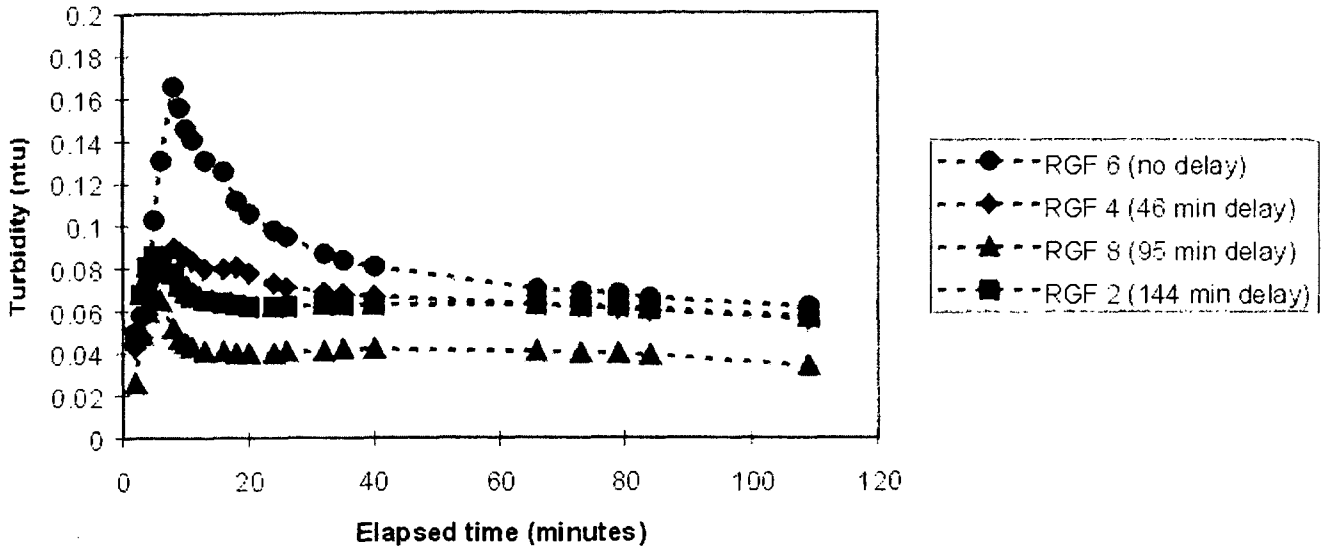

Figure 7.3 Delayed Start Trial 1: Turbidity data

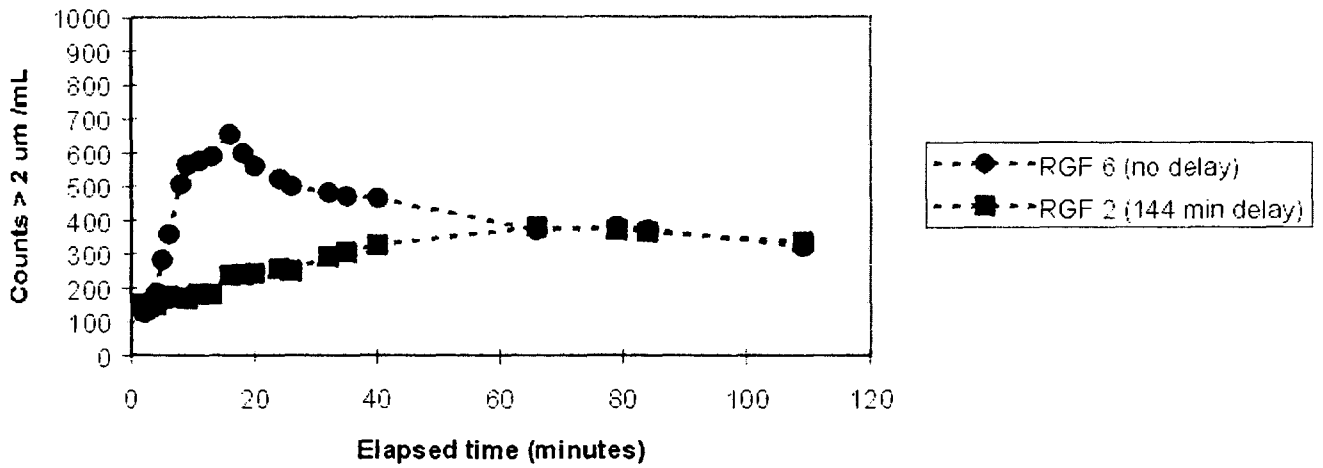

Figure 7.4 Delayed Start Trial 1: Particle count data

CHAPTER 8

PRETREATMENT: CHEMICAL DOSAGE, SELECTION, AND MIXING

INTRODUCTION

Chemical pretreatment has a very substantial effect on the quality of water produced by rapid rate filtration of water through a bed of granular filtering materials. When chemical conditioning, mixing and flocculation are not performed properly, quality of the filtered water will be impaired. Pretreatment is a performance-limiting factor in many filtration plants. Of the ten commonly identified problems encountered in surface water plants (Consenery et al. 1997), three were directly related to pretreatment. Successful pretreatment is necessary for optimized filter performance, and an investigation of pretreatment may be needed when filtered water quality problems are encountered. Pretreatment issues related to chemical dosage and mixing are discussed in this chapter. The first part of this chapter contains a brief discussion of pre-oxidation as it relates to filtration issues. Considerations for maintenance of chemical feeders and mixers are also presented. Flocculation and clarification are the topics of Chapter 9.

Much of the focus of this chapter is on attaining proper chemical dosages in pretreatment. When pH and chemical dosages in pretreatment are incorrect, operators can expect to see filtered water having poor quality. Conversely, filtered water quality can be optimized when pretreatment is correct. Among the approaches to attaining effective treatment chemistry are performance of jar tests, use of historical dosage charts, adjustment of pH and alkalinity, measurement of zeta potential and streaming current, use of pilot filters, visual observation of results, measurement of natural organic matter or surrogates, and use of tests for filterability.

PREOXIDATION

Purposes and Benefits

General

Pre-oxidation is carried out for a variety of purposes including control of zebra mussels, control of tastes and odors, algae control within the treatment plant, oxidation of iron and manganese, and disinfection. For some source waters use of pre-oxidation can substantially improve coagulation and filtration performance, so for those waters pre-oxidation becomes an important step in filter performance optimization. Disinfection is another important treatment process for which some of the pre-oxidant chemicals (chlorine, chlorine dioxide, and ozone) play a key role. The pre-oxidant dosage needed to treat a particular water will depend on the source water characteristics and the purpose of pre-oxidation. In general, if the pre-oxidant is also used as a disinfectant, the dosage would need to be adequate to satisfy oxidant demand and then to provide for a disinfectant residual after a period of contact time. For other purposes, such as pre-oxidation for improved filtration performance, dosages may not need to be as large.

Pre-oxidation has been shown to provide better filtration performance in some waters. Yates et al. (1998) showed that particle counts in filtered water in the size range equal to or greater than 2μm were somewhat lower than 100/mL for filtered water treated without any pre-oxidant. Particle counts were about 10 to 20/mL for filtered water with free chlorine pre-oxidation, and about 1/mL for filtered water with ozone as the pre-oxidant. The beneficial effects of pre-oxidation also were observed by this manual's senior author in pilot plant testing of Lake Mead water in the mid-1990's. During direct filtration testing with pre-chlorination and later during testing with pre-ozonation, loss of the pre-oxidant caused rapid increases in particle counts in the filtered water. As in the work by Yates et al., use of ozone gave lower particle counts than use of chlorine as a pre-oxidant. A disadvantage of using pre-oxidation is that the pre-oxidants form oxidation byproducts or disinfection byproducts or oxidant degradation products in the treated water.

Additional information on filtered water quality improvement as a result of prechlorination is presented in Chapter 13 in a case study entitled, "Monitoring and Review of Rapid Gravity Filter Performance Using On-line Particle Counters at Hope Valley Water Treatment Plant, Adelaide, South Australia."

Iron and Manganese Removal

In ground waters, iron and manganese generally are found in solution in a chemically reduced state, as ferrous iron (Fe^{2+}) or as manganous manganese (Mn^{2+}). In some surface waters, such as the water near the bottom of a reservoir, oxygen can become depleted, and here also dissolved iron and manganese may be encountered. To remove dissolved iron and manganese, these compounds first are oxidized to form insoluble compounds, and then they are removed by clarification and filtration, or by filtration with no prior clarification. Iron and manganese removal is discussed in this chapter because oxidation is the key to effective removal in processes generally used to remove these contaminants. Dissolved iron and manganese can be removed by ion exchange, but ion exchange processes are beyond the scope of this manual.

Iron can be oxidized more readily than manganese. Aeration often is adequate for oxidizing iron from Fe^{2+} to Fe^{3+}, so aeration towers are sometimes used for pre-oxidation of waters containing dissolved iron. The rate of oxidation of iron is pH-dependent, and Kawamura (2000) recommended that for complete oxidation of iron in 15 minutes, pH should be higher than 7.5, preferably 8. Some iron removal plants function as direct filtration plants, with no clarification before the filters. Depending on the iron concentration in the source water, clarification may be helpful or even necessary. A dissolved iron concentration of 2 mg/L in source water is the equivalent of a coagulant dosage of about 10 mg/L, for ferric sulfate having a formula of $Fe_2(SO_4)_3 \cdot 9H_2O$. Wagner and Hudson (1982) suggested that high-rate direct filtration treatment might be marginal if coagulant (aluminum or iron not specified) dosages were between 6 or7 mg/L and 15 mg/L, and use of direct filtration would be doubtful if coagulant dosages were over 15 mg/L. Those authors did not define "high-rate" filtration in the portion of the text in which chemical dosages for direct filtration were discussed, but in their summary of the paper rates of 5 to 15 gpm/sf (12 to 37 m/h) were mentioned. Twort, Ratnayaka, and Brandt (2000) indicated that filtration without clarification may be applicable at iron concentrations as high as 5 mg/L, but for that concentration they suggested a filtration rate of 2 gpm/sf (5 m/h).

Manganese is much more difficult to oxidize than iron. Twort, Ratnayaka, and Brandt (2000) indicated that for oxidation by oxygen the optimum pH for iron is >7.5, but for manganese, optimum pH is >10.0 unless a special filter medium is used. (One special filtering material used for manganese removal, greensand, is discussed in Chapter 11.) For filtration through beds of sand or anthracite, oxidation of manganese by oxygen would be practical only for lime softening plants operating at pH levels above 10.0.

Chlorine, potassium permanganate, chlorine dioxide, and ozone can be used to oxidize both iron and manganese. According to Twort, Ratnayaka, and Brandt the optimum pH for oxidation of iron by chlorine, potassium permanganate, or chlorine dioxide is >7.0. The optimum pH for oxidizing manganese by chlorine is > 9.0 in the absence of a special filter medium such as greensand or manganese oxide-coated media. When chlorine dioxide is used for manganese oxidation, optimum pH is either $\leq$7.0 or $\geq$7.5. For potassium permanganate the optimum pH is >7.0. Potassium permanganate is effective, but overdosing permanganate can cause "pink water." Ozone is effective for oxidizing manganese, but an overdose of ozone can oxidize manganese to the permanganate oxidation state, and this would cause "pink water." A limiting factor in use of chlorine dioxide may be the limits put on its degradation or disproportionation products. In the United States, as of January, 2002, a maximum contaminant level of 1.0 mg/L will be in effect for chlorite, which forms in water when chlorine dioxide degrades.

Removal of manganese by oxide-coated filter media in the presence of free chlorine was reported by Knocke, Hamon, and Thompson (1988). Mechanisms for removal of manganese by oxide-coated filter media were presented by Knocke, Occiano, and Hungate (1991). According to the publications of Knocke and his co-authors, free chlorine promotes the removal of Mn^{2+} onto filter media coated with oxides of manganese. They reported that the addition of chlorine just ahead of the filter resulted in oxidation of Mn^{2+} on the oxide surface coating on the filter media. Free chlorine oxidizes manganese slowly, compared to stronger oxidants such as potassium permanganate, chlorine dioxide, and ozone, but when chlorinated water is in continuous contact with oxide-coated filter media, the sorbed Mn^{2+} is oxidized to manganese oxides (MnO_x). The continual formation of more manganese oxides on the filter media renews the surface oxide coating with oxides that have not sorbed reduced manganese, enabling the removal process to continue. Removal is very efficient when pH is 6.0 or higher. Significantly, the authors reported that low water temperature did not slow the reaction. Filter loading rates of up to 5 gpm/sf (12 m/h) were reported to be effective.

Many upland waters in Northern Europe have low alkalinity, low hardness, low turbidity, and highly colored raw water with significant levels of iron, manganese, and aluminum. It has been found necessary to optimize treatment at three distinct pH and treatment process stages to adequately remove all impurities (Morris, Robinson, and Wilson 1979). The three stages of treatment are usually dissolved air flotation (DAF), primary filtration and secondary filtration. Ferric coagulants at pH 4.5 to 5.0 are preferred to alum for coagulation in order to remove sufficient natural organic matter to meet

disinfection byproduct goals. DAF is often the preferred clarification process because of the light floc produced when soft, colored waters are coagulated. Following clarification at low pH, the pH of the clarified water is raised to a range of 6.5 to 7.0 prior to filtration. This facilitates removal of any dissolved aluminum that had been present in the source water during the first filtration stage. The remaining manganese is then removed by chlorinating to a free residual, followed by high rate (7 to 10 gpm/sf or 18 to 24 m/h) filtration at pH 8.5 to 9.0 in the second filtration stage. This manganese removal process is autocatalytic and therefore this high filtration rate is practical.

In the process described by Morris, Robinson, and Wilson the manganese is not removed initially until a coating of manganese oxides is built up on the media, which can take two to three weeks. The process then operates efficiently provided the correct chemical conditioning is maintained. The backwash process controls the buildup of manganese on the media, but it is advisable to avoid combined air/water backwashing in the secondary filtration step as the beneficial manganese oxide coating can be stripped from the media. These second stage filters operate with relatively low head loss buildup and also provide useful polishing by removing many of the remaining particles that escape from the first stage filters.

Arsenic Removal

Studies on removal of arsenic by coagulation (Sorg and Logsdon 1978) have demonstrated that removal of arsenic is more effective when the arsenic is in the oxidized form ($Arsenic^{+5}$) rather than the reduced form ($Arsenic^{+3}$). Although generally arsenic in surface waters will be found as $Arsenic^{+5}$, in some instances preoxidation may be needed for effective arsenic removal.

Oxidants and Disinfectants

This discussion of oxidants and disinfectants is presented primarily in the context of operation and maintenance of filtration plants. The disinfection of drinking water for public health protection is not discussed in detail in this manual. For information on disinfection for control of pathogens and on use and handling of chlorine, users of this manual should refer to publications available from AWWA, such as:

- *The Chlorine Dioxide Handbook*
- *The Chlorine/Chloramination Handbook*
- *Handbook of Chlorination and Alternative Disinfectants*
- *Chlorine Institute -- Chlorine Safety Reference Set*
- *Chlorine Institute -- Chlorine Handling Reference Set*

Safe handling and use of oxidants and disinfectants is a major concern in the water industry. Operators need to learn and understand all appropriate safety procedures for any oxidant they are handling. Discussions of safety are beyond the scope of this manual, and as safety regulations can change from time to time the publications of AWWA, The Chlorine Institute, and chemical manufacturers should be referred to.

Potassium Permanganate

Potassium permanganate is an oxidant used for control of tastes and odors, control of zebra mussels at raw water intakes, and oxidation of iron and manganese. Addition of potassium permanganate does not cause formation of trihalomethanes in drinking water, and this is an advantage for applications such as zebra mussel control. Potassium permanganate should be used with care, as an overdose can cause pink water if some of the permanganate ion does not react in the water and become reduced. Furthermore, water pretreated with permanganate must be filtered carefully so manganese does not pass through the filters and into the distribution system.

Maintenance and calibration of permanganate feeders are needed on a periodic basis. Failure of a permanganate feeder, underfeeding the permanganate, and overfeeding all have the potential to cause serious water quality problems from the perspective of water utility customers. The most straightforward method for checking permanganate feed rates is to pump the solution from a graduated cylinder for a few minutes, noting the exact volume pumped and the time involved. From these data the feed rate can be determined. The dosage then can be calculated based on the flow of water, the chemical feed rate, and the strength of the permanganate. Careful handling of potassium permanganate is mandatory for safety reasons and for purposes of cleanliness. This chemical can cause stains that are difficult to remove, if spilled in the plant.

Chlorine Dioxide

Chlorine dioxide (Gates 1998) is an oxidant that must be produced on-site. If produced so no free chlorine is present in the oxidant solution, chlorinated disinfection by-products are not formed in drinking water. This oxidant is effective for control of tastes and odors, color, and zebra mussels; oxidation of iron and manganese; and control of algae in water treatment plant basins. It is a strong disinfectant also.

When used as an oxidant or disinfectant in treatment of drinking water, chlorine dioxide breaks down over time, forming chlorite ion. In the Disinfection/Disinfection By-Products Rule (U.S. Environmental Protection Agency 1998) a maximum contaminant level (MCL) of 1.0 mg/L (as chlorite) was set for chlorite in water distribution systems. In the same rule, the USEPA set a maximum residual disinfectant level (MRDL) of 0.8 mg/L as ClO_2 for chlorine dioxide.

Control of chlorine dioxide generation requires analysis of water samples for chlorine dioxide, chlorite, and chlorate. Analytical procedures are more complex than procedures for free or combined chlorine. Furthermore, because chlorine dioxide is present in water as a gas, samples must be collected and handled with care to avoid losing some of the chlorine dioxide in the water before it is analyzed. For more information on analytical procedures, see *The Chlorine Dioxide Handbook* (Gates 1998).

Operation and maintenance of chlorine dioxide generators and associated equipment and piping were discussed by Gates (1998). Instructions are specific to the equipment being used. Operators should consult their instrument manual for details. Gates recommended making a daily check of piping, chemical pumps, and equipment for potential chlorine or sodium chlorite leaks. Regular preventive maintenance checks are recommended for all equipment, storage tanks, piping and valves. Dry sodium chlorite can be ignited by sparks or by compression, and great care has to be exercised whenever working around this chemical. Traces of dry sodium chlorite must be washed off any piping, tanks or other equipment. Consult *The Chlorine Dioxide Handbook* for details.

Ozone

Ozone is the strongest oxidant in use by the water industry. Like chlorine dioxide, ozone must be produced on site. Ozone is a powerful disinfectant, capable of inactivating *Cryptosporidium parvum* oocysts and other less resistant, microorganisms. Ozone is a very effective chemical for controlling taste and odor in water. It readily oxidizes iron and manganese. Ozone is effective for

oxidizing and breaking down natural organic matter, but as it breaks down large molecules of natural organic matter, it forms smaller organic molecules and molecular fragments that are readily used as a food source for bacteria. Ozone has been shown to improve coagulation and filtration in numerous source waters.

Ozone is expensive, and its use is sometimes justified by having multiple purposes for ozonation, such as taste and odor control, iron or manganese oxidation, pesticide destruction, DBP reduction, reducing chlorine demand and improving coagulation. Use of ozone for oxidation of iron and manganese can have drawbacks. Other less expensive oxidants are available for iron, and when ozone is used to oxidize manganese, if the ozone dosage is excessive, manganese will be oxidized to permanganate, forming pink water.

When ozone is used to aid coagulation and filtration, it should be employed all of the time. Loss of ozone feed has disrupted filtered water quality at sites where preozonation was beneficial for coagulation and filtration. Ozone has been demonstrated to be a superior pre-oxidant as compared to free chlorine, in a limited number of direct filtration plants where high quality source waters were treated with a low dosage of coagulant (Cleasby et al. 1992).

Frequently when ozone is used ahead of filtration, no other chemical disinfectant is used until after filtration. When chemical disinfectants other than ozone are applied after filtration but not before filtration, water filters operate in a biological mode. To some extent, any filter that is operated without the presence of a disinfectant residual in the water being filtered is operating as a biological filter. Ozone accentuates or maximizes biological activity in the filter bed, by breaking down complex organic molecules and forming organics that can be used as food by bacteria in the filter bed. Biological growth in filter beds is a concern for some treatment plant operators and regulatory officials. Biological filters may require a more careful backwashing procedure, to avoid long-term problems such as development of mudballs. Growth of pathogenic bacteria in biological filters is highly unlikely, so shedding of bacteria from such filters is very unlikely to result in shedding of pathogens into treated water. Bacteria shed by biological filters should be controlled by post-filtration disinfection.

Ozonation systems are complex, usually involving several pieces of equipment. If air is used for generation of ozone, air compressors, a refrigerant dryer or a dessicant dryer, and a moisture separator and air filter are among the equipment that will need maintenance. Liquid oxygen facilities also will require maintenance if liquid oxygen is used instead of air. The ozone generator, of course, will require periodic maintenance, as will the ozone destruct unit and the ozone contactor. Langlais,

Reckhow, and Brink (1991) discuss maintenance of ozone facilities in detail. Consult the manufacturers' operations and maintenance manuals for specific directions on the maintenance of ozone generators and related equipment.

For safety reasons in Thames Water the ozone residual is destroyed by sodium bisulphite dosing under Redox potential control before the water leaves the ozone contactor. Waterloo also reported that good results were attained by use of a sodium bisulfite system for destruction of ozone before it reached the filters.

Experiences with ozone. Numerous studies have found that pre-ozonation is beneficial for attaining lower turbidity or particle counts in filtered water. Use of ozone in some instances improves removal of algae. On the other hand, in many other waters, no such benefits have been observed (Singer and Reckhow 1999). Effects of ozone on filtration were discussed by Edzwald et al. (1998). They state that whether ozone will aid coagulation and filtration depends on the raw water quality. Factors influencing results include the concentration of natural organic matter, the turbidity, presence of algae, and concentrations of iron and calcium in the water being treated. These authors noted that coagulating effects of ozone often occur at ozone dosages of 0.5 to 1.5 mg/L and state that excessive ozone dosages can deteriorate coagulation performance.

The surest way to find out if use of ozone as an oxidant is beneficial to filtration performance is to perform a pilot plant study on site. Use of ozone can have detrimental effects as well as benefits. When source water has bromide in concentrations of about 0.1 mg/L or higher, ozonation can cause formation of bromate, a regulated contaminant. Depending on the level of bromide in the water, the bromate MCL (0.010 mg/L) might be exceeded.

Free Chlorine

Use of free chlorine to disinfect municipal water supplies began in the United States at Jersey City, NJ, in 1908 and has spread across the country. In a survey carried out in 1989 and 1990 (AWWA Committee 1992), about 72 percent of the 267 utilities that responded reported using free chlorine as a disinfectant. For several decades, free chlorine has been a very popular disinfectant. Free chlorine can oxidize iron so it can be removed subsequently by filtration, and free chlorine also can promote removal of manganese. When free chlorine is used as a disinfectant, chlorine substitution reactions occur with natural organic matter, and DBPs are formed.

Pre-oxidation with free chlorine can improve the filterability of water and produce lower filtered water particle counts, as compared to water that had not been treated with a pre-oxidant. This benefit probably will be available, however, only to water utilities having source waters with very low concentrations of TOC, because of the formation of DBPs that occurs when natural organic matter in water is exposed to chlorine.

Maintenance of chlorination equipment and facilities is complex. White (1999) devoted 20 pages of his text book on chlorination to maintenance issues. He placed a strong emphasis on detection of chlorine leaks, stating that the primary objective of maintenance at a chlorination facility is the prevention of leaks. This is understandable because of the dangers associated with chlorine leaks. Consult White's text for more information on this topic.

PRESEDIMENTATION

Presedimentation may be used when source water turbidity is very high. By settling out some of the heavy particulate matter ahead of conventional treatment, the load on the conventional plant can be reduced. Historically, presedimentation was used to treat water from rivers in the Ohio, Missouri, and Mississippi River basins. When used without any coagulation to enhance settling, presedimentation has been referred to as plain sedimentation. In this mode, its purpose was mainly for removal of particles large enough to settle on their own in quiescent water. Present design practice calls for addition of a coagulant or coagulant aid to enhance particle settling and improve clarification before water enters a conventional treatment train. The presedimentation process can help equalize influent water quality, shaving off peaks or extremes in source water turbidity, and making the task of optimizing coagulation less difficult.

For pre-sedimentation basins that utilize chemical coagulation, refer to the section on coagulation, which follows this section.

Operating Presedimentation Facilities

Operating issues include residence time in pre-sedimentation facilities, as it relates to short circuiting and deteriorated basin performance, and also to algal growth in uncovered basins. For a basin to provide effective settling, short circuiting must be prevented. Older pre-sedimentation basins may have been designed with inlet and outlet works that cause short circuiting. Tracer tests are

recommended for evaluation of basin performance. Pre-sedimentation basins can provide extended detention time for water in conditions that promote the growth of algae. Treatment with copper sulfate might be an option for algae control, if the treatment does not raise copper concentrations to levels near or exceeding the action level for copper.

Pre-sedimentation basins can sometimes be used as off-stream storage, permitting the intake to be closed when contaminated water is passing by. If pre-sedimentation basins are used to avoid taking in water when a chemical spill passes by, treatment plant staff need to know the concentration of the chemical in the river or stream and the estimated time of passage of the contaminant. Shutting off an intake prematurely could result in exhaustion of water stored in the pre-sedimentation basin and in the distribution system, necessitating the reopening of the intake before the worst of the spill had passed. A good understanding of the source water situation is required for effective use of pre-sedimentation basins during spills, but when reliable data are available, some utilities have used these facilities very effectively to avoid problems caused by spills. Monitoring water quality in presedimentation basins can help operators prepare for quality changes at the treatment plant.

Maintenance for Pre-sedimentation Facilities

Maintenance aspects include periodic cleaning of accumulated sludge and mud from basins, to prevent accumulated deposits from causing deteriorated sedimentation performance; and checking the condition of valves, gates, baffles, and other flow control devices in the basin or related to its operation. Allowing excessive deposits of mud and sludge to build up in the basin will gradually decrease the available detention time for sedimentation. If septic conditions develop in the deposits, taste and odor problems might occur and oxidized iron or manganese might become soluble and be present in the plant's influent water. Also, if the facility is operated at a high rate of flow, some previously-settled materials might be resuspended, increasing the treatment burden on the remainder of the treatment plant. Maintenance should be timed to occur when source water quality is best, so treatment in the absence of pre-sedimentation will not suffer. Past experience at the plant is the best guide for determining when to schedule maintenance.

COAGULATION

Importance of Attaining Optimum Coagulation

Granular media filters do not perform at their optimum capability unless the water to be filtered has been carefully pretreated and correct coagulation chemistry has been attained. Important factors are which coagulant to use (e.g. iron coagulants, aluminum coagulants, or polymers), the pH of coagulation, and the coagulant dosage. If multiple coagulants are added, or if pH is adjusted, the order of chemical addition can influence treatment. In addition, the extent of chemical mixing and dispersion of chemical throughout all of the water being treated are important. The importance of effective coagulation has long been recognized. In a discussion of water treatment, Conley (1965) stated, "It is well to stress, at this point, that everything that follows is of no consequence if the coagulation is not properly done. No water plant can achieve good results, regardless of the excellent design of flocculators, settling basins, and filters, unless the coagulation is correctly done."

Research on coagulation and filtration for removal of *Giardia* cysts and *Cryptosporidium* oocysts has shown that removal of these microorganisms is most effective when coagulation is optimized. Table 8.1 summarizes results of some research on this topic. The data in the table may be compared within a researcher team's data, but because of differences in methods used to detect the microorganisms, comparisons between researcher teams should not be made. Note that in each study, removal of *Giardia* or *Cryptosporidium* was not as effective when coagulation was sub-optimum. Deterioration in full-scale plant performance for removal of microorganisms by filtration should be expected if coagulation is not practiced properly.

Treatment Plant Practices for Coagulant Selection, Dosage Determination, and Coagulation Performance Monitoring

Techniques used for determining the proper coagulation strategy were reported by water utilities in this project. Table 8.2 summarizes information from 37 plants practicing coagulation. Data from lime softening plants are not included in these tables.

Table 8.1

Comparison of protozoa removals in granular media filters operated with optimum coagulation and sub-optimum coagulation

Research team	Test condition	Turbidity, mean & (range) (ntu)	Log removal, mean & (range)	
			Crypto-sporidium oocysts	*Giardia* cysts
Logsdon et al. 1981	Optimum coagulation	0.08 (0.08 - 0.08)	Not done	3.2 (2.6 - 3.7)
	Sub-optimum coagulation	0.27 (0.24 - 0.32)	Not done	2.0 (0.4 - 2.9)
	Minimal coagulation	0.7 (0.5 - 1.0)	Not done	0.7 (0.1 - 1.2)
DeWalle, Engeset, and Lawrence 1984	Optimum coagulation	0.05 (0.02 - 0.19)	Not done	3.0 (2.6 - 3.7)
	Sub-optimum coagulation	0.44 (0.37 - 0.52)	Not done	0.8 (0.4 - 1.1)
Hendricks et al. 2000	Optimum coagulation	0.08 (0.07 - 0.09)	3.4	3.2
	Sub-optimum coagulation	0.5 - 0.8	2.5	1.6
Ongerth and Pecararo 1995	Optimum coagulation	0.03 (0.02 - 0.08)	2.9 (2.5 – 3.4)	3.3 (2.8 - 3.7)
	Suboptimum coagulation	0.36 (0.34 - 0.40)	1.5 (1.2-1.9)	1.3 (1.0 – 1.7)

Table 8.2

Methods used for determining and monitoring coagulation chemistry by this AwwaRF project- participating utilities 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

Water utilities reported that they used a variety of approaches to determining coagulation chemistry and monitoring coagulation. Perhaps the most important observation from the results summarized in Table 8.2 is that the vast majority of plants used three, four, or five different approaches for evaluating coagulation. Using only one or two ways to set and monitor coagulation chemistry is not typical at the plants participating in the AWWARF study. Some techniques, such as visual observation, are clearly a means of watching for problems rather than determining actual dosages. When plant operators have more kinds of information on coagulation performance available, they have a stronger basis for making decisions about coagulation chemistry.

Procedures for Coagulant Selection, Dosage Determination, and Evaluation of Coagulant Dosage Used

Selection of the right chemical coagulant and determining the correct dosage are critical steps for optimizing the operation of granular media filters. Effective coagulation is essential. "Chemical pretreatment prior to filtration is more critical to success than the physical facilities at the plant," according to Cleasby et al (1992). This section of the manual describes a variety of ways to evaluate chemical coagulation and determine the proper dosages, because coagulation control techniques will vary from plant to plant. As noted by Cleasby et al. (1992), "The operating staff must use a well-defined chemical control strategy that has been verified at that particular plant for the varying raw water qualities." What works well at one plant may not be appropriate at another plant using a different treatment approach for the same source water. Careful investigation of coagulation control techniques is advisable before large amounts of money are spent on sophisticated equipment for this purpose.

Symptoms of improper coagulation or out-of-control coagulation at a treatment plant may include one or more of the following:

- hazy or cloudy water in settling basins or on top of filters, and poor settling, related to improper coagulation pH or insufficient coagulant dosage
- excessively large floc in settling basins and carry over from sedimentation basins, perhaps caused by excessive coagulant dosage
- poor performance in a dissolved air flotation clarifier
- weak floc and turbidity breakthrough at low head losses, related to improper coagulation pH or insufficient coagulant dosage
- high filtered turbidity throughout run, related to improper coagulation pH or insufficient coagulant dosage
- high initial turbidity at start of filter run and very long and slow decline of filtered turbidity after startup, possibly related to use of cationic polymer as the sole coagulant
- high rate of head loss increase and short filter runs caused by floc carryover from sedimentation, perhaps caused by excessive coagulant dosage
- accumulation of mudballs in the filter, caused by excessive dosages of coagulant or polymer

When problems like those noted above are observed, one aspect of plant operations to check is whether the coagulation dosage and pH of coagulation are in the appropriate range for optimum treatment. Other causes for problems like those listed above may exist, but coagulation chemistry is a potential source of these difficulties, so it should not be overlooked.

Jar tests

Jar tests have been used for decades by water treatment plant operators to develop information on the chemical dosages that should be used to achieve effective coagulation and sedimentation. A typical jar test apparatus is shown in Figure 8.1. Many of the water utilities using jar tests have developed modifications or variations to adapt this procedure to the specific conditions encountered at their plants. This is appropriate, but certain common aspects of the jar test procedure should be considered and incorporated by most water utilities.

Detailed and very useful discussions of jar tests and procedures for jar testing can be found in a variety of sources, including "Chapter 1, Jar Testing," in AWWA Manual M37, Operational Control of Coagulation and Filtration Processes (AWWA 2000). Other references related to jar testing include a *Journal AWWA* paper (Neuman 1981) and "Chapter 3 Jar Testing and Utilization of Jar Test Data" in *Water Clarification Processes: Practical Design and Evaluation* (Hudson 1981). Suggestions for jar test procedures are summarized below. A more detailed discussion of jar tests is presented in this manual in Chapter 14. In jar tests, the water treatment chemistry scales up well, but physical (engineering) parameters are much more difficult to scale up.

Plant operators who perform jar tests should put a strong emphasis on quality control aspects of jar testing and should be aware of what to do to get good jar test data and what to avoid.
Examples of practices to avoid include:

- Performing jar tests at room temperature in winter when water in the plant is near freezing.
- Improper dilution of treatment chemicals and polymers or holding diluted chemicals beyond their shelf life, resulting in use of ineffective treatment chemicals.
- Improper collection or storage of raw water, giving non-representative raw water for jar test studies.

- Mixing at energy inputs that have no relationship to the actual plant, and settling for unrealistic times to obtain data.
- Attempting to use sedimentation results from jar test when raw water turbidity is very low and direct filtration is being used in the plant.
- Disturbing settled water in the jar when sampling for turbidity.

Examples of good practices include:

- Carefully documenting of preparation of treatment chemicals, including date of dilution and recommended expiration date beyond which chemical should not be used.
- Manual M37 recommends that dilution of inorganic coagulants should not result in solutions having a strength of less than 0.1 percent, or 1000 mg/L (1 mg/mL). Stock solutions of inorganic coagulant at a concentration of 10 mg/mL should be prepared each day. Polyaluminum chloride and other inorganic polymeric coagulants degrade rapidly and so should not be diluted.
- Manual M37 also recommends that stock solutions of polymer having a strength of 0.2 mg/mL (200 mg/L) should be prepared each day.
- Pre-measuring chemicals to the prescribed dose for addition during the test so that all of the additions can take place within the shortest possible time once the test procedure has begun. Ways to do this include:
  - use a tilting rack, to which test tubes are secured with spring clips, to add contents of all the test tubes into the jars simultaneously.
  - use relatively small syringes that can hold up to 1 to 5 mL, placed at the jar test apparatus in a manner that will eliminate confusion about which syringe or syringes are to be used for a given jar.
  - use a device that can be used to inject chemical dosages simultaneously by means of syringes. Instructions and a diagram have been presented in Opflow (Mical 1997; and Mical 1998).
- Using test water that is representative of water being treated, for both chemical and physical characteristics, including temperature.
- Checking the accuracy of the tachometer for measuring rpm of stirrers.

- Periodically performing a jar test with 4 to 6 jars having identical chemical dosing, mixing, and flocculation times, as a check on reproducibility of the procedure in the hands of those who perform the tests.
- Performing jar tests in which conditions are similar to plant conditions, to verify that jar tests are a good predictor of plant performance.
- Calculating the settling time before sampling for turbidity measurement, based on the overflow rate for the full-scale settling basin. This typically results in sample collection after just a few minutes of settling in a jar test jar. For example, if the overflow rate to be simulated is 1 gpm/sf (about 24 m/h or 4 cm/min) the sampling time at the 10 cm depth would be 10 cm / 4 cm/min = 2.5 minutes.
- For studies of turbidity removal and DBP formation, sampling for turbidity after a few minutes, but sampling of water for measurement of DBPs based on the actual detention time in the full-scale settling basin.
- Maintaining jar test results and records for at least several years, for purposes of historical review and for future reference when raw water quality may be similar to that encountered in the past.

As a shortcut for jar testing, some treatment plant operators take a sample of water entering the flocculator and place it in jar test jars, stirring at the appropriate rotational speed. They view the floc for size and may evaluate its settling characteristics. This method could provide a quick insight into an existing treatment practice and has merit for this. It would not give information on the effect of other dosages.

As an aid to operators who wish to evaluate floc as it forms, a floc size comparison chart is presented in Figure 8.2. This chart shows flocs ranging from less than 1 mm to about 5-mm apparent diameter, so floc may be classed by comparing the appearance in the jar tester to the pictures on the chart. The chart can simply be fixed to the wall near to the jar tester, or laminated and kept with the jar tester. The pictures help different operators to have a common standard for estimating floc size.

Floc charts can be used in several slightly different ways:

- When a jar test is carried out the operator can note the time it takes for a floc of each size to form.
- When testing different coagulant doses the operator can compare and record the size of floc produced after a standard slow stirring duration.
- The time and size of floc formation with different stirring velocities can me measured.
- If the settled jar test suspension is filtered, the results of filtered water quality against floc size at the end of slow stirring can be recorded.

The chart allows a visual cross check to be made which helps in understanding whether the floc is too small to settle well, too large and open-structured to settle well, and so on. Once it is known what size floc works best for the treatment plant, the floc size comparison chart helps by providing a standard way of assessing the results of multiple jar tests. The operator can set up the jar tests to determine the right combination of coagulant dose, mixing energy (stirrer speed) and residence time. By comparing the results of the jar tests with the standard chart of floc sizes the operator can select the combination of operating conditions that produced the floc of the desired size. Table 8-3 gives overflow rates and minutes of settling time for sampling at the 10-cm depth in jar test jars.

The jar test procedure must be evaluated in the context of the type of data being sought, and the procedure used must fit the circumstances that are appropriate to the purposes of the testing. In the case of DBP formation, sampling for turbidity and information on floc settling could be done after a few minutes, as described above, but sampling of water for measurement of DBPs would need to be done after the actual detention time in the full-scale settling basin had been attained in the jar. In jar tests, the water treatment chemistry scales up well, but physical (engineering) parameters are much more difficult to scale up.

When jar testing is conducted to evaluate treatment of low-turbidity waters, the typical procedure of rapid mix-flocculate-settle may not provide adequate information. If raw water turbidity is near 1 ntu, measuring settled water turbidity may not reveal much about effective coagulant dosages. In such a situation, after the flocculation step, flocculated water should be filtered through Whatman #40 filter paper, as recommended by Wagner and Hudson (1982). This simulates treatment by direct filtration, for estimating chemical dosages needed for coagulation.

Table 8.3

Surface overflow rates and corresponding settling times for jar tests

Overflow rate (gpm/sf)	Overflow rate (meters/hr)	Overflow rate (cm/min)	Minutes to settle 10 cm in jar test jar (minutes)
0.4	1	1.6	6.1
0.6	1.5	2.4	4.1
0.8	2.0	3.3	3.1
1.0	2.4	4.1	2.4
1.5	3.7	6.1	1.6
2.0	4.9	8.2	1.2

At the Washington Suburban Sanitary Commissions's Potomac Water Filtration Plant, operators use Gelman Type A/E 47-mm diameter glass fiber filters having a 1 μm pore diameter to quickly simulate how well floc will filter. Water from six test jars is filtered to identify trends associated with dosages. When raw water turbidity is 2 ntu or lower and clear coagulants such as PACl are used, visualizing jar test results is difficult, and in this situation the filtering technique is helpful. Filtrate turbidities are higher than the turbidity produced by full-scale filters, but the trends are indicative of full-scale performance. When ferric chloride is used at this plant, filtered water iron tests are also performed to identify trends related to dosage.

Note that filtration through paper or glass fiber filters can NOT provide any data on time variations of filtrate quality or on head loss development in direct filtration, so using jar tests for estimating chemical dosages to be used in direct filtration is merely a first step in determining the appropriate chemical treatment. Head loss development data can be obtained only by operating either a pilot filter or a full-scale granular media filter.

Recording jar test data. The following data should be recorded for each jar test performed:

- raw water temperature just before treatment chemicals are added
- raw water turbidity

- raw water pH
- raw water alkalinity
- settled water temperature at end of settling period
- settled water turbidity, each jar (with depth of sampling and time of sampling identified)
- settled water pH, each jar
- dosage of coagulant chemical, each jar
- dosage of caustic or acid, each jar

Additional analyses can be performed if thought appropriate for the particular coagulant chemical being tested. When jar tests are performed for purposes of removing constituents from water other than turbidity, other analyses may be necessary. For example, jar testing for enhanced coagulation would involve TOC analysis, and testing for control of DBPs could involve chlorination of settled water samples and subsequent testing for DBPs in water samples incubated for specified periods of time.

Bench-scale procedures for alternative clarification processes

Bench-scale testing procedures can be used for alternative clarification processes, such as dissolved air flotation and ballasted flocculation. Some specialized equipment is required. Bench-scale testing procedures for dissolved air flotation were described by Plummer, Edzwald, and Kelley (1995) and specialized DAF jar test apparatus is available commercially in the U.K.. Figures 8.3 and 8.4 show DAF jar test apparatus during a jar test. In DAF bench-scale tests, water is coagulated and flocculated, and then a measured amount of water containing supersaturated air is introduced near the bottom of the jar. Floc floats to the top. Typical coagulation variables such as coagulant dosage, coagulant chemical, and coagulation pH can be investigated. In addition, the DAF jar test apparatus can be used to evaluate the effect of air bubble volume on flotation by varying the air pressure used in the saturator and by varying the volume of saturated water added to the test jar. The latter simulates changing the percentage of recycle flow in a full-scale plant.

The ballasted flocculation process can be simulated in a procedure described by (Desjardins et al. 1999). To evaluate this process jar test jars are raised so the bottom of each paddle is only 3 mm from the jar bottom.

The stirrer has to be very close so the ballasted floc that contains sand will not settle to the bottom of the jar and remain there during the treatment step when microsand and floc are bonded together by polymer. At treatment plants where these processes are used, the above references can provide useful guidance.

Historical data on raw water quality and dosage

Use of historical data on water treatment is an approach to coagulant dose determination that has been practiced for many years. This approach has been used for decades, as it was discussed in a water supply text in the 1950s (*Water Supply Engineering*, Babbitt and Doland 1955). Use of historical data is site-specific. When two or more nearby water utilities are using the same coagulant chemicals and treatment processes to treat water from a common source, information about treatment at one utility may be helpful for another nearby. Such information should be considered as a guide rather than as an absolute answer to treatment, as the design of processes may differ sufficiently from plant to plant such that different chemical dosages are needed, even for similar source waters.

Data tables or charts can be based on local records over a period of years. An example would be a chart of raw water turbidity versus the alum dosage in mg/L used for coagulation of river water, over a wide range of turbidity. Coagulant dosage requirements are influenced by water temperature, total organic carbon (TOC) concentration, and coagulation pH in addition to turbidity, so different dosage charts may be needed for different ranges of water quality. CAUTION. Historical data may not be useful if treated water quality goals have changed since the time when the original data were developed.

JAR TEST DATA SHEET

Test ID:_____ Date:_____ Operator:_____

Jar Number		Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
Rapid Mix	RPM						
	Time, Sec.						
Flocculation	RPM						
	Time, Min.						
Settling Time, Min.							
Chemical Used		Dosage Used, mg/L					
Parameter	Raw	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
pH							
Turbidity, ntu							
Temp., °C							
Alkalinity, mg/L		-----	-----	-----	-----	-----	-----

Notes:

Chemical dosages that were adequate to produce 1 ntu filtered water may not be appropriate for producing 0.1 ntu filtered water. Also if chemical strength changes or a different chemical is used, historical data may not be useful. The following advice is provided for preparation of a coagulant dosage chart based on raw water turbidity:

- Use only data developed during the time when your present filtered water quality goal was applicable, as dosages appropriate for 1 ntu or 0.5 ntu filtered water would not be expected to produce 0.1 ntu water.
- Use data only for days when the present filtered water quality goal was attained.
- Use only data developed with the presently-used coagulant chemical was being used. If the same chemical was used but different manufacturers supplied the chemical, verify that the chemical strength was the same for each manufacturer's product.
- Develop a table, chart or graph of raw water turbidity (independent variable) versus coagulant dosage, for a temperature range of about 10 °F or 5 °C. Examples are 32-40 °F, or 0-5 °C, etc. When temperature varies over a wide range, several charts may be needed.
- Review the pH of coagulated water for successful treatment during different seasons. If water temperature seems to influence the value of pH needed for successful treatment, be sure to specify the applicable pH range for each coagulation chart.
- When charts or tables are developed and coagulant dosage is plotted as the dependent variable (Y-axis) and raw water turbidity is the independent variable (X-axis), the graph should not display a wide spread of dosage values for a given raw water turbidity.
- If the range of dosages associated with a given raw water turbidity seems too wide for effective use of the chart or graph as a tool for setting the actual coagulation dosage, consider using the chart or graph as a guide for the range of dosages to try in jar testing.

If raw water turbidity and coagulant dosage are not closely related (i.e. if the data show considerable scatter rather than a linear plot), then one or more additional factors may be influencing the coagulation chemistry. One example would be the concentration of total organic carbon. When several variables influence coagulation, developing tables or charts or graphs for use in determining coagulant dosages in the future may become too complex to be practical. The benefit of a simple,

reliable means of estimating coagulant dosages is lost if dozens of charts or tables are needed to cover all of the treatment situations that may be encountered.

Multiple variations of raw water quality can be dealt with in a data table by setting up a matrix that provides for variations in two parameters, such as turbidity and TOC. Some kinds of natural organic matter (measured as TOC) exert a coagulant demand, and this could result in the need for higher alum dosages when TOC was in a higher range. To develop a matrix table for coagulating water with variations in turbidity and TOC, a raw water turbidity column would be prepared, with two or more columns for different ranges of TOC. Coagulant dosages would be filled in for each of the TOC ranges, for every turbidity range in the table.

An example of a coagulant dosage chart is presented in Table 8.4. The turbidity ranges given are some of those used in a dosage table developed by the Elizabethtown Water Company. No coagulant dosages are presented in this example table. The appropriate coagulant dosages will vary according to source water, treatment plant design, rate of flow, and a variety of site-specific factors.

pH and alkalinity

Control of coagulation by use of data on the raw and coagulated water pH and alkalinity can be very useful at some treatment plants. For example, at plants where pH is about 7 or lower in raw water and alkalinity is quite low, addition of alum or ferric salts lowers the pH and alkalinity and can change coagulation efficacy. It is advisable to track pH and alkalinity and feed chemicals to adjust pH and alkalinity for optimum coagulation. At plants where enhanced coagulation is practiced, careful tracking of TOC, pH, and alkalinity should be standard practice. Required TOC reductions are related to alkalinity of source water, and pH and alkalinity may be severely depressed by higher dosages of inorganic coagulants needed for enhanced coagulation. Post-filtration adjustment of pH and alkalinity to enhance corrosion control and water quality stability in the distribution system may be needed at some plants practicing enhanced coagulation.

At the Lake Michigan Filtration Plant, operated by the City of Grand Rapids, alkalinity has such a strong influence on coagulation and effective filtration that an on-line coagulation monitor is used to track raw water alkalinity. An increase in the raw water alkalinity signals the need to increase coagulant dosage.

Table 8.4

Hypothetical example of coagulation dosage chart

Raw water turbidity, ntu	Alum dosage for water at 39 °F to 45 °F (4 °C to 7 °C) and increasing turbidity	Alum dosage for water at 39 °F to 45 °F (4 °C to 7 °C) and decreasing turbidity
0 to 5	A	N
6 to 10	B	O
11 to 15	C	P
16 to 20	D	Q
21 to 40	E	R
41 to 70	F	S
71 to 100	G	T
101 to 150	H	U
151 to 200	I	V
201 to 250	J	W
251 to 300	K	X
301 to 400	L	Y
And so forth to 5000 ntu in 10 more intervals		

This example table is based on the type of alum dosage tables used by the Elizabethtown Water Company. Dosages are given for both increasing and decreasing raw water turbidity. Generally their dosages are slightly lower when raw water turbidity is decreasing as compared to dosages when turbidity is increasing.

Zeta Potential

Zeta potential (ZP) measures the electrical potential near the surface of small, colloidal-sized particles. Zeta potential is a laboratory analytical method, and is described in AWWA Manual M37, Chapter 4, "Electrophoretic Mobility Measurements" (AWWA 2000). Particles having a highly negative ZP are not likely to agglomerate into flocs and settle. The vast majority of particles in water have a negative surface charge or zeta potential, so positively charged chemicals including aluminum

salts, iron salts, and cationic polymers are used as coagulant chemicals. Bringing the ZP closer to a neutral value improves the opportunities for small particles to stick together when they collide in the flocculator, and to stick to filter media when water passes through the granular media filter bed.

When cationic polymers are used as primary coagulants, ZP measurements can be used to estimate whether the polymer is underdosed, about right, or overdosed. With cationic polymers, a ZP that is near zero (neither highly negative nor highly positive, perhaps between –15 mv and +15 mv) would be appropriate. Appropriate values of zeta potential are likely to vary from site to site, depending on the concentration and type of dissolved minerals (e.g. chlorides, sulfates, etc.) present in the raw water.

When inorganic coagulants are used, estimating coagulant dosages by ZP measurements can be more difficult. Optimum flocculation kinetics can be observed at negative zeta potential or positive zeta potential depending on water temperature and pH (Kang and Cleasby 1995). Increasing concentrations of sulfate ion can shift the zeta potential more negative at optimum flocculation (Kang and Cleasby, 1994). If minimal dosages are used to produce a very small floc, and particle destabilization to reduce the ZP to slightly electronegative is the goal of coagulation, then ZP could be helpful. In some treatment plants operators use large dosages of inorganic coagulant, forming voluminous floc to improve settling. When this approach to coagulation is used, ZP measurements will not be very useful, as the particles in suspension are likely to have an electropositive charge, but the charge may change little with increases in coagulant dose.

Some waters are not good candidates for using ZP. Waters with high concentrations of total dissolved solids (TDS) are in this category. Multi-valent ions can suppress the magnitude of the surface electrical charge of particles, particularly when TDS concentrations exceed 500 mg/L. For a given water there is usually a constant ratio between TDS and electrical conductivity (µS/cm). As conductivity can be quickly measured, the TDS can be estimated reliably by conductivity measurements.

When water is treated by lime softening, chemical reactions related to precipitation of calcium carbonate and magnesium hydroxide are the controlling factors for chemical dosage determinations. For lime softening, use of ZP measurements would not be appropriate.

ZP determinations take time but can provide valuable data on the nature of the particulate matter in the source water and on its condition in coagulated water when use of zeta potential is

appropriate. Pictures of zeta potential instruments are shown in Figures 8.5 and 8.6 at the end of this chapter.

Streaming Current Instruments

Measurement of streaming current is an on-line technique for assessing the condition of particles in water. Use of streaming current instruments is described in AWWA Manual M37, Chapter 2, "Streaming Current Detectors" (AWWA 2000). A streaming current instrument installed in a water utility is shown in Figure 8.7 at the end of this chapter. These devices were evaluated in an AwwaRF project (Dentel 1988) and reported upon in *Journal AWWA* (Dentel and Kingery 1989). A streaming current instrument would be used downstream from the rapid mixer to estimate the treatability of coagulated particles in water. The concept is related to ZP, which was discussed above. Streaming current instruments can be used to provide information for plant operators, to assist in their making decisions about coagulant dosage. They also can be linked to chemical feeders to control changes in chemical dosage. Using a streaming current instrument can enable plant operators to rapidly respond to a coagulant feed failure, as the drastic change in streaming current caused by absence of coagulant feed should be immediately noticed (with an appropriate alarm signal) and action taken to restore coagulation.

Regardless of how streaming current data are used, the instruments must be calibrated by optimizing coagulation at the treatment plant by other methods such as jar tests, measurements of filtered water turbidity or particle counts or both, pilot filters, or other techniques independent of zeta potential and streaming current. The streaming current reading under conditions of optimum coagulation is then used as the "set point". When the reading deviates from the "set point" the coagulant dosage is modified until the reading returns to the set point. The streaming current instrument's readout must be checked periodically to verify that the set point has not changed. Periodic maintenance would include cleaning the instrument and water line that feeds coagulated water to the instrument.

Streaming current measurements can not be used in all water treatment situations. Streaming current is related to electrophoretic mobility and to zeta potential, and the limitations are similar. The streaming current value is affected by pH as well as by the coagulant dosage. If the pH of the coagulated water varies, the streaming current set point or target value for optimizing coagulation also will change. This could make use of streaming current instruments more complicated. Source waters

having high concentrations of TDS would not be good candidates for application of streaming current instruments, nor should this technique be applied at lime softening plants. Dentel (1995) suggested that use of streaming current for controlling coagulant dosage may be difficult when pH is 8 or higher. Watts (1994) found that streaming current potential showed a poor sensitivity to coagulant dosage in water with a conductivity greater than 600 µS/cm.

A case study, "Application of Streaming Current Instruments at Philadelphia," is presented in Chapter 13. This case study describes some of the difficulties encountered with use of these instruments under unfavorable conditions, and relates the success attained with streaming current instrumentation when water quality and operating conditions were appropriate.

Pilot Filter

Pilot filters are discussed in AWWA Manual M37, Chapter 5, "Pilot Filters for Process Evaluation and Control" (AWWA 2000). In M37 under the heading "PILOT FILTERS FOR COAGULATION CONTROL" the use of these filters as on-line monitors for the adequacy of coagulation is discussed. are Two examples of pilot filters for coagulation control are shown at the end of this chapter in Figures 8.8 and 8.9.

Pilot filters that are used to assess the adequacy of coagulation are operated for relatively short filter run times, receiving the water after coagulant addition. The purpose of such pilot filters is not to learn about filter run length but merely to estimate the filtered water turbidity that would be produced by full-scale filters. In this approach to coagulant dosage monitoring, two pilot filters generally are used. Because no solids removal occurs before the filter, the entire load of suspended solids in the raw water plus the floc formed by coagulation must be removed in the pilot filter. While one filter is on line, the other filter is backwashed and made ready for the next run.

Turbidity of the filtered water from the pilot filter is continuously monitored, and this serves to indicate the turbidity that will be attained when the coagulated water being treated in the pilot filter is finally filtered in the treatment plant, after having passed through pretreatment. Pilot filters can be used for coagulant dosage assessment and control for a wide range of source water turbidities. When turbidity is high and large coagulant dosages are needed for successful coagulation, the pilot filter will clog more rapidly. If the entire procedure for backwashing and switching over to the clean filter is not automated, more operator time would be required when treating a highly turbid water. Even so, the time needed for effective use of pilot filters may be considerably less than the time needed for jar

testing when source water quality is changing, in which case the benefits of using the pilot filter could be substantial.

Maintenance of pilot filters should include periodic checking of the piping and valves, as well as the filter columns and media. As with other filters, improper backwashing could cause media loss. For best results the design of the media in the pilot filter should be the same as the design of the media in the full-scale filters.

Some pilot filters of this sort have been sold commercially, and some water utilities have built their own pilot filters.

Visual observation of results

Visual observation of treatment results probably was the first method used by operators to make decisions about the adequacy of treatment. In *Water Purification Plants and Their Operation* (Stein, 1915) the author, an assistant engineer at the Cleveland Filtration Plant, advised that floc should be about half the size of a pin-head. Stein advised that if the water appeared clear or smoky with no floc visible, more alum should be used. On the other hand, if flocs were large and feathery, the alum dose should be decreased. Stein also noted that smoky coagulation was more common in winter because of the slow reaction rate of the chemicals.

Checking on coagulant dosage and performance of pretreatment by visual observation of the results is commonly practiced at conventional filtration plants. Operators should check the condition of floc, especially in the last floc basin before the settling basin and also should inspect the condition of the floc in the settling basin. Look for the size of the floc and for carry over from the settling basin to the filters. Presence of a haze or cloudiness in water, but absence of distinct floc particles, would be a visual indication that coagulation is not correct in a conventional plant. Presence of very large floc particles rising up to the effluent weirs of a sedimentation basin may be an indication that the floc density is similar to that of water, and floc does not settle well in this circumstance. Compact, rapidly settling flocs are easier to remove in sedimentation than low-density, fluffy flocs.

Some filter plants have powerful spotlights located just above the surface of the water at appropriate observation points so operators can view floc on cloudy days or during the night. Operators who work at plants equipped with such lights generally regard the lights as a very valuable tool.

Natural Organic Matter

Natural organic matter (NOM) in water can sometimes react with coagulant chemicals, resulting in the need for higher coagulant dosages when the concentration of (NOM) increases. UV absorbance at 254 nanometers is an approximate measure of (NOM) in water and as such can be used as a guide to the amount of coagulant that may be needed to interact with the organic matter present. Using data on UV absorbance in the raw water is a procedure that could be helpful for setting coagulant dosages at treatment plants having source waters low in turbidity but high in color or other kinds of (NOM) . The coagulant demand exerted by natural organic matter tends to be proportional to the concentration of (NOM) in the raw water, and generally this coagulant demand must be satisfied in order to attain effective coagulation of inorganic particles such as clay. UV absorbance may be a particularly useful measurement when source waters have high concentrations of (NOM) that can be readily removed by use of inorganic metal coagulants.

A word of caution is needed for those contemplating use of UV absorbance as a guide to plant operations.. When ozone is used in water treatment, it can change the nature of the organic molecules so they do not absorb UV radiation as well, but the total organic carbon concentration may be the same. Therefore it is possible for UV absorbance to decrease following ozonation, without any actual removal of organic matter. UV absorbance can be useful for assessing treatment before and after coagulation, flocculation, and sedimentation. This has been done now for nearly two decades, beginning with work by Edzwald (Edzwald, Becker, and Wattier 1985) in which use of UV as a surrogate for organics was reported. Concepts of Specific Ultraviolet Light Absorbance (SUVA) and enhanced coagulation are discussed in *Water Quality & Treatment, 5th Ed.* (Letterman, Amirtharajah, and O'Melia 1999). SUVA is the UV absorbance at 254 nm expressed in units of m^{-1} divided by dissolved organic carbon (DOC) concentration in mg/L (SUVA = UV_{254}/DOC). Jar testing and enhanced coagulation are discussed in numerous *Journal AWWA* papers, including those by Krasner and Amy (1995) and White et al. (1997).

Dolejs (1994) said that NOM was some ten times more important in influencing coagulant dose than turbidity. Janssens and Buekens (1993) presented findings that if the SUVA of the water was less than 3, the coagulant demand of dissolved organic carbon (DOC) was small, whereas at values of 4 to 5 it was DOC, not turbidity, that determined coagulant dose.

Chlorine demand can be an indicator of natural organic matter in water. At Grand Rapids' Lake Michigan Filtration Plant, chlorine demand influences alum dosage. When chlorine residual in

the raw chlorinated water decreases (an indication of an increase in chlorine demand) this is a signal that the alum dosage will need to be increased.

Filterability Index

Assessment of pretreatment by use of a treatability or filterability index tends to be plant-specific. The Chester Water Authority (CWA) has a standard operating procedure for a filterability index for use at their conventional treatment plant. A sample of flocculated water is withdrawn from the discharge end of the flocculation basin and allowed to settle for 30 minutes. Settled water is obtained and 200 mL are filtered through an 0.45 μm filter membrane. Time for filtration is measured and recorded. The 200 mL of filtered water is filtered a second time through a new membrane and the time is again recorded. The ratio of the time for filtering settled water divided by time for filtering filtered water is calculated and recorded as the filterability index. The procedure used by the Chester Water Authority is similar to the Silt Density Index used for reverse osmosis installations.

Coagulant Feed, Dosage Monitoring, and Control

Coagulant Feed Pumps and Systems

Problems associated with chemical feed pumps include drifting out of calibration, with the resulting failure to deliver the desired chemical dosage; and pump failure, with no chemical fed. Pump calibration can be checked by methods described later in this section. Loss of coagulant feed is likely to be characterized by absence of floc. In a direct filtration plant, failure of a coagulant feed pump or exhaustion of the coagulant supply probably would be indicated by a sharp rise in turbidity in less than one hour after the failure. At a conventional treatment plant, loss of coagulant feed could result in filling a sedimentation basin with uncoagulated water before filtered water turbidity began to rise. At conventional plants, the absence of floc in flocculation basin effluent would provide an earlier warning of feed pump failure than a filtered water turbidity increase.

Chemical feed flexibility and proper handling of coagulant chemicals both contribute to effective pretreatment. Ability to feed either ferric or alum coagulant gives plant staff the flexibility to use either chemical as appropriate. Some utilities responding to the utility information survey for this Maintenance and Operation Manual project noted problems with alum coagulation in very cold water,

and one utility changes to using a ferric coagulant in the winter because of this. Cleasby et al. (1992) recommended provision for feeding both alum and ferric coagulants.

According to Cleasby et al. (1992) most filtration plants feed liquid alum or liquid ferric coagulants without dilution. This practice, they report, avoids the problem of excessive dilution, but feeding undiluted liquid alum or ferric can cause problems with formation of aluminum or iron precipitates at the point of injection.

When dry chemicals are used, Cleasby et al. (1992) caution against over-dilution of the chemical. If alum or ferric coagulants are diluted excessively, precipitates can form in the coagulant tank or feed piping, as the coagulant hydrolyzes. When this happens, the coagulant solution loses some of its effectiveness, and the dosage of effective coagulant will be less than the actual dosage that had been calculated by plant staff. If the pH of a diluted ferric solution is 2.2 or lower or if the pH of a diluted alum solution is 3.3 or lower, the coagulant will not hydrolyze and lose strength.

In small water treatment plants and in package plants, diaphragm pumps are commonly used to feed chemicals. Diaphragm pumps function in a manner similar to how a human heart pumps. Liquid being pumped enters a chamber, a valve closes to prevent backflow, and the chamber is squeezed, forcing liquid to move forward. Like human hearts, diaphragm pumps move liquid in pulses. The pumping rate for a diaphragm pump can be modified by varying the stroke length (which varies the volume change that occurs with each stroke) and by changing the number of strokes per minute. If the rate of strokes per minute is slowed down in an effort to feed chemical at the low end of the pump's range, then a diaphragm pump is feeding chemical into the pipe line and into the rapid mixer on an intermittent basis. When a diaphragm pump is used in conjunction with an in-line mixer, where residence time is maybe only one or two seconds, the on-off pumping action of a diaphragm pump could result in some raw water being overdosed with coagulant and other raw water receiving no coagulant until all water was blended together in a flocculator. This does not make the most effective use of coagulant chemicals.

The pulsing action of a diaphragm pump can be dampened by installing a vertical, capped piece of pipe one or two feet (0.3 to 0.6 m) in length at a location downstream of the pump (between the pump and the rapid mixer). This device is called an accumulator and may be available commercially. To work properly, the capped vertical pipe must contain air. During the pumping phase, chemical is forced into the pipeline, and some goes into the vertical pipe, compressing the air. During the pump's resting phase, the compressed air forces chemical out of the pipe, causing it to flow down the pipeline.

This provides a flow of chemical that is more nearly uniform, ensuring that all raw water is exposed to coagulant chemical. Installation of an accumulator pipe to dampen flow pulsations is a task that can be performed easily by most water treatment plant operators if such a device is lacking on a chemical feed line supplied by a diaphragm pump.

One chemical feed problem reported by some utilities in this project was oversizing of pumps. If chemical feed pumps are sized to provide the maximum chemical dosage at the maximum rate of flow, they may be too large to reliably feed low chemical dosages at low flows. This situation might be encountered in a new plant designed for peak flows expected 20 to 30 years in the future. In such a situation operators might have to turn down the pump to 5 percent or 10 percent of its capacity, which is not desirable. A possible remedy involving design and equipment rather than operational procedures is to provide one smaller chemical feed pump to manage low flow situations, but to use the larger pumps whenever flows and dosages make their use practical.

Location and Order of Chemical Addition

The location of chemical addition points can influence pretreatment efficacy. Chemicals may not be as effective if more than one chemical is added at the same place. For example, fluoride and aluminum form a chemical complex, so adding fluoride ahead of or with alum will tie up (complex) some of the alum. For this reason the dosages determined by jar testing may be inadequate in the full-scale plant. Another situation to avoid is adding concentrated solutions of alum or iron in the same location where caustic is added. If the concentrated coagulant and caustic react before being diluted throughout all of the water, aluminum hydroxide or ferric hydroxide may form. These compounds are not effective for destabilizing the negative surface electrical charges on most contaminant particles found in surface waters.

Chapter 13 contains a case study, "Improved Filtered Water Turbidity by Continuous Dosing of Supplementary Coagulant at Thames Water Utilities," that describes how filtered water quality was improved by dosing a supplementary amount of ferric chloride at the weir where clarified water was discharged to the filter flume at the Shalford Works. Generally in the United States, the chemical added at this location would be a filter aid polymer, but at Thames Water the use of additional primary coagulant was found to be effective. Details are in Chapter 13.

When pH adjustment is used in conjunction with coagulation, the order of chemical addition should be evaluated in jar tests. Sometimes adjusting pH before addition of coagulant may give better

results, but in other instances, adding the coagulant first may produce better water quality. After jar test results are known, if the bench-scale testing has indicated that the order of chemical addition in the full-scale plant ought to be changed, this should first be done in a temporary manner until the preferred order of chemical addition can be verified.

Monitoring Coagulant Dosage

Volumetric monitoring. Coagulant dosage can be tracked by measuring the volume of coagulant fed over period of time, and relating that to the volume of water treated. Changes in volume in day tank over a period of time, or changes in total volume of liquid fed as measured by a positive displacement fluid flow meter to do this. Hudson (1981) discussed using a plastic nutating disk water meter to measure chemical flow, provided the meter was appropriate for the range of flow. Cleasby et al. (1992) suggest using a day tank sized so that each day's feed can be measured with sufficient precision so that the operators really know how much chemical is being fed per day. For a cylindrical tank, volume change is proportional to depth change. To really know what is being fed, an operator needs to be able to measure a one day's depth change to +/- 5 percent at worst, and +/- 1 or 2 percent would be much better. The precision of chemical dosing can't be any better than the precision of measuring the volume fed.

A quick way to monitor chemical feed rate is to have piping arranged so the chemical feed pump can be supplied from a graduated cylinder that holds about 1 minute's worth of chemical at the maximum pumping rate. The cylinder must be located on the suction side of the feed pump and must be plumbed so the coagulant chemical feeds into and out of the cylinder from the bottom. Merely dropping a small hose into the cylinder to withdraw the chemical would cause an error in measurement due to the volume of the hose inside the cylinder. Precision of this measurement will decrease when the feed pumps are turned down, unless a longer pumping time is used with the graduated cylinder, but a few minutes at most should suffice to provide a quality check for chemical feed rate. This method gives operators a rapid means of checking feed rate that does not depend on feeding large measurable volumes of chemical from a day tank. "Spot checks" of chemical feed rates can be performed whenever the operator chooses. For purposes of quality control both the quick check of feed rate and the longer term measurement of day tank volume change should be used, as the long term measurements confirm the quantity fed over a period of hours or a day. A pump calibration curve can be developed in a relatively short time by using the graduated cylinder method.

When monitoring coagulant dosage, others places to check for potential problems are the day tank, if one is used, and the actual chemical addition point, or a location close to it. Make sure that the day tank is not empty but contains an adequate supply of chemicals. Also be sure that treatment chemicals are flowing into the point where their addition is intended. If the actual point of addition is under water or within a pipe, it is a good idea to be able to verify that chemicals are indeed flowing, as close to the point of injection as possible. This would permit treatment plant staff to detect a break in a chemical feed line, if one should occur. Also make sure that the dilution water or carrier water supply, if used, is functioning properly.

Streaming current instrument. For waters having low to moderate concentrations of TDS, and at plants where coagulation is practiced for removal of particulate matter rather than for removal of natural organic matter, streaming current instrumentation can be very useful as a guide for operators to monitor coagulant dosage. When a streaming current instrument is used for coagulant dosage monitoring, a sudden, large change in the streaming current can signal loss of coagulant chemical feed, and as such may serve as an indication of coagulant feed problems.

Control of Coagulant Feed

Chemical dosages have to be changed in response to changes in source water quality. Cleasby et al. (1992) recommend using caution when making these changes if the source water quality is changing slowly. For source water that is gradually changing in quality, they suggest making small incremental changes to the pretreatment chemical dosages, and then allowing sufficient time to evaluate the effect of each change before making another. Otherwise the operating staff will not be able to pinpoint the effect of a chemical change. They note that for a conventional filtration plant having several hours of detention time, the effect of a chemical change on the filterability of the water might not be noted for two or three detention times. When source water quality is changing quickly, Cleasby et al. (1992) suggest use of tools that provide a rapid response, such as the pilot filter or a streaming current instrument.

Streaming current instrument output. This technique is not useful for water softening, and may not work at water treatment plants where enhanced coagulation has to be practiced to attain the required extent of removal of TOC. This technique is most appropriate where particle destabilization is the purpose of coagulation. At some treatment plants, chemical feeders are directly linked to streaming current readout, whereas at other plants, plant operators check the streaming current readout

and then make chemical dosage decisions based on this and other information and on their experience and training.

Coagulant dosage paced to raw water flow. To improve operations efficiency and reduce the amount of "busy work" for operators whenever a change in plant flow occurs, pacing coagulant dosage to raw water flow is very helpful. This is especially valuable for maintaining proper coagulation dosage when raw water flow needs to be changed frequently, such as one or more times per day. Use of flow-paced chemical feed simplifies the operator's job, enabling him or her to focus on other matters at the plant when flow has to be changed frequently.

Inspection and Routine Maintenance of Coagulant Chemical Feed Pumps

Routine maintenance and periodic inspection are necessary if chemical feed pumps are to perform dependably over the long term. Plant operators should keep spare parts on hand, and if needed also keep extra or spare pumps, especially those that wear more rapidly. Rapid rate granular media filters do not function effectively unless coagulation is correct. Operating such filters without any coagulant will not result in effective treatment, so failure of a simple feed pump could force a shutdown of the entire filtration plant unless spare parts or a spare pump is on site. This is especially important at a small plant where a single chemical feed pump is used. Larger plants may have multiple pumps, so failure on a single pump would be less serious.

For accurate feeding of chemicals, don't rely on the pump calibration to be valid forever. Periodically do a volume versus time calibration check. Pumping from a large graduated cylinder for a measured time (use a stopwatch) is a good way to quickly verify that the pump setting as indicated by the calibration curve is valid and the pump is performing as it should. Another way to check this is to pump from a larger volume over a longer time. The volume and the time should be measured to +/- 1 percent or 2 percent so the operator can have confidence in the data. Thus for a graduated cylinder test,

- pump for 60 seconds or longer +/- 1 second,
- pump more than half of the volume of a full cylinder, and
- read the volume pumped to the nearest graduation on the cylinder, as for cylinder sizes of 100 mL and larger, the graduations are typically 1 percent of the total volume.

Pumps tend to wear with the passage of time, and a calibration curve that was valid for a new pump may not be good after several years of pump use. Whenever a calibration test is performed, the results must be recorded where they can be easily found for future reference. That way, the performance of a pump over a long period of time can be documented, and plant operators may be able to anticipate the need for a complete recalibration or rebuilding of the pump based on its long-term performance.

CHEMICAL TREATMENT: PRECIPITATIVE LIME SOFTENING

Precipitative lime softening is used to remove calcium and magnesium ions, the main causes of hardness, from water. Addition of lime (calcium hydroxide) to water converts bicarbonate ion to carbonate ion and results in an increase in the concentration of calcium carbonate. If sufficient lime is added, calcium is precipitated in the form of calcium carbonate. If bicarbonate is not present in water, sodium carbonate or sodium bicarbonate can be added to precipitate calcium. When magnesium is present, adding sufficient lime to raise the pH of the treated water above 10.5 to 11 will cause the precipitation of magnesium hydroxide. When calcium carbonate or calcium carbonate and magnesium hydroxide are precipitated, sludge is created and sludge disposal must be considered.

Lime Softening Plant Practices Reported by Utilities

Five plants treating surface water by lime softening reported on their practices in this project. Data from the lime softening plants are NOT included in Table 8.2. At lime softening plants the approaches to treatment differed somewhat from practices at coagulation plants, particularly in regard to chemical dosage determinations, as a key goal at softening plants is to meet water quality goals for pH, alkalinity, and hardness in the treated water. Raising pH to accomplish softening and lowering pH before filtration (generally by addition of carbon dioxide) to minimize calcium carbonate deposition in filters and in water mains are process steps not used in coagulation plants.

Monitoring pH is quite important at lime softening plants. Three of the five measured settled pH on-line, one used 6 grab samples/day, and one used grab samples (no frequency given). Two plants measured combined filtered water pH on-line; one used 8 grab samples/day, and one used grab samples (no frequency given). Turbidity monitoring is required at surface water plants. Two monitored raw turbidity on-line, and four monitored the turbidity of each filter on-line. None of the five reported using on-line particle counters for raw water or for each filter.

For determination of chemical dosage, two lime softening plants reported using jar tests. Three used chemical dosage charts based on historical data of plant performance and water quality. All five used pH and alkalinity, and one measured pH and alkalinity each 2 hours for monitoring and control of lime softening. At one plant where GAC/sand filter adsorbers were used, UV absorbance was measured. Four of the five plants used visual observations of basins to assess plant performance. None used streaming current instruments, zeta potential, or pilot filters as these are not appropriate for use at plants employing lime softening.

Chemical Dosage Determination

Chemical dosage determinations for lime softening, and adjustment of water chemistry after softening, must be done correctly to avoid problems. If softening is not done properly, the plant may not attain the desired amount of hardness removal, or hardness removal might exceed the utility's goal, which would be costly in terms of chemical consumption. Failure to properly adjust water chemistry after softening can cause a variety of problems. One sign of this is filter media that become coated with calcium carbonate. Media can grow in size, making backwash difficult. In a worst-case situation, the entire filter bed can become cemented together. At one filter plant this situation was discovered when the filter bed would not expand during backwash. This sort of problem requires acid to dissolve the calcium carbonate, or jack hammers to remove the filter media that turned into a limestone conglomerate. At another utility where workers were removing cemented media, someone punched a hole through the underdrain with a jack hammer and this was not discovered until the filter was returned to service and filter materials were lost through the hole in the underdrain. Another serious problem related to failure to properly adjust water chemistry after softening is the deposition of large amounts of calcium carbonate in water mains. A thin layer may protect pipes from corrosion , but a 1 to 3 inch layer of calcium carbonate would reduce the carrying capacity of a main.

Lime Softening: Removal of Hardness and Control of Particulate Matter

When ground water is treated by lime softening, chemical dosages for lime and other chemicals such as soda ash are dependent on the chemical content of the source water and on the desired hardness of the finished water. Lime softening examples showing how to calculate dosages of lime and other chemicals are given in *Water Quality and Treatment, 5th Ed.* Chapter 10, "Chemical Precipitation,"

(Benefield and Morgan 1999) and in *Hoover's Water Supply & Treatment,* 12th Ed. (Pizzi 1995). Key chemical constituents are hardness, alkalinity, pH, and carbon dioxide, as all of these are related to lime softening chemistry.

When a surface water source, or a ground water source under the influence of surface water is treated, the water treatment plant will have to comply with regulatory requirements for turbidity while treating the water to remove hardness constituents. In this situation, turbidity and TOC would have an influence on the amount of coagulant needed in conjunction with lime softening. When surface waters are treated by lime softening, it is common to use multi-stage treatment so coagulation and settling can be performed independently of the treatment process in which lime softening is carried out.

As noted in Chapter 7 of this manual, among softening plants providing information about control of turbidity spikes at the start of filter runs, three of the seven plants did not consistently control the initial spike to 0.3 ntu or lower. One possible cause for this is the nature of lime softening precipitates. Calcium carbonate forms dense cubic crystals that are negatively charged (Randtke 1999) whereas magnesium hydroxide forms as floc with a large surface area and positive charge. Magnesium hydroxide is an excellent coagulant, so high pH lime softening processes that remove magnesium are creating a coagulant in the softening process. When softening pH is not high enough to remove magnesium, addition of a cationic polymer or positively charged metal coagulant such as ferric chloride or ferric sulfate may be necessary to coagulate the calcium carbonate crystals and enhance removal of the particulate matter formed during lime softening.

For surface waters treated by lime softening, provision must be made for removal of both the particulate matter in the source water and the calcium carbonate crystals formed during lime softening. If softening is performed first and then followed by coagulation and clarification, the softening process effluent can be used in jar tests to evaluate coagulant and polymer dosages needed to attain effective removal of particulate matter. When lime softening follows coagulation and clarification, doing both the clarification testing (with different dosages of coagulant) and lime softening in jar tests may be necessary for evaluation of effective coagulant dosages. In the latter situation, addition of polymer during softening may be needed to attain effective settling of calcium carbonate precipitates.

Adjusting Water Quality after Softening

Adjustment of water quality after softening was dealt with in *Water Quality and Treatment, 5th Ed.* Chapter 10, and in *Hoover's Water Supply & Treatment, 12th Ed.,* revised by Pizzi. Hardness,

alkalinity, and pH have to be controlled to control the potential for precipitation of calcium carbonate after the softening process. Precipitation of $CaCO_3$ on sand, anthracite, or GAC media can gradually increase the size of the filter media. Coating GAC with calcium carbonate would eventually destroy the adsorptive properties of the GAC. Media that is larger than intended may be less effective for filtering out particulate matter.

If excess calcium carbonate can pass through the filter beds, it may precipitate out in large volumes in the utility's water mains, building up a limestone layer on the inner walls of pipes and reducing their capacity to carry water. Figures 8.10 and 8.11 at the end of this chapter show pipes with excessive build-up of calcium carbonate. When excess lime is used in softening, the excess lime can be neutralized and pH can be lowered by adding carbon dioxide in a process known as recarbonation. Mineral acids such as sulfuric acid also could be used to neutralize excess lime and lower pH. Some utilities add polyphosphate to sequester calcium and prevent its deposition in the filters. Figure 8.12 shows an example of filter media mounding in a lime softening plant. This was caused by inadequate recarbonation and cementation of media. Backwash water could not flow up through cemented areas of media, so upflow was concentrated in localized areas where the mounds developed.

Use of a sequestering chemical should be given careful thought, as sometimes other problems can result. In a field study involving evaluation of zinc chloride to precipitate a protective layer on asbestos-cement water mains (Weston Water Utility 1984), interference from polyphosphates was believed to have interfered with the protective effect of zinc on asbestos-cement pipe that had been demonstrated in earlier studies.

Chemical Handling and Feed

Handling and feeding lime presents operational challenges at any lime softening plant. Hydrated lime is more expensive than quicklime, but the latter has to be slaked. Use of either chemical involves handing a dry powder or granules, with potential for dust in the plant. Lime dust should not be inhaled, so dust control equipment must be used when working with hydrated lime, quicklime, or soda ash. Cleanliness, careful handling, and a good maintenance program are necessary to keep a clean and neat plant.

Transportation of lime slurry from the chemical building to the treatment units can be problematic because of the tendency of the slurry to form deposits. Use of open troughs or troughs

with covers makes maintenance of lines much easier than if pipes are used. Periodic pigging of pipes used to carry lime slurry may be needed to prevent plugging.

Monitoring and Control of Lime Softening

Careful monitoring and control of the lime softening process is mandatory at softening plants. When surface waters are treated, the regulatory requirements for surface water treatment apply, so filtered water turbidity must be monitored continuously and carefully controlled. At all lime softening plants, regardless of whether the source water is ground water or surface water, the chemistry of the lime softening process has to be monitored and controlled closely to avoid serious problems that can be caused by deposition of excessive precipitates of calcium carbonate on filter media, treatment plant equipment, and water distribution pipe walls.

Managing treatment for particulate removal and turbidity control can be more difficult at softening plants than at coagulation plants. At some plants, coagulation and sedimentation are done first, and in these plants, the techniques for coagulation control described earlier in this chapter could be used. When softening is used ahead of coagulation and settling, options for coagulant dosage selection and control may be somewhat limited. Use of zeta potential or streaming current would not be appropriate. Pilot filters would be difficult to use. Jar tests and historical data charts may be among the most useful techniques for selection of coagulant dosages in lime-softened water. When multi-stage processes are used in conjunction with lime softening of surface waters, use of multi-stage jar test procedures also may be needed.

The lime softening process and subsequent chemical treatment of softened water to prevent unwanted calcium carbonate precipitation require diligence on the part of plant operators. If softened water is unstable, with a tendency to precipitate calcium carbonate, filters can be clogged or cemented into a mass of conglomerate consisting of calcium carbonate and filter media. Water mains can be filled with calcium carbonate so that the available carrying capacity is a small fraction of the original capacity. The economic consequences of precipitating calcium carbonate in filter beds and in water mains can be quite serious. Cleaning filter beds is labor-intensive, and removing deposits from water mains is costly. The energy wasted by clogged mains would be a continuing economic drain on a water utility. Financial incentives for proper management of lime softening are abundant.

Control of filter influent quality can be managed by calculation of the Langelier Saturation Index on a regular basis, but calculations are complicated. For treatment plant staff, using Caldwell-Lawrence diagrams would be a quicker approach. 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 a water has been softened, if the three values for pH, alkalinity, and calcium do not intersect at a single point, then 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, then 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. Use of the Caldwell-Lawrence diagrams was explained by Benefield and Morgan (1999) in *Water Quality & Treatment, 5th Ed.* And in greater detail by Merrill (1979). Another option would be use of the Rothberg, Tamburini, and Windsor Model for Corrosion Control for which computer software is available from AWWA. (Check current AWWA Bookstore Catalog for details.)

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 1/2 hour or longer, or else 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 supersaturation or undersaturation.

Chemical Feed Maintenance

A well-conceived program of inspection and maintenance is necessary at a lime softening plant to keep chemical feeders operating dependably. As with chemical feeders in coagulation plants, loss of a chemical feeder in a lime softening plant could cripple the process and might necessitate shutting down a small plant, if a spare pump or spare parts were not available. Regular cleaning is a must for feeders, storage facilities, and feed lines as lime softening is a dusty process because of the chemicals used in treatment. Dusts, especially chemical dusts, are hard on instruments and equipment. If allowed to accumulate, dust will be carried to many areas in the treatment plant and will create problems. Moving parts on feeders should be checked according to the schedule recommended by the manufacturer. Spare parts must be kept on hand so repairs can be made quickly if needed.

POLYMERS FOR COAGULATION, FLOCCULATION, AND FILTRATION

Selection, polymer feed, dosage determination, and dosage control

Polymers are important in water treatment in the United States. They are used in many plants. Reasons for polymer use include strengthening weak floc, decreasing usage of metal coagulants as a means of reducing sludge production, and improving the turbidity and particle count in water at the beginning of a filter run after backwashing. Symptoms of problems caused by polymer use can include mudball formation in the media, high rates of head loss build-up with little penetration of floc down into the filter media, and inability to filter out turbidity if a cationic polymer is seriously overdosed.

Overfeeding of coagulants and/or filter aids is very detrimental to the integrity of pressure filter media. This operational error will in time lead to the accumulation of mudballs and impacted mud in a pressure filter, but because the media in such a filter can not be visually inspected without taking the filter out of service, problems can progress without operators being aware. Operators of pressure filter plants need to be especially careful to avoid overfeeding problems.

Polyelectrolyte coagulants are discussed on pages 6.40 through 6.44 in *Water Quality and Treatment, 5th Ed.* (Letterman, Amirtharajah, and O'Melia 1999). Letterman (1991) also presented information on polymers in *Filtration Strategies to Meet the Surface Water Treatment Rule.* Users of this manual are referred to the AWWA book and Letterman's guidance document for additional information beyond what is presented herein. Polymers are categorized by their charge. Those with mostly positively charged sites are cationic polymers, while those with mostly negatively charged sites are anionic polymers. If a polymer has very few or no charged sites it is considered a nonionic polymer. Use of polymers in water treatment is fairly common in the United States. Cleasby et al. (1989) reported that 20 of 23 plants that they evaluated were using polymers to attain effective filtration.

Cationic Polymers

Cationic polymers can be used to aid or supplement positively charged metal coagulants, and when used in this way they are often added simultaneously with the metal coagulant. Sometimes cationic polymers are used as the only coagulant chemical. Cationic polymers may be used in conjunction with iron or aluminum coagulants to reduce the dosage of the metal coagulants. Polymer sludge is less voluminous than metal coagulant sludge, so cationics are sometimes used in combinations of metal coagulants when an important goal in treatment is reduction of the volume of sludge produced. The positive charge on these polymers is used to neutralize the negative surface charge found on most kinds of particles encountered in raw water, just as the positively charged alum or iron coagulant can be used to neutralize the negative charges on particles in water. Cationic polymers tend to have molecular weights of 500,000 or lower. This is about one tenth of the molecular weight typical for anionic and nonionic polymers.

When cationic polymers are used as the primary coagulant or as a coagulant aid, polymer dosage must be controlled carefully. Typical dosages range from 0.1 mg/L to 5 mg/L (Montgomery 1985). When cationic polymer is added to water, the positively charged polymer at low dosages

neutralizes some or all of the negative charge on particles in the water. If more cationic polymer is added, though, the charge on the particles can become positive. A particle with a high positive charge resists joining with other positively charged particles in flocculation, and may not be removed by filtration. Overdosing with cationic polymer can lead to treatment results that are as bad as results of underdosing. With polymers, it is not true that "If a little is good, a lot is even better." The senior author has seen filters at a plant where cationic polymers were overdosed. At one facility polymer blobs resembling small jellyfish formed, and they were extremely difficult to remove by backwashing. At a lime softening plant, excess cationic polymer bound up calcium carbonate crystals in to very small particles shaped like wood shavings from a pencil sharpener or big iron filings. These also were difficult to deal with in backwashing.

Cationic polymers can be quite effective for turbidity removal, but they are not as effective as metal coagulants for removal of natural organic matter. Typically the dosage of metal coagulant required for removing natural organic matter is proportional to the amount of organic matter present in water, and metal coagulants are used in dosages large enough to form somewhat voluminous floc for removal of organic matter, as in enhanced coagulation. Cationic polymers do not compete well when the goal of treatment is removal of natural organic matter.

Flocculent aid (anionic and nonionic) polymers

Polymers used to aid flocculation tend to be nonionic or anionic, with molecular weights of one million or more. Dosages used are lower than dosages of cationic polymers. The very high molecular weight enables these polymers to "bridge" between tiny coagulated particles and helps to hold them together. This bridging forms stronger floc, but excessive dosages of flocculent aid polymers can form a floc so tough and large that it can not penetrate into a granular media filter bed more than a few inches. This causes rapid increase in head loss and short filter runs.

Another potential problem with high dosages of anionic or nonionic polymers is the difficulty encountered when filters are backwashed. Observations of filter washing in clear plastic filter columns revealed that polymer use could cause filter media to become somewhat cemented together, and when the media broke up during backwash, it first broke into chunks with angular shapes, similar to the shape of broken concrete. With extensive and vigorous surface washing, these chunks of polymer-cemented filter media could be broken up and the media freed from the floc-media matrix. These personal observations lead to the suggestion that the tenacity with which polymer can hold

media grains and floc together in chunks could be a factor that promotes mudball formation when polymers are used and backwashing is inadequate. Pictures of mudballs are presented in Chapter 10.

One consideration in the use of flocculent aid polymers is the possible need for delay time between addition of the metal coagulant (alum or iron) and adding polymer. Some plants are designed for addition of alum or iron coagulant with a very turbulent rapid mix. Adding a flocculent aid polymer at a second, gentler stage of mixing is common. Letterman, Amirtharajah, and O'Melia (1999) wrote that flocculent polymers are often added after flocculation to increase the size and strength of floc. For existing plants, trial and error placement of polymer addition may reveal the best location. For a plant being designed, jar testing may give helpful guidance on polymer addition, if the jar test mixer can mimic the intensity of mixing that will occur in the full scale plant.

Filter aid polymers

Filter aid polymers are typically high molecular weight nonionic polymers, and they are generally used in dosages of 0.005 to 0.05 mg/L (Letterman, Amirtharajah, and O'Melia 1999). Filter aid polymers are used to strengthen floc or to improve attachment of particles within the filter. Filter aid increases the floc's resistance to shear forces within the filter bed, so that turbidity increases associated with filter rate increases can be minimized or eliminated. Filter aid polymers may also be added to backwash water or to water flowing into the filter box after backwash to reduce the initial turbidity spike at the start of a filter run. This is discussed in Chapter 7.

Filter aid polymer dosages must be evaluated by using pilot filters or by dosing filter aid into a full-scale filter. A trial-and-error procedure for evaluating filter aid dosage when using dual media filters has been described (Harris 1972). Harris explained how a sample extraction pipe and screen could be built into a dual media filter. He presented data showing how an underdosing of filter aid polymer could result in penetration of floc through the upper anthracite layer in a dual media filter, but increasing the filter aid dosage was able to reduce the penetration of turbidity to the interface between the coal layer and the sand layer. Harris attributed the penetration of turbidity through the coal layer to weak floc. He advocated starting use of filter aid with a low dosage. If the interface turbidity is satisfactorily low after several hours of operation with the initial dosage, that dosage is satisfactory. If the interface turbidity is not satisfactory, a small increase in dosage is applied. Several progressively higher dosages might need to be tried to find the appropriate filter aid dosage. Harris noted that use of excessive dosages of filter aid would result in high rates of head loss gain, so an excessive rate of head

loss gain would indicate use of too much filter aid. Harris presented results of a trial-and-error filter aid dosage selection in Fig. 11 in his 1972 presentation. That figure is reproduced at the end of this chapter as Fig. 8.13.

Location of dosing point for adding filter aid can influence efficacy of the polymer because of the amount of mixing that may be attained after polymer addition and because of residence time between polymer addition and filtration. If differences in filter performance are noted, with higher turbidity produced by filters closest to the filter aid addition point and lower turbidity produced by filters farthest from the filter aid addition point, this may indicate insufficient time for the filter aid to be in the water and interact with particles in the water before they are filtered. Generally pretreated water flowing to filters is not stirred or mixed, but a small amount of hydraulic mixing or gentle mechanical stirring may help distribute the filter aid more uniformly through the water so it can do a better job. Determining the appropriate location for adding filter aid polymer has to be done in a pilot plant or full-scale facility.

Inspection and Routine Maintenance of Polymer Feed Pumps

Concepts for chemical feed pump inspection and maintenance also apply to polymer feed pumps. Whereas a polymer feed pump may be considered less essential than a coagulant feed pump (unless the polymer being fed is used as a coagulant), failure of a polymer pump could result in loss of a floc-strengthening polymer. This might lead to turbidity breakthrough problems. Operating a polymer feed pump that is out of calibration could cause filter blinding, short filter runs, and mudballs. A good program of inspection and maintenance can aid in maintaining treatment process integrity.

RAPID MIXING

Mixing of treatment chemicals into water is key process for treatment plants employing either coagulation or lime softening. According to Cleasby et al. (1992), "Rapid mixing is an essential and important unit operation in chemical pretreatment." The various types of rapid mixing techniques used include back-mix reactors (a propeller mixer stirring a tank), hydraulic jump, baffled tanks, static in-line mixers, motorized in-line mixers, hydraulic injectors, pump-injected mixers, and injection of chemical into the impeller of a centrifugal pump.

Mixing for Coagulation

Rapid mixing needs to be very fast and thorough when inorganic coagulants are added to water, as the rate of chemical reaction is very swift. If alum or ferric coagulants are used, the key aspect of rapid mixing is to get the chemical into the water and dispersed uniformly throughout the water as quickly as possible. When the less complex hydrolysis (dissolution) products of aluminum or ferric coagulants contact particles in water, the particles can be destabilized and prepared for flocculation. This is why very rapid dispersion of coagulant chemical is recommended for coagulation plants where direct filtration is practiced.

On the other hand if the less complex hydrolysis (dissolution) products of aluminum or ferric coagulants have time to contact each other, aluminum hydroxide or ferric hydroxide flocs will form. Use of high dosages of coagulant is common in plants that employ the sweep floc mechanism of coagulation, relying on large flocs to aid clarification. Some plants have attained greater efficiency in coagulant usage by converting from a situation of ineffective mixing to one of very effective mixing.

Mixers that are well suited for rapidly dispersing coagulants include in-line mixers, pump-injected mixers, some applications of mixing using a hydraulic jump (if the chemical is dispersed across the entire cross-section of the water just before the jump), and a centrifugal pump impeller (although these are not designed as mixers). Backmix reactors are not very effective for instantaneously dispersing coagulant chemicals, but their use as rapid mixers in coagulation plants has been common. Sometimes operators have reported that mixing seems as effective when the mixer is turned off in a backmix reactor, as it is when the mixer is running. This probably is an indication that the backmix reactor is not very effective, and another type of mixer would do a better job of dispersing the coagulant chemical.

Treatment problems can result from inadequate mixing or from discharge of coagulated water from more than one point in a single mixing chamber. At one plant with inadequate rapid mixing, evidence of unequal distribution of chemical was seen by the black-gray trail of powdered activated carbon (PAC) traveling down the flume that delivered coagulated water to flocculation basins. The carbon was on the side of the flume away from the take-off points for the flocculation basins, and very little appeared to be getting into the first basin. This could have been happening with alum also, but the PAC could be detected visually. At another plant, a rapid mix basin consisting of a box-shaped tank with a propeller mixer (a back-mix process) had two different discharge points. The rotation of

the water in the mixing tank tended to cause water with a higher dosage of coagulant to go to one flocculation basin, and that one achieved better results. The solution for these problems lies with equipment rather than operations, but operators are the persons most likely to observe mixing problems that need attention. An example of inadequate mixing is shown in Figure 8.14.

One way of checking whether mixing is even is to take a series of water samples just downstream of where the coagulant is introduced. These should be collected in clear jars and examined for coagulant color, floc color and possibly placed in a jar tested to determine floc formation of a given time (use floc size comparator chart, figure un-numbered from Paterson Candy). It should be possible to infer whether mixing is unsatisfactory if different samples have a very different appearance (Lauer 2001, pers. comm.).

Mixing for Precipitative Lime Softening

Lime softening is often done in solids contact clarifiers that function by carrying high solids in suspension in the mixing zone. The presence of calcium carbonate crystals promotes more rapid formation of calcium carbonate, and intense rapid mixing is not needed. Some lime softening plants are built with a conventional treatment train consisting of chemical addition and mixing, flocculation, sedimentation, and filtration. At lime softening plants with separate rapid mixing, the mixing intensity does not have to be as great as for coagulation, and the chemical reaction with lime is not as fast as the coagulation reaction with alum or iron.

Inspection and Maintenance of Rapid Mixing Equipment

For mechanical mixers, the usual precautions about motors, bearings, gear drives, and shafts apply. In addition, mixers need to be periodically inspected for build-up of chemical precipitates on mixer impellers and shafts. Concentrated chemical solutions are introduced into water during mixing, and depending on the strength of the chemical being fed and the quality of the source water, precipitates may form. Precipitates that accumulate on mixer shafts can create an imbalance and potentially cause the impeller and shaft to wobble while rotating. Unless corrected, this could lead to equipment damage.

Another potential problem in the rapid mix compartment is the accumulation of chemical precipitates at the point of coagulant chemical or lime injection into the water. The nozzles of delivery pipes can become clogged with precipitate, depending on raw water quality and treatment chemical concentration. Where sparge pipes are used to add coagulant across a weir or channel it is not uncommon to find that some holes become blocked. In-line mixers also may be susceptible to build-up of chemical precipitates. Delivery points where coagulant chemical is added should be given periodic inspections to detect precipitate formation and remove deposits before clogging occurs, as one possible cause of pretreatment problems is fouling of coagulant injection / mixing points at a treatment works. Periodic inspection of in-line mixers will show the extent to which precipitates are building up on mixer surfaces.

Chemical feed is the key to effective coagulation and effective softening, so regular and diligent efforts must be made to be sure that chemical feed problems do not develop as a result of failure of mixing equipment.

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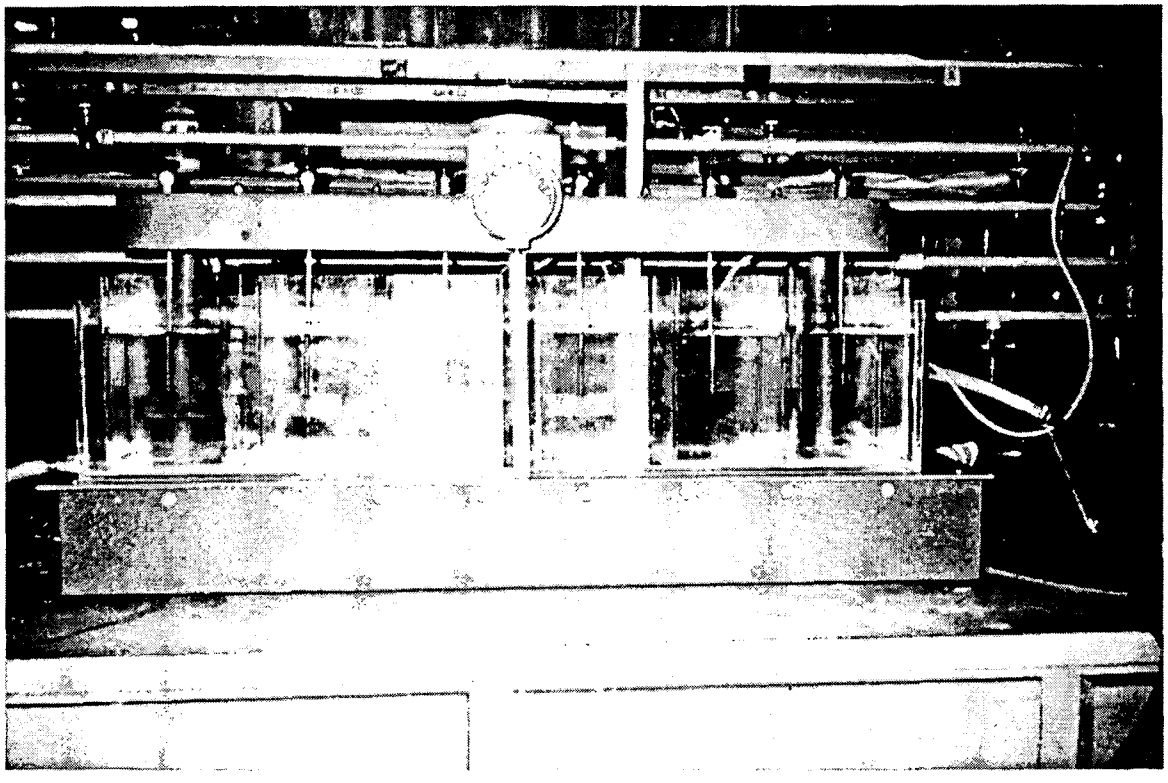

Figure 8.1 Jar test with low turbidity raw water

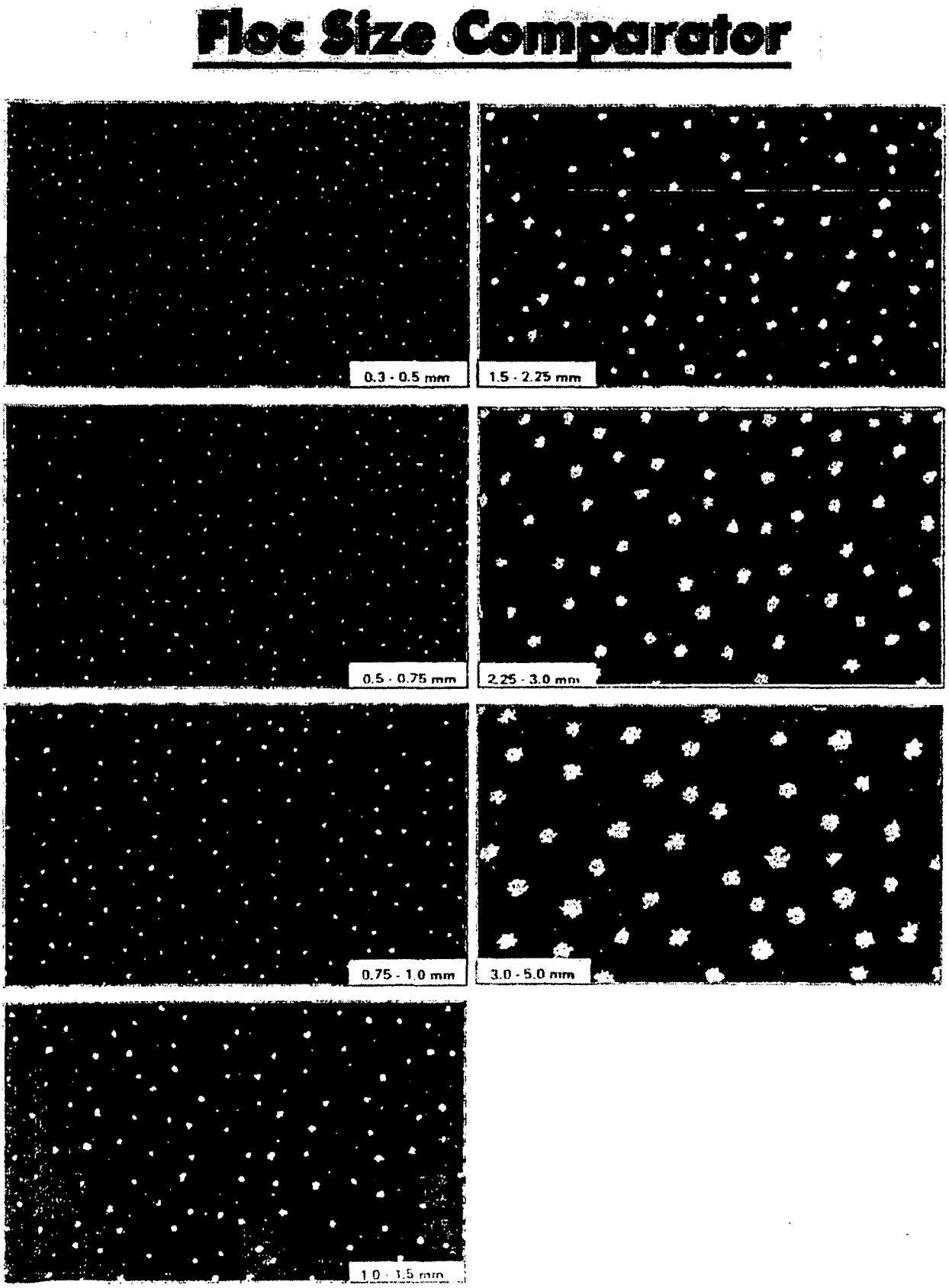

Figure 8.2 Floc size comparator (*Source:* Patterson Candy 2000)

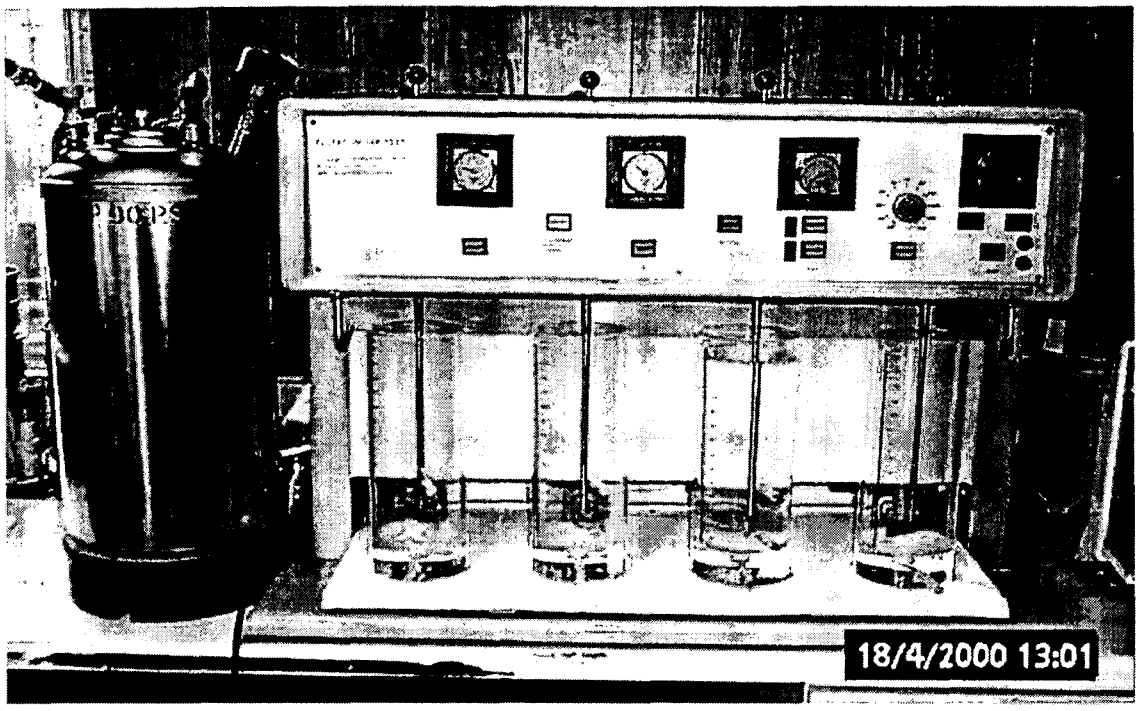

Figure 8.3 DAF jar tester (one jar in use) (*Source:* Thames Water Utilities 2000)

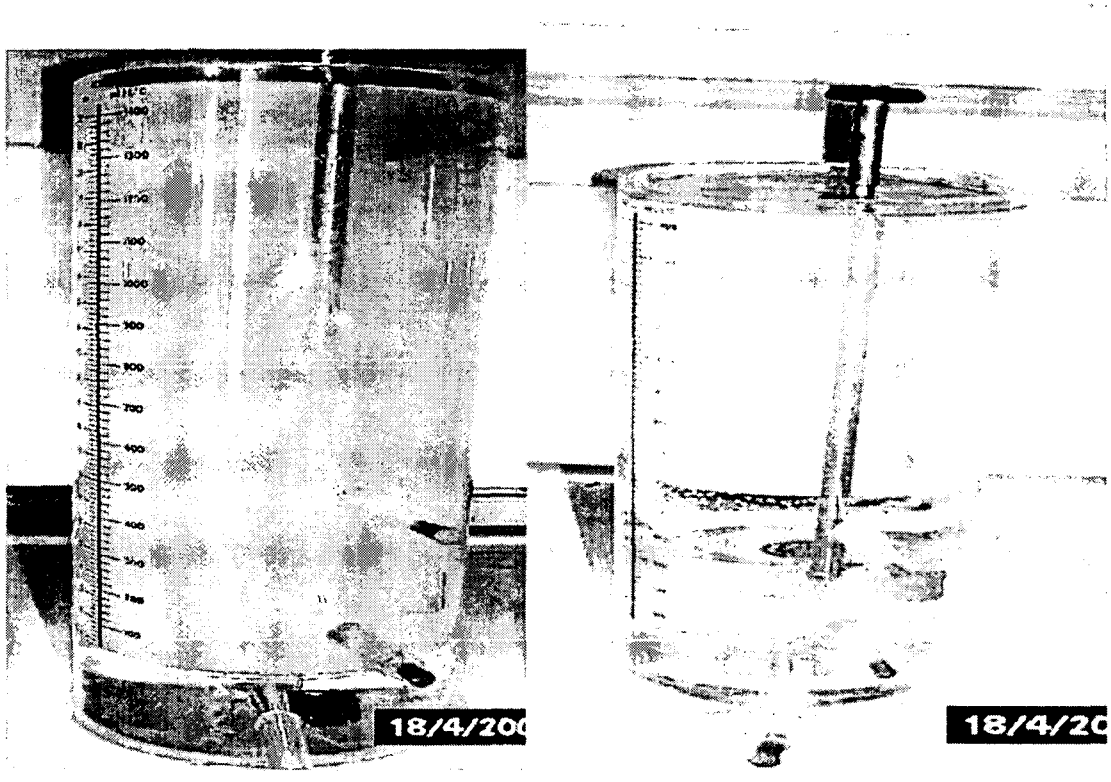

Figure 8.4 DAF jar tester (just after addition of air on left, and after 3 minutes of flotation on right) (*Source:* Thames Water Utilities 2000)

Figure 8.5 Zeta potential instrument in use

Figure 8.6 Zeta potential instrument with cell on top of instrument case

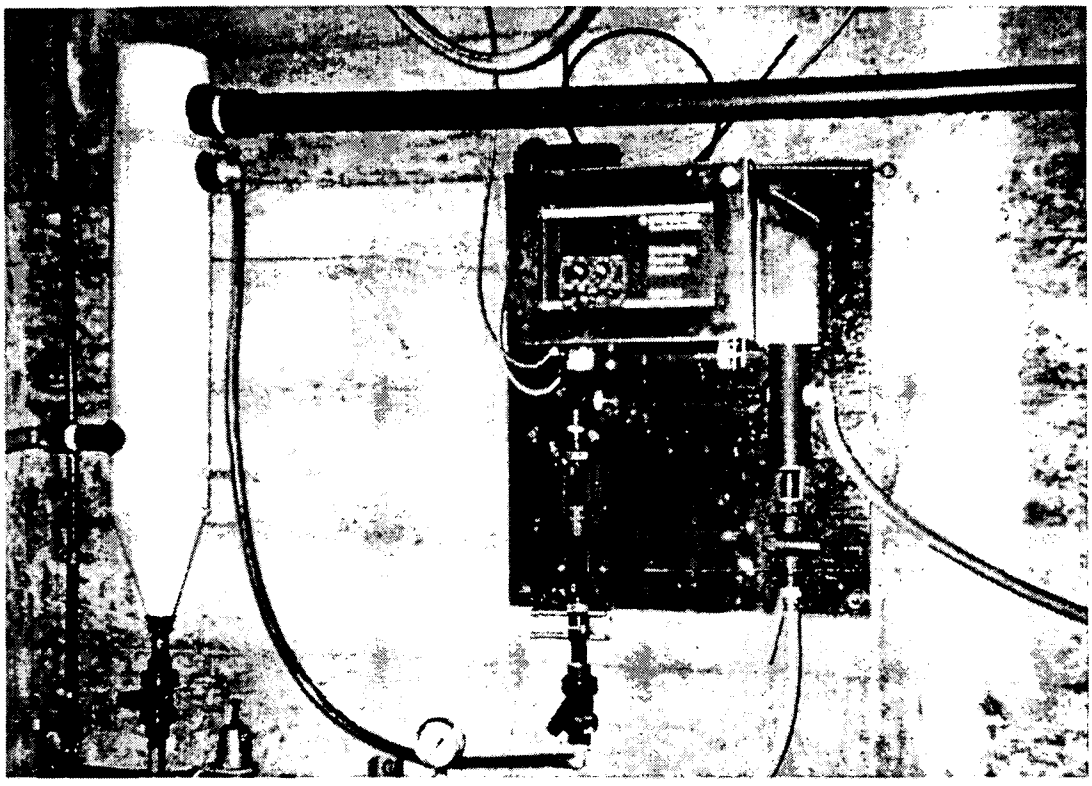

Figure 8.7 Streaming current monitor at Eugene, Oregon (*Source:* Black & Veatch 2000)

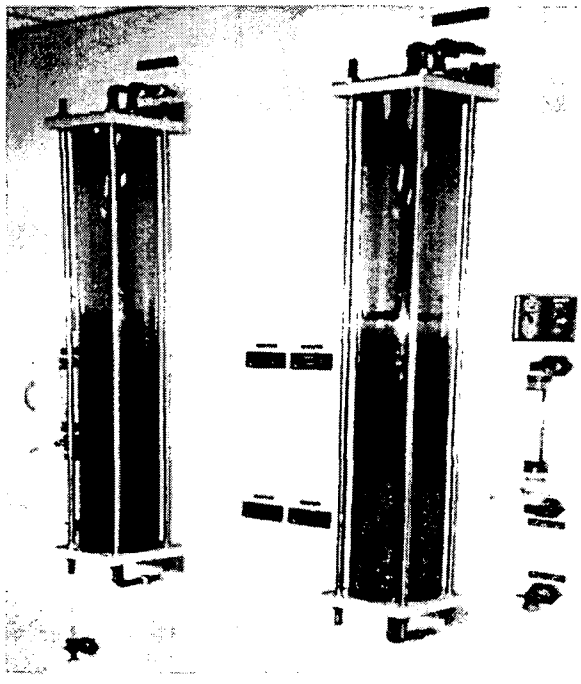

Figure 8.8 Pilot filters for coagulant dosage evaluation at Eugene, Oregon (*Source:* Black & Veatch 2000)

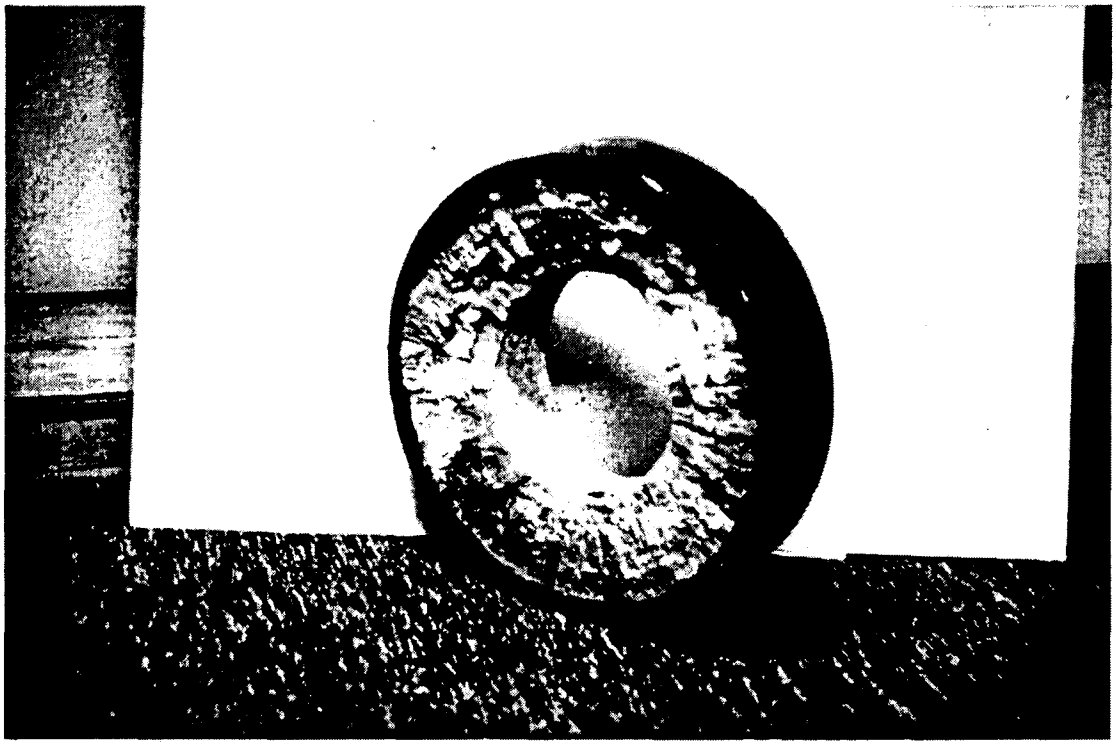

Figure 8.9 Water main with excessive $CaCO_3$ deposits

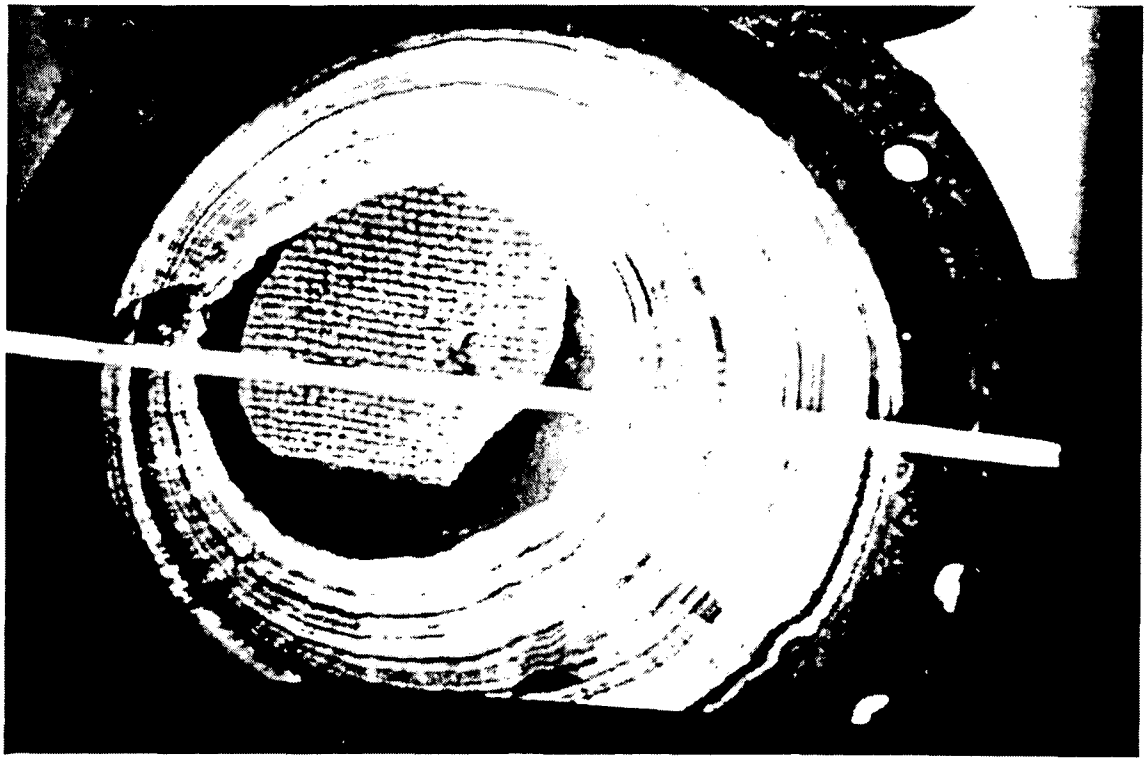

Figure 8.10 Water main excessive $CaCO_3$ deposits

Figure 8.11 Filter media mounding caused by inadequate recarbonation at softening plant (*Source*: Cleasby 2000)

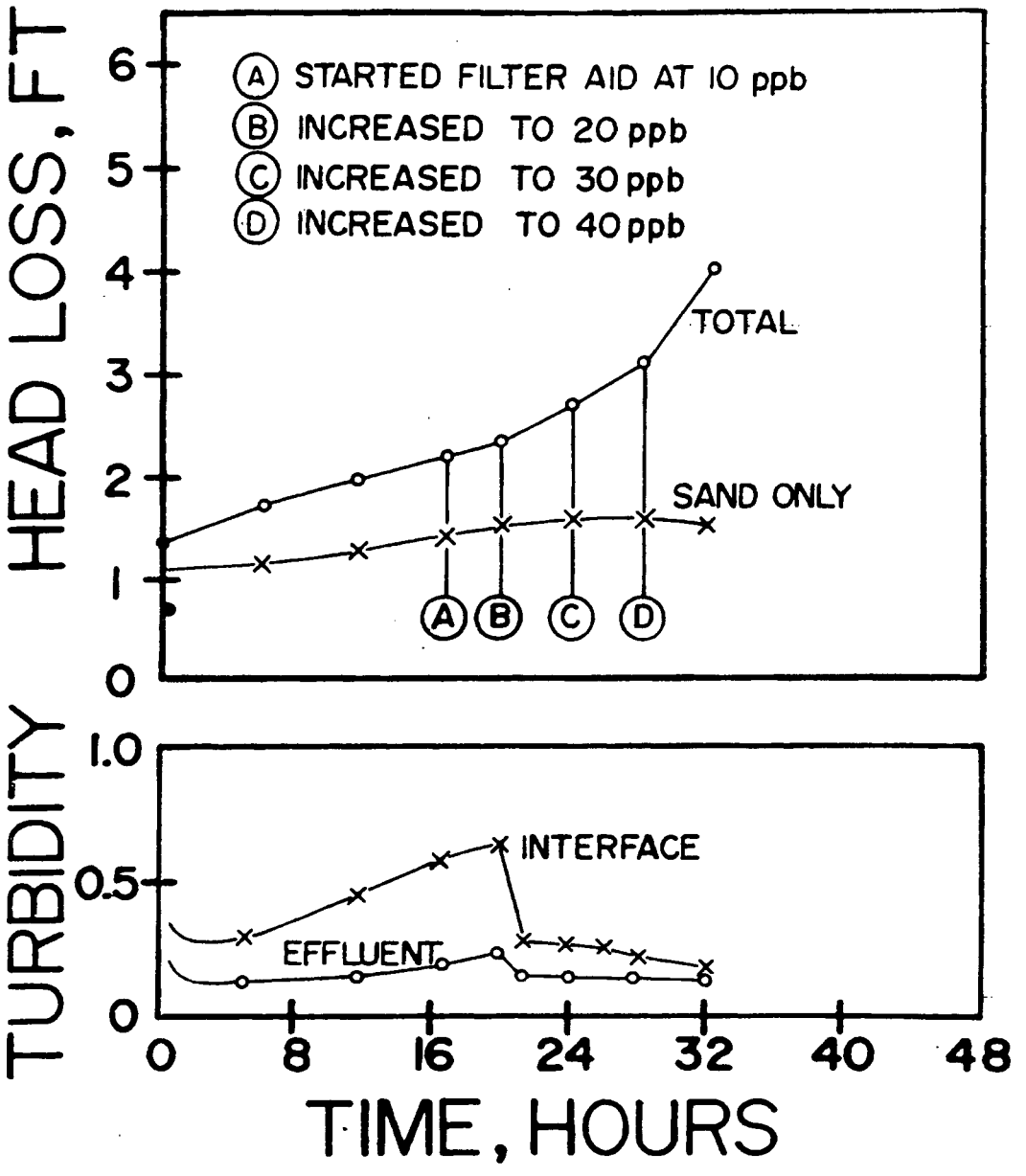

Figure 8.12 Use of interface turbidity to control filter aid at Spindale, N.C.(*Source*: Harris 1972)

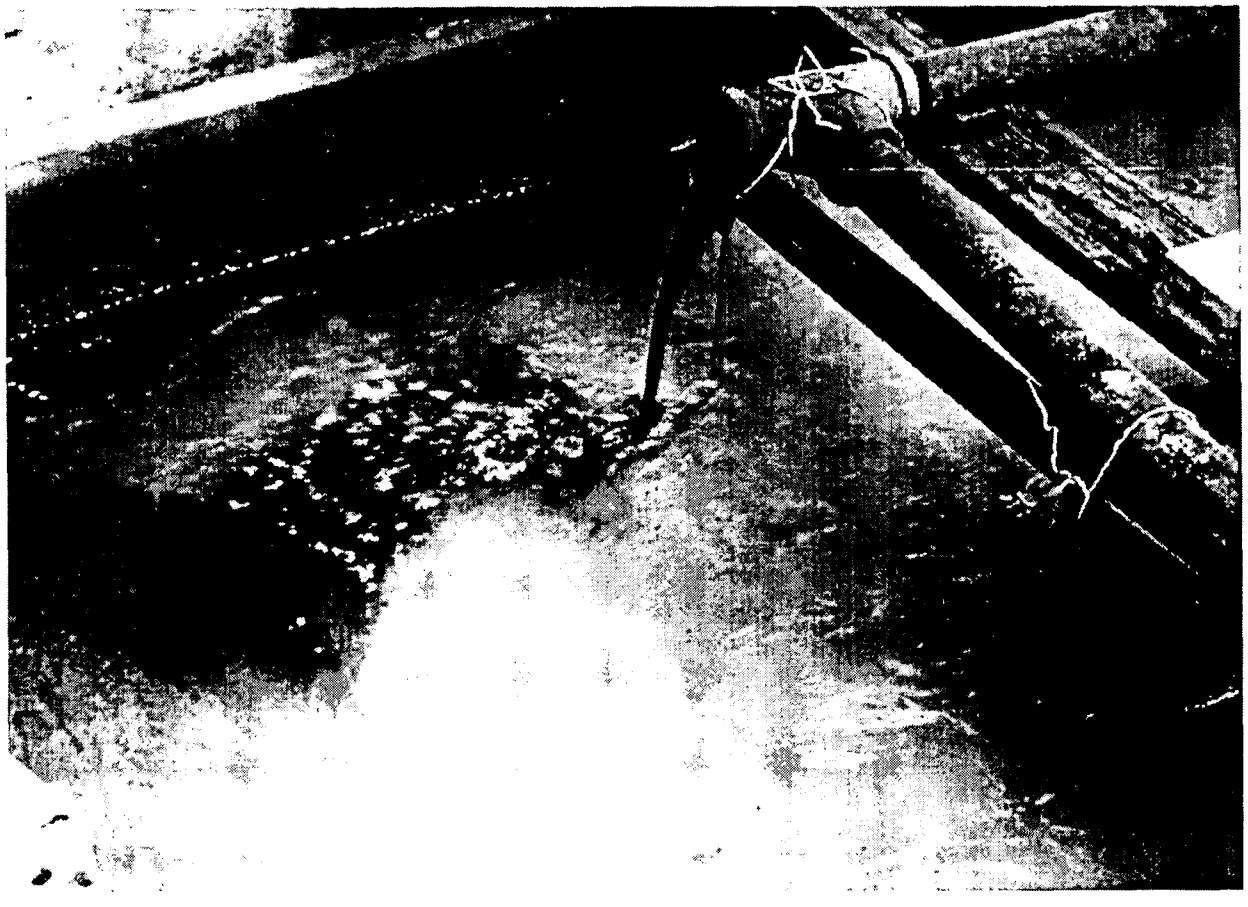

Figure 8.13 Inefficient chemical feed (*Source*: Black & Veatch 2000)

CHAPTER 9

PRETREATMENT: FLOCCULATION AND CLARIFICATION

INTRODUCTION

Flocculation and clarification are employed as pretreatment processes at most filtration plants. Sedimentation is the clarification process most commonly used in the United States. Roughing filters, or flocculator-clarifiers are used at some plants. Dissolved air flotation (DAF) has been used as a clarification process in water treatment for three decades, and in the 1980s and 1990s DAF plants were built and placed into service in the United States. Flocculation and clarification are discussed in this chapter in the overall context of optimizing water filtration plant performance, with the understanding that producing the minimum turbidity in clarified water may not necessarily result in optimum filter performance. Some aspects of flocculator and clarifier maintenance are discussed.

FLOCCULATION

Concepts

Flocculation is employed at most treatment plants following coagulant addition and rapid mixing to promote particle-to-particle collisions and to build floc size. When coagulated particles collide, they have a greater tendency to stick together because of the coagulation process, but without flocculation the rate of collision would be very slow. Flocculation sometimes is omitted at plants that do not employ clarification (sedimentation or flotation). Flocculation is a crucial process if sedimentation is employed, as the very small colloidal particles present in raw water would not settle in a reasonable length of time, even if coagulated. The combination of coagulation plus flocculation properly applied brings about the formation of settleable floc particles. A short period of flocculation is necessary to form the small flocs that can be floated to the water surface in a dissolved air flotation (DAF) plant and often is helpful in the direct filtration process.

Flocculation is an engineered process designed to increase the rate of particle-particle collisions and floc formation. Collisions between particles are promoted by imparting energy into the water. The energy input is expressed as *Gt*. The factor *G* in flocculation energy input is the velocity gradient. A velocity gradient could be thought of in terms of (feet per second) per foot or ft x sec^{-1} x ft^{-1}. The ft

units cancel out, leaving sec^{-1} for units of *G*. The second factor in total energy input during flocculation is the time of flocculation, t, measured in seconds. The *Gt* product is used to express energy input in flocculation, and because the seconds units cancel out, *Gt* is a dimensionless number. Further discussion of *G* and *Gt* and examples of calculations involving *G* are presented in Chapter 14.

The nature of the floc produced depends on the type of treatment being used. Large floc is needed if it is intended to settle in sedimentation basins; small compact flocs are appropriate for direct filtration and dissolved air flotation.

The literature suggests that *G* values need to be in the range from 300 - 5000 s^{-1} for rapid mixing, depending on mixer type and coagulant type. *G* values less than 100 s^{-1} are used for flocculation but the *Gt* values should be in the region 10^4 - 10^5. It appears therefore that recommended *G* and *Gt* values vary widely in the literature, and the correct value for any plant should be determined locally by jar testing both at the design stage and when necessary to assist routine operation. Further details of this complex and important subject were presented by Ives (1978), Amirtharajah and O'Melia (1990) and Amirtharajah et al. (1991).

AWWA *Manual M37* (AWWA 2000) presents a discussion of determination of flocculation detention time. When attempts are made to study flocculation, using the theoretical detention time in the flocculation basin as the detention time for flocculation in the jar test may not yield appropriate results. No short circuiting exists in the jar test jars, as that procedure is a batch process. In contrast, a full-scale flocculation basin tends to have some short circuiting, although this can be greatly minimized by using multiple stages of serpentine flocculation rather than cross-flow flocculation. *Manual M37* recommends that flocculation basin detention time should be evaluated by tracer testing, so the appropriate time for flocculation can be used in jar testing. Fluoride has been used as a tracer at some utilities. It should be stressed that operators should aim to optimize the combined result of clarification *and* filtration to meet filtered water quality and filtration performance goals with economical dosages of coagulant chemicals and polymers (if the latter are used). Filters can not compensate for poor clarifier performance - either quality will be unsatisfactory or filter runs will be shortened, increasing the backwash costs and the relative proportion of time the filter is spent in its ripening phase. Excessively good clarified water quality can prolong the filter ripening time.

At one Thames Water plant a good quality clarified water of 0.3 ntu was achieved but problems were experienced with reducing this further by filtration. While causes of this were still under investigation at the time of writing, a solution has been proposed which has showed initial good results.

A supplementary dose of 0.3 mg/L as Fe of iron coagulant has been dosed into the falling stream of water as it leaves the clarifier. This has resulted in filtered water turbidity less than 0.1 ntu.

Types of Flocculation

The formation of gentle eddy currents or mild turbulence in water brings about the particle-particle collisions needed to form flocs. The currents or turbulence can be induced in the water by mechanical stirring, by bubbling air into a basin, or by creating multiple changes in flow direction in a long channel (hydraulic flocculation).

Hydraulic

Hydraulic flocculation was the type of flocculation typically employed in water treatment plants designed in the first couple of decades in the 20th century. An example of an early design still in existence is the Chain of Rocks Plant in St. Louis, which was brought on line about 1905 for the St. Louis Exposition. Energy input in hydraulic flocculation is measured as head loss. The presence of many baffles in a flocculation channel or basin causes the water flow to twist and turn, causing turbulence. Energy input increases as head loss through the basin increases.

Both flocculation energy input and flocculation time can vary with rate of flow unless special provisions made to vary energy input. Hydraulic flocculation basins can be designed with movable baffles, allowing plant operators to change the energy input by changing the baffle position and therefore changing head loss incurred as water flows past the baffles. This approach has been used in some recently-constructed plants such as one operated by the Contra Costa Water District in California. Hydraulic flocculation in a spiral configuration is used by the Rand Water Board in South Africa.

Mechanical

Mechanical flocculation processes use a variety of stirring devices to gently agitate water and form flocs. In contrast to hydraulic flocculation, energy input is independent of the rate of flow. One advantage of mechanical flocculation is that operators may be able to vary energy input by changing the speed of the stirring device. Mechanical flocculation has largely supplanted hydraulic flocculation in

plants designed in built in the last half of the 20th century. The types used include paddle wheel, turbine, and walking beam flocculators.

Cleasby et al. (1992) noted that the appropriate type of mechanical flocculator was related to the treatment process train in use at a plant. Vertical shaft, multi-speed, pitched blade turbine flocculators were being designed and installed in treatment plants more often when Cleasby et al. prepared their AwwaRF report. They commented that this type of mechanical flocculator was well suited for direct filtration plants operating at low dosages of coagulant chemical. For dissolved air flotation, flocculation equipment that produces small flocs is desirable, as small floc particles are readily floated. On the other hand, the paddle wheel flocculator was considered more appropriate (Cleasby et al. 1992) for conventional treatment plants employing sedimentation, because this type of flocculator can be used to build settleable flocs.

Importance of Baffling

The effectiveness of the flocculation process is highest when the flocculation basins have been designed to avoid short-circuiting. When short-circuiting occurs in a basin, water flows through in a time that is shorter than the theoretical detention time. Although short-circuiting in flocculation basins can not be totally eliminated, minimizing this problem is important, because attaining a uniform floc retention time yields a more uniform floc size. When floc sizes range from very small to very large, the larger flocs may settle well while the smallest do not, and are carried over to the filters. Attaining a fairly uniform floc size can improve sedimentation performance, particularly when plate settlers are employed.

Floc size is related to the flocculation time and energy dissipated into the water. Floc particles subjected to constant mixing intensity tend to grow larger with the passage of time. Flocs passing through the flocculation basin quickly have less time to grow and are likely to be smaller. Formation of uniform-sized flocs is promoted by use of multiple floc basins in series, or by placing multiple sets of baffles in a single floc basin to subdivide it. This causes the flow pattern to be closer to plug flow and gives a greater uniformity of detention times.

Flow patterns in flocculation basins are determined by the arrangement of baffles. Figure 9.1 shows the flow pattern for transverse or cross-flow baffles, while Figure 9.2 depicts a serpentine baffle

flow pattern. The function of baffles is to promote plug flow and prevent water from being discharged from a flocculation zone prematurely.

In a basin with transverse flow, baffles are set up across the width of the basin. Influent flow is distributed across the width of the basin, and water flows down the length of the basin, perpendicular to the baffles, from the entry end to the discharge end. In a basin set up for serpentine flow, coagulated water enters at one corner of the flocculation basin and flows from across the influent end from one side to the other, then turns a corner and flows back. The flow of water moves progressively closer to the outlet of the basin only at the corners, but otherwise flow is perpendicular to a line running from the entry to the exit of the basin.

Transverse flow was commonly used in flocculation basins for many years. If this type of flow pattern is present, check for short-circuiting across the bottom of flocculation basin and if it is a problem, reduce this tendency with over-and-under baffling. According to Kawamura (1973), the open area in baffle walls between flocculator stages should be 5 percent or less, with good results obtained when the open area is 3 percent. Baffling is often very poor when transverse flow is used in flocculation basins, as most existing plants have an open area much more than 3 percent in their flocculation basin baffles (Cleasby et al. 1992).

The serpentine flow arrangement carries the flow back and forth across the width of the basin in long, narrow channels, and thus is closer to plug flow than a basin with a transverse flow pattern. A successful conversion of a flocculation basin from transverse flow to serpentine flow was carried out at Fort Collins, Colorado (Bryant et al. 1990). In this plant, horizontal shaft, paddle flocculators were being used. The shafts of the flocculators were parallel to the baffle walls. The flow pattern was changed so the water entered a flocculation chamber at one end and flowed through the chamber parallel to the flocculator shafts in a series of stages, exiting at the opposite end. This conversion produced floc particles having a much smaller size distribution and resulted in a substantial improvement in performance of a lamella plate settler. Settled water turbidity produced by the serpentine flocculator pattern averaged 0.7 ntu versus 1.5 ntu for average settled water turbidity from the transverse flow flocculation pattern.

Figure 9.3 shows the effect of baffling at the transition from a flocculation basin to a sedimentation basin in a lime softening plant. Suspended solids are settling quickly after passage through the baffles into the sedimentation basin.

OPTIMIZING GT

Some flocculation basins are designed to have the highest energy input at beginning of flocculation and the lowest energy input in the final stage of flocculation. This is referred to as tapered flocculation. When very small, coagulated particles are present in the water, as immediately after rapid mixing, substantial energy input is needed to stir the water and cause particle to particle collisions. Later on, after flocs have formed, if the stirring energy is too high, the floc might break up, so lower energy input is attained by decreasing the area of the flocculator paddles or by operating the paddles at a lower rotational speed.

The rate of floc formation decreases as water becomes colder. At locations where water temperature varies by 20° to 30° C over a year's time, operators ought to consider evaluating flocculator energy input seasonally and changing flocculation energy input as appropriate.

Floc Size Determination

Determination of floc size has been a technically difficult procedure. Usually this has been done as part of a research effort. Light microscopes have been used although this is tedious.
Particle counters likely to break up floc during process of measuring floc particle size, making those results questionable. Some processes, such as plate settling, seem to be sensitive to floc size. Plate settlers work best when the flocs are uniform in size, rather than when flocs have a wide range of sizes. With some practice, though, plant operators may be able to examine flocculated water in a well-illuminated beaker and make a reasonable estimate of the condition of floc and the distribution of sizes. The floc size comparison chart in Chapter 8 can be used to estimate the sizes of the floc in the effluent of the flocculation basin.

As a rule larger flocs are required for sedimentation, and smaller "pin point" flocs for DAF and direct filtration. Note, however, that large, fluffy, low-density flocs may not settle well. When charge neutralization is the filtration mechanism, for example in contact and direct filtration, the production of visible flocs is not expected. Contact filtration experiments at Thames Water's pilot plant in the early 1990s showed severe breakthrough of turbidity and iron when using coagulant doses large enough to form flocs. The same author did see flocs at another contact filtration plant when iron and two

polymers were used ahead of deep coarse media filters and the filtrate was around 0.03 ntu and the particle counts were less than 20 particles/mL for sizes >2μm.

Inspection and Maintenance

Inspection and observation of flocculation basins on a periodic basis is a good practice. At conventional treatment plants, where a goal of flocculation is to form a settleable floc, substantial changes will be noted as the coagulated water moves from the inlet of the flocculation basin to the outlet. Floc that moves into the sedimentation basin will begin to settle rather quickly if effective flocculation has been attained. Observation of the transition from flocculation to sedimentation is valuable at plants where these processes are contained in a large common basin and separated by baffles. Balanced distribution of water flow into the sedimentation portion of the basin will produce a fairly uniform floc cloud moving into the sedimentation zone. Uneven flow distribution can result in a large cloud of floc moving noticeably farther into the settling basin in one portion of the basin.

Floc patterns in flocculation and sedimentation basins can be viewed most effectively from a high elevation. An observer looking across a body of water from near the water surface can see much less detail down in the water than an observer positioned high above the water and looking straight down. Therefore inspections of flocculation and sedimentation basins can be much more productive if they are made from a vantage point higher than the basins. In some situations the roof of a building at the treatment plant can be a helpful viewing site. If unusual flow patterns are detected, then corrective measures can be taken. Often this would involve improving baffles between basins.

Flocculation equipment

Preventive maintenance is the key to keeping flocculation equipment in good working order, as important portions of this equipment often are under water and out of sight. A failure of flocculation due to equipment breakdown could lead to poor pretreatment and marginally effective or ineffective filtration. Periodic inspection of flocculation equipment is important for continued effective operation.

Many types of flocculators have moving parts or seals under water. These are especially vulnerable and need to be checked at intervals sufficiently short that preventive maintenance can be carried out rather than repairs on broken equipment. Chain drives, gear boxes, shafts and bearings,

and other power transfer machinery require periodic attention. An advantage of vertical shaft flocculators is that the drive motor and gearbox are accessible above the water and only a pivot bearing is needed at the base; the upper bearing can be above water. The whole shaft and blade, etc. can be lifted out of the water for maintenance without shutting down the flocculation tank.

Lubrication of moving parts must not be neglected, but prevention of lubricant (grease and oil) spills into the water being treated is also important. Exercise care in handling oils, as they must not be spilled into the water. At places where machinery is lubricated, consider providing devices to catch spills, if the manufacturer did not build these into the equipment. If food-grade lubricants can be obtained that meet the equipment manufacturer's specifications, their use is recommended.

Flocculation basins, including baffles

Flocculation basins, like all basins, require periodic inspection. For buried basins, checking for leaks is necessary. Baffles must be inspected as well, particularly if made of wood. When a flocculation basin is drained for inspection, pay attention to floc deposits that may have built up in basin corners or near baffles. This may reveal dead zones in the flocculation basin.

GRAVITY SEDIMENTATION CLARIFIERS

Gravity Sedimentation Concepts

Particles with a density greater than water have a downward settling velocity in quiescent water. When such particles flow through a tank of nearly quiescent water, they move toward the bottom of the tank as they flow from the entry towards the discharge end of the tank. If the particle has a downward, or settling, velocity great enough to enable the particle to settle to bottom of the basin before water exits clarifier at the far side, then the particle can be removed by settling. This concept is depicted in Figure 9.4 at the end of this chapter. The settling velocity theoretically needed to remove a particle in a basin can be calculated on the basis of the basin's dimensions and the rate of flow through the basin. If the distance a particle has to settle can be decreased while maintaining a constant horizontal velocity, then the residence time needed for settling also can be decreased.

Some factors affecting settling velocity are evident in Stokes' Law. Stokes' Law indicates that settling velocity increases as the difference between the specific gravity of the particle and the specific

gravity of water increases. Settling velocity also increases as the square of the diameter of the particle. Denser flocs, and larger flocs settle faster. Settling velocity decreases as the viscosity of water increases, so in cold water the resistance to settling is greater and settling occurs more slowly.

Causes of Problems in Settling Basins

Short-circuiting in sedimentation has been the cause of many sedimentation problems. Short-circuiting reduces detention time in the basin, decreasing the opportunity for suspended solids to settle to the bottom where they can be removed, and causes floc carryover from the clarifier when strong currents cause basin velocities to be excessive.

Causes of short-circuiting include poorly designed clarifier inlets, poorly designed clarifier outlets, currents within the basin caused by sustained strong winds, and differences in the specific gravity of water. Poor inlet baffling often is a cause of short-circuiting in sedimentation basins. Thermal differences within a basin also can cause short circuiting. Water is denser at colder temperatures, and so cold water can go to the bottom after it enters a clarifier containing warmer water. Water is less dense at warmer temperatures, so if the influent water is warmer than the water in the tank, it can flow to top of clarifier, and "floats" across the denser, colder water already in the clarifier. Water also is denser at very high turbidity (suspended solids concentrations); such water can flow to the bottom of a clarifier containing water low in turbidity. Strong sustained crosswinds can cause water to roll over in clarifier, creating a different form of short-circuiting in this manner. When sustained winds occur and cause short-circuiting, barriers can be built to serve as windbreaks.

In regions that have hot days and cool nights some source waters, such as shallow rivers, may be subject to diurnal water temperature variations. Temperature changes of this type can present serious problems to clarifiers by causing inversion of the water and sludge layers. A consequence of an inversion in a clarifier could be severe carry-over of floc, with high settled water turbidity and short filter runs. According to Hudson (1981), water temperature changes at the rate of 2° F (about 1°C) per hour have caused problems, and a total temperature change of (7°F) 4°C caused difficulties in treatment at a plant with horizontal flow settling basins and at one with solids contact reactors.

Another cause of operating problems related to water temperature and density is the rapid change of temperature that can occur on a large lake, such as the Great Lakes, when a change in wind direction causes a change in lake currents, bringing warmer water to the intake. Winds blowing from

the shore toward the lake tend to push surface water away from the shore, bringing water from the bottom towards the shore. Winds blowing from the lake toward the shore tend to push the surface water toward the shore, where it turns and dives down. The later phenomenon can push warmer water down toward an intake, and in strong, sustained storms this has resulted in stirring up bottom sediments near the western end of Lake Superior.

Settling basin performance can be deteriorated by build-up of sludge in weirs and in the basin. Build-up of deposits on weirs and in collector troughs can interfere with flow patterns for withdrawing settled water from the basin. Excessive deposits of sludge reduce the effective volume of the basin, reducing detention time, and promote the resuspension of sludge by water flowing through the basin. Manual cleaning of a sedimentation basin is depicted in Figure 9.5. A clogged weir and a weir with precipitates built up are shown in Figures 9.6 and 9.7. Effective sludge removal and keeping weirs clean are necessary for optimum settling basin performance.

High Rate Sedimentation Processes

Sludge Blanket Clarifiers and Reactor-Clarifiers

Sludge blanket clarifiers and reactor-clarifiers are designed to have a mixing zone, a flocculation zone, and a sedimentation zone, all within one basin. Treatment chemicals are added and mixed, floc forms, and then water rises through the sedimentation zone. The upward flow of water through the sedimentation zone causes the floc to rise. A variety of designs have been developed so that the upward velocity decreases as the water moves toward the top of the clarifier. They include the original hopper-bottomed tanks and subsequent designs of flat-bottomed tanks with multiple hoppers, a circular wedge, or other design concepts intended to allow the upward velocity to decrease as water flows up to effluent weirs (Gregory, Zabel, and Edzwald 1999). In basins employing this design concept the floc blanket rises to a point where the upward velocity is not sufficient to carry floc higher. As other flocs pass through the blanket, they can combine with floc in the blanket and are removed in this manner. This allows floc blanket clarifiers to be operated at higher rates than conventional settling basins.

One factor that is important in sludge blanket clarifier and reactor-clarifier operation is the need to maintain an equilibrium in the clarifier. The height of the blanket in the clarifier is a function of the floc particle size and density, and the upward velocity of the water. A floc blanket that is subject to

decreasing water velocity will fall to a lower level in the clarifier, and perhaps could drop to the bottom of the basin, out of suspension. When the floc blanket is at equilibrium a higher water velocity will cause the blanket to move up toward the basin outlet. If the velocity is excessive, the floc blanket will be washed out. For these reasons, floc blanket processes perform best when they are operated at a constant rate, as in a base-loaded plant. The worst mode of operation for sludge blanket clarifiers and reactor-clarifiers is an on-off operation with daily start-up and shutdown. When flow stops, the suspended solids settle to the bottom of the basin, so no blanket is functioning when the units are restarted.

Sludge blanket clarifiers and reactor-clarifiers are designed to operate at overflow rates that are higher than the rates for conventional sedimentation basins. Like conventional sedimentation basins, sludge blanket clarifiers and reactor-clarifiers are vulnerable to short circuiting caused by density differences resulting from sudden changes in water temperature. When such events occur, operators may have few options other than reducing flow through the plant to downrate the clarifiers sufficiently that floc does not wash out and go onto the filters.

Sludge recirculation clarifiers

In this system a portion of the sludge is withdrawn and recirculated together with polymer and the coagulated water. For plants practicing coagulation, the purpose of sludge recirculation is to provide a greater contact opportunity for flocculation and to form a floc that will settle better by incorporating some existing suspended solids into the newly-forming floc. This objective is different from the purpose of sludge recirculation in the lime softening process, in which presence of calcium carbonate crystals promotes the more rapid precipitation of additional calcium carbonate. In reactor (solids-contact) clarifiers, sludge is recirculated in the mixing/flocculation zone to facilitate particle growth and sedimentation performance.

Inclined Tube Settlers

Inclined tube settlers were developed to provide for very short travel distances to reach the bottom collecting surface. Whereas a floc particle might have to travel down 12 to 16 feet (4 to 5 m) from the top of the water to the floor of a conventional sedimentation where it would be removed from

flowing water, in a tube settler a particle needs to travel down only a few inches to contact the bottom of the tube. The tube settler concept is presented in Figure 9.8 at the end of this chapter. The detention time needed for effective settling in tube settlers is much shorter than the time needed in conventional sedimentation basins. Tube settler modules are fabricated with many tubes stacked together. Tube shapes include square, rectangle, hexagon and others. Inclined tube settling modules have been retrofitted into numerous settling basins to improve their performance.

Because of the way they are placed into sedimentation basins and supported, tube settler modules need to be fabricated of light-weight, non-corroding materials. Some are made of plastic. Treatment plant staff and their contractors must be very careful to avoid welding or other activities that could generate intense heat near the tube settler modules, as some tube settler modules have caught fire as a result of careless maintenance and repair activities.

Figure 9.9, at the end of this chapter, shows a tube settler giving effective solids separation in a conventional coagulation plant. In Figure 9.10, an operator is hosing a tube settler to clean out sludge deposits.

Inclined Plate Settlers

Inclined plate settlers, like tube settlers, accomplish settling in a short time by reducing to inches the distance a particle must settle in order to contact the "bottom" of the basin. Figure 9.11 is a schematic diagram of an inclined plate settler. Installing the inclined plate assemblies in existing basins often is difficult, so this equipment frequently is used in new facilities rather than in retrofits of older settling basins. Basins equipped with inclined plate settlers are better able to cope with changing rates of flow than conventional sedimentation basins.

Like conventional settling basins and inclined tube settlers, performance of inclined plate settlers is optimized when the size of the floc is uniform, having uniform settling characteristics. A change from cross-flow flocculation to serpentine flocculation resulted in improved performance for an inclined plate settler in Colorado.

Weighted or Ballasted Floc Clarifiers

Use of weighted or ballasted floc to accelerate settling is a relatively new concept in the United States, although it has been used for a number of years in Europe. Floc resulting from coagulation often has a low settling velocity, necessitating design of settling basins with detention times as long as four hours. By weighting floc with a dense particle, it can be made to settle much more rapidly, so sedimentation can be accomplished in less than one-half hour.

In this process, very fine sand and coagulant chemical are added to raw water in a flash mixing tank where coagulation occurs. Then polymer is added to make the sand adhere to the floc, and gentle stirring builds floc sizes up so the floc settles very rapidly. Settled floc and sand are continuously removed by sedimentation, and are pumped to a cyclone separator where the floc is separated from the sand. Clean sand is then reused to weight floc.

Some operational aspects of this process are different from other sedimentation processes. The key to the very rapid settling attained in this process is the attachment of floc to very fine sand. Addition of fine sand to flocculated water would be futile if the two kinds of particles did not attach. Without the attachment the sand would settle very rapidly and floc would remain suspended in the water. Therefore control of polymer addition to attain effective sand-floc attachment is essential for successful operation of the process. Another aspect not encountered in other sedimentation processes is that a very small amount of sand is lost in the process so make-up sand is needed and would be added on a periodic basis.

Clarifier Optimization and Management

Clarifier optimization and management can be approached in a number of ways. Perhaps the most important action is to eliminate or minimize short-circuiting and to reduce wind effects and the warming effect of the sun, which can disturb the uniform upward flow in the floc-separation zone. Sometimes windbreak shielding is sufficient, without provision of a complete covering. Operators need to manage sludge withdrawal to avoid interference with sedimentation. Accumulation of excessive deposits of sludge decreases the detention time available in the basin. Sometimes equipment used to remove sludge from a settling basin can deteriorate the quality of settled water exiting the basin by stirring up and resuspending sludge while removing it. Sludge also can become septic as time passes,

and rising gas bubbles would upset sedimentation of floc. Some clarifiers may need to be covered to avoid damage to sludge scrapers caused by ice formation.

Inspection and Maintenance

Inspection of flocculation and sedimentation basins can be done periodically while they are operating. Hudson (1981) showed an aerial photograph of a plant in which the sedimentation basins had poorly designed inlets. He explained that localized clouds of floc that were generally situated in the same location were an indicator of inlet problems. He also recommended close observation of sedimentation basin outlets as a way of finding problems there. Observation from the air or even from a high point on the treatment plant property is recommended. Some plants have tall chemical buildings situated so that observation of flocculation and sedimentation basins can be done from the building roof. Observations during routine operation (for background or baseline information) and during clarification upsets may be helpful as operators try to determine the cause of the upset.

Inspection and maintenance of sedimentation basins and sludge removal equipment should be done at least annually. Sedimentation basin scrapers are under water and not easily observed. Preventive maintenance is needed to keep equipment in good working order. Breakdown of sludge scrapers during a season of peak water demand might cause a utility to operate a sedimentation basin without sludge removal for an excessive length of time. Alternatively, taking the basin out of service for repairs during peak flows could overload the basins remaining in service. Either situation ultimately might cause excessive floc carryover to the filters and impaired filter performance.

During a season of low water demand, basins are drawn down one at a time, for inspection and cleaning. Before sludge is removed, study the pattern of deposits to gain clues about where settling is happening and where it is not. Check the walls and floor for integrity. Check and do maintenance work on sludge removal equipment. In some processes, sludge scrapers operate in a circle even though the basin is square in cross section. Typically such scrapers are equipped with "wings" that move out at the corners to collect sludge that has settled outside of the circular pattern covered by the main scrapers. The mechanisms for the moveable "wings" operate under water and can be troublesome to maintain. Pay close attention to these devices.

When chain and flight scrapers are used, inspect the scrapers, the chains, and the drive mechanisms. Watch for wear and try to anticipate problems such as breakage ahead of time and do

preventive maintenance rather than being caught with broken equipment when water demand is high and taking a basin out of service would cause serious problems.

Sludge removal equipment often has moving parts under water. These are especially vulnerable and need to be checked at intervals sufficiently short that preventive maintenance can be carried out rather than repairs on broken equipment. Chain drives, shafts, underwater seals, and other such equipment require periodic attention. Lubrication of moving parts must not be neglected, but prevention of lubricant (grease and oil) spills into the water being treated is also important. Exercise care in handling oils, as if they must not be spilled into the water. At places where machinery is lubricated, consider providing devices to catch spills, if the manufacturer did not build these into the equipment.

There should be no large gaps between the plates or tubes in lamella clarifiers, either due to poor installation or movement of plate packs in service. Routine inspection of the integrity of these structures is necessary to ensure optimum clarifier performance. The optimum angle of 50° to 60° needs to be maintained for these plates and tubes.

FLOCCULATOR-CLARIFIERS OR ROUGHING FILTERS

Flocculator-clarifiers, or roughing filters are used in some package or pre-engineered water treatment equipment, as the clarification step before rapid rate, granular media filtration. In these filters, water flow may be downward, as in a conventional filter, or it may be in an upward mode. Filter media are coarse, and may consist of mineral media or plastic media. As water flows through the coarse material, flow separates and combines many times, and the flow of water passes through many twists and turns. The effect is to promote particle-particle collisions and to form floc particles and attain partial removal of particles in the coarse bed of filtering material. Substantial particle removal takes place, so the flocculator-clarifier or roughing filter has to be backwashed periodically. The flocculator-clarifier is effective for removing floc that would be difficult to settle in a conventional sedimentation basin. This approach to flocculation typically is used in package plants.

Flocculator-clarifiers have some characteristics that are different from other flocculation and clarification processes, and thus have some distinctive O&M requirements. Most flocculator-clarifiers are incorporated in package plants. They are typically used by small water systems.

Some units consist of two pressure filters in series, one with coarse media (the flocculator-clarifier) and one with multi-media for filtration. These package plants require the kind of maintenance typical of pressure filters.

Other flocculator-clarifiers utilize open basins. Some employ a large medium having a specific gravity lower than 1.0 (the specific gravity of water). In these units, the medium floats. A screen holds the medium in place during operation. During cleaning, an air scour is used, and the medium no longer floats, as the average specific gravity of the air bubbles and water combined is less than that of the medium. Influent water enters the unit at the bottom and flows up through the coarse medium. If debris is present in the raw water, it can clog the flocculator-clarifier. Evergreen needles are an example of the kind of debris that could cause problems. If the screen holding the medium develops holes or separates from the tank wall, medium can be lost. Dense medium with a specific gravity greater than 1.0 is used in some flocculator-clarifiers, and in these the medium does not float. Otherwise the maintenance concerns are similar.

One aspect of some flocculator-clarifiers is quite different from other clarification processes. Typically a sedimentation basin can operate continuously, because sludge is drawn off the bottom of the basin at periodic intervals. Flocculator-clarifiers remove particles from water by filtration through the coarse medium. As the medium clogs with solids that have been removed, head loss builds up. In some equipment, the multi-media filter is not ready to be backwashed when the flocculator-clarifier needs to be washed. This can result in interruption of the multi- media filter run before it needs backwashing, and operators may stop and re-start the multi-media filter without washing it. Stopping and restarting filters without backwashing is not recommended by authors of this O&M manual.

Annual maintenance for flocculator clarifiers operating in an upflow mode includes cleaning the coarse medium, cleaning holes in air scour pipes (if used), checking the screen that holds the medium in place (if one is used), and checking to be sure that the necessary amount of coarse medium is present in the unit. Annual maintenance for flocculator clarifiers that use pressure vessels would include the maintenance practices needed for other pressure filters, described in Chapter 10 in this manual.

DISSOLVED AIR FLOTATION (DAF) CLARIFIERS

Concepts of Dissolved Air Flotation

Dissolved air flotation is an especially effective clarification process for removal of particulate matter that has poor settling characteristics. Low turbidity (< 100 and preferably < 30 ntu) waters with high loadings of low-density particles such as algae or flocculated colored organic material are the major DAF applications. Raw waters from reservoirs, with heavy clay, silt and sand settled out but with algal loads or upland colored, low turbidity sources are now commonly treated by DAF rather than by gravity sedimentation in the U.K., Scandinavia, and Australia. DAF plants recently have been built for such applications in some US communities.

In the DAF process (shown in Figure 9.12), a side stream of treated water (about 6 to 10 percent of the process flow) from the DAF clarifier is pumped through a pressurized vessel where it contacts air under pressure typically ranging from 60 to 80 psi (420 to 560 kPa). With respect to normal atmospheric conditions, the water leaving the saturator is supersaturated. It passes through one or more pressure reducing nozzles or needle valves into the inlet zone, close to the bottom of the DAF clarifier, where flocculated water is introduced. When the pressure on the supersaturated water reverts to atmospheric pressure, the supersaturated air leaves the water, forming a cloud of microscopic bubbles and a zone of "milky" water. If the DAF clarifier is properly designed and operated, this cloud of tiny bubbles rises to the top of the water in the clarifier. Floc particles attach to the rising bubbles and are carried to the water surface. Over a period of time, ranging from a fraction of an hour to several hours, the floc builds up on the water surface forming a floating scum. Periodically the floated floc is scraped or floated off of the water surface, before it can become so compact and heavy that it settles to the bottom of the DAF clarifier.

Figure 9.13 is a profile view diagram of a DAF flocculator and clarifier. Flocculated water and supersaturated water enter the clarifier at the bottom left of that basin in the diagram. Bubbles form and rise, passing over the inclined baffle. In this zone, bubbles and floc make contact and attach. Flocs are carried up and over the baffle, and the rising cloud of bubbles continues to carry the flocs to the water surface, where they become part of the floating scum. The figure also depicts some floc that could no longer float and is settling into the clarified water zone of the DAF clarifier.

In-filter DAF, a process in which the DAF clarification zone is in the water above filters, is increasing in popularity for shaving the peaks of algal blooms and preventing short filter runs in otherwise low turbidity raw water treatment systems. This type of equipment generally is proprietary, being produced by a number of manufacturers. When the area of the filter bed is the same as the area of the DAF clarifier, the clarifier operating rate for DAF and the filtration rate are the same. DAF clarification must be interrupted for filter backwashing, but because DAF clarification can be restarted very rapidly, this is not a serious problem. A schematic of the COCO-DAFF™ process in which flocculation, injection of the recycle stream, and release of the cloud of bubbles all occur in the same basin is shown in Figure 9.14.

Edzwald's concept of the mechanism of particle removal in DAF, the White Water Collector Model, was explained in *Water Quality & Treatment, 5th Ed.*, Chapter 3 (Gregory, Zabel, and Edzwald 1999) and is shown in Figure 9.15. In Edzwald's DAF concept the continuously rising cloud of bubbles in the DAF clarifier is compared to a filter bed of granular media. In a granular media filter, the filtering material grains are immobile and the particles are moving down through the filter bed, whereas in a DAF clarifier, the floc particles are relatively immobile until rising air bubbles capture them. The coagulated and flocculated particles are removed in the DAF clarifier basin by becoming attached to very small bubbles that are so numerous as to give a "milky" appearance to the water in the clarifier's reaction zone. This attachment and removal are said to be similar to attachment and removal of coagulated particles in a granular media filter. Bubbles effective for particle removal are considered to be in the 10 to 100 μm size range. Particle removal by DAF is a function of the number of bubbles in the clarifier, which Edzwald defines as the bubble volume. Increasing the number of bubbles in the water increases the bubble volume and can improve particle removal.

DAF is an appropriate treatment process for waters in which the suspended solids concentration in the raw water is relatively low or the specific gravity of particles is low (e.g. color and algae). As compared to conventional gravity sedimentation basins, DAF has the advantage of start-up times that are only a matter of minutes, so it is a process that can be operated effectively on a start and stop basis. This is in contrast to sludge blanket clarifier processes, which should be operated continuously to maintain the blanket in suspension. As with any process involving coagulation, DAF can not perform properly without proper control of chemical dosing. Proper hydraulic design is required for DAF to work correctly. DAF also requires correct management of saturated water recycling.

Role of Pretreatment for Effective DAF Clarification

As with coagulation and sedimentation, effective coagulation is necessary for successful operation of DAF clarifiers. Floc particles and particulate matter in the raw water are carried to the water surface by attaching to the rising bubbles. Suspended particles that have not been properly coagulated will not be as likely to stick to the bubbles and float to the top.

Flocculation for the DAF process can have a shorter detention time than flocculation for a conventional settling basin because the objective is to have small flocs of destabilized particles that readily attach to rising bubbles. Edzwald et al. (1999) have successfully operated DAF pilot plants having flocculation detention times as short as 5 minutes and DAF hydraulic loading rates as high as 12 to 16 gpm/sf (29 to 39 m/h). Flocculation for a DAF clarifier would bear a stronger resemblance to flocculation for a direct filtration plant than for a conventional plant with a settling basin.

The DAF Clarifier

Recycle water percentage and operating pressure for saturator are two factors that govern the amount of air bubbles introduced into the DAF clarifier. If the particle concentration in raw water is high, a higher volume of bubbles may be needed for successful flotation of the floc and particles. More bubbles can be introduced into the clarifier by raising the air pressure in the saturator, or by increasing the recycle water percentage. Additional operating costs are caused by either action, so to hold down operating costs, higher recycle percentages or higher saturator pressures would not be used unless necessary. Depending on the nature of the pump performance curve for the recycle pump, raising the saturator pressure may decrease the recycle flow percentage. In such a situation, adjusting both saturator pressure and pump flow might be necessary to obtain a higher volume of bubbles in the clarifier.

Removal of floated sludge, called float, from the clarifier surface has to be done periodically, before the float begins to break up and settle to the bottom of the clarifier. If the float remains on the top of the clarified water for a long period of time, the float at the edge of the clarifier may adhere to the clarifier wall during removal. This tendency can be mitigated by spraying water on the clarifier wall and in the floc sludge channel for a short time before and during removal of the float. Floated solids from a DAF clarifier can have solids content ranging from 1 percent to 3 percent, sometimes exceeding

3 percent (Gregory, Zabel, and Edzwald 1999). The solids should be transported to the site for treatment or disposal with use of a minimum quantity of water, to avoid diluting the solids with more water and thus increasing the amount of water to be removed later. If the water level of the clarifier is raised to remove the float by flooding, the solids content of the sludge can be less than 0.2 percent (Gregory, Zabel, and Edzwald 1999).

DAF clarifiers usually are covered to prevent disturbance of the floated solids by natural phenomena, including rain, hail, and high wind. If the floated solids were to be broken up and sunk, their removal would be very difficult, probably accomplished only by shutting down the process, and draining and cleaning the basin. Disruption of the floated solids could cause high loadings of particulate matter onto filters, if the solids found their way to the discharge ports in the DAF clarifier.

Maintenance Issues

DAF plants have some unique maintenance requirements. Nozzle adjustment and maintenance is an important maintenance duty at a DAF plant. Some DAF equipment uses multiple discharge ports across the width of the clarifier, at the inlet end of the basin, with a valve for each port. The valves must be adjusted so the flow is balanced across the clarifier basin. Furthermore, the valves need to be adjusted so the discharge of water from the saturator produces a cloud of fine bubbles. Properly adjusted valves will produce "milky" looking water at the inlet zone in the clarifier basin. If big bubbles are seen, resembling the bubbles that might occur if someone hooked up an air compressor and a pipe and injected air into the DAF basin, then there is a problem. Big bubbles rise too fast and do not carry along the flocculated particles the process is intended to remove. They also could disrupt the floated floc and cause some of it to sink. If a vigorous bubbling action with big bubbles is observed, this situation should be worked on and corrected promptly.

The recycle facilities at DAF plants need maintenance. The recycle pumps require periodic maintenance. The air compressor facilities must be checked periodically, and the saturator should be inspected. If packing is employed in the saturator, the condition of the packing should be checked for built-up slime or precipitates. Recycled water must be clean water from a screened or filtered water source to avoid blockages or fouling of the internal packing of the saturator vessels. Water and air pressures must be carefully regulated to optimum values to achieve satisfactory saturator performance.

Drainage pipework should be adequately sized to allow the clarifiers to be drained down and de-sludged without undue delay. Use of pressurized water hoses to drive old sludge out is ineffective if the water and sludge can not drain away quickly enough. This is a major cause of complaint from DAF plant operators.

In-filter DAF systems require careful design of inlet hydraulics to avoid disturbing the floating sludge. Large floc agglomerates have the potential to settle out on top of the filter media and can be difficult to remove by backwashing. This could lead to formation of mudballs.

Thames Water's COCO-DAFF™ plant at Walton had the design benefit of one hydraulic flocculation stage needed to serve seven Flotation / Filtration tanks. COCO-DAFF™ is a proprietary process in which flocculation, injection of the recycle stream, and release of the cloud of bubbles all occur in the same basin. This minimizes space requirements for treatment processes ahead of the DAF clarifier.

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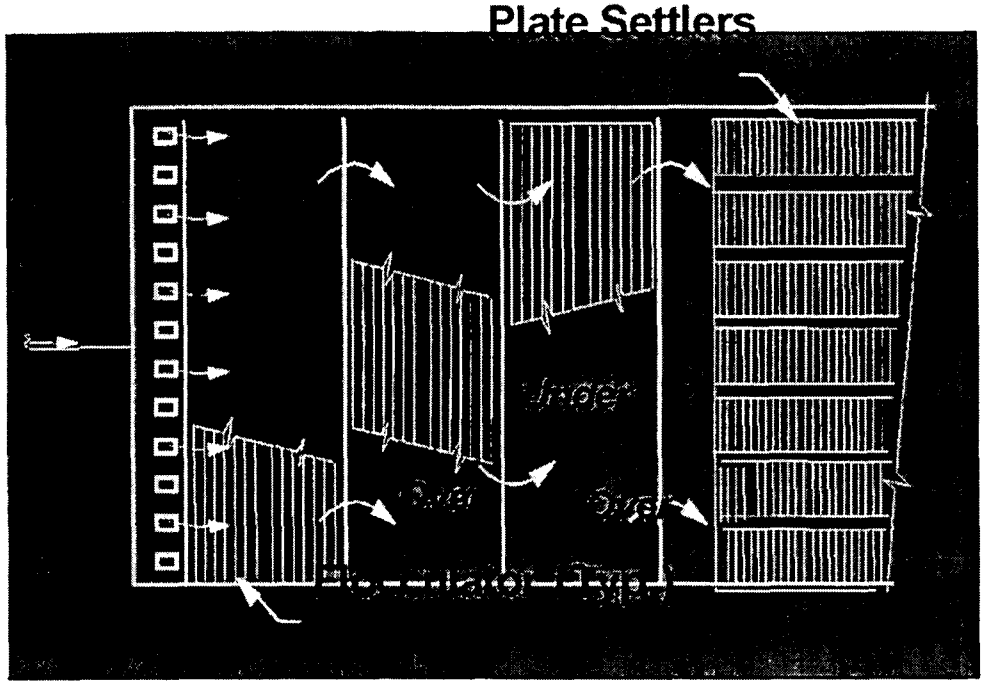

Figure 9.1 Example of cross-flow flocculation baffle (*Source*: Black & Veatch 2000)

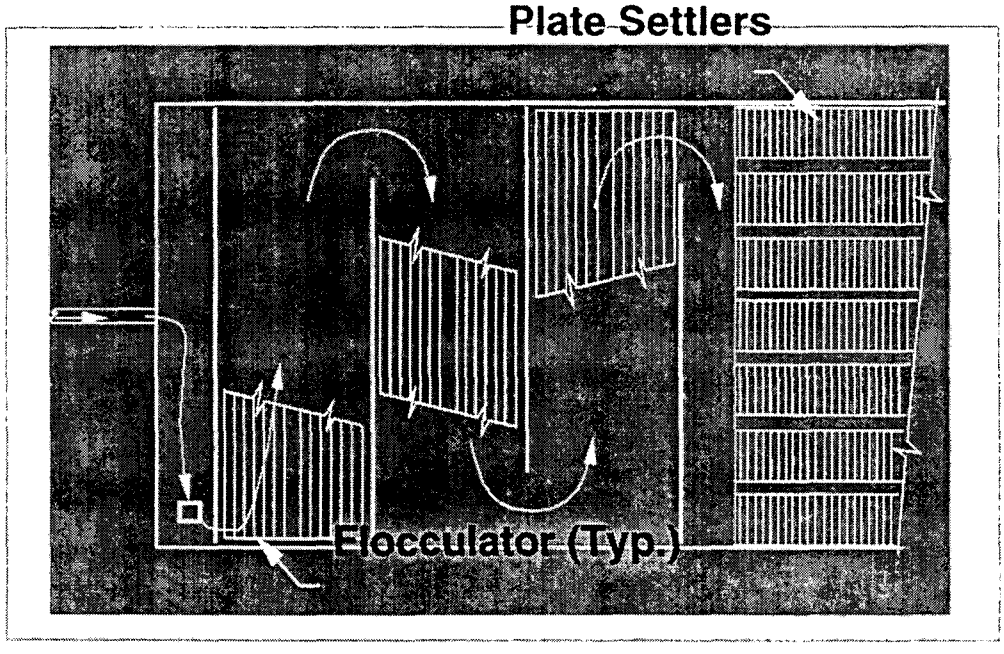

Figure 9.2 Examples of serpentine baffles (*Source*: Black & Veatch 2000)

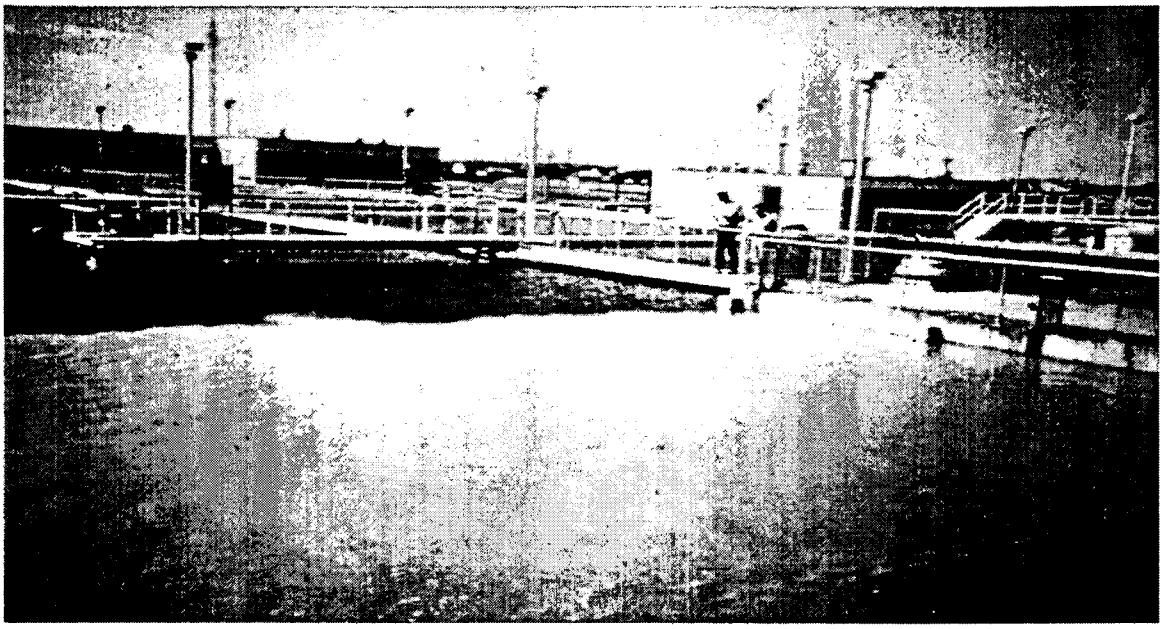

Figure 9.3 Baffles between flocculation and sedimentation giving good setting at a lime softening plant (*Source:* Black & Veatch 2000)

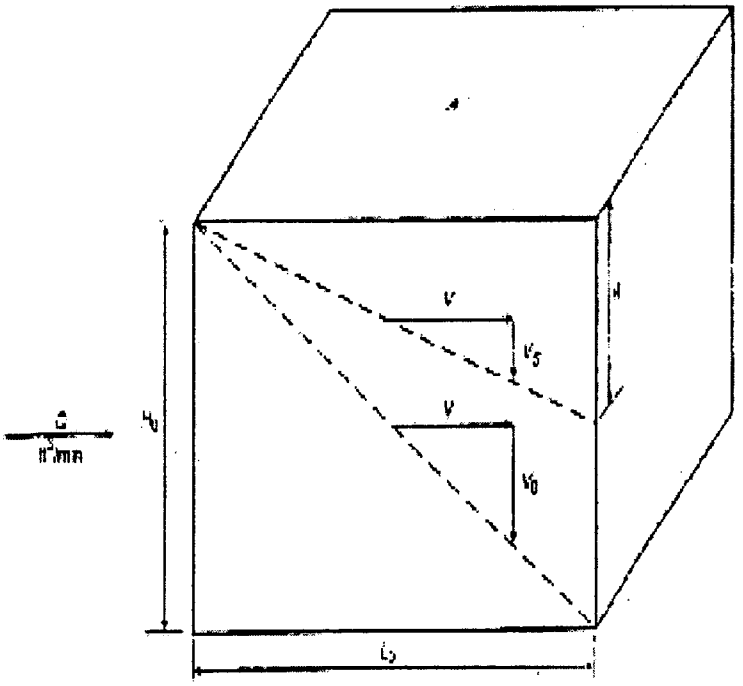

Figure 9.4 Shallow-depth sedimentation theory parameters (*Source*: McEwen 1998)

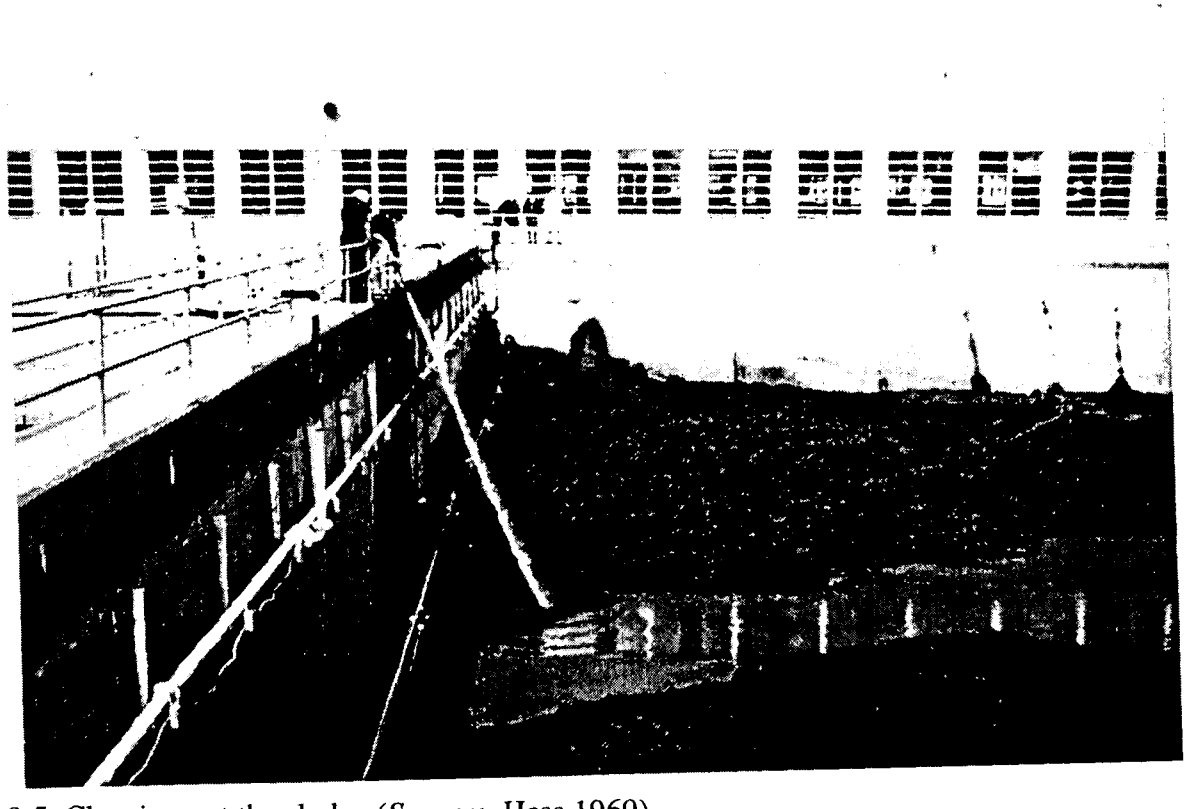

Figure 9.5 Cleaning out the sludge (*Source:* Hess 1969)

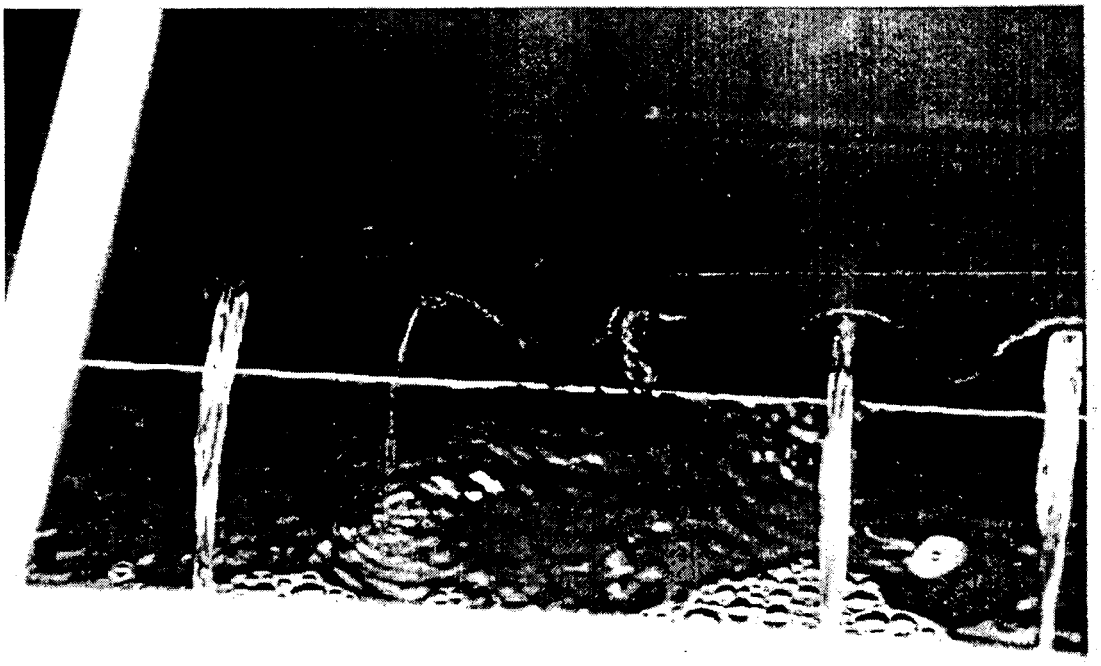

Figure 9.6 Clogged settling basin water (*Source*: Hess 1979)

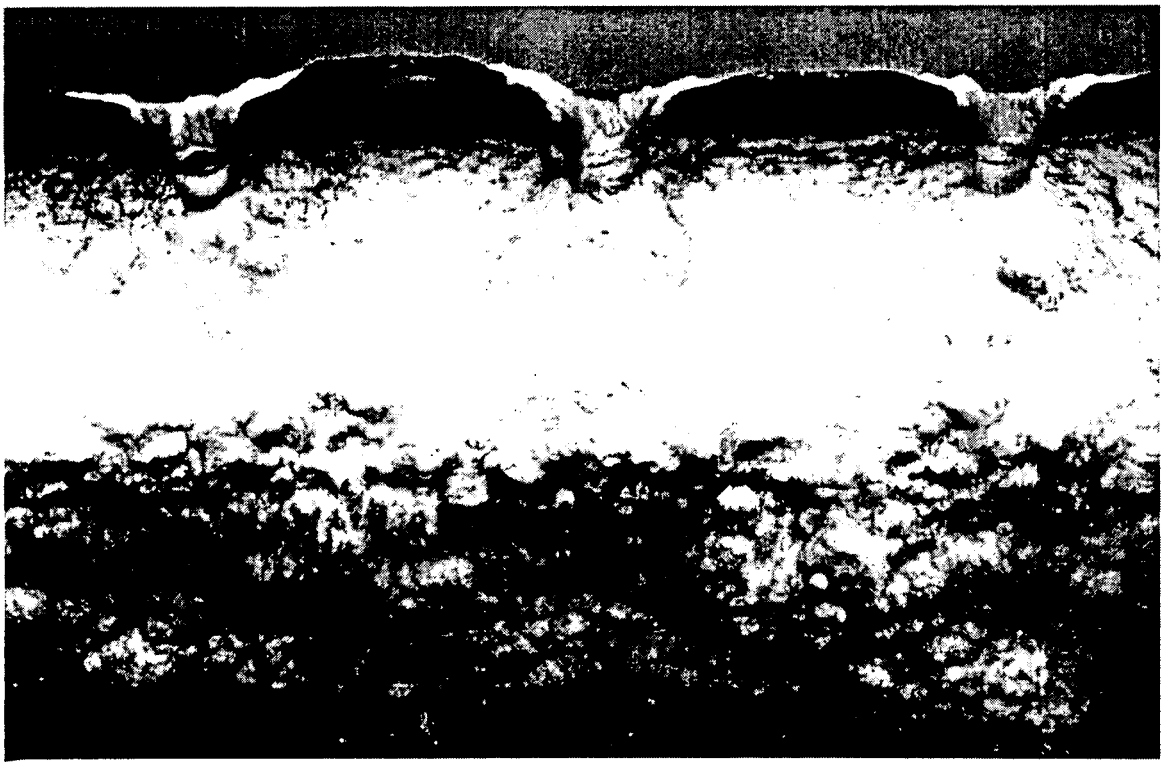

Figure 9.7 Deposits on weir (*Source*: Hess 1984)

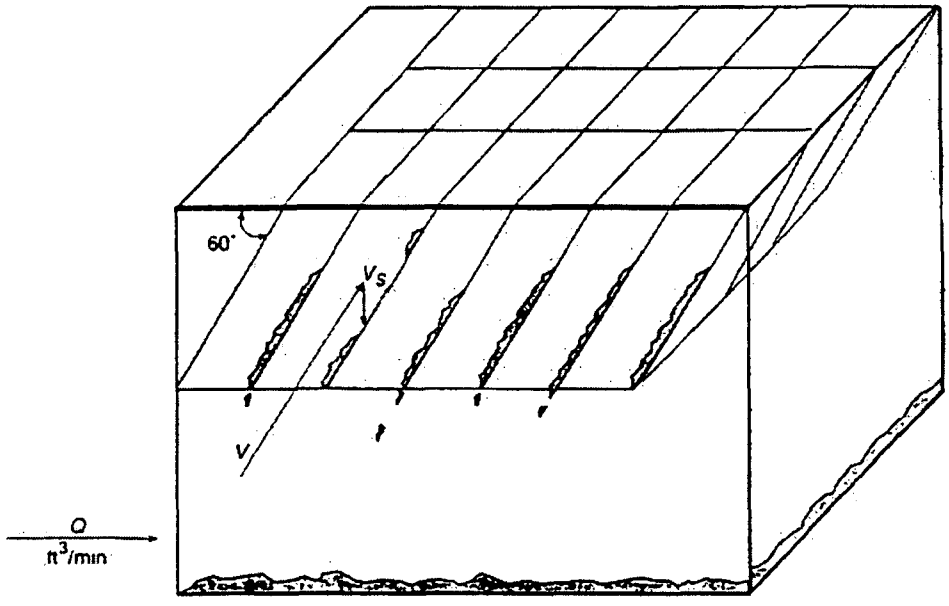

Figure 9.8 Tube settler shallow-depth sedimentation (*Source*: McEwen 1998)

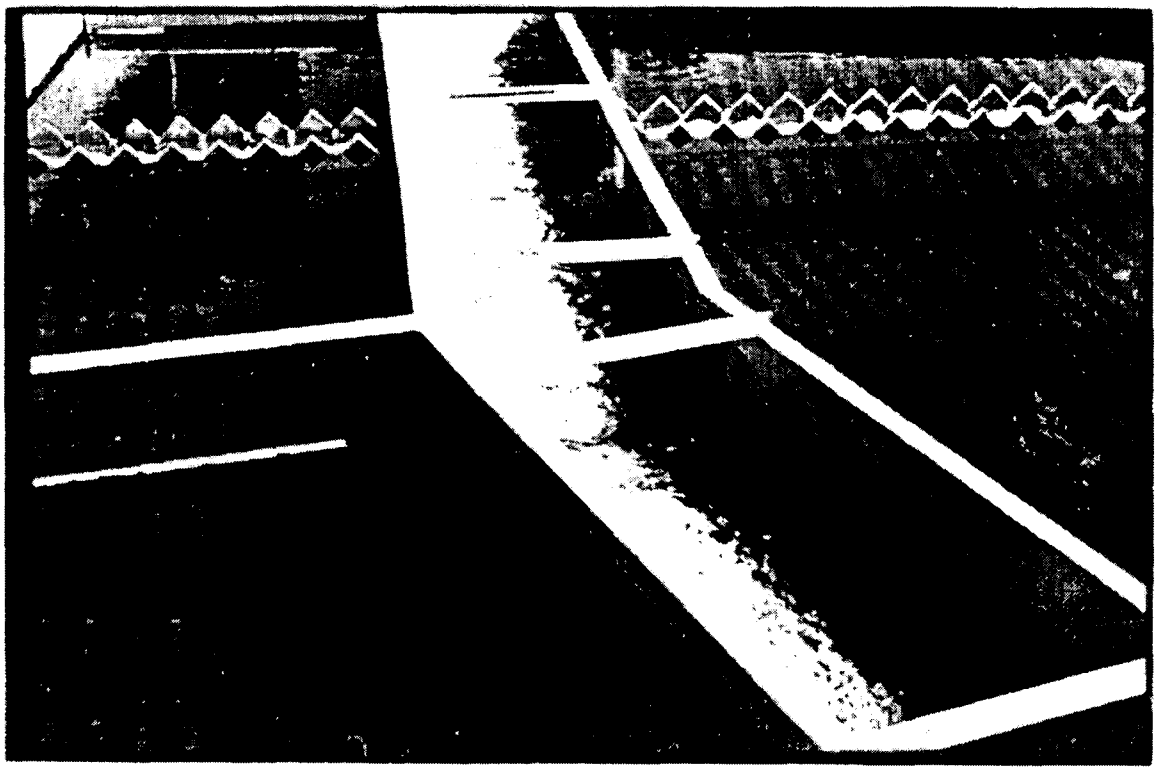

Figure 9.9 Tube settler functioning well in coagulation plant (*Source:* Black & Veatch 2000)

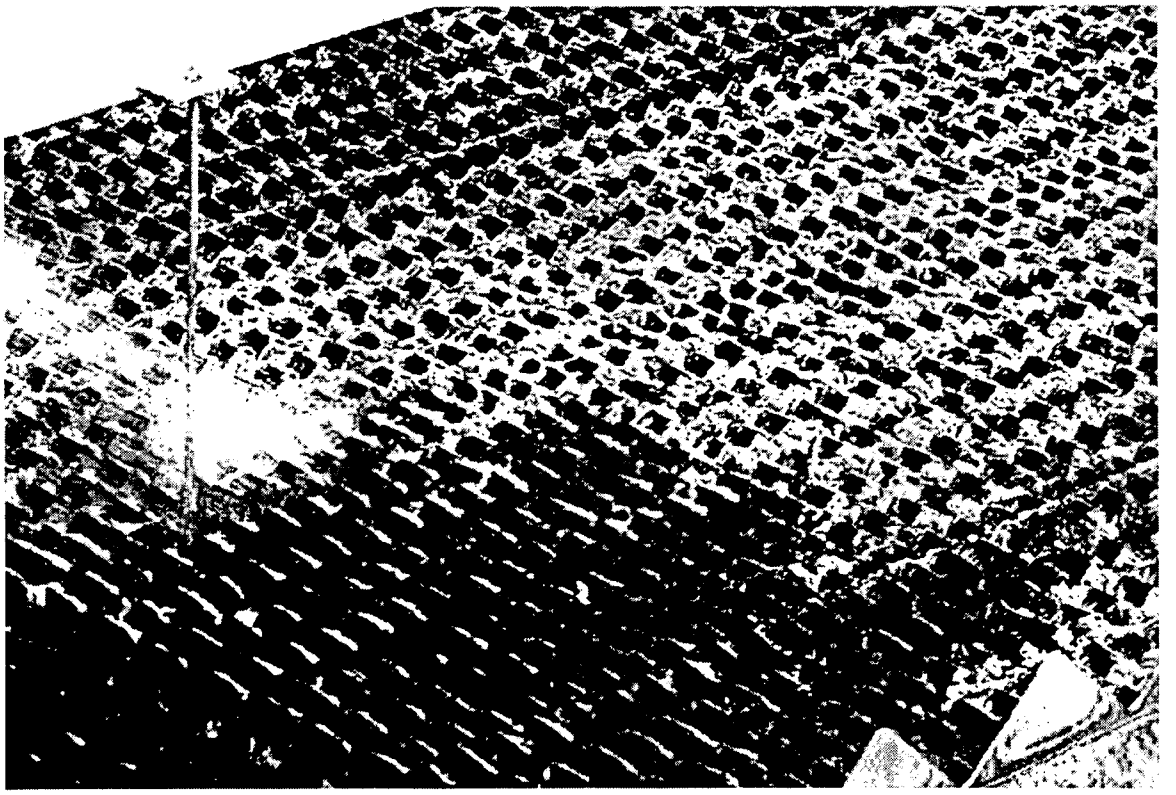

Figure 9.10 Hosing sludge deposits off tube settler (*Source:* Thames Water Utilities 2000)

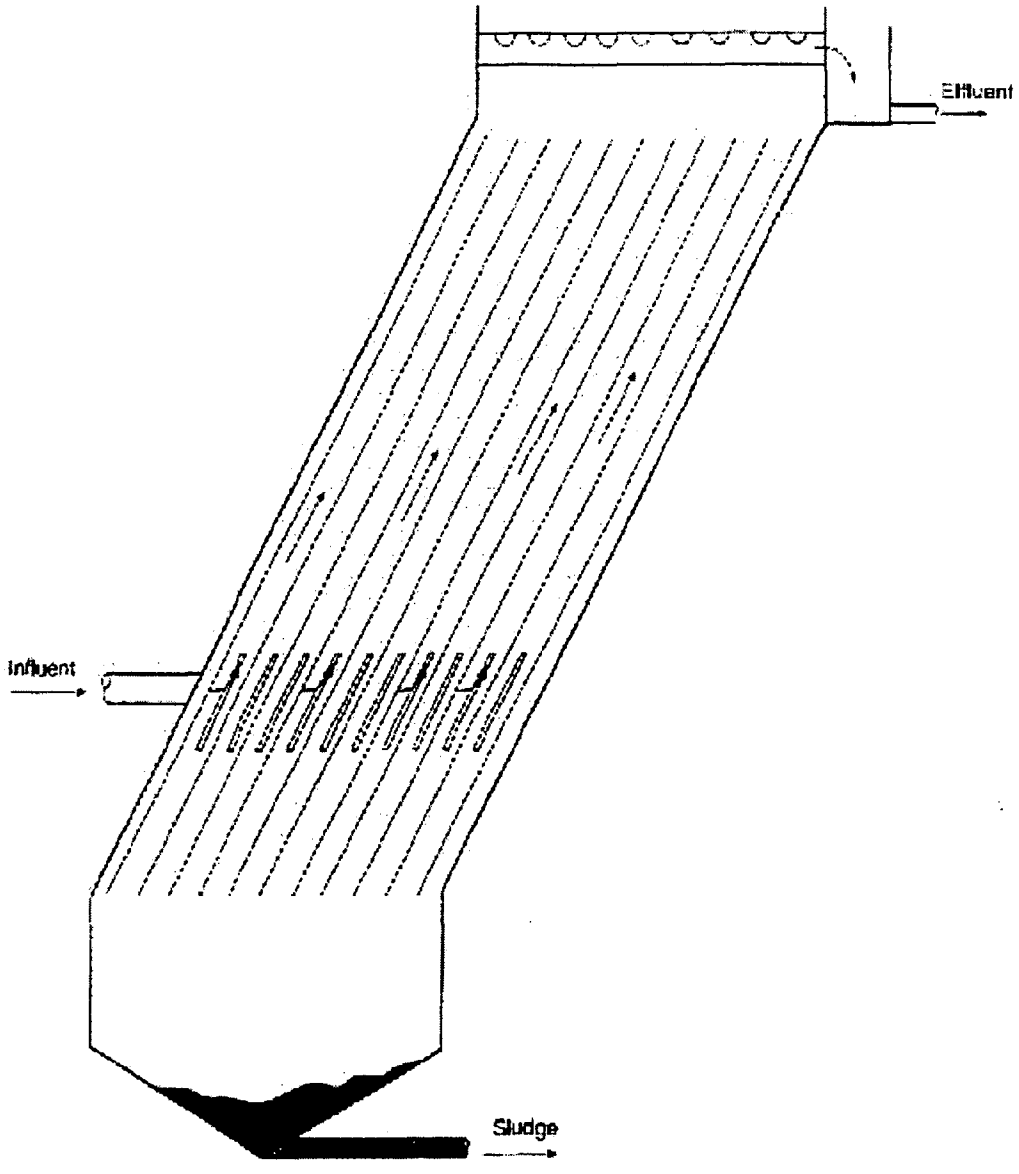

Figure 9.11 Inclined plate separator (*Source*: McEwen 1998)

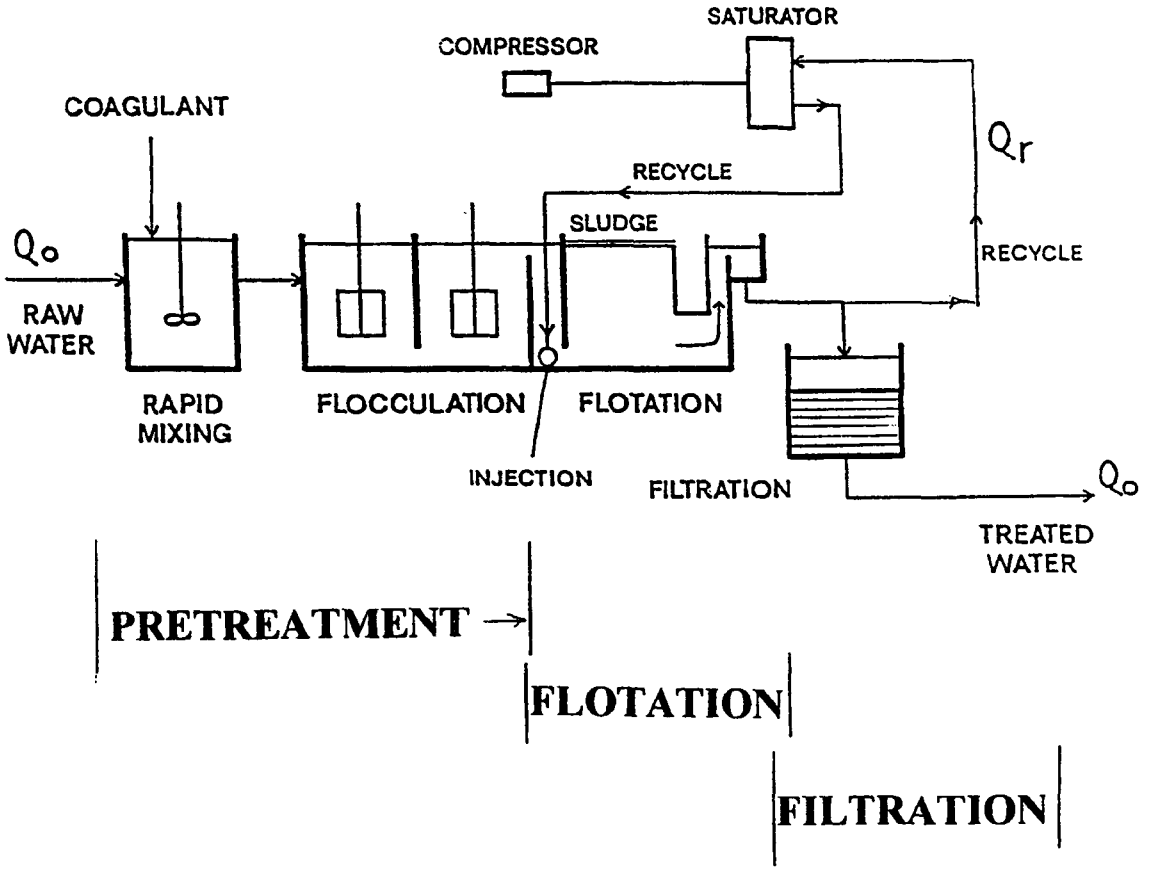

Figure 9.12 DAF treatment plant schematic (*Source*: Edzwald 2000)

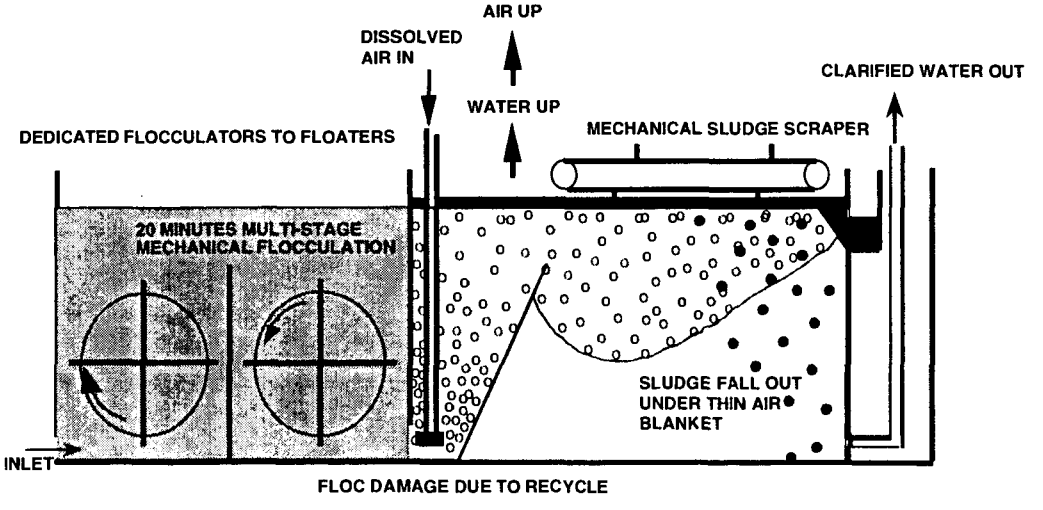

Figure 9.13 DAF treatment plant schematic (*Source*: Thames Water Utilities 2000)

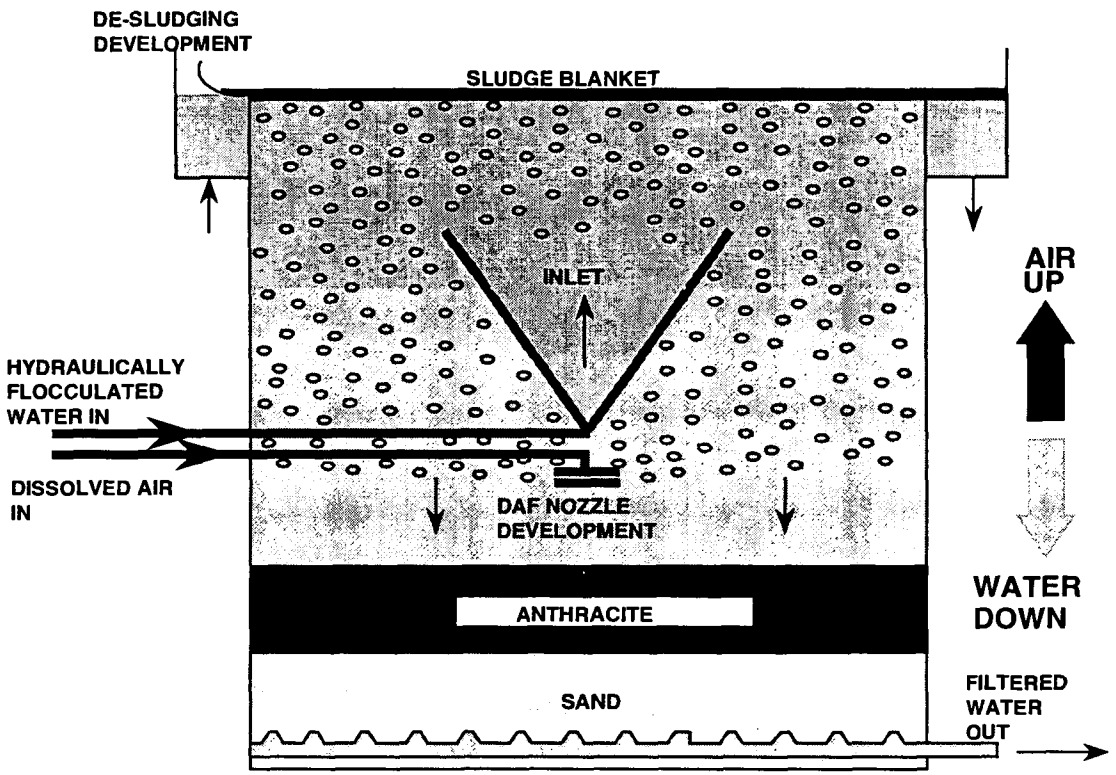

Figure 9.14 COCO-DAFF schematic (*Source*: Thames Water Utilities 2000)

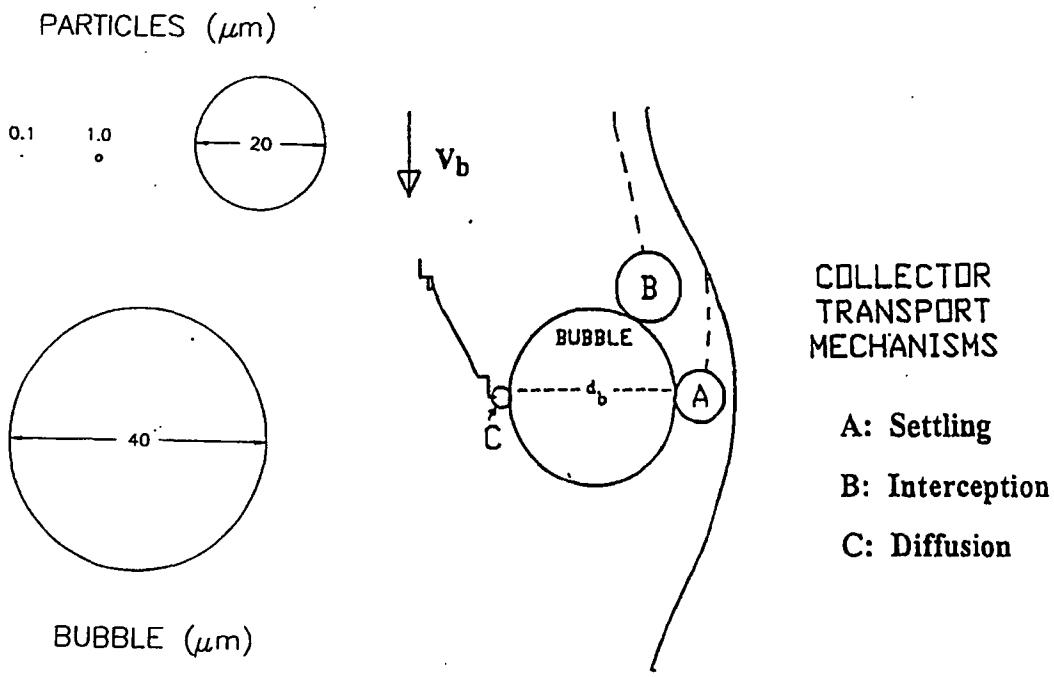

Figure 9.15 Concept of particle-bubble collisions and size (*Source*: Edzwald 2000)

CHAPTER 10
FILTER INSPECTION AND MAINTENANCE

INTRODUCTION

The greatest effect a filter plant operator can have on optimizing filtered water quality is through optimizing chemical pretreatment and maintaining the filter beds in good condition. This chapter presents detailed procedures operators can use for the inspection of filter beds. The steps recommended for complete periodic inspections and for quick filter inspections are described. Methods for eliminating mudballs and for chemical treatment of media are discussed also. Some forms that may be useful for inspections are included. These can be adapted to the specific needs of the user.

SETTING PRIORITIES FOR INSPECTION AND MAINTENANCE

Operating a water filtration plant to produce safe drinking water involves a multitude of tasks. To meet the goal of producing water that is safe to drink, operators have to evaluate the tasks that must be accomplished and then set priorities for getting the job done. The routine backwash observation described below is important, and this is recommended for each backwash. A major filter inspection involves removing a filter from service for an extended period of time, and it requires a substantial amount of operator time. Except in a situation involving filter failure, a major filter inspection is something that would be scheduled during a time of low water demand, and when plant staff will have the hours to devote to the job to do it properly. This is one example of setting priorities in scheduling work.

Another example of setting priorities is related to the type of inspection and maintenance work that might be done. Some inspection and maintenance activities are carried out so the plant can produce filtered water of the highest quality, and these protect public health. Other activities are important for the preservation of the physical facilities, and thus protect the capital investment. Still other activities could be considered "housekeeping" in nature. These involve maintaining a neat and clean appearance in the plant. Even if the most up-to-date treatment processes are employed, if a plant is dirty and messy with litter, trash and chemical dusts or water on the floors, the public is unlikely to have confidence in the quality of water produced by a plant that looks run-down and filthy. The "housekeeping" or janitorial work may not contribute much to water quality or to long-term preservation of the plant, but

this too is important. In the short term, the activities that protect public health absolutely must be carried out. Waterborne disease outbreaks described in print or on radio or television by local and national news organizations are a reminder of the need for constant vigilance. Over the long term, the physical plant must be maintained properly or very large rehabilitation or replacement costs may be incurred. Aesthetics, or "housekeeping", while very important, must not be done at the neglect of water quality and physical plant.

Having stated the above as general guidance, this manual can not prescribe an exact order of priorities for plant inspection and maintenance activities. The needs will vary from plant to plant. Some operators may have a piece of equipment that does not seem to work as well as they would like, and that will require more time. The saying, "The squeaky wheel gets the grease," certainly will apply. For example, if rotary surface wash nozzles were likely to become plugged within six months, a maintenance schedule would be set up so those were inspected and cleaned out or replaced every four to five months. At a lime softening plant, if a pipe is used to deliver lime slurry to the raw water, operators may need to flush or pig that pipe at a greater frequency than is required for other inspections. The process or equipment that causes the most difficulties will be the one that receives the most attention, and plant staff will be aware of this by their past experience. The overriding principle is to perform inspection and maintenance activities at a frequency sufficient to prevent deterioration of water quality and deterioration of the physical plant.

FILTER INSPECTION AND ASSESSMENT

Performing a major filter inspection and assessment requires a significant commitment of labor and time for filters to be out of service, but this commitment is an essential part of long-term efforts to optimize filtered water quality. Filters must be in good physical condition if they are to perform at optimum levels. Major inspections are not performed frequently, but they provide lots of valuable information. Inspection results must be recorded and saved where they can easily be found in future years, so reviews of long-term trends can be made. If records of major inspections of a filter are kept as long as the filter media remains in the filter, a historical record of the condition of the filter and the media will be available throughout the useful life of the media.

Workplace Safety

During a filter inspection, operators will be climbing in and out of filters and working in filters. All appropriate safety precautions must be observed, for open gravity filters and for pressure filters.

Prior to any investigation on a water treatment plant where there is a potential, however small, of the health and/or safety of personnel being put at risk a thorough review should be held to identify the potential hazards and to put in place an acceptable method statement of how the investigation may be undertaken safely. This written statement needs to be agreed to and implemented by the site manager and the operator and by the persons undertaking the investigation.

Some water filters may be considered to be "confined spaces" within the context of Occupational Safety and Health Administration (OSHA) regulations, even if they are open, gravity filters rather than pressure filters. Such a determination may depend on the geometry of the filter (for example the distance between the top of the filter media and the top of the filter box) as this relates to whether the filter has limited access and egress. Whether a filter has the potential to have a hazardous atmosphere may depend on whether the filter is indoors or outdoors (where natural ventilation may be much greater than ventilation provided within a building) and on whether granular activated carbon is used as a filter medium. An atmosphere might be oxygen-deficient or might contain hydrogen sulfide or elevated concentrations of carbon dioxide in a filter with GAC medium or high biological activity, but this should not happen when sand or anthracite are used. The confined space issue must be resolved by each water utility on a plant-specific basis, as filter designs vary widely.

Whether or not a filter is a confined space for occupational health and safety purposes, some fundamental aspects of safety must be followed. These include:

- When the vertical drop to get down into the filter is over 6 feet, the issue of fall prevention may need to be addressed.
- Procedures related to Lock out-Tag out must be initiated, so that a filter can not be accidently placed into service or backwashed when personnel are working within the filter box.
- Test the filter media to ascertain that it has been sufficiently dewatered before stepping into a filter bed. A granular media bed with the water level just below the media surface does not provide firm footing.
- Always work in teams of two or more persons when going into a filter, with one person positioned outside the filter, able to observe the worker or workers in the filter. This is

essential for safety. Working in teams also facilitates data recording, as it is awkward for one person to be responsible for both the inspection and measurement work and for recording the observations made during inspection and measurement.

A comprehensive review and discussion of OSHA regulations is beyond the scope of this manual. For specific information on those regulations, users of this manual in the United States should consult the Federal Register (29 CFR 1910.146 and 29 CFR 1910.147).

Consult relevant safety handbooks for information on requirements related to working in open filter beds and in pressure filters. In addition, sanitary precautions such as disinfecting boots and equipment must be observed.

Material provided in this chapter was based on a variety of sources, including the survey of participating water utilities, experience of the manual authors, information presented in the AWWA Filter Surveillance Workshop at Springfield, Illinois on November 16-17, 1999, and the AWWA videotape, "Filter Surveillance Techniques for Water Utilities" (AWWA 2000). The AWWA filter surveillance video is an excellent supplement to this manual, as it shows many of the techniques described herein. Smith, Wilczak, and Swigert (1997) recommended a number of procedures that ought to be included in a major filter assessment and gave step-by-step instructions for these procedures. Muldowny et al. (1996) described procedures for filter assessments and inspections and explained how the inspections are a useful and necessary tool for attaining optimum filter performance.

Getting Ready for a Filter Inspection

Carrying out a major filter inspection is a key aspect of preventive maintenance for filtration plants. If filters are neglected and not thoroughly inspected on a periodic basis, plant staff may find that major preventable damage has occurred. A thorough annual inspection is good maintenance practice. Once per year is a recommended frequency unless experience has shown that the interval between inspections can be longer without serious problems developing between inspections. A 5-year interval is considered the maximum time between inspections, if filters are not likely to develop any problems in the interval between inspections.

A considerable amount of advanced planning is likely to be needed before an effective inspection can be carried out. Smith, Wilczak, and Swigert (1997) recommended forming a filter inspection team consisting of at least two people. Labor times discussed in this chapter are based on two workers

carrying out the task and represent the clock time rather than labor hours required. The time needed is substantial, one half to one day or more per filter, so these inspections require carefulcoordination with management to ensure availability of workers. The inspection of a filter may also require up to twice the usual volume of wash water. Again, advanced scheduling is appropriate. Major inspections of filters for preventive maintenance (rather than as a response to discovery of serious filter problems) should be planned for times when water demands are low and filters can be removed from service without interfering with needed water production. Don't schedule a filter inspection when the filter will be needed for water production, unless a very urgent situation has developed, and the filter probably will have to be removed from service for inspection and perhaps repairs regardless of water demand. Examples of this circumstance include discovery of a depression in filter media after backwashing, indicating serious loss of media through a hole in the bottom of the filter, or observance of a large filter boil during backwashing

Before the actual inspection begins, Smith, Wilczak, and Swigert suggested that over two dozen different kinds of equipment and materials be assembled for use. Their list, with minor modification, has been put into Table 10.1, which may be copied for convenient future use. An important item on the list is a camera. Although not required for the inspection, a camera can be a valuable tool during inspections. Photographs of media condition will prove very useful in future inspections, when questions may arise about the extent of changes in the filter bed with the passage of time. A digital camera may be the most useful type to use, as the quality of the photos taken can be ascertained right away, and if a picture does not show what the photographer wanted to depict, another can be taken. Laboratory instruments to be used during the inspection must be checked before the inspection, to verify that they are properly calibrated and will give valid data if used correctly.

Smith, Wilczak and Swigert recommend reviewing the historical data to evaluate past performance of the filters before beginning the inspection. The persons who will be doing the inspection should discuss filter performance with other plant staff. Those who operate the filters regularly may be aware of idiosyncrasies or problems with the filters. (At the McKenzie River Filtration Plant of the Eugene Water & Electric Board, plant operators have been able to tell which filters need to be rebuilt on the basis of continuous turbidimeter data obtained for each filter.) Documents to review include:

- Plant operating records for past year (filtration rate, water production, 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.
- Filter inspection records for last year
- Specifications on filters, from construction or rehabilitation
- Standard Operating Procedures for plant (backwashing filter, placing filter in service, wash water disposal or recycling)

After the documents have been reviewed and the inspection team has picked a date and time for the inspection, personnel at the filtration plant should be notified of this.

A routine filter inspection form developed by the Modesto Irrigation District's treatment plant staff is also provided.

Table 10.1

List of materials and equipment for major filter inspection*

Items	Have
Two, 2-ft x 4-ft sections of 3/4-inch plywood to stand on in filters	
A 4-ft or a 6-ft level	
25-ft tape measure	
Flashlight	
30 feet of heavy string or cord	
Duct tape	
0.5-liter or 0.25-liter wide-mouth plastic bottle	
Cap for 1.5-inch 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 washwater troughs (alternative to lowering bottle to trough by cord)	
Bench-top turbidimeter	
5-ft to 6-ft steel or metal rod for probing gravel (1/4-inch diameter may be preferred for older filter beds of sand only. 3/8 or 1/2-inch 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 inch in diameter)	
10 to 16 bottles, 1000 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-gallon plastic food storage bags for filter media samples, per filter	
Tablespoon	
Four, 100-mL glass or plastic beakers	
Filter media expansion tool	
Ten feet of ¾ inch galvanized pipe to support bed expansion tool	
Twenty-four 12-inch 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.	

*Obtain and assemble these items before beginning filter inspection

Adapted from Smith, Wilczak and Swigert, 1997

Routine Filter Inspection Form

Date _____ **Filter** _____

Use a Separate Sheet to Draw Pictures as necessary

- **DRAW FILTER DOWN ---FIRST VISUAL CHECK**
- Look for cracks in filter bed and check to see if bed has pulled away from walls
- Comments:_____
- As water surface reaches top of media, is media level? Watch for mounding or depression bubbles during d/d_____
- **DURING BACKWASH**
- Watch to see if surface air scour is working properly-how is it distributed
- _____
- Look for boiling of media or dead spots_____
- Watch for uneven flow with a trough having more water or less water than the others
- Comments_____
- **AFTER BACKWASH**
- Check troughs for media_____
- Check media for mounding_____
- Visually inspect media for cleanliness- describe the amount and location of anything on media surface_____
- Use net to collect samples from surface-Mudballs?_____
- 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
- Measure rise rate at 20 MGD backwash water flow=_____MGD observed
- Measure the bed expansion with "pipe organ" device-_____inches
- Record the water temperature=_____
- calculate percent expansion
- p:\wtpstaff\ops\forms\filtdocs\Routine Filter Inspect.doc (developed by Modesto)

Filter Inspection

Filter inspection should be done both before and after filter washing, so operators can see the results of filter washing and observe the extent of cleaning attained by filter washing. At the beginning of the inspection, take the filter out of service. Note the date of the inspection and the number of the filter. Document the length of hours in service, the filtered water turbidity, and head loss. Water usage for filter washing will be important, so note the readings on the wash water meter, the surface wash meter (if there is one), the level of water in the wash water tank. If the plant has a tank for receiving spent wash water, record the level of water in that tank.

Filter inspection programs consists of numerous steps. The suggested interval for a major filter inspection is annually, although some water utilities may need to carry out these procedures twice per year. Recommended frequencies for filter observation and inspection in Table 10.2 are based on BV-TWU experience and survey information submitted by participating water utilities inthis project. On the matter of frequency for inspection of filters and filter appurtenances, "one size does not fit all." An inspection frequency that is adequate for filters that show no signs of problems may be quite inadequate at a different plant where filter maintenance problems chronically occur. The frequency of inspections ought to be tailored to the specific needs of each plant. Recommended steps for a major filter inspection are listed in Table 10.3. A quick filter inspection can be done by two persons in about an hour. A quarterly interval is recommended for the quick inspections. Steps to undertake in a quick inspection are listed in Table 10.4.

A case study of filter rehabilitation work and filter maintenance procedures used at the Elm Fork Water Treatment Plant of Dallas Water Utilities is presented in Chapter 13. The title of the case study is "Filter Inspection and Maintenance at a Lime Softening Plant."

Some of the procedures described in this chapter are invasive procedures, in which plant staff walk on filter media, obtain core samples, or actually dig down into the media by hand or with shovels. These procedures disturb the filter media, and even support gravel, if excavation goes to the filter floor. If a hole larger than a core sample has been made in a filter bed, replace the filter materials after the inspection has concluded. After filter coring has been completed, or the hole created during the excavation has been refilled, conduct an extended backwash to clean the media and give it the opportunity to restratify (if originally stratified) and return to a normal condition, before the filter is placed into service. One utility reported that invasive inspections disrupted their filters, so that several runs were required before a filter subjected to invasive inspection procedures would display optimum

performance. Another utility expressed concerns about possible deterioration of water quality being caused by inspections, especially by excavation of the bed. Filter bed disruptions do occur when invasive inspections are carried out, but inspection is necessary. Operators must be sure to adequately backwash and prepare an inspected filter for service again after the inspection has been completed.

After completion of any filter inspection, store the records of the inspection, using a good filing system so the records can be retrieved in the future and comparisons of filter condition over time can be made. Without records of the past condition of a filter, interpreting the findings from a filter inspection can be very difficult. Long-term, gradual trends or changes in filter condition are unlikely to be detected unless inspections are made periodically and accurate, detailed records are kept. Keeping records of inspections is important even at a plant where staff turnover is minimal. At plants where the operating staff has changed, written records on paper or on a computer are essential for enabling the new staff to compare the past and present condition of a filter.

Details of the inspection procedures listed as bullet items for the major filter inspection and for the quick filter inspection are given in the following portion of this chapter. Note from the bullet lists that some procedures are performed more than once.

Drain filter to media surface and inspect

If the filter is drained slowly, one quick way to determine if the media is level is to stop draining the filter just as the water surface reaches the media. As water seeks its own level, depressions will appear as pools, and mounds will appear as hills or islands protruding above the water level. The depressions and mounds identified in this way should be given careful scrutiny when elevations of the media are determined later. If filter draining is interrupted to check for mounds and depressions, once that task is finished, complete the draining of the filter. Figure 10.1 shows mudballs or lumps on the filter media surface. In Figure 10.2, the surface of a filter, except for a small light-colored area, is covered with mudballs. Mudballs removed from a filter surface (shown in Chapter 6, Figure 6.7) are displayed in Figure 10.3. Figure 10.4 shows a depressed area in a filter bed.

Table 10.2

Recommended frequency for observing and inspecting filters

Recommended Frequency	Task
Daily	Observe at least one filter backwash each day and check flow meter readings;. Over a period of one month be sure to observe 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.
	Check filter before backwashing
Quarterly or seasonally	Check backwash rise rate and filter media expansion
	Conduct backwash turbidity profile
Quarterly, semi-annually, or annually	Drain water to media surface to observe media before backwash
	Check filter media elevations (levels)
	Measure distance between surface wash orifices and media
	Perform flow meter calibration
Annually	Probe gravel elevations (levels)
	Conduct major filter inspection
	Inspect surface wash sweeps and nozzles
	Core media for acid solubility (strongly recommended for lime softening plants)
Annually or once per 2 to 5 years, depending on past experience.	Core media for sieve analysis, and for floc retention analysis
	Core media for acid solubility for coagulation plants)

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.

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 multi-media 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.

(continued)

Table 10.3 (Continued)

Major filter inspection program

- 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.

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.

Check filters visually for cracks, mounds, or mud balls

After the filter is drained for the first time, carefully inspect the media for cracks, holes, mounds, or depressions. Also note whether the media might have separated from the wall. Pay close attention to media at the corners of the filter, where washing may not be as effective. Also look for mudballs on the surface before getting into the filter bed. A closer inspection may be made by getting into the filter box after the backwash is completed and the filter is drained. Stand on the 2-ft x 4-ft (or similar metric-sized) plywood pieces rather than standing on the media directly (Figure 10.5). The plywood will protect the media from the concentrated load that would be caused by standing directly on the media.

Condition of filter box, troughs, piping and valves

After the filter has been drained, the condition of the filter box should be ascertained and documented. Muldowney et al. (1996) presented a comprehensive list of potential problems to watch for when inspecting the physical condition of the facility. Look for cracks, spalling, or other signs of aging concrete, or for rust in steel filter vessels and for failing paint, exposed steel rebars, as well as erosion caused by surface sweeps. Visible piping should be inspected for corrosion and signs of leakage and the condition noted. Filter troughs should be inspected for damage to coating (if applicable), cracks, and the stability and security of their connection to the filter. Check each trough with a level parallel to the trough, in three locations on each side of the trough. Then place the level across the trough in three locations to see if the trough is level in that direction. Place the level between troughs to check for level from trough to trough. For cast-in-place concrete troughs, checking with a level is not necessary on an annual basis but is needed if the area where the plant is located has experienced an earthquake. The annual inspection is a good idea for troughs that were attached to filter walls rather than integrally cast. Checking to be sure a trough is level is shown in Figure 10.6.

An alternative way to learn if troughs are level is to fill the filter box as in backwashing, but use a very slow rise rate and watch to see if the water surface (which is level for nearly still water) reaches the crests of all troughs at the same time. If a trough has water flowing over one end but not the other, or if some troughs are overflowing but one is not, this would indicate problems in trough elevation.

Measure elevation of media in bed at rest

The elevation of the filter media should be recorded during each major inspection, as these records will show the extent to which media have been lost in the time between inspections. One method is to measure the freeboard, that is, the distance between the top of the filter media and the top of the filter box. This can be done by measuring around the perimeter of the filter, using the 25-foot tape. Another way to determine the media elevation is to use the wash water troughs as reference points after they have been determined to be level. Take an elevation measurement on each side of the trough, every 5 feet (1.5 m). This work is shown in Figure 10.7. For a small filter, make six measurements per trough (three on each side). In addition to those measurements, document the elevation of mounds or depressions that were noted earlier as the water drained out of the filter box. At plants where a surveyor's level or transit and level rod are available and are used to check the elevation of the filter media, use of surveyor's tools will provide more accurate readings than using the troughs as a reference elevation. When a surveyor's level and level rod are used, elevation readings are obtained in a grid pattern throughout the filter bed to facilitate mapping the media surface later.

The design of the measuring device used should be documented so it can be reproduced if lost or damaged. One utility reported that their measuring device for determining media profiles was damaged in storage, and a new measuring tool appeared to show media gains because it had not been fabricated to be identical to the old tool.

Document the location of each site and keep records of those locations for future reference. This facilitates development of media contours and enables the staff to check the same locations in the future. If data collected over a period of months or years show that filter media elevations are dropping, this indicates media loss. Media loss can happen through excessively vigorous backwash that washes media out of the bed. Media loss also can occur if the filter material breaks up during backwash, and the smaller grains resulting from media disintegration are washed out at backwash rates that would be appropriate for properly-sized media. A rise in the media surface may be caused by accumulation of precipitates on the surface of the granular material in the filter bed. At lime softening plants this is not uncommon. Even at plants that practice coagulation but not softening, the gradual accumulation of precipitated materials sometimes can cause media grains to increase in size, and this may result in an apparent increase in the depth of the filter bed. When media grains increase in size, chemical treatment, as described later in this chapter, may be needed.

At one participating water utility careful surveys of media elevation are carried out periodically. Survey results revealed a ¾ inch (2 cm) decrease in the average elevation of media in one filter in a seven-month period. Surveys of media elevation at this filtration plant also indicated that the procedure used to refill filters after backwashing was causing some redistribution of the media, resulting in media surfaces that were not level. The refilling procedures were changed and the media distribution problem was solved, with the media elevations varying by less than an inch across the filter surface. This experience indicates that if problems with media loss or uneven (non-level)_distribution of media are occurring, three months or six months may be an appropriate interval between media elevation studies.

Another way to learn if media loss occurs during backwash is to have a small basin through which spent washwater passes, with the basin designed to trap rapidly setting solids such as filter media. Periodic inspection of the media trap would reveal if filter media had accumulated, but this would not indicate which filter was losing media.

Case studies on the efforts of participating water utilities to document the profiles of filter media and support gravel are presented in "Determining Profiles and Contours of Filter Media and Support Materials in Filter Beds" in Chapter 13.

Probe support gravel

If the media has support gravel, perform this step. If not, go on to the next step in the inspection. Smith, Wilczak and Swigert recommend the following:

- Ascertain and record the location of a place to be probed within the filter bed and the elevation of the media surface at that spot. This will be used as a benchmark for the gravel depth. Pick a place where the media is level and not mounded or depressed, for use as the benchmark location. As with measuring elevation of the media surface, note and record the location of each gravel probing site. A contour map of the gravel surface can be prepared using these data.
- Using short, repeated downward strokes to gradually penetrate the media, insert a metal rod to probe for the gravel at this location. As the probe is forced into the filter media, listen to the sound it makes. Pay close attention for a change of sound that indicates passing from the media to the gravel layer. After the gravel layer is reached, mark the probe with a permanent marker at the top of the filter media. This depth of media will be used as the benchmark

depth and is recorded in the inspection report. Do not probe into the gravel. If the filter media consist of sand only, use of a 1/4 inch (6 mm) rod may be appropriate, as penetration of sand media can be difficult for a 3/8 or ½ (10 or 13 mm) inch diameter rod. Rods used for probing can be produced in the shop at the water utility. Use a smooth metal rod with a flat end, and grind or file a notch at every inch. Paint all notches with a bright-colored paint that will easily be seen, and at 1-foot intervals use a contrasting color so the depth of penetration can be read more easily.

- Dig a hole in the media, down to the gravel at the benchmark location. This confirms the accuracy, or lack of accuracy, of the probing technique. If the depth to gravel as determined by probing is more than an inch off the depth as measured by digging, try again in another location. The technique for digging into the media is described in more detail in the following section, *Mudball, media interface, and media depth inspections.*
- The probe is used at each location where a measurement was made from the top of the filter box or the top of the trough, or at each location where an elevation was determined by surveying tools.
- After half of the filter is probed, repeat steps 2) and 3) to confirm the accuracy of the probing technique, but do not create a new benchmark this time.
- Adjust for variations in the elevation of the media to determine the total media depth and the variation in the top of the gravel layer. Graphing these variations can be helpful to producing a visual picture of the gravel. The techniques for graphing the media surface or the top of the gravel layer are the same as those used in preparing topographic maps after a land survey has been completed. Details in how to do this can be found in elementary surveying texts.

Figure 10.8 shows an operator probing gravel. Figure 10.9 shows gravel-probing tools that have been marked to show the depth of penetration.

If plant staff have difficulty locating the gravel surface with a probing rod, another technique used by the San Francisco Public Utilities Commission may be helpful. San Francisco uses a graduated steel rod with a 6-inch square plate fastened at the end of the rod, perpendicular to the rod. When a filter is being washed using a low rise rate to attain minimum fluidization, the rod is placed into the filter. The rod passes through the fluidized bed and the plate comes to rest on the surface of the support gravel, which is not fluidized. This technique has been found to provide a good approximation of the gravel

bed surface as compared to an actual field survey that was conducted during a filter media replacement project.

Alternative procedures for determining the elevation or profile of support gravel and of filter media include using the washwater troughs as references for elevation, after they have been checked and are known to be level along the length of each trough top, and all troughs are determined to be located at the same elevation. Another approach to establishing the media elevation or gravel elevation is to use a flat-bottomed probing tool like that used by San Francisco (as described above), and attach the probing tool to a graduated rod. Then obtain readings for filter media with the filter at rest, using a surveyor's transit or level to obtain readings. Obtain readings for support gravel by using the probing tool with the attached graduated rod, and a transit, when the filter media is fluidized so the probe can be inserted to the top of the gravel.

In addition to using a grid pattern to obtain data on the gravel depth at specific locations throughout the filter, probing at the location where backwash water enters the underdrain can give valuable information. If air is unintentionally introduced into backwash water in a filter not designed for air scour, the air is likely to pass from the underdrain into the filter bed at a location close to where the water enters the underdrain. Introduction of air into filters not designed for air scour can disrupt the media and the support gravel. If an episode involving unintentional introduction of air into a filter occurred during backwash but was not observed by operators, probing the gravel could alert plant staff to a potential problem.

Disturbance and displacement of support gravel is a serious problem that can be caused by physical problems in the underdrain or by use of improper backwashing procedures. The latter include unintended introduction of air into the backwash water and starting the flow of backwash water at an excessively high rate. When mounding or depressions are found in support gravel, a follow-up inspection using the filter excavation box is necessary. Based on the more extensive inspection, a decision can be made on the need to remove media and repair or rehabilitate the filter.

One utility participating in this project reported that variations in gravel depth of greater than 3 inches (8 cm) were considered serious. As gravel layers may vary in depth from plant to plant, the authors suggest that where practical a 30% deviation from design is worthy of filter inspection.

Mudball, media interface, and media depth inspection

Inspections of the filter media for mudballs, location of the media interface for multi-media filters, and confirmation of depth to the support gravel (if present) are carried out by digging into the filter media. This is done after draining the filter but while the filter material is still wet so it does not collapse into the hole during excavation. The benchmark locations used in determining media elevation are used as sites for digging into the media. In this way the accuracy of gravel probing can be confirmed. The AWWA filter surveillance videotape (AWWA 2000) recommends that the media depth as measured by gravel probing should be within 1 inch of the depth found by excavation of the bed at the same location.

When holes are dug into the media for inspection, the procedure recommended by Smith, Wilczak, and Swigert is to dig by hand (see Figure 10.10). This is done while positioned on the 2-ft x 4-ft plywood sheet. The limitation of digging by hand is the depth to which a person can dig, which is determined by the length of his or her outstretched arm and hand. If the filter media is deeper than about thirty inches (0.8 m), some other method will have to be employed for at least part of the media removal. The advantages of digging by hand include the ability to create a smaller hole, the ability to feel what is being removed with greater sensitivity, reduced likelihood of damaging filter nozzles, and perhaps a shorter time needed for digging. Smith, Wilczak, and Swigert recommend shaking a handful of media gently to sift media through the fingers and watch for mudballs. When media is dug out by hand, larger mudballs will be felt as they are excavated, an advantage over using tools for digging. As mudballs are found, their size and depth within the filter bed should be noted. Mudballs should be saved for further investigation in the laboratory, in an attempt to determine the make-up of the mudballs. Those that fizz when soaked in acid contain calcium carbonate, whereas mudballs that disintegrate in an alkaline soak probably contain things like floc, polymer, coagulated color and mud.

In a multi-media filter, as the interface between media layers is encountered, note the depth at which intermixing is first noted, continue digging and note the depth when the lower media layer has little media intermixed from the top layer. This will define the depth of media in which substantial media intermixing has occurred. Digging should continue until all of the media is removed down to the support gravel or the support cap. Then the total depth of the media can be confirmed. Figure 10.11 illustrates probing with a pipe and digging into the media to find mud balls and lumps and to locate the coal-sand interface.

The extent of intermixing will depend on the effective size, the uniformity coefficient, and the specific gravity of each filter medium. Smith, Wilczak and Swigert (1997) indicate that if the depth of intermixed media exceeds 6 inches (15 cm), this may indicate that the last stage of backwashing is not attaining adequate restratification before the media settles down, or the different types of media may not be properly matched with regard to effective size, uniformity coefficient, and density. Generally as the uniformity coefficient increases, the depth of the intermixed layer can be expected to increase.

The media excavated from the hole is placed in a container such as a 5-gallon (19-L) bucket, so the total volume excavated can be estimated. The volume of mudballs found is also estimated by placing them in a beaker or graduated cylinder and gently packing the mudballs together to eliminate large void spaces. Kawamura (2000a) recommended the following guidelines for assessing the condition of the bed, based on the percentage of the volume occupied by mudballs:

- Less than 0.1% by volume, bed is clean
- 0.1 to 0.5% by volume, bed is in good condition
- 1 to 5% by volume, filter bed is in bad condition
- over 5% by volume, the filter media needs to be replaced

(NOTE: Chemical (acid or caustic) cleaning of media may be advisable before making the decision to replace the media.)

Another technique for inspection of filter media is the use of an excavation box in which a worker stands and digs out the media. Use of an excavating box or caisson enables the filter inspector to check a greater volume of filter media and to actually get down to the bottom of the filter media where additional inspection could be accomplished. This box has an open top and open bottom with a tapered edge or chisel-edge. The box is pushed down into the filter like a caisson; then media is dug out and the open box is pushed still deeper into the filter bed. This sequence of pushing down the box and digging out media continues until the bottom of the filter (support gravel or support cap) is reached. Use caution when digging close to filter nozzles with a shovel, as nozzles can be damaged if struck.

A second method of using the inspection box is to place the box into the media while it is fluidized during a backwash. This method does not permit inspectors to view a cross-section of the filter before dirt and floc have been washed out. If the box is placed in a fluidized bed, attach handles or ropes to the box and carefully lower it while the bed is fluidized but with air scour or surface wash <u>not</u>

operating. The box must not be tilted or turned over while it is being lowered into the fluidized bed. Lowering the inspection box into a fluidized bed is likely to require the teamwork of from three to five persons and some very careful manipulation of the box to ensure that it is plumb after placement into the media. When the box is in place, the backwash is ended, the filter is drained, and the box is excavated.

As the box is excavated, media is examined for mudballs. This inspection technique lets the inspector view a larger cross-section of the filter bed than the core sample method or hand excavation of a small hole, but it is quite labor-intensive. At most filter plants it would be used as a follow-up inspection method after earlier examination had revealed filter media problems. Limacher et al. (1999) noted that box excavation is somewhat time-consuming and difficult. They recommended using box excavation at only one or two locations in a filter, noting that it should be reserved for special investigations rather than used on a routine basis.

The excavation box demonstrated at the AWWA Filter Surveillance Workshop in Springfield, Illinois in November 1999, was fabricated from Plexiglas (see Figure 10.12). A stronger material, Lexan, is recommended. The thickness of the walls will depend on the depth to be excavated and the strength of the material being used. Boxes for deeper beds may need to have thicker walls to resist the inward pressure from the filter media as the hole is dug. The dimensions of the filter inspection box, or filter caisson, are 3 feet (1 m) long, 3 feet wide (1 m), and deep enough to reach the bottom of the filter media while leaving a few inches of freeboard on top. The greater ease of working in an inspection box having 9 square feet (1 m^2) of work area ("floor") will probably overcome the cheaper cost of making a smaller inspection box. The clear plastic filter excavation box depicted in Figure 10.12 is shown in Figure 10.13 in place in a filter. Figure 10.14 shows the excavation box built by Grand Rapids. The rectangular shape of this box allows more room for the worker(s) to dig out the media, but the volume of media to be removed is greater with this shape.

Treatment plant staff who plan to build excavation boxes would be wise to try working within a big cardboard box having the same dimensions as the proposed excavation box, to be sure that sufficient working room will be provided by their design. Simply place the box on top of filter media, stand inside, and dig out some of the media while checking for freedom of motion and ease of maneuver with the tool that will be used for media excavation.

Obtain core samples

Core sampling procedures were discussed by Limacher et al. (1999) who recommended collecting samples in 1-inch (2.5 cm) PVC tubes. They also suggested using a 1-meter grid pattern for taking samples, measuring both perpendicular and parallel to the filter wall. Grid locations should be noted, identified, and recorded. They indicated that a coring program of this nature could take about three hours, for two workers, per filter.

Core samples of filter media are obtained so further analysis can be carried out, so it is very important to collect samples that are representative of the entire filter bed and to maintain the integrity of the samples as they are taken. The AWWA filter surveillance videotape (AWWA 2000) recommends that core samples be collected at six different locations within the bed and then combined for analysis. A variety of cylindrical devices can be used as core samplers. The length of a sampler will depend on the depth of the media to be sampled. For most filters in the 24 to 30 inch (0.61 to 0.76 m) depth range, a length of 3 feet (1 m) would be sufficient, but a sampler about 4 to 5 feet (1.2 to 1.5 m) in length would be easier to manipulate. A diameter of 1 to 2 inches (2.5 to 5 cm) is appropriate. Professor John Cleasby of Iowa State University has used metal electrical conduit of 1-inch (2.5-cm) diameter and 5/8-inch 1.6 cm) diameter when media was not retained in a 1-inch (2.5 cm) tube (J. Cleasby, personal communication, March, 2000). Materials of construction could be galvanized pipe, PVC pipe, copper tubing, or electrical conduit. Plastic golf club tubes are an inexpensive alternative. A grain sampler is another device that can be used for obtaining core samples from a filter bed. These are used to sample grain from railroad cars, and to function properly in a granular media filter, a grain sampler probably would need to be used when the filter material was dry.

The interior of smooth-walled pipes or tubes, such as PVC pipe, does not hold a core sample well when the sampling device is removed from the filter. The holding capability of smooth tubes or pipes can be improved by coating the interior wall with a thin film of epoxy or PVC pipe dope and then sprinkling a small amount of fine sand on the pipe or tube wall. After the adhesive material dries, rub off the loosely-held sand before using the coring tool. Galvanized pipe and electrical conduit are somewhat rough and may not need to be roughened to aid in retaining media

When media cores are to be taken successively from greater depths within the filter bed, the coring tool should be marked with lines at 2, 6, 12, 18, 24, 30, and 36 inches (5, 15, 30, 46, 61, 76, and 92 cm) (or deeper, depending on the depth of the media). A permanent ink marker of contrasting color is needed for this task.

A core sampler for taking out a complete core from the top to the bottom of the filter in one sampling can be made by taking one of the above-mentioned tubes, and sawing it in two so it is split into two half-cylinders, up to a point about 6 inches (15 cm) longer than the media depth. Above this point at least 6 inches (15 cm) of intact pipe must remain. Thus to sample a 30 inch (61 cm) filter bed, a cylinder at least 42 inches (110 cm) long would be needed. After the half-cylinder is cut and removed from the tube, it is fastened back in place on one side by using two strips of strong duct tape, placed on one side along to length of the tubing. One strip is placed first and the second is placed over it to act as reinforcing. The duct tape will serve as a hinge later. After the longitudinal hinge of duct tape is placed, duct tape is wrapped around the tubing to hold the cylinder closed. Wrap at the bottom, 1/3 and 2/3 of the length of the half-cylinder, and at the top of the half-cylinder. Again use two layers of duct tape for reinforcing. This taping forms a strong cylinder or tube that can be progressively forced down into the filter media. Figure 10.15 shows a core sampling device, both closed for extracting a sample and opened, as it would be after media collection.

When core samples are removed from a filter, the sampling device is pushed into the media gradually, as the person obtaining the sample moves the top end of the sampling device in a circle of about 6 to 9 inches (15 to 23 cm) in diameter. The rotating action tends to push the media away from the hole and consolidate it. This way, when the sampler is removed from the hole, filter media is less likely to slough off the sides of the hole and fall into it. Using the rotating technique to firm up the hole is particularly important if successive small cores are removed from the media, rather than one long core. When the coring device has been pushed into the media the desired distance, based on the marks on the side of the device, the sample device and the media core are carefully removed. If the media is still damp when cored, it should come out with the coring tool when the tool is removed. The degree of dampness is very important. The damp filter media adhere to the inside of the pipe due to the "stickiness" of damp media. Grains of sand or anthracite or GAC may fall out of the core sampling tube if they are either too wet or too dry. Begin core sampling after the filter is drawn down, and if the moisture content is too high, conduct other inspection tasks and then collect core samples after the media has time to dry somewhat. Figure 10.16 shows an operator taking a core sample. .

After media has been removed it can be examined immediately or placed into plastic bags for future inspection or testing. A sample of media taken from the top of the filter to the bottom of the filter media can be subjected to sieve analysis. Taking a single core through the entire depth of the filter bed

causes the media inside the sampler to be compacted as it is shoved up into the sample tube. Therefore the length of a single media core will be shorter than the depth of the filter bed at rest, uncompacted.

Careful coring technique is important, especially as the bed penetration is nearing completion. If the sampler strikes the filter nozzles, they could be damaged, particularly if the sampler is made of heavy metal pipe. The person taking core samples also has to avoid penetrating the sampler into the coarse sand and support gravel. When a single core sample is taken through the entire depth of the media the sampler must be particularly careful not to penetrate too deeply into the bed because of the greater force required to penetrate the entire depth of filter media at one sampling. Core samples taken before backwashing are used for floc retention analysis. Core samples for sieve analysis, acid solubility, and other measures of media cleanliness need to be collected after a filter is backwashed and drained for a selected time interval.

A case study of how core sampling led to identification of a problem with filter media placement is presented in Chapter 13. This case study is "Coring of Dual Media Leads to Identification of Cause of Media Loss."

Sieve analysis is a complicated and specialized procedure. Unless a water utility has a large laboratory operation, it is not likely to have equipment for sieve analysis and thus would send media samples out to a commercial laboratory for this testing. For dual media or multi-media filters, the testing laboratory will need to separate the different types of media before doing the sieve analysis. To some extent this can be done by carrying out an initial sieving to separate different media types by size.

Observation of Filter Washing

Observation of surface wash

Procedures for observing the surface wash were given at the AWWA Filter Surveillance Workshop. This procedure is adapted from the manual provided at the workshop.

When surface wash is observed, the filter for which this is done should be one that has not been previously disturbed by other inspection procedures. Drain the filter to the customary depth of water over media before surface wash begins. Documentation of surface wash conditions should include the following:

- Describe the type of surface wash system (rotary sweep, fixed grid, or other)
- Distance from top of media before surface washing, to the rotary sweep orifices or fixed nozzle orifices (sweeps can lose their effectiveness if they are too far above the filter bed. Follow manufacturer's recommendation on this.)
- Temperature of wash water
- Flow rate, in gpm, and in gpm/sf
- Water pressure at pipes leading to rotating nozzles or to grid, psi
- Duration of surface wash, minutes

During the surface wash, observe the washing action and assess its effectiveness. Note how well the solids trapped at the top of the filter and in the first few inches of media are broken up. For filters equipped with rotary sweeps, pay close attention to the corners of the filter bed, because filter media in the corners are the farthest from the sprays coming from rotating nozzles and may not be broken up as effectively. It should be recognized that the most effective surface wash action occurs when the backwash upflow expands the top dirty layer so that the surface wash jets are dissipated in the surrounding fluidized filter medium.

Muldowney et al. (1996) provided a list of problems to watch for during surface wash. These included:

- Vibration
- Clogged nozzles
- Leakage or problems with bearing operation
- Unbalanced sweeps, or non-uniform rotation of sweeps

When surface wash equipment is inspected, look for clogged nozzles, as this problem was frequently noted by water utilities participating inthis project. Muldowney et al. also recommended inspecting coatings for deterioration and noting the condition of nozzle caps. A surface wash sweep with a clogged nozzle was depicted in Figure 6.4 in Chapter 6.

Observation of air scour

When air scour is observed, the filter for which this is done should be one that has not been previously disturbed by other inspection procedures. Drain the filter to the customary depth of water over media before the air scour begins. Documentation of air scour conditions should include the following:

- Describe the type of air scour system (air added through underdrain tiles and media support, air added through plenum and filter nozzles, fixed grid at bottom of filter media, or other)
- Depth of water over the filter media when the air scour is started
- Air flow rate, in scfm/sf
- Duration of air scour, minutes
- If backwash water flow is used during air scour, flow rate, in gpm, and in gpm/sf; and the time for water to rise to the top of the washwater trough
- Temperature of backwash water
- Duration of each step in the sequence including the time of the start and stop of air scour and time when water backwash begins and times when water backwash rate is changed

During the air scour, observe the pattern of air bubbling, watching for areas of excessive agitation or minimal agitation. Air scour with uneven distribution in a filter is shown in Figure 10.17, while Figure 10.18 shows an even distribution of air.

Observation of backwash

During filter washing, observe the backwash, look for "boiling" or uneven water flow or unwanted air in washwater. Look for "dead spots where backwashing seems to be ineffective and where longer times are needed for wash water to clean up. Corners of the filter bed are susceptible to problems of this nature. For a filter inspection, document the following:

- Depth of water over media at beginning of backwash
- Temperature of wash water
- Flow rate, in gpm, and in gpm/sf for each step of the backwash

- Duration of backwash, minutes for each step of the backwash

Measurement of filter media expansion

Backwashing removes dirt from filter beds by carrying it up and over the washwater troughs. If filter washing were focused mainly on washing the dirt out of the bed, an operator might use a backwash rate that was excessive and wash media out of the bed. On the other hand, a concern for avoiding water wastage during backwashing could lead to use of an insufficient backwash rate. Measuring the filter media expansion during backwash can take the guesswork out of setting the backwash rate by providing information on the actual extent of media expansion when the media is backwashed. At water utilities where source water temperature changes more than about 18 to 20 °F or about 10 °C over the seasons, filter media expansion should be measured four times per year, on a seasonal basis. For beds washed with full fluidization of the filter media, an expansion of 20% will usually ensure that the bed is fluidized. Measuring filter bed expansion during the backwash period with no auxiliary scour is useful for determining the percentage of expansion attained when the filter bed is being washed clean after the vigorous wash with scour applied. If expansion is insufficient to fluidize the bed during this step, the bed may not restratify properly and dirt may remain in the bed due to inadequate washing action.

Tools for measuring filter bed expansion include the Secchi disk or a similar device and the "pipe organ" sampler, a rack of vertical tubes of various lengths (resembling a set of organ pipes) attached to a long handle.

If a water utility has a Secchi disk for measuring the clarity of a lake or reservoir, this tool could be used to estimate filter bed expansion. The wash water must be fairly clear so the operator can see the disk as it is submerged into the filter in the latter stages of backwash with full expansion of the media. When the filter media is barely visible on the top of the white portion of the Secchi disk, the upper boundary of filter expansion has been determined. Secchi disk measurements should be taken several times and averaged, because the method lacks precision.

The "pipe organ" expansion tool is a device that can be built in a water utility shop by someone with sufficient mechanical talent to work with plastic pipe. The main activities involved are cutting PVC pipe and sheet into specified lengths or shapes and fastening the parts together with PVC cement. Pipe lengths of 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 inches (or 3 to 30 cm in 3 cm increments) are recommended, unless the filter bed expansion might exceed 10 inches (25 cm). After the backwash has ended the longest pipe containing media indicates the height to which media was expanded during

backwash. To be sure that the full range of expansion is observed, pipes longer than the estimated expansion are needed so one or more pipes will have captured no media during the backwashing. In this way the upper limit of expansion can be ascertained. If clear PVC pipe is used rather than opaque pipe, the filter media can be seen in each length of pipe.

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 install the "pipe organ" sampler by placing it on the filter media and securing the tool so it will not move during backwash. Then again backwash the filter without using air scour or surface wash, and after backwash has ended, examine the pipes to see which are full or partly full of media, and which are empty. Figures 10.19 through 10.21 show the "pipe organ" sampler, giving views of the sampler in place before backwashing, the sampler removed after backwashing, and a close-up view of the sampler tubes with anthracite in tubes ranging in height from 2 inches to 10 inches (5 cm to 25 cm). Little or no anthracite was in the 11-inch and 12-inch (28-cm and 30-cm) tubes, so the bed expansion during this wash was 10 inches (25 cm).

Checking rise rates for surface wash and backwash

Rise rates for surface wash and for backwash should be checked quarterly to verify that flow meters are accurate. The procedure for doing this is presented in Chapter12, Quality Control and Instrumentation Issues.

Surface Wash

At filtration plants where surface wash equipment is in use, plant staff need to inspect the nozzles in surface wash systems on a regular basis. Clogging of surface wash nozzles is a common problem, and if some of the nozzles are clogged, the surface wash action may not be as effective as it needs to be. Clogged nozzles must be cleaned or replaced, and records kept of which sweeps and which nozzles had to be replaced. Figure 6.4 in Chapter 6 showed a surface wash sweep with a clogged nozzle.

During a filter inspection, data to be collected include the type of surface wash system, the rate of flow for surface wash, water pressure, and the length of time for the wash. Note whether or not the surface wash is effective in breaking up the floc on top of the media. When the filter inspectors are in

the filter box, the distance between the top of the filter media and the surface wash orifices should be measured and recorded.

Procedures for Evaluating Effectiveness of Filter Washing

A question frequently asked by water plant operators is, "How do I know when a filter has been backwashed sufficiently?" Procedures for making this evaluation can be carried out before or during a filter inspection, and they are described in this section. These procedures are analysis of backwash water turbidity, and evaluation of floc retention in a filter.

Analysis of backwash turbidity

The backwash turbidity analysis is intended for use on a filter that has not undergone a major disturbance, such as use of a filter excavation box to inspect media. Taking core samples and performing the hand excavation of media while working on plywood boards in the filter bed is not likely to disturb the media so much that this test can not be used afterwards. Analysis of backwash water turbidity is carried out by collecting samples of backwash water at 30-second intervals, beginning with the first wash water to come over the trough, and collecting samples each 30 seconds thereafter until the backwash is ended. Samples are taken from the wash water trough. They can be collected using a plastic 0.5-liter or 0.25-liter bottle attached to a handle sufficiently long to reach from the operating floor to the trough. If this is awkward, or if the distance is too great, samples can be collected by lowering a weighted bottle into the trough. The weight to use is the 1 1/2-inch galvanized pipe cap listed in Table 8-1 (or some similarly-sized heavy object), and it is fastened to the sampling bottle using a liberal amount of duct tape. As samples are obtained, they are emptied into pre-marked 125-mL plastic, screw cap sample bottles (the type used for bacteriological samples) and capped. Two persons are needed to do this task, with one person collecting the samples at the specified time, and the other keeping time and saying when to sample, as well as handing the proper empty sample bottle to the sample collector at each 30-second interval.

As soon as the backwash is over, the samples are analyzed for turbidity. A graph of turbidity versus time is prepared, with time on the X-axis and turbidity on the Y-axis. In a typical backwash cycle not preceded by air scour, the turbidity of the first water coming over the trough should be low, as it is pretreated water. Turbidity rises rapidly during a backwash, peaks, and then declines. The latter stages

of backwashing may show a very gradual decline in turbidity. The turbidity versus time graph can be studied to learn how much time is required to wash away nearly all of the dirt released from the filter media by the scouring action during backwash.

As discussed earlier in Chapter 6, Kawamura (2000) recommended that filter beds should be washed until the spent washwater turbidity was between 10 and 15 ntu. Cleasby and Logsdon (1999) recommended washing the filter until the turbidity of the spent washwater was 10 ntu. Some utilities do not operate to a turbidity level this stringent, whereas others wash filters until spent washwater turbidity is lower than 10 ntu.

Floc retention analysis

The floc retention test was developed (Kawamura 2000) to show how much floc and particulate material is trapped within a filter bed during a filter run, to indicate which part of the filter bed is trapping and storing floc, and to show how much remains after backwashing. From this information, plant staff can form a judgment about the adequacy of filter washing. This test is used to evaluate filter media collected at different depths within the filter bed, so core samples must be taken from the same hole at successive depths, beginning with a sample in the 0 to 2 inch (0 to 5 cm) depth. Kawamura recommended selecting three representative locations within each filter for this analysis.

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 still wet and will adhere to the coring tool. Prepare a minimum of six sample bags for each coring point. Plastic Zip-lock bags will work well.
2) Place two pieces of 2-ft x 4-ft plywood having a thickness of 3/4 inch at the coring location to minimize media disturbance by the filter inspector.
3) Collect core samples at depths of 0 to 2 inches; 2 to 6 inches; 6 to 12 inches; 12 to 18 inches; 18 to 24 inches; 24 to 30 inches; and 30 to 36 inches (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 deeper filter beds, continue collecting core samples at 6-inch (15-cm) increments until the bottom of the filter is reached. Place each core sample into a separate bag marked to indicate the depth from which it was withdrawn.
4) When the core sampling is completed, backwash the filter

5) After the backwash is over, drain the filter completely and repeat steps 2 and 3.

6) From each sample bag, prepare a 50 mL sample from each sample bag 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.

7) Repeat the procedure in step 6 four more times, until a turbid water volume of 500 mL has been collected in the beaker.

8) 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 perform step 8 three times as a check on the quality of this measurement.

9) 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.

In the above procedure, similar-sized materials produced to metric dimensions may be used.

Data obtained by using Kawamura's method can be used in two ways. 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 will indicate the relative amounts of material being removed at different depths within the filter bed. The turbidity data from samples obtained after the filter has been backwashed are again graphed, as described above. The cleanliness of the bed can be estimated on the basis of the turbidity remaining on the core samples after backwashing. Kawamura suggested the following criteria for evaluating the cleanliness of a filter after it has been backwashed:

- 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

Figure 10.22 depicts a plot of hypothetical floc retention data for a filter before and after backwash. Typically before a filter is backwashed, the upper portion of the filter bed contains a large amount of floc, whereas the lower part of the bed has moderate to small quantities of floc. Backwashing removes much of the floc stored in a filter bed, but some does remain, as indicated in the figure. Some deposits remain on the media after backwashing. The results of the floc retention test can be interpreted with the aid of Kawamura's recommendations that were given above.

Acid Solubility

The procedure for the acid solubility test is described in the AWWA Standard for Filtering Material, ANSI/AWWA B100-96 (AWWA 1996). Clean filter media can be tested for acid solubility to measure the extent to which the filtering material has been coated with acid-soluble materials. At lime softening plants, the coating will be calcium carbonate. Growth of calcium carbonate on filter media is a symptom of inadequate recarbonation and instability (with respect to calcium carbonate saturation) in the softened water. Results of the acid solubility test can give a long-term indication of how well recarbonation is working. At coagulation plants, acid solubility testing can be used to measure the accumulation of some types of particulate material on filter media. Iron precipitates and iron floc, manganese precipitates, and alum floc can be dissolved in hydrochloric acid.

Tools and Instruments to Inspect or Evaluate Media

Endoscopic examination, coupled with high-speed videotape recording, has been used by Ives and Fitzpatrick at University College London to provide detailed observations of the behavior of deposits and media grains in laboratory scale filters during filtration and backwashing. There has been no suggestion from these authors that this could become a tool for filter O&M at full scale. The depth of field of the endoscope is limited to a few grains from the end of the endoscope. The location to be studied can be anywhere, subject to the position of the endoscope and its length.

An endoscope was adapted for use as a filter inspection tool by the water treatment plant staff at Fort Collins, Colorado. The following description of use of the Fort Collins "Borescope" is based on material presented at an AWWA meeting in Austin, Texas on September 21, 1998 (Smith, Gross, and Gertig 1998, unpublished).

Endoscopes have been used for inspections in various situations, and one had been used for filter observation at a research scale. Fort Collins purchased a rigid instrument rather than a flexible one because of the lower price. Flexible endoscopes, as used in medicine, transmit the view to the eye or camera using optical fibers. These must be set in a matrix to maintain the optical integrity of the picture, and clarity is lost. In addition to being used to examine filters, the endoscope would be useful for other applications in the plant. At Fort Collins the filter inspection plan is worked out in advance. On the day of inspection the filter is taken out of service. Each operator wears a harness and hard hat and is tied off for safety purposes. A communication plan is worked out. The filter is backwashed to expand the media, and clear plastic inspection tubes with closed bottoms are inserted at locations to be inspected. After the tubes are inserted, the filter is drained to just below the surface of the media. The inspection tubes must be full of tap water to prevent condensation. The Borescope is inserted into the inspection tube stopping above the media surface. Operators coordinate lowering the Borescope very slowly and recording data while observing the media picture on a TV monitor located on the filter operating floor. By noting the depth and coordinating that with observations made within the bed, operators can locate mudballs, the media interface, and could also learn of the condition of the topmost layer of support gravel. Figures 10.22 through 10.24 show the Borescope, monitor and the insertion tubes. Figure 10.25 is a view of filter media as observed by the Borescope.

In addition to direct in-line borescopes, others have been manufactured with lateral (90° and 45°) viewing, and with rotatable heads to scan the surface of a filter bed, for example.

Using the Data from a Major Inspection

Carrying out the procedures included in a major filter inspection will provide a treasure trove of information, but the inspection can require 16 person hours of labor, or perhaps more, per filter. This substantial investment in filter surveillance is an important component of a comprehensive filter performance optimization program, but the maximum value of filter surveillance can not be attained unless the results are saved for future reference. When results of past filter inspections are compared to the results obtained most recently, the treatment plant staff can look for long-term trends that might not be obvious in only one or two years. Saving the information collected during a major filter inspection is essential for continued long-term excellence in operation. The written records, neatly recorded and properly organized and filed, will serve as a valuable source of information for many years to come. They are as important as the as-built drawings and specifications related to filter construction. After the

major inspection of each filter is completed, make sure that the results are documented in a way that can be understood by persons who were not a part of the inspection effort; that is, provide documentation that is clearly presented and stands alone without need for someone to interpret or explain the procedures and results to others who may want to review and use the information.

CHECKING MEDIA SUPPORT AND UNDERDRAIN INTEGRITY

The integrity of filter nozzles (if used) and the filter floor or support gravel must be maintained for a filter to perform as intended. Integrity of a filter floor and nozzles or of support gravel can be judged in a number of ways. Checking for the gravel profile was described earlier in this chapter. This section deals with the filter floor and nozzles. Examples of underdrain failures and support gravel problems are shown in Figures 10.26 through 10.30. Figure 10.26 documents an upset Wheeler bottom with some balls missing. Figure 10.27 shows support gravel migration. In Figure 10.28 sand has leaked into the underdrain. Underdrain failures are shown in Figures 10.29, 10.30, and 10.31.

Air Scour Patterns

Air scour uniformity is best observed before any media are installed in the filter during the construction phase. However, even after media installation, the pattern of bubbles can be observed when air scour is active. If an area of very large bubbles is seen, not typical of the rest of the bubbles in the filter, this would be a reason for further investigation. An appropriate follow-up would be filter media excavation in the area where a problem was suspected. A vigorous air scour was shown in Figure 10.17.

Patterns of Water during Washing

During a period of water-only backwash, boiling areas may indicate disrupted support gravel, broken nozzles, or other underdrain problems. The boiling area is a sign of excessive water flow in a localized area causing an upwelling of the surface of the media higher than the surrounding fluidized media. Again, if this is seen, a localized filter bed excavation would be appropriate.

Dead spots in corners or elsewhere may show where media is plugged and not fluidizing. Like boils, the dead spots can signal the need for further inspection or maintenance procedures. If media is plugged in a coagulation plant, mudballs that have sunk down into the filter to the support gravel or to

the interface in dual media filters may be the cause. Filter forking or use of a hydropneumatic wand may be called for. These procedures are described later in this chapter.

Media Accumulations in Plenum under Filter Floor

Provision should be made to inspect the filter underdrains or plenum to look for signs of media penetration of the underdrain that could have a deleterious effect on filter backwash flow rates and distribution. Unfortunately, many existing smaller filters have no provision for inspection of the underdrain for media penetration. Accumulation of media beneath the underdrain system is a sign of serious problems with the filter. An example of sand in a center manifold of an underdrain is shown in Figure 10.28. Some European filter designs enable endoscopic examination of the underside of the filter floor and filtered water plenum.

Concerns with Duplex Filters

Some filters are built as two halves in one box. These are referred to as duplex or bifurcated filters. This design feature provides economies in construction as a common inlet and outlet channel can be provided for two filter halves, each of comparable surface area as a conventional filter, say 600 to 800 ft^2 (56 to 74 m^2). In some designs each half can be backwashed separately, reducing the backwash flow rate required and therefore pipework and pump sizes. Each half has its own effluent pipework and can be sampled independently, although balanced flows from each half may be coupled up to one turbidimeter.

It is an arguable point whether a duplex filter actually consists of two filters, and each half should be independently checked for filtrate quality, media depth and condition. If one half has become blocked then the majority of the flow may be passing through the other filter half, with no direct way of measuring this through head loss or flow measurement. Special care is needed in the operation and maintenance of duplex filters and in interpretation of operational data.

TROUBLE SHOOTING AND MAINTENANCE: NON-ROUTINE PROCEDURES

During the development of this manual, information on non-routine maintenance procedures was found in the literature and reported by water utilities. Table 10.5 contains a summary of these procedures and their objectives.

Table 10.5

Non-routine filter maintenance procedures

Procedure, device, or tool	Objective
Garden rake	Break up media during backwash, also remove mudballs
Mudball Nnet	Remove mudballs from fluidized bed
Forking media	Break up large mudballs using a modified pitchfork
High-pressure wash	Break up mudballs on surface. Can be a substitute for surface wash at plants lacking this auxiliary scour capability.
Hydropneumatic wand	Breaks up mudballs with air agitation and water jet
Pulsating sprinkler on surface wash piping	Clean filter walls during surface wash
Acid treatment of media	Clean media, remove calcium carbonate deposits
Caustic treatment of media	Clean media, remove mud and coagulant chemical deposits

Dealing with Mudballs

Mudballs must be removed from filter media if they form and grow. A quick inspection of the filter surface before and after washing can help early detection efforts. Mudball growth can lead to more serious problems if it is not detected early and dealt with. Mudballs may be noticed when they grow to the size of peas, and they can grow as large as 1 to 2 inches (2.5 to 5 cm), or bigger. If mudballs sink beneath the surface, they may accumulate at places in the filter bed where the backwashing action and auxiliary scour are not adequate. If this happens, the flow of water may be decreased in the area of mudball accumulation, causing higher rates elsewhere in the filter bed. Elimination of mudballs from filter beds is a recommended preventive maintenance activity. Treatment plant operators have developed a number of ways to accomplish this task. Some of these are described in this section.

Garden Rake for Small Filters

Staff of the Pennsylvania Department of Environmental Protection's Safe Drinking Water Program recommends use of a common garden rake (of the type with stiff prongs) for mudball control occasionally during filter backwash. Filter raking is an appropriate practice for smaller water systems

where the filter bed is small enough to be reached with a rake. Raking helps remove and breakup mudballs and is especially helpful when the wash rate is not sufficient (due to low pump capacity or poor underdrains) to expand the media. Also, if a poor sedimentation process tends to overload the filters, raking can help keep the filters clean.

This procedure is applicable to smaller filter beds where the middle of the bed can be reached with a tool as long as a garden rake, either as purchased or with an extended handle. An operator standing on the filter wall can reach into the media with the rake, and dip it into corners and along the wall to loosen media not reached very effectively by rotary sweeps. The sweeps must be turned off when this is done to avoid catching the rake by a rotating sweep. This raking is done at the beginning of a backwash. An example of this practice is depicted in Figure 10.32.

This is not a practice that is completed during every backwash, but operators use this bed cleaning technique about once per week to once per month. Even if surface washers are available, some operators may quickly dip the rake several times throughout the filter in the first five minutes of the wash and then allow sufficient time for the dirt to purge to waste and the media to restabilize. Operators do not rake when the surface washers are "on".

Raking becomes a potential safety issue because to rake a filter the operator needs to walk along the wall overtop the filters and bend over while dipping and pulling the rake. The top of the walls could be slippery if it is wet. Some filters have "cross-walks" overtop them to facilitate easy access to the middle of the filters. Do not engage in any unsafe practices while cleaning filters by this method.

Mudball Net

The Clackamas River Water District uses a ½ inch (1 cm) mesh screen having dimensions of 11 inches x 21 inches (28 cm x 53 cm) mounted on a pole, sweeping through the media during backwashing to check for mudballs. The device can be thought of as a type of landing net, with the quarry being mudballs rather than fish. The mesh size is sufficiently large to permit passing the mudball net through the media when it is fluidized but sufficiently small to catch small mudballs before they become large enough to cause problems. The mudball net is shown in Figure 10.33.

"Forking" Media

Filter media "forking" is a procedure used to deal with mudballs at the filtration plants of Colorado Springs Utilities. The "fork" is a tool that resembles a pitchfork with flatter, wider, and less pointed tines. In Figure 10.34 an operator is holding a filter fork, and Figure 10.35 shows a close-up view of the fork. The length of the forks is determined by the depth of the media. The length of the handle is determined by the distance from the top of the media to the top of the wash water troughs plus the length of the handle needed for the person using the tool. Forking a filter begins with a clean filter that has been backwashed. For a work platform, 2 x 12 boards are placed over two adjacent wash water troughs. A backwash rise rate about 40% to 50% of the normal rate is used, and the forking process then is used to search for mudballs. As the fork is moved through the bed, above-normal resistance to moving the fork is a sign of presence of mudballs. In an area where mudballs are encountered, repeated forking motions are used to break apart mudballs. Because of the rising water, a "cloud" of material may be observed after the mudball breaks up. This procedure is done about once per year at Colorado Springs

During the forking procedure, when mudballs are encountered their location is noted and recorded. A log of mudballs is kept for future reference. The benefit of doing this is preservation of information on mudballs, a troublesome aspect of filters. If records show a persistent formation of mudballs in a particular area of a filter bed, a complete inspection of that filter may be indicated. Without written records, the utility would have to rely on the memory of plant operators, and institutional memory can disappear with the retirement or departure of employees.

High-Pressure Wash

Some utilities use a high-pressure hose, such as a fire hose, to apply a vigorous surface spray to filter media. Operators at the East Bay Municipal Utility District use a 2-inch (5-cm) fire hose that is reduced to a 1-inch (2.5-cm) nozzle. Water pressure on the hose is 80 to 90 psi (550 to 620 kPa). Operators take about an hour to hose a 1000 square foot (93 m^2) filter. Before hosing, the water level is reduced to one or two inches. Water is sprayed on the media surface to break up or inhibit mudballs. Figure 10.36 shows a filter being hosed. From the figure it is apparent that hosing can clean or agitate a limited area of filter surface at a given time; however, hosing does apply a very vigorous scouring action in the limited area where the water jet is directed.

High-pressure washing may be done particularly at filter plants lacking surface wash and air scour. If no auxiliary scour facilities are provided, use of a periodic high pressure spray may help to prevent some mudball formation, although this technique would not reach mudballs that have sunk deep within the media.

Hydropneumatic Wand

A device called a *Hydropneumatic Wand* or "Thing-a-ma-bob" was used at Fort Collins to deal with mudball formation (King and Skold 1997) before filters were rebuilt to include air scour. In their *Opflow* article, these authors described the construction and use of a device to scour filter media with a combination of air and water. The *Hydropneumatic Wand* used 1-inch (2.5-cm) pipe to deliver the air and water into the media. An air supply of 3 to 5 cfm (85 to 140 L/min) at 80 psi (550 kPa) and a water supply of about 15 to 20 gpm (57 to 76 L/min) at 80 psi 550 kPa) were used to agitate media in the filter bed. The jetting action of the device was observed in a clear-walled pilot filter during development. The shape of the tool facilitated its use near filter walls and in the corners of filter boxes. Figures 10.37 and 10.38 show a *Hydropneumatic Wand*

The *Hydropneumatic Wand* was used each month to combat mudball formation. Benefits included a reduction of mudballs and better cleaning of places in the filter bed where the surface wash and regular backwash did not clean sufficiently. This tool can be used whenever a plant has backwash problems or if operators want to see if there is more "dirt" in the filter bed after a cleaning, or to dislodge an accumulation of dirt after some sort of plant upset. It is also helpful for breaking up filter aid accumulations. In general, this tool could be used to deal with localized filter problems that do not respond to ordinary cleaning attained by surface wash and fluidized backwash, if those problems are not caused by calcium carbonate precipitation and cementation.

Keeping Filter Vessels Clean

Keeping filter vessels free from scum and unsightly deposits can be a problem at some treatment plants. At Grand Rapids, operators have fastened pulsating sprinkler heads of the "Rainbird" type to the top of surface wash pipes. When surface wash is operated these sprinklers spray the filter walls to aid in cleaning them. One of these sprinklers is shown in Figure 10.39.

Algal accumulation in filter vessels can lead to several problems. Problems caused by algae were discussed in Chapter 4. Filamentous algae can interfere with the function of capacitance level probes. Algal filaments on walls and launders can trap mud and media, preventing media displaced by air scour from falling back into the filter bed. Filaments can break off and form filament / mudball mixtures in the filter that are hard to break up with backwashing. Algae growth looks unsightly and may give visitors a poor impression of the care and quality of operations at their local water supplier.

Algae can be hard to remove. High pressure washing can be used or manual scraping of walls. Care should be taken to ensure the cleaning process doesn't knock mudballs down into the filter. If manual cleaning is employed use boards or plastic sheets to walk on and catch the debris. Filamentous algae will dry out if the filter is left dry over summer, although if water demand is high in summer (a typical situation in the United States) this may not be feasible. It may be easier to peel off walls when dry and presents less of a weight and volume for disposal.

Covering the filter is a possible solution for this problem. One plant engineer warned against simple covers for filters as they restricted access to the filter and made routine inspection very difficult. These covers had originally been placed as midge fly (chironomid) eggs were laid in the filters and the flies were a nuisance to neighboring residents. A proper building was preferred by this engineer.

At one participating water utility maintenance of filter walls used to be done by painting the concrete, usually once per year, with a mixture of lime and copper sulfate. This gave the walls a pleasant pale blue appearance and inhibited attachment of algae.

Chemical Treatment of Media

Backwashing is commonly used to remove deposits of materials from filter beds, but sometimes the materials are bonded to the filter media so strongly that backwashing is not adequate to clean the media. In this kind of situation, chemical cleaning of filter media may be needed. Chemical cleaning is more likely to be a concern at a lime softening plant than at a plant that practices chemical coagulation. Treatment employed in softening plants may result in softened water that is supersaturated with calcium carbonate. If this is not corrected by recarbonation or by liquid acid addition, some of the excess calcium carbonate might precipitate in the filter media. When this has happened to a filter, acid cleaning can restore the condition of the filter media to like new. Four examples of mounded filter medium and cemented lumps of various filter media are shown in Figures 10.40 through 10.43. The figures illustrate

some of the problems that can occur at lime softening plants and underscore the importance of careful control of lime softening chemistry and the need for periodic examination of filter beds at these plants.

The need for chemical cleaning of media can be assessed by reviewing data from annual filter inspections and comparing results with benchmark values. A sieve analysis of media will provide data on the effective size and uniformity coefficient of the media. Media may vary by +/- 10% from a specified size, as delivered originally. Thus an effective size of 1.0 mm would have an acceptable size range of 0.9 mm to 1.1 mm. A 20% increase from the specified size of 1.0 mm or a 10% increase over the upper limit of the effective size is probably a good indication of the need for acid cleaning. In addition, ANSI/AWWA B100 specifies that the acid solubility for filter media should not exceed 5%. If acid solubility increases substantially, this can be attributed to the growth of a calcium carbonate layer around a filter material grain. If the filter material originally met the AWWA standard for acid solubility, an increase in acid solubility to about 30% would signal the need for a sieve analysis to check for media growth and possible need for acid cleaning.

Testing for chemical cleaning is done first on small samples of filter media, so estimates of the amount of cleaning chemicals can be made and the chemicals can be purchased. Before any testing is done, one or more core samples of the media are obtained for evaluation. Take the core all the way from the surface to the bottom of the media, to avoid underestimating the amount of chemical needed for the job.

Chemicals used for cleaning filter media are likely to require careful handling to avoid hazards to workers. Be sure to obtain Material Safety Data Sheets and follow all safety precautions contained on the sheets.

When any chemical cleaning of filter media is carried out, disposal of the neutralized acid, alkaline soaking water, or any other diluted chemical, and disposal of dirty wash water has to be planned for. The wastewater generated by media cleaning must not be recycled back to the head of the plant. Disposal to a sewer may be the best option. Techniques used for disposal of residuals such as liquid from a centrifuge or a belt press, or other highly concentrated liquid wastes may be appropriate for disposal of chemical cleaning wastes. In some instances waste neutralization may be necessary before disposal of the cleaning wastes. Local and state water pollution control regulations should be reviewed before decisions are made on which chemicals to use to clean filter media as the residuals disposal challenge may vary, depending on the chemical used.

A word of caution is appropriate when a filtration plant has been removing manganese. When manganese is present in water applied to a filter bed, maintenance of a chlorine residual going onto the filter has been shown to facilitate manganese removal (Knocke et al. 1990, Knocke et al. 1991). Soluble manganese (Mn^{+2}) is sorbed onto filter media that is coated with solid manganese oxides. Presence of a free chlorine residual oxidizes the sorbed Mn^{+2}, forming more solid manganese oxides and providing for the sorption of more soluble manganese. If all of the manganese oxides are removed from filter media by chemical cleaning, the filter media will not remove manganese until a coating of manganese is restored again.

Before any chemical cleaning procedures are undertaken, take steps to ensure that valves will not allow any cleaning solutions to leak into finished water. Check valve integrity before adding acids, alkalis, or chemical dispersing agents. Procedures to use when testing the functioning of filter valves are described in Chapter 12.

"Chemical Cleaning of Filter Media" is a case study on this topic. It can be found in Chapter 13.

Acid Cleaning

Acid treatment of filter media works because calcium carbonate is soluble in acid. Calcium carbonate can be redissolved by adding enough acid to the filter bed to lower the pH to the point where dissolution occurs. Cleasby and Logsdon (1999) reported that lowering the pH of water in the filter bed to about pH 4 aids in dissolving calcium carbonate precipitates as well as oxides of iron, aluminum, and manganese. One of the key tasks in acid cleaning is to determine how much acid to use, and which acid. After these decisions are made the actual cleaning is done with necessary safety precautions in place.

Presence of calcium carbonate in a filter bed may be indicated by encrustation of filter media with calcium carbonate, or by presence of lumps of media and calcium carbonate. The depth of the filter bed may increase, as the media grows because of encrustation, and this can be a sign of calcium carbonate build-up. The extent of the build-up can be estimated by obtaining one or more core samples, drying and weighing the media, acid washing the media, and drying and weighing it again. The procedures for doing this are described in the acid solubility test in the AWWA Standard for Filtering Material, B100. In the acid solubility test, a sample size larger than the minimum weight may be used, and using the entire media core eliminates the need to split the sample before doing the acid solubility test. After the acid solubility test has been completed, the data can be used to perform calculations for the quantity of acid needed to clean the filter. Chemical requirements are related to the weight of media

in the filter bed, the weight of calcium carbonate removed from the filter media sample, and the weight of the media sample after the calcium carbonate was removed. From these numbers, the weight of calcium carbonate in the filter bed can be estimated, and then the quantity of acid needed. In addition to acid solubility data, measurements of the elevation of the filter media in the bed are needed before the treatment begins so a before-and-after comparison of the media elevation can be carried out.

A second way to estimate the amount of acid required for filter cleaning is to obtain one or more core samples, mix the media thoroughly, and then take known volumes of media and treat each volume with a different quantity of the acid that will be used. The minimum quantity of acid that successfully cleans the known volume media can be used to estimate the amount of acid required for the entire filter bed, based on the ratio of the volume of the entire filter media to the volume of the media cleaned in the test.

Chemicals used to clean filters include 3.0 percent food grade phosphoric acid and NW-310 dispersant cleaner (Arnold and Schneiders, 1999), food grade glacial acetic acid (Mayhugh et al. 1996) and muriatic (hydrochloric) acid (Underwood 1995). Citric acid has been used at the lime softening plant in St. Louis, Missouri (Cleasby and Logsdon 1999).

When acid is used to clean filters, thorough safety precautions are necessary. The most important precaution is that one person must never work alone when cleaning the filter with chemicals. At least one other person must be present. Protective goggles and clothing must be worn by any persons handling acid, to protect against spills, and precautions must be taken with regard to a safe atmosphere. The fizzing action that happens when acid is put on limestone or on filter media with calcium carbonate encrustation is caused by the liberation of carbon dioxide. The amount of carbon dioxide that will be liberated when a filter is acid cleaned is directly proportional to the amount of calcium carbonate that reacts with the acid and can be substantial, as indicated in this example:

- Filter dimensions are 20 ft x 25 feet, with 2 ft depth of sand. (6.1 m x 7.6 m x 0.61 m)
- Filter volume = 1000 cubic ft. (28.4 m^3)
- Using a weight of 100 pounds per cubic foot (1600 kg/m^3) for loose dry sand, the weight of media in the filter would be 100,000 pounds (45,400 kg).
- If acid solubility indicated that 5 percent of the weight of media is calcium carbonate, the dry weight of the bed = 105,260 pounds (47,800 kg) and the weight of calcium carbonate

in the bed = 5260 pounds (2400 kg). The weight of carbon dioxide gas released by the calcium carbonate is 2310 pounds (1050 kg).

If the filter being cleaned is indoors, liberation of carbon dioxide will reduce the concentration of oxygen in the atmosphere in the room where the filter is located. Safety concerns require use of testing equipment to measure the amount of oxygen in the atmosphere as the filter is acidified. Adequate ventilation has to be provided, and extra fans may be needed to ensure adequate turnover of the atmosphere in the room.

After acid is added to a filter, its action will be faster and more effective if the acid is mixed throughout the filter bed. Generally acid is added into supernatant water and then the diluted acid is drawn down into the filter by opening the filter drain valve to cause the desired depth of drawdown. Mayhugh *et al.* reported using air scour to stir the media after acidification. For plants that do not have air scour equipment, it may be helpful to bring in a portable air compressor and use a length of air hose and a long pipe to introduce air into localized spots in the filter bed. The stirring action caused by the rising bubbles would help to mix the acid and water in the filter bed.

When the acid cleaning is completed the filter is thoroughly backwashed, until the pH of the spent wash water is the same as the pH of the wash water entering the filter. After the backwash ends, the elevation of the filter media is again determined, so an estimate of the change in bed depth and the amount of material removed from the bed can be made.

An alternative to acid cleaning is replacing the encrusted media with new media. The cost of this alternative can be compared with the cost of the acid cleaning alternative.

Alkaline Soak

An alkaline soak may be useful for cleaning filter media in some situations. This was done at Berlin, NH during a waterborne disease outbreak in the latter 1970s (Lippy 1978). During this outbreak, eight pressure filters built before World War II were inspected, and three were found to be severely upset. Filters containing only anthracite appeared to be in satisfactory condition, but three rebuilt with graded gravel under anthracite filter material were in bad shape. Figure 10.44 at the end of this chapter is an example of the condition of the media in one filter. The depth of the valleys between peaks in the media in Figure 10.44 was as much as 12 inches (30 cm) (Lippy 1978). The filters contained masses of clumped media that prevented effective backwash. One author of this manual was present in New

Hampshire and examined the media. It was coated with "muck" and was so sticky that a ball of media formed by hand was sufficiently cohesive to stick together on a laboratory countertop. When the media was placed in an alkaline solution in a laboratory beaker by the manual author, the liquid took on the color of strong coffee. Lippy reported that prolonged backwash and raking with garden rakes failed to clean the media satisfactorily. Finally an alkaline soak was tried, with chelated sodium hydroxide (Lippy 1978). About two days were required to treat, flush, and return a single filter to service.

Use of a caustic soak to remove organic deposits and solids resulting from the use of alum was reported by Cleasby and Logsdon (1999). Caustic soda (sodium hydroxide) at a rate of 1 to 3 pounds per square foot (5 to 15 kg/m^2) of filter surface is described. The alkaline soak is done for 1 to 2 days, and then the filter is backwashed thoroughly to remove the alkali and impurities released from the media before it is returned to service.

In addition to using a mudball net, the Clackamas River Water District has used a tri-sodium phosphate soak followed by a sodium bisulfite soak to break up mudballs. Tests were done first in beakers. A 24-hour soak was used for mudballs with diameters generally ranging from ¼ to ½ inch (6mm to 13 mm). More information on chemical treatment of filter media is presented later in this chapter.

The Tuolumne Utilities District (TUD), which has both pressure filters and open, gravity filters, uses a caustic soak to clean media. When a filter is found to have accumulated mud and or mudballs in the upper layers of the bed, this utility has found that using sodium hydroxide can be very effective for cleaning and removing the accumulated mud from the media. In one instance a pressure filter whose media would have otherwise been replaced was in fact "rescued" through the use of a caustic soaking/cleaning process.

Initially, a small amount of the mud-impacted media (approximately 1 cup) was placed in a beaker for a bench evaluation of the effects of the caustic soak. A caustic solution equivalent to a dosage of at least 50 parts per million was added to the beaker, submerging the media. After a 30-minute soaking period, the media sample was rinsed with fresh water. With a successful caustic treatment, the mud dissolved and the liquid solution took on a very dark brown color. It should be noted that the media also contained small mud balls up to ½ inch (about 1 cm) in diameter. These mud balls were completely dissolved and rinsed away.

Following the initial bench analysis, the utility has utilized the caustic in an actual plant environment in two different ways. First, if the process allows for a filter to be taken out of service, the

filter is drained down, and the appropriate amount of caustic is fed into the fill water during the refilling of the filter to achieve the desired 50 ppm dose. Once the filter is filled, it is left to soak overnight. The following day, the filter is backwashed extensively to remove the dissolved mud. This can take quite sometime and use a larger volume of water than a typical backwash, as the dissolved mud is very dirty.

The second method for performing caustic cleaning is to inject the desired dose of caustic into the backwash inlet line and feed the caustic throughout a filter backwash cycle. This method is practiced annually at some plants as a general media maintenance procedure, and maintains the media in very good condition with respect to the accumulation of mud. This method also works well in removing existing mud accumulations, sometimes necessitating lengthier backwash durations or repeated cleanings on successive days to achieve a thorough media cleaning.

Special Techniques for Pressure Filters

Inspection and maintenance of pressure filters are quite difficult, as compared to open, gravity filters. The filter bed is enclosed within a pressure vessel, making observation of backwash nearly impossible. Therefore operators are not able to watch for uneven backwash or to observe surface wash or air scour in action. In fact many pressure filters do not have auxiliary scour systems. Examination of media for cracks, mudballs, or depressed areas can be done, but usually only if the pressure vessel is drained and opened. A diagram of a pressure filter is shown in Figure 10.45. Measuring the media depth in a cylindrical pressure vessel having a vertical axis (like the filter depicted in Figure 10.45) would be made difficult by the lack of a level vessel surface that could be used as a reference point. In the diagram shown, the surface wash arm might be used, but first the operator would have to verify that the arm was level. For a cylindrical pressure vessel having a horizontal axis (like a tin can laid on its side) the top of the pressure vessel could be used for reference for media depth measurements in the center of the filter bed, along the vessel's axis. This technique would use the top of the cylinder as the reference point, all along the length of the cylinder. Difficulties associated with operation of pressure filters were discussed by Cleasby and Logsdon (1999). A pressure filter with the hatch removed to permit inspection is depicted in Figure 10.46.

As a result of the improbability of easy and frequent inspection it is recommended that pressure filter vessels be opened for a brief inspection at least once each three months This would involve inspecting a backwashed filter to see if mudballs are present and to see if the media surface is smooth and level. This kind of quick inspection is recommended for each open, gravity filter at least once per

month after such a filter is backwashed. Once per year core samples should be removed from a pressure filter and inspected, and a floc retention test before and after backwash is strongly recommended. The State of California requires that pressure filters be inspected once per year. When core samples are taken, note the total depth of media at the location where the core was extracted. Due to the shape of pressure filter vessels and limitations on head space, obtaining core samples may be difficult in pressure filters, except in the center of the filter or in the vicinity of the hatch. As with all filters, keep records of all inspections.

At the Tuolumne Water District (TUD), pressure filters are inspected twice per year, usually in the spring after the high turbidity winter season and again in the fall after the high water production season. Especially important to the proper operation of pressure filters is optimization of coagulant and filter aid (if used) dosages, and adequate backwashing at the appropriate flow rate. The TUD backwashes pressure filters from 12 to 15 gallons per minute per square foot (29 to 37 m/h rise rate) as a general rule of thumb. With respect to coagulant and filter aid dosages, it is very important to avoid the "if a little is good, then more is better" mindset. Overfeeding of coagulants and/ or filter aids is very detrimental to the integrity of pressure filter media. This operational error will in time lead to the accumulation of mudballs and impacted mud in a pressure filter. Because the media in a pressure filter cannot be visually inspected without taking the filter out of service, problems can develop and sometimes it is too late when the problem is discovered.

Additionally, a filter whose media becomes impacted with mud can develop fissures, thereby short-circuiting and not effectively removing particulate matter, which poses a health risk. At TUD filter aid polymers are used sparingly, and are not utilized until bench testing with filterability apparatus is completed to determine what the optimum dosage is.

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Figure 10.1 Mudballs or lumps on media surface (*Source*: Cleasby 2000)

Figure 10.2 Sand filter covered with small mudballs except for small light-colored area (*Source*: Cleasby 2000)

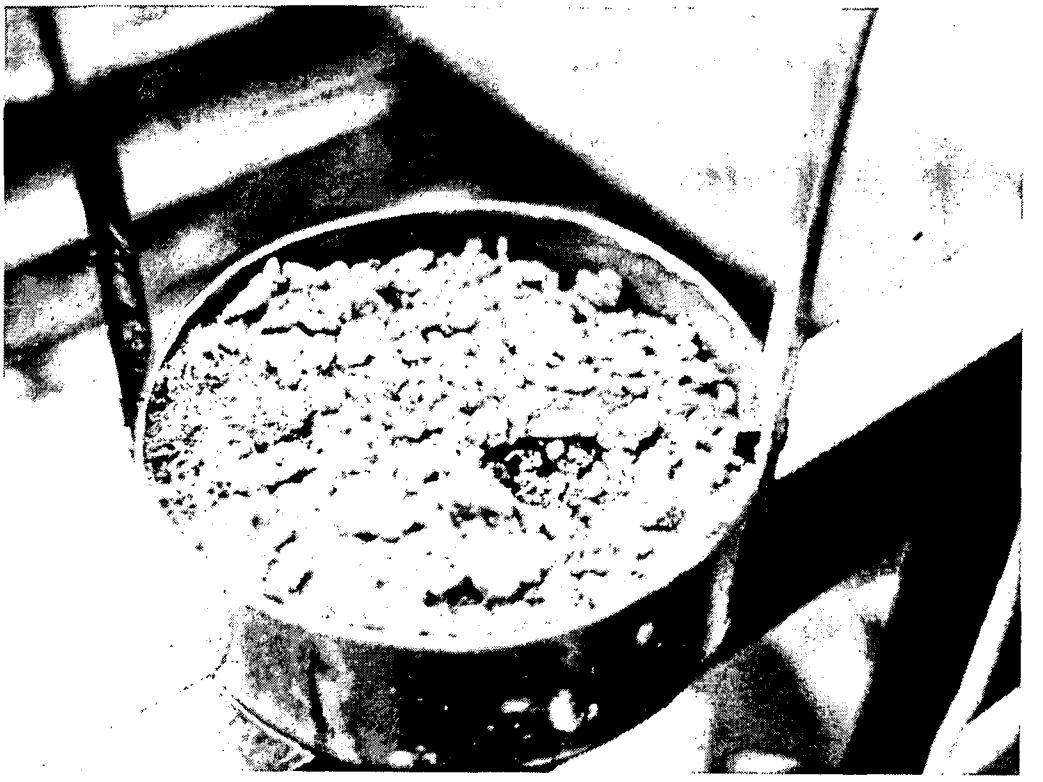

Figure 10.3 Mudballs and anthracite removed from filter shown in Figure 6.7 (*Source*: Cleasby 2000)

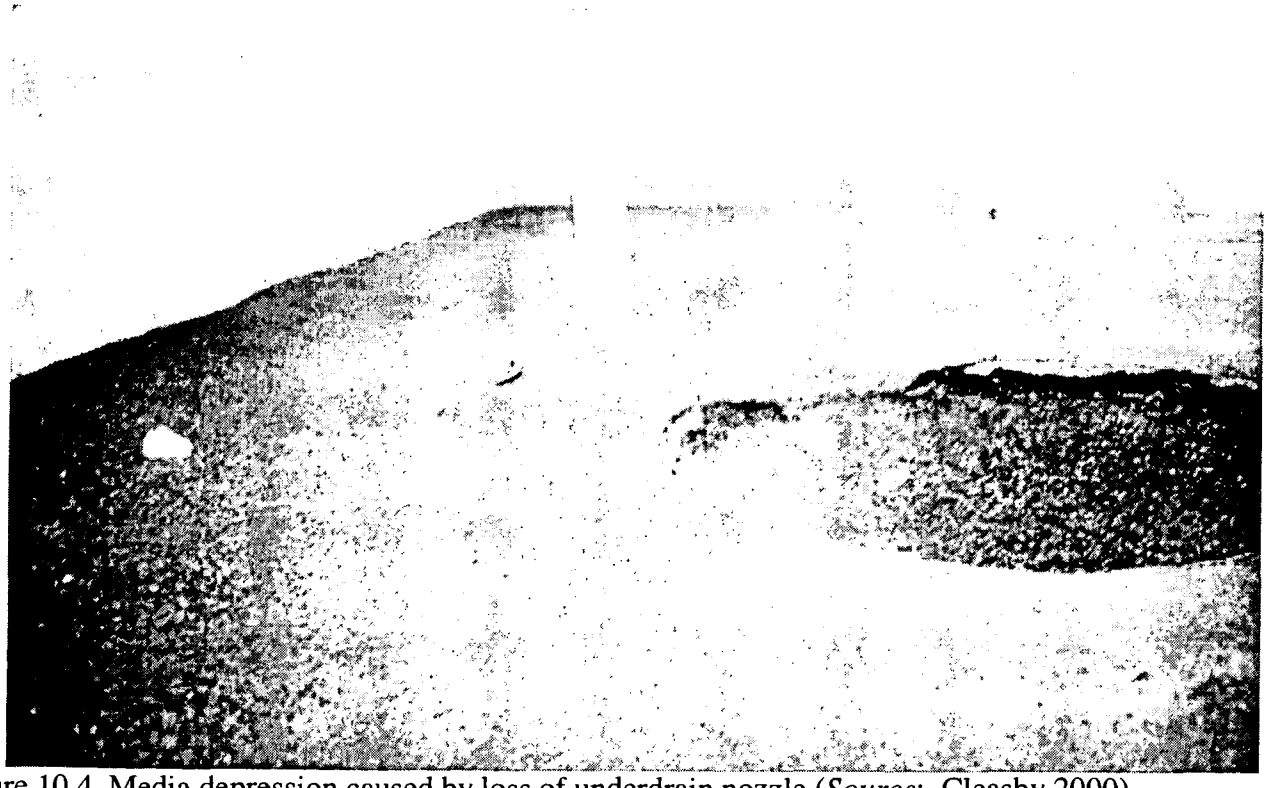

Figure 10.4 Media depression caused by loss of underdrain nozzle (*Source*: Cleasby 2000)

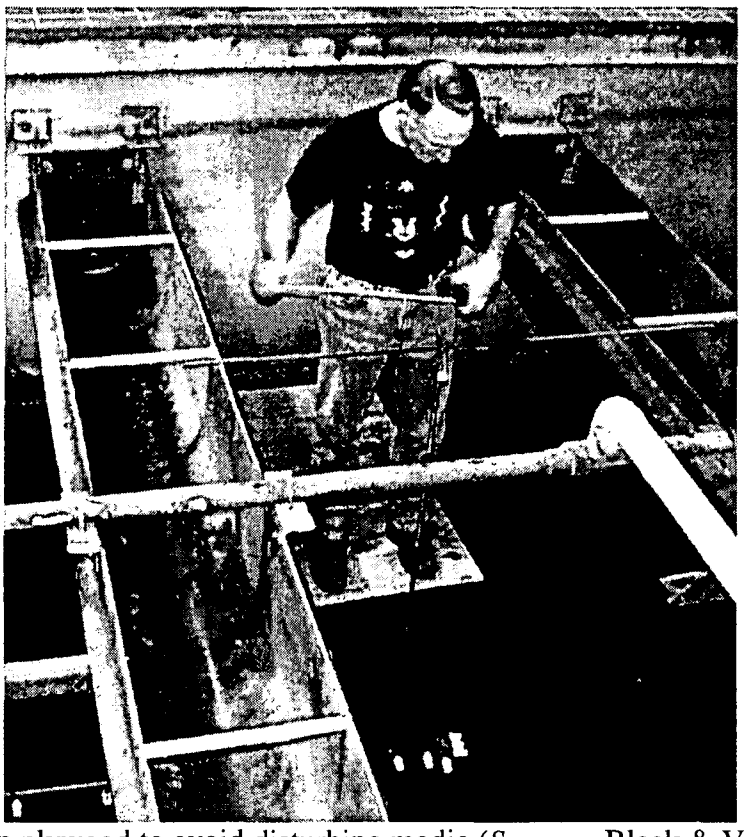

Figure 10.5 Working on plywood to avoid disturbing media (*Source:* Black & Veatch 2000)

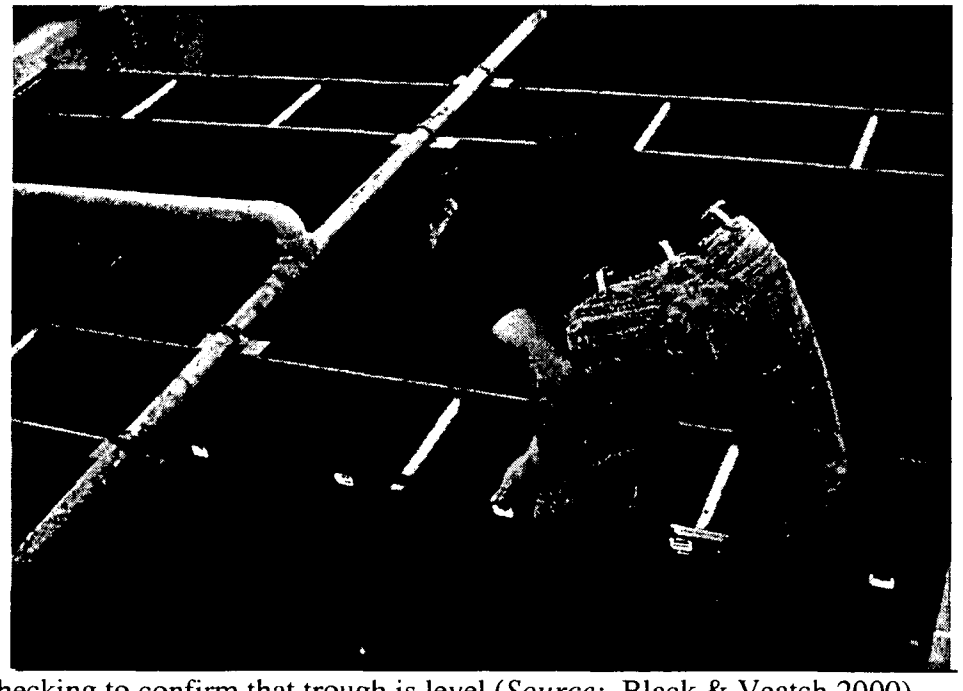

Figure 10.6 Checking to confirm that trough is level (*Source:* Black & Veatch 2000)

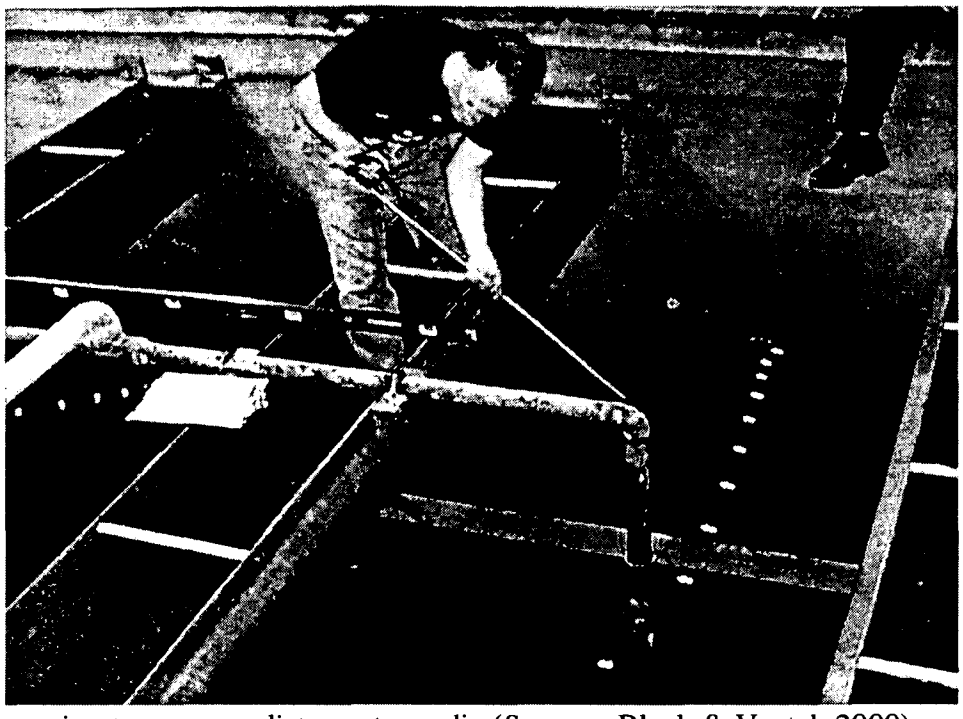

Figure 10.7 Preparing to measure distance to media (*Source:* Black & Veatch 2000)

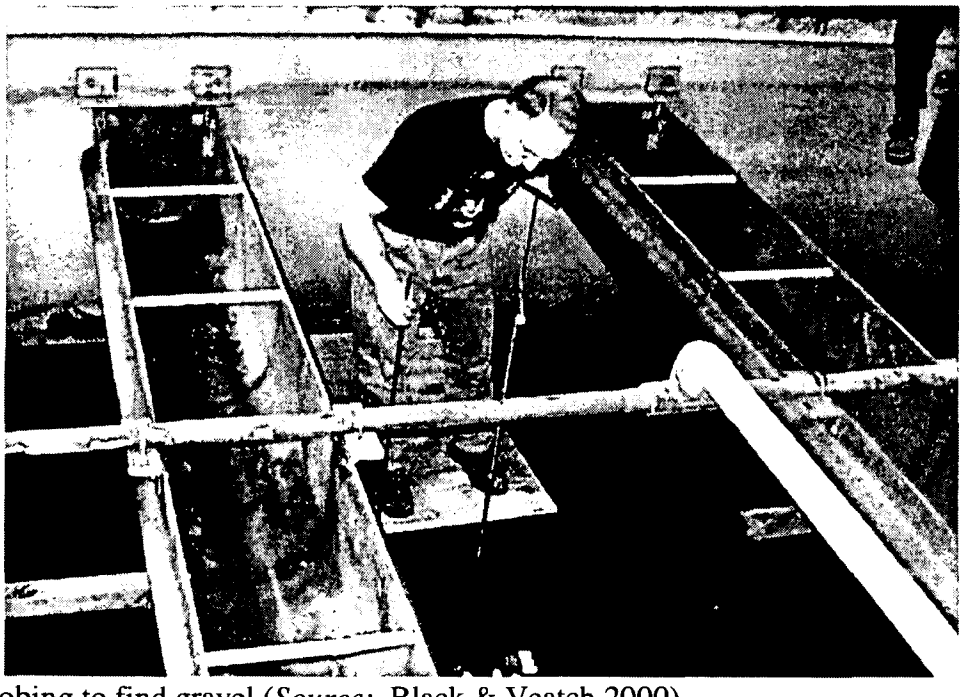

Figure 10.8 Probing to find gravel (*Source:* Black & Veatch 2000)

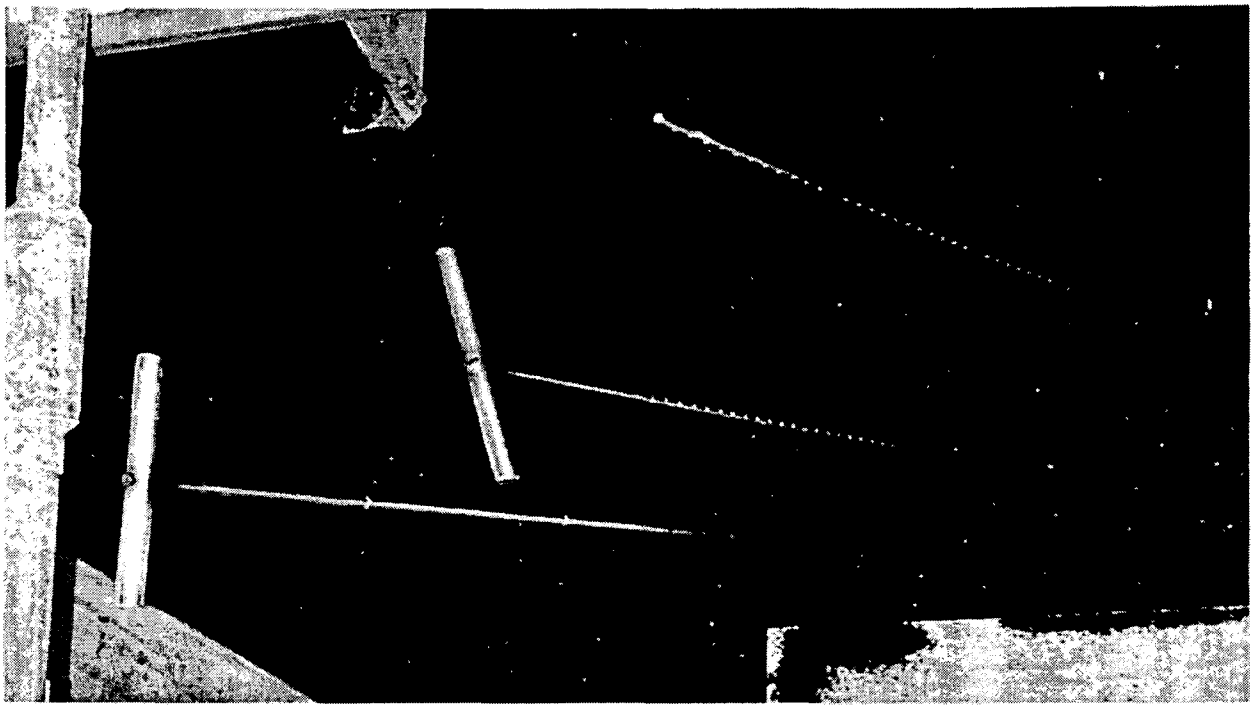

Figure 10.9 Gravel probing tools (*Source:* Black & Veatch 2000)

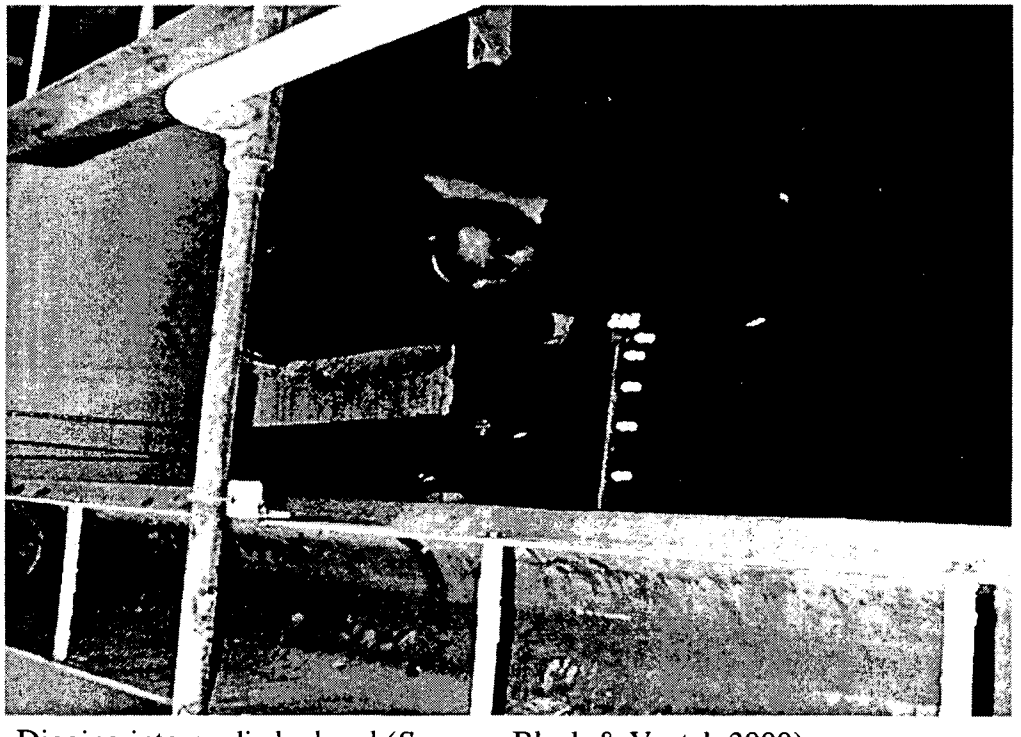

Figure 10.10 Digging into media by hand (*Source:* Black & Veatch 2000)

Figure 10.11 Digging and probing for lumps in filter bed (*Source:* Black & Veatch 2000)

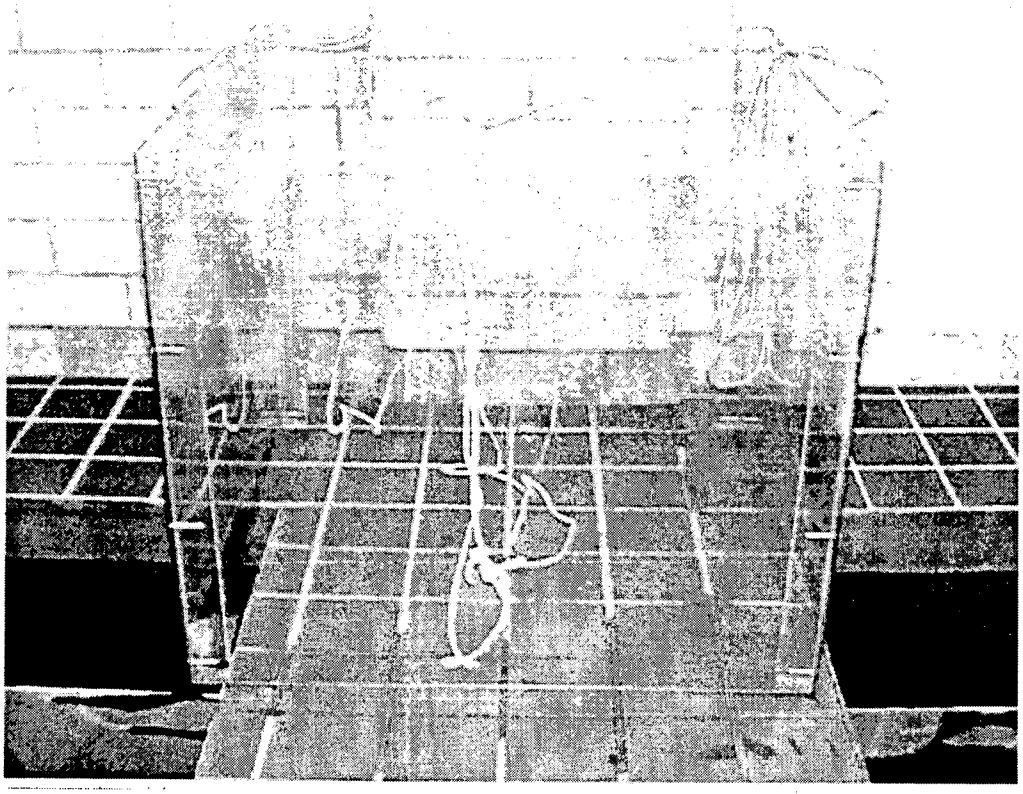

Figure 10.12 Plexiglas filter excavation box (*Source:* Black & Veatch 2000)

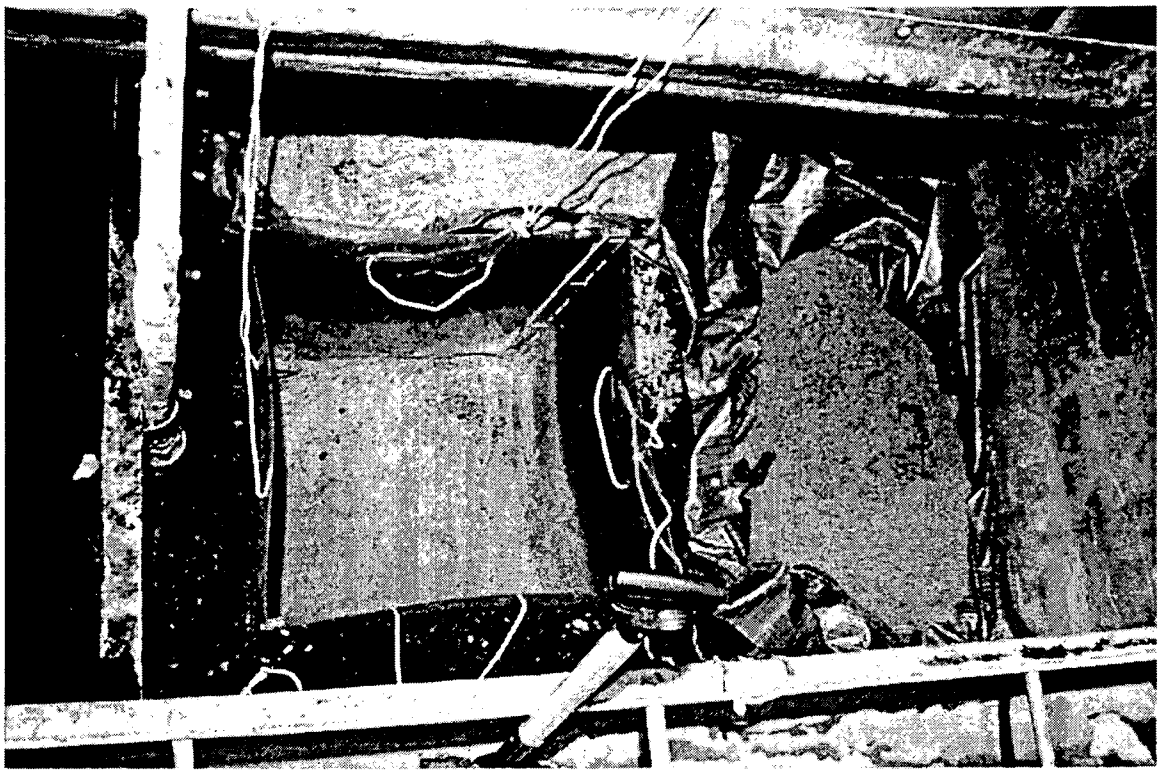

Figure 10.13 Filter excavation box in use (*Source:* Black & Veatch 2000)

Figure 10.14 Filter excavation box built by water utility at Grand Rapids (*Source:* Grand Rapids 2000)

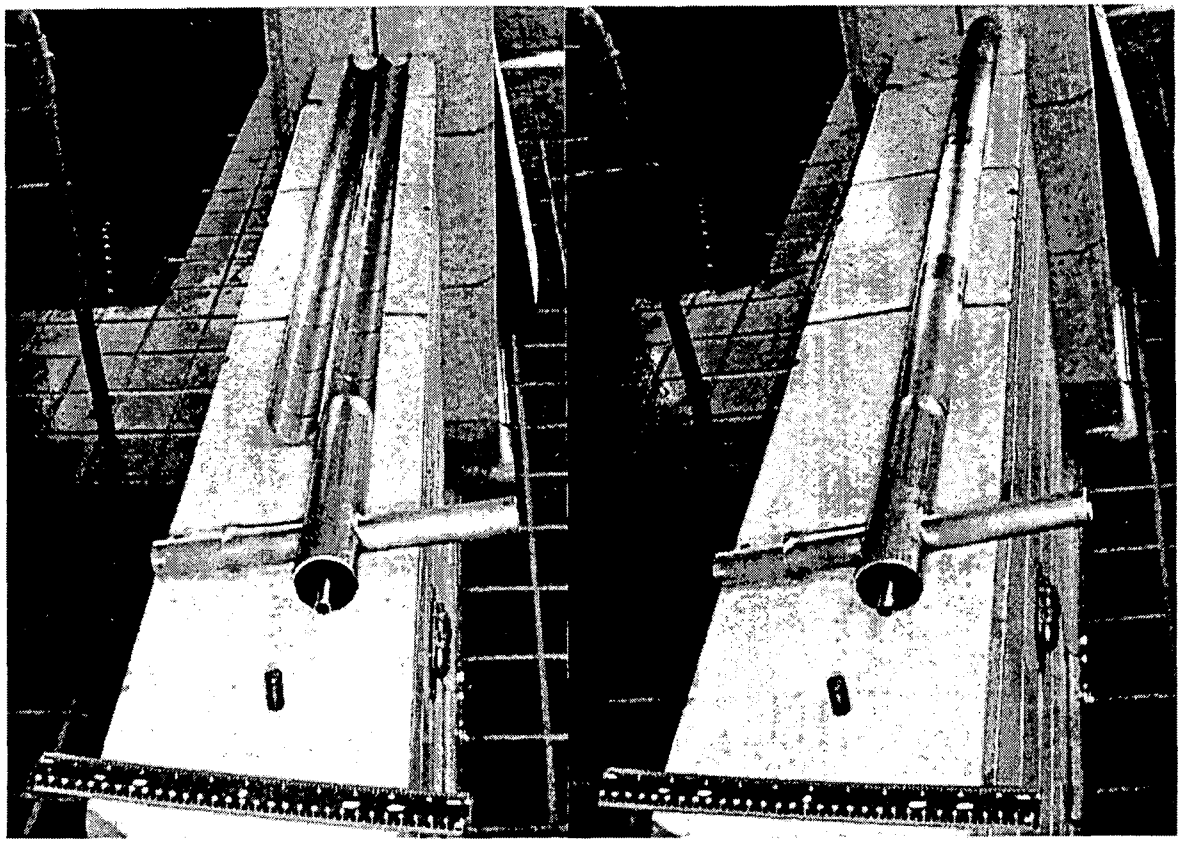

Figure 10.15 Core sampler, viewed both open for inspection and closed for use (*Source:* Black & Veatch 2000)

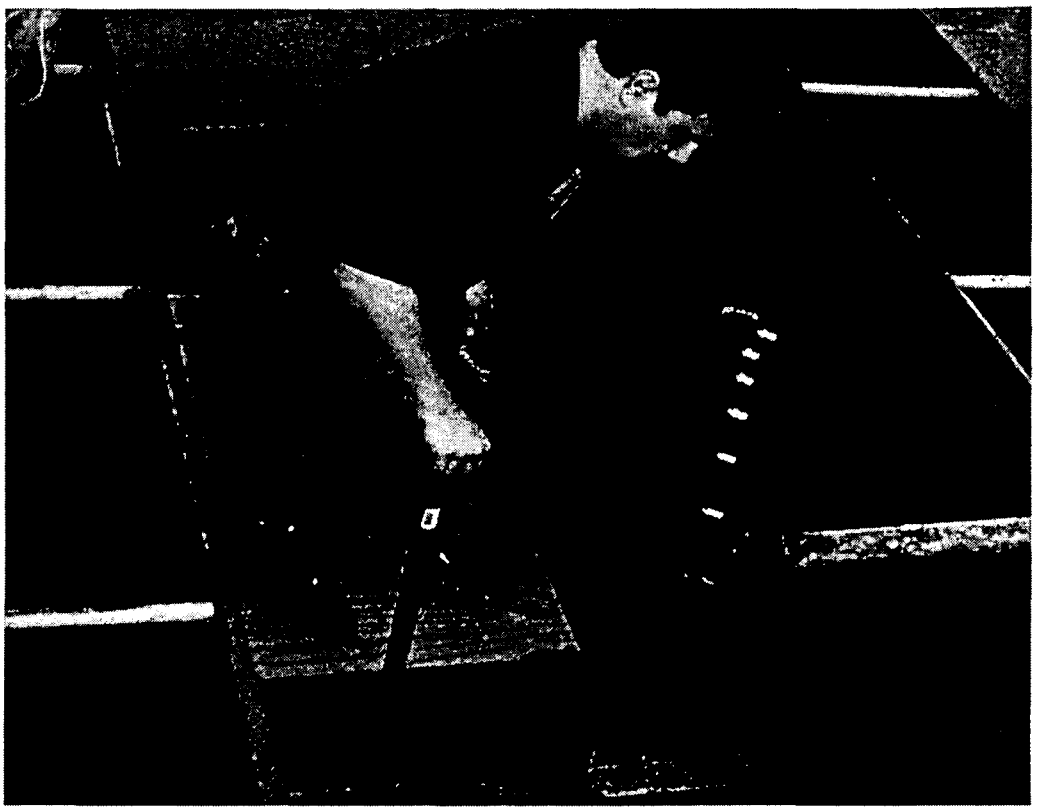

Figure 10.16 Taking a core sample from a filter (*Source:* Black & Veatch 2000)

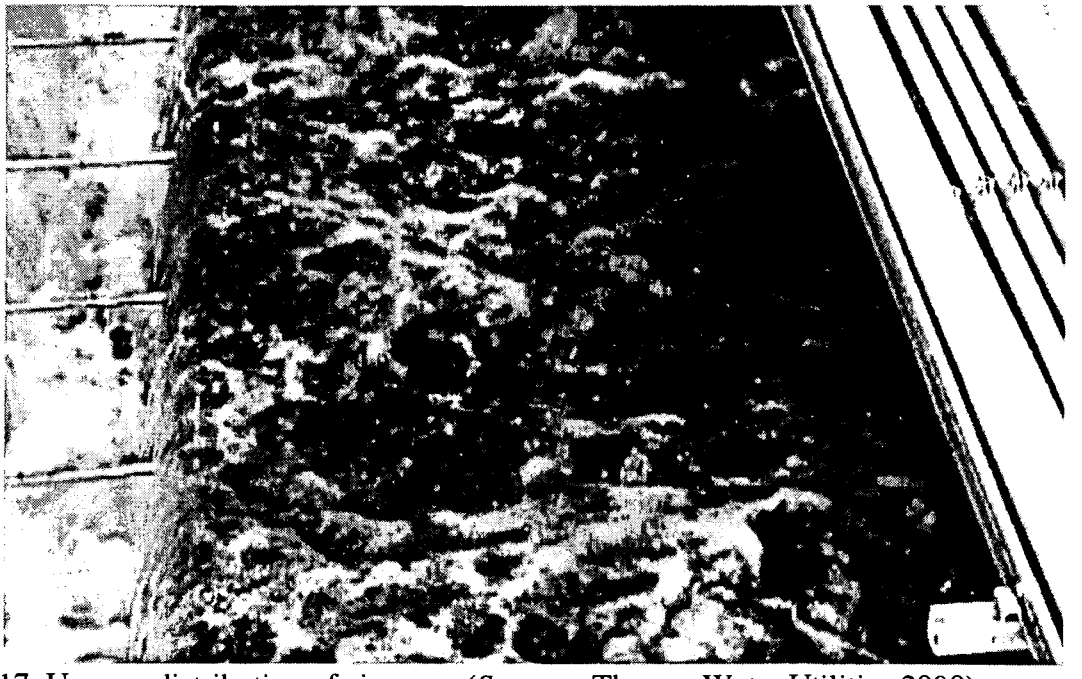

Figure 10.17 Uneven distribution of air scour (*Source:* Thames Water Utilities 2000)

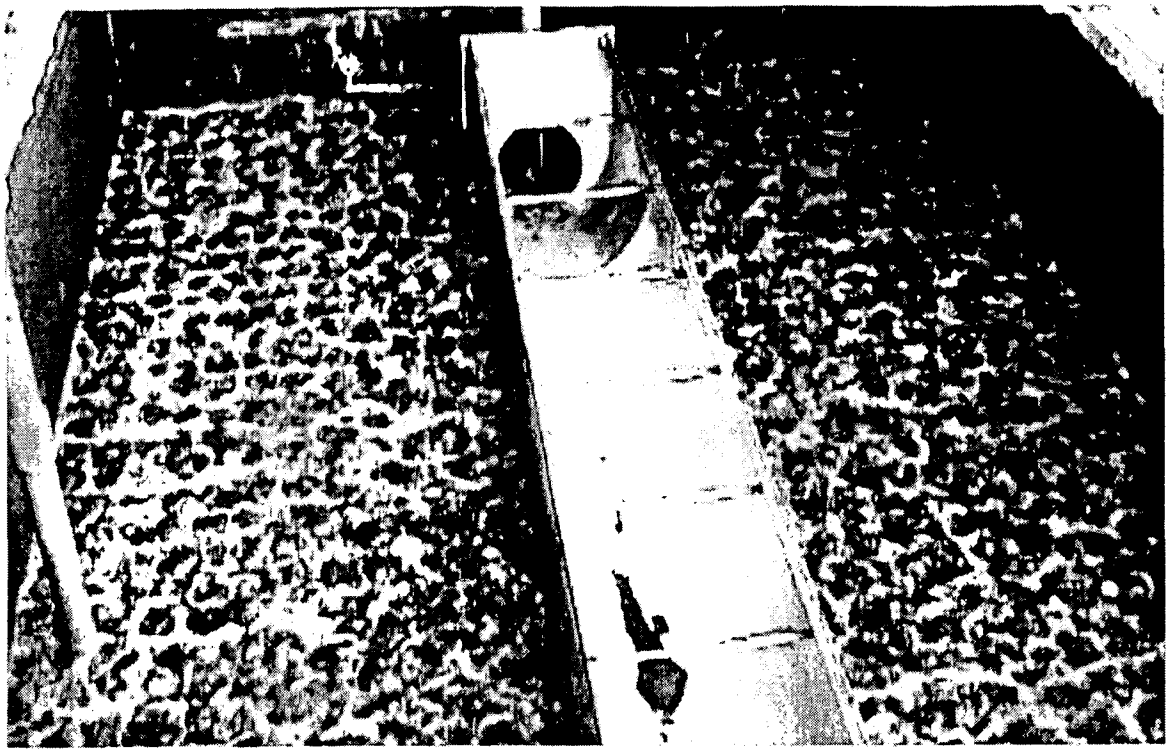

Figure 10.18 Air scour with even distribution (*Source:* Thames Water Utilities 2000)

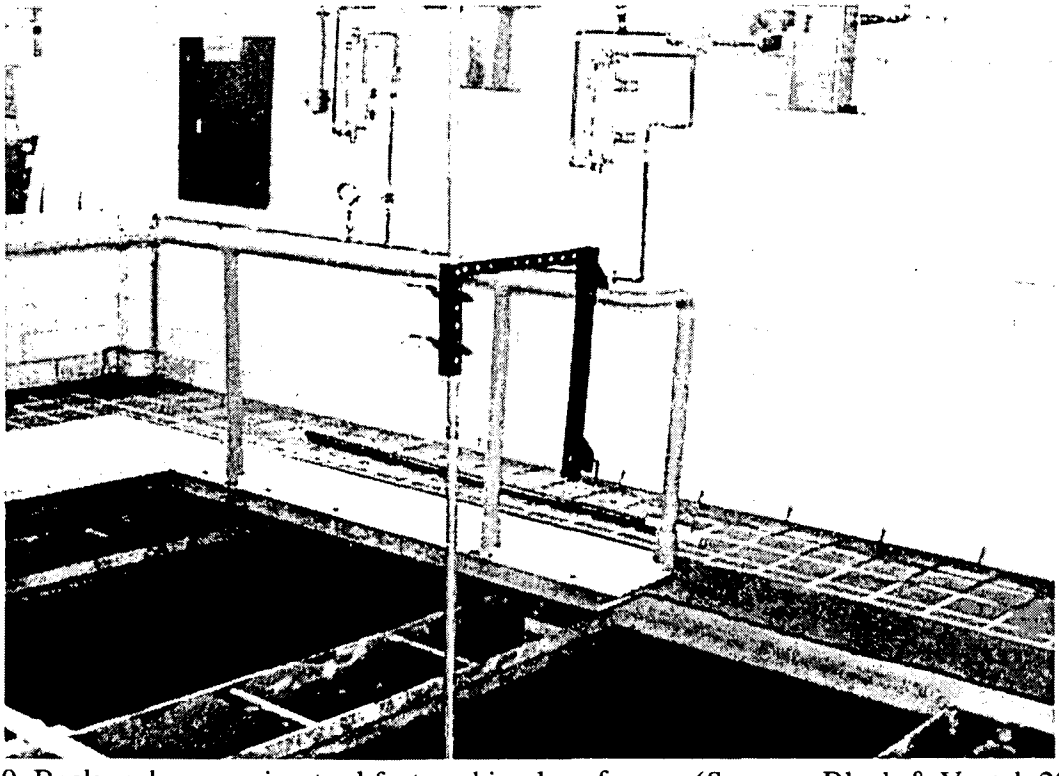

Figure 10.19 Backwash expansion tool fastened in place for use (*Source:* Black & Veatch 2000)

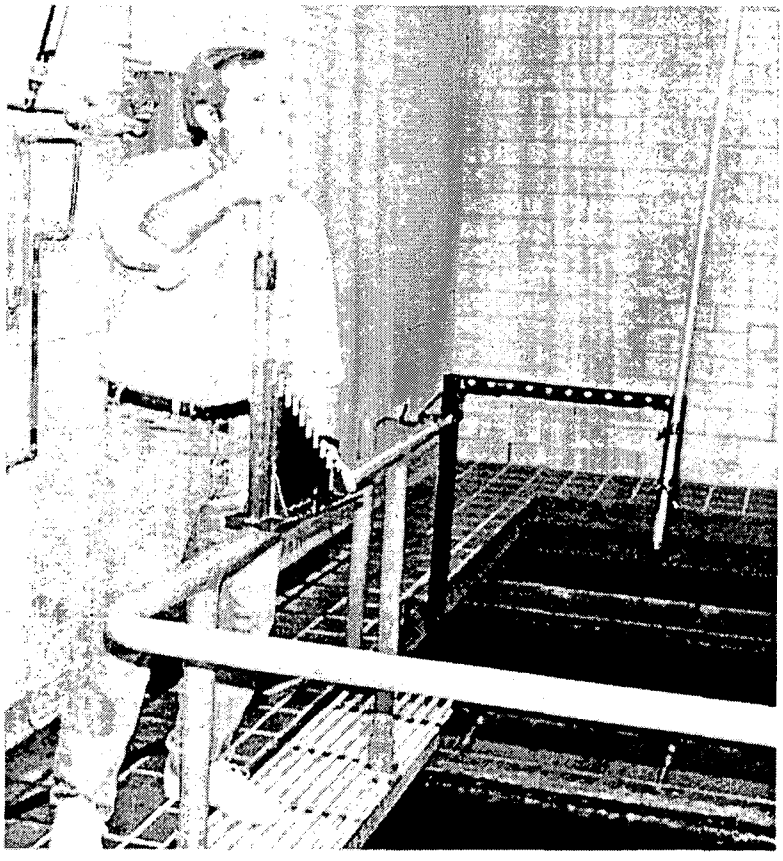

Figure 10.20 Backwash expansion tool after use and removal (*Source:* Black & Veatch 2000)

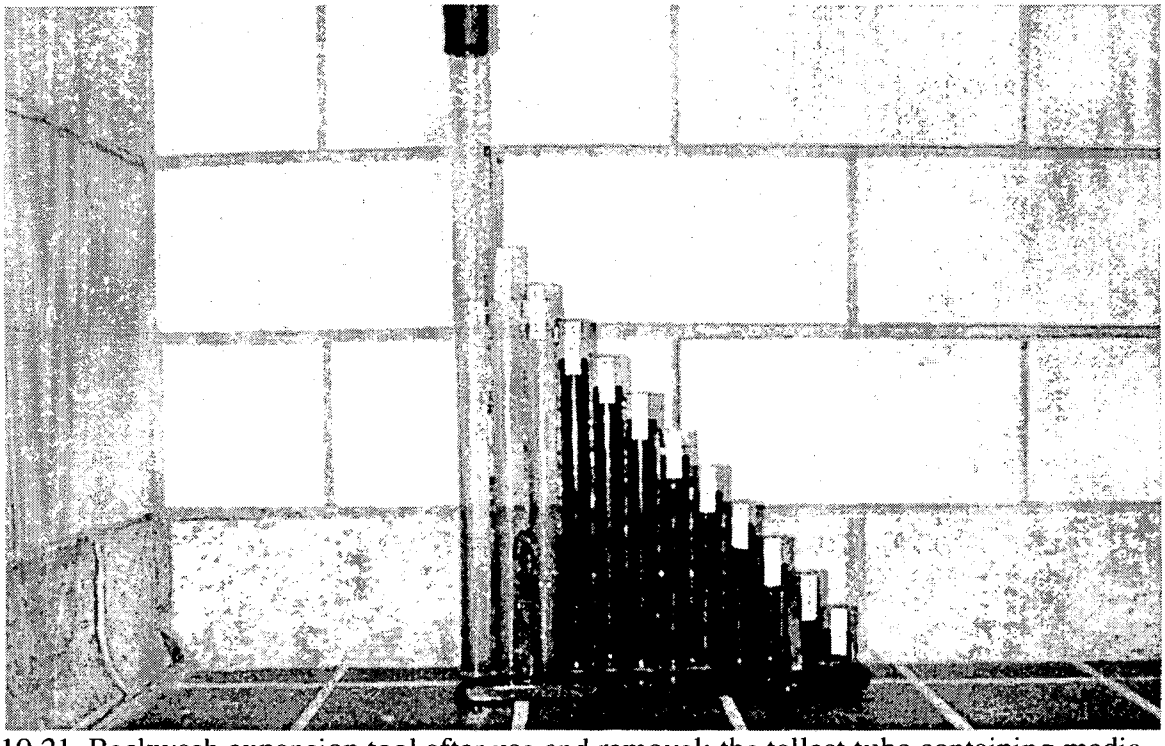

Figure 10.21 Backwash expansion tool after use and removal; the tallest tube containing media expansion (black) shows height of media expansion during backwash (*Source:* Black & Veatch 2000)

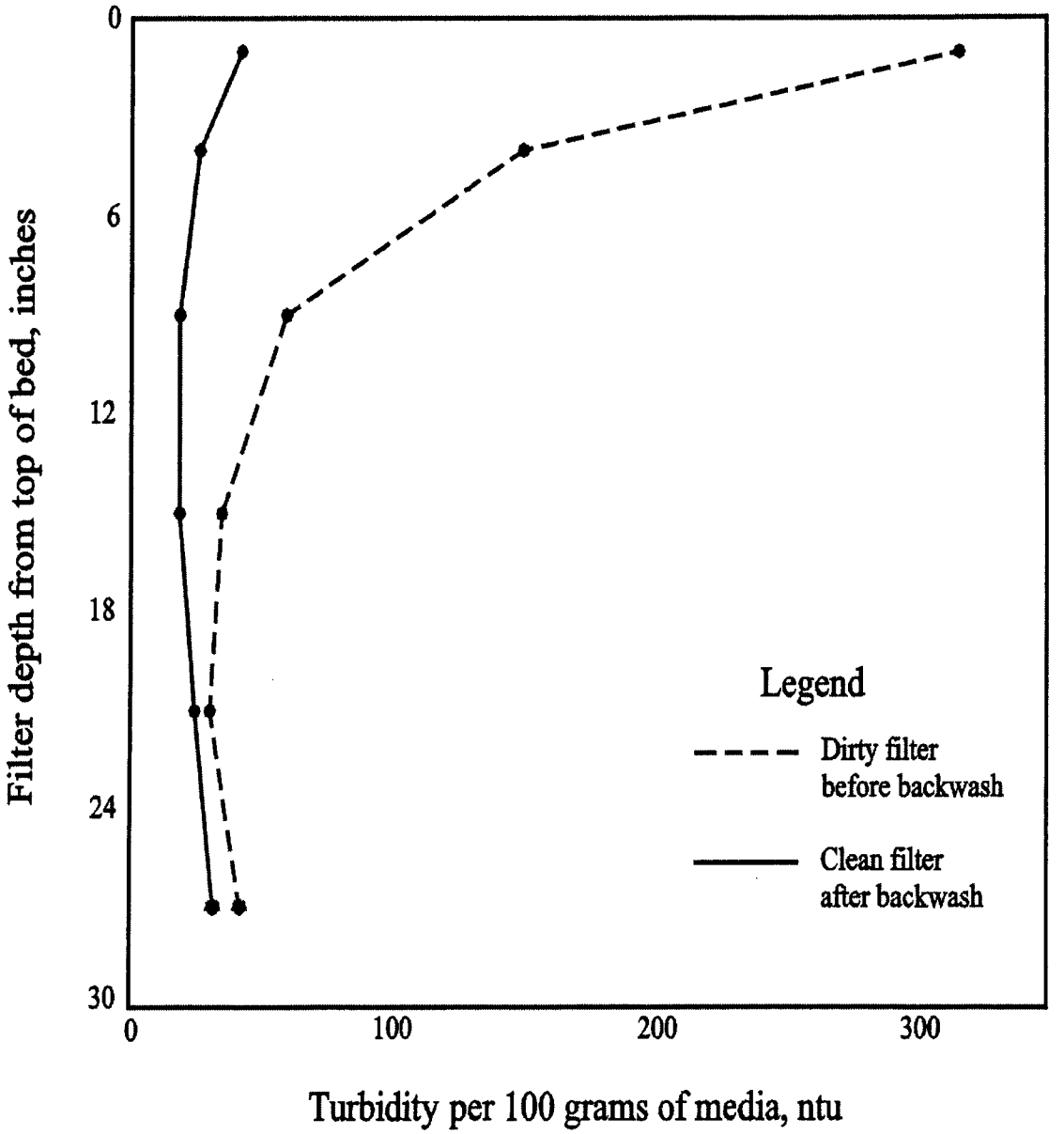

Figure 10.22 Floc retention analysis

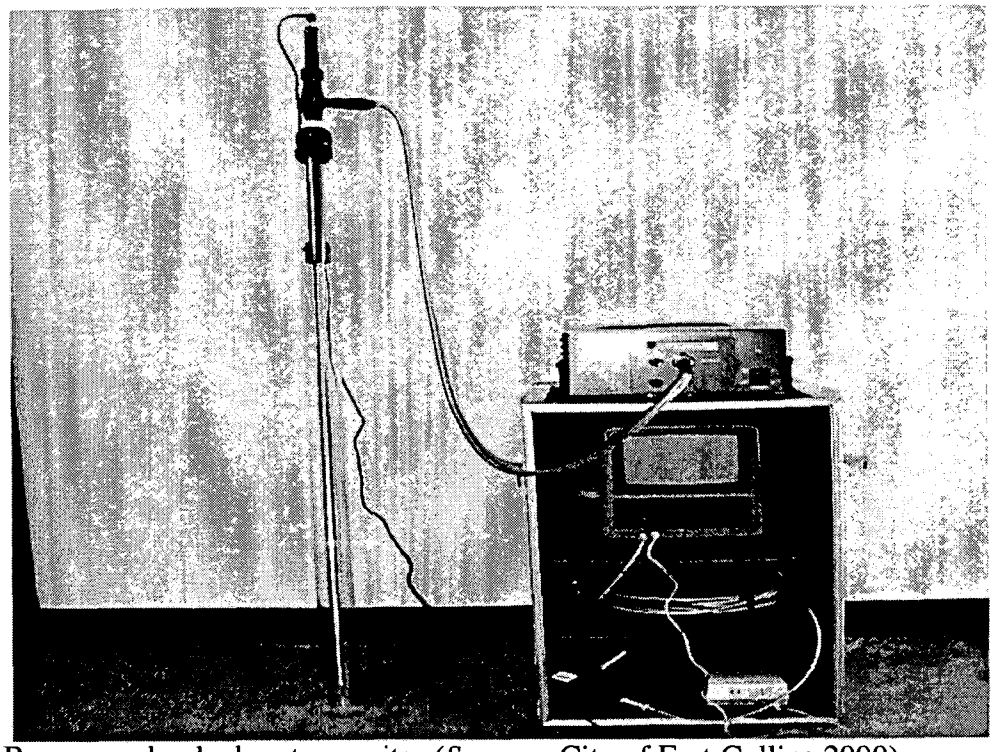

Figure 10.23 Borescope hooked up to monitor (*Source:* City of Fort Collins 2000)

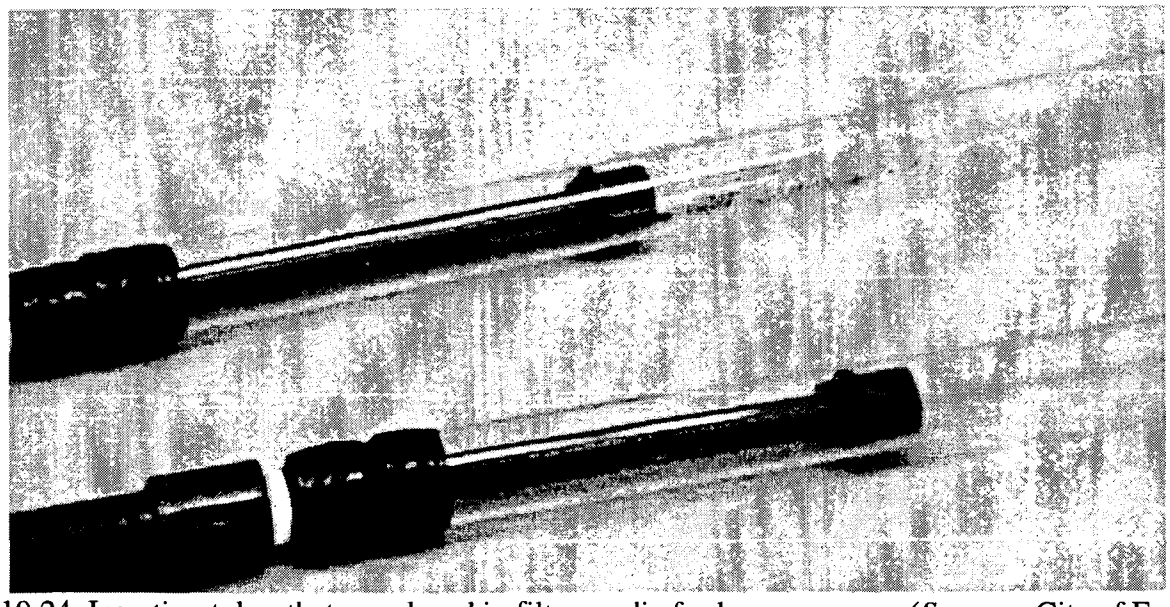

Figure 10.24 Insertion tubes that are placed in filter media for borescope use (*Source:* City of Fort Collins 2000)

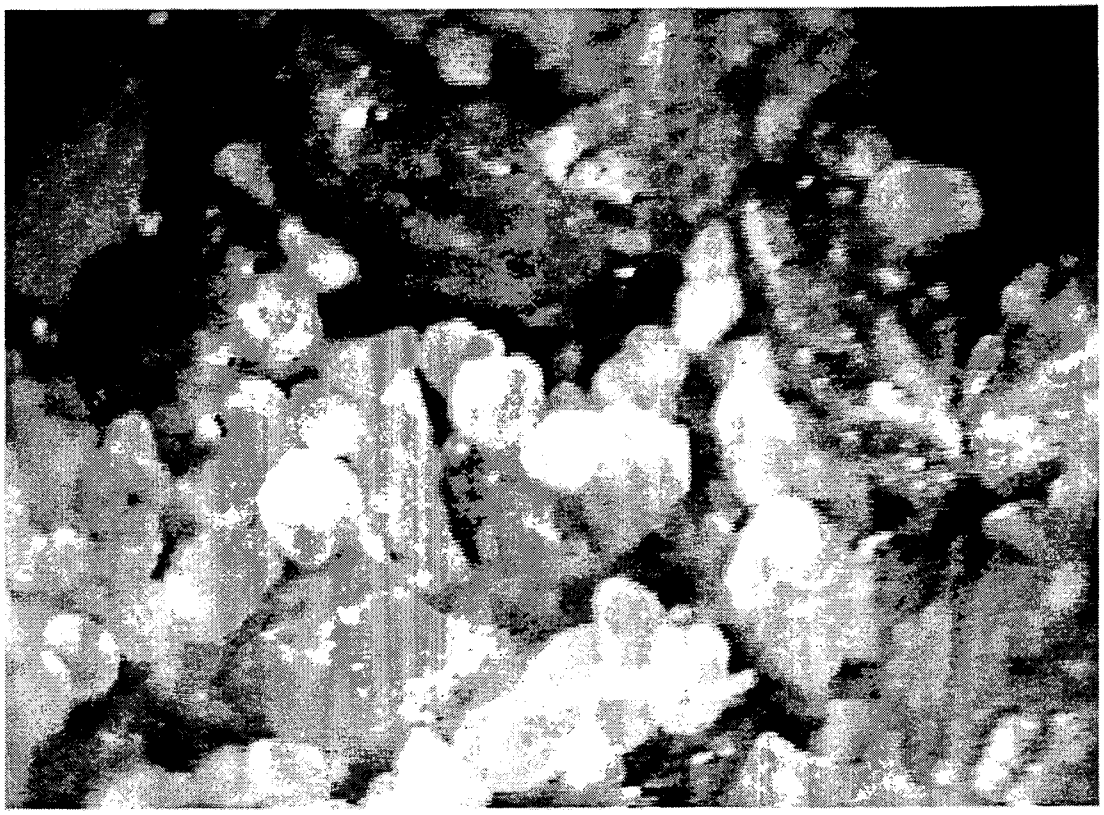

Figure 10.25 Sand and anthracite viewed through borescope during filtration (*Source*: City of Fort Collins 2000)

Figure 10.26 Wheeler Bottom, upset, with smaller gravel missing or under large balls, and some large balls missing (*Source*: Black & Veatch 2000)

Figure 10.27 Example of support gravel migration caused by backwashing (*Source*: Cleasby 2000)

Figure 10.28 Filter sand that has leaked into underdrain (*Source*: Cleasby 2000)

Figure 10.29 Side view of false floor and nozzle underdrain that failed in uplift (*Source*: Cleasby 2000)

Figure 10.30 Clay block underdrain that failed in uplift (*Source*: Cleasby 2000)

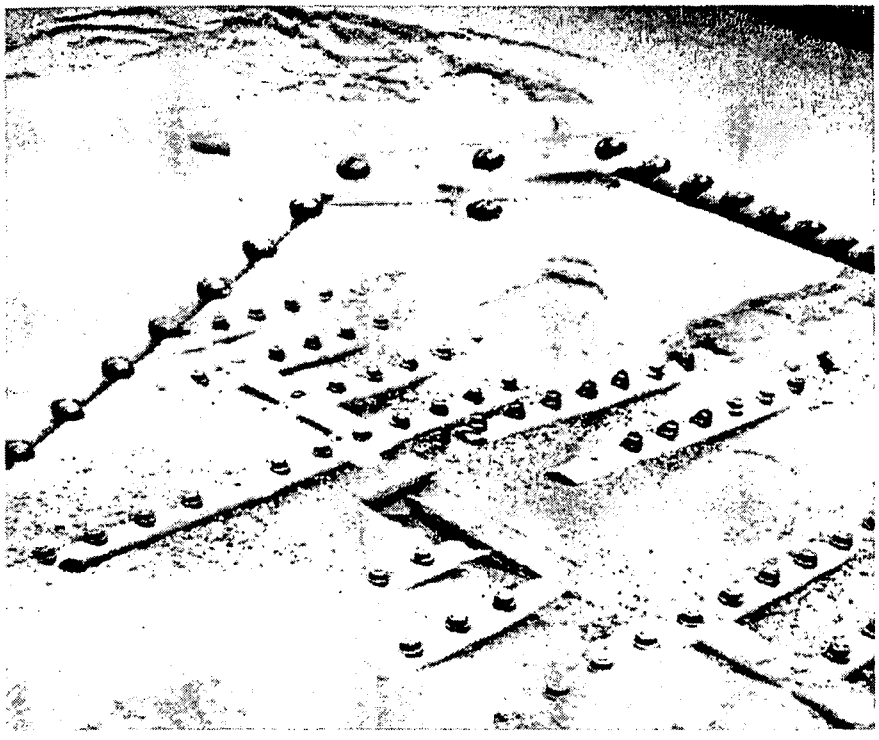

Figure 10.31 A lateral and nozzle floor that has blown up (*Source:* Thames Water Utilities 2000)

Figure 10.32 Using garden rake to remove mudballs (*Source:* Consonery, Pennsylvania DEP 2000)

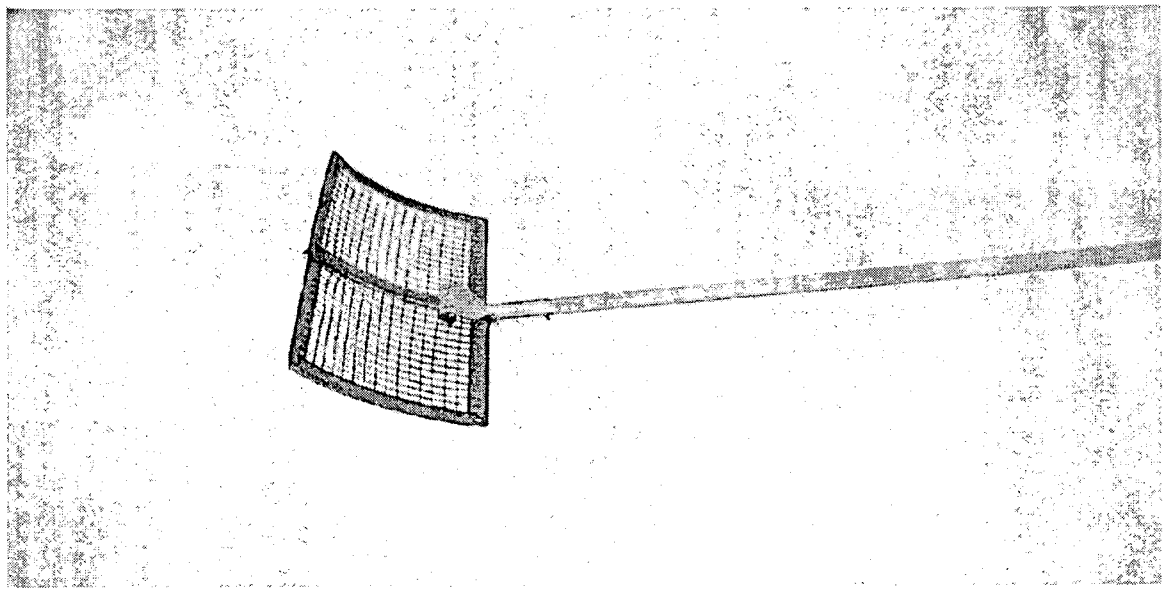

Figure 10.33 21" x 11" Mudball Net (*Source*: Clackamus River Water District 2001)

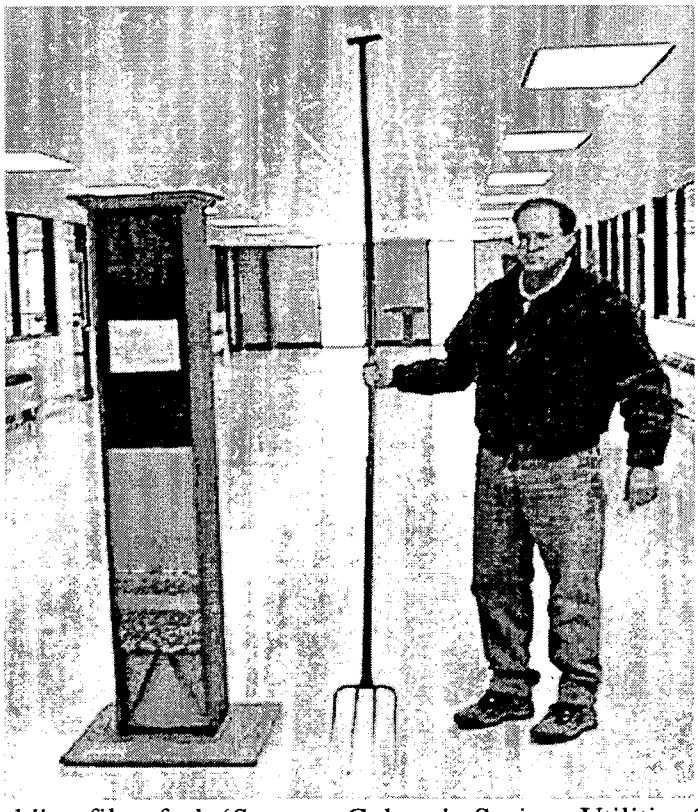

Figure 10.34 Operator holding filter fork (*Source:* Colorado Springs Utilities 2000)

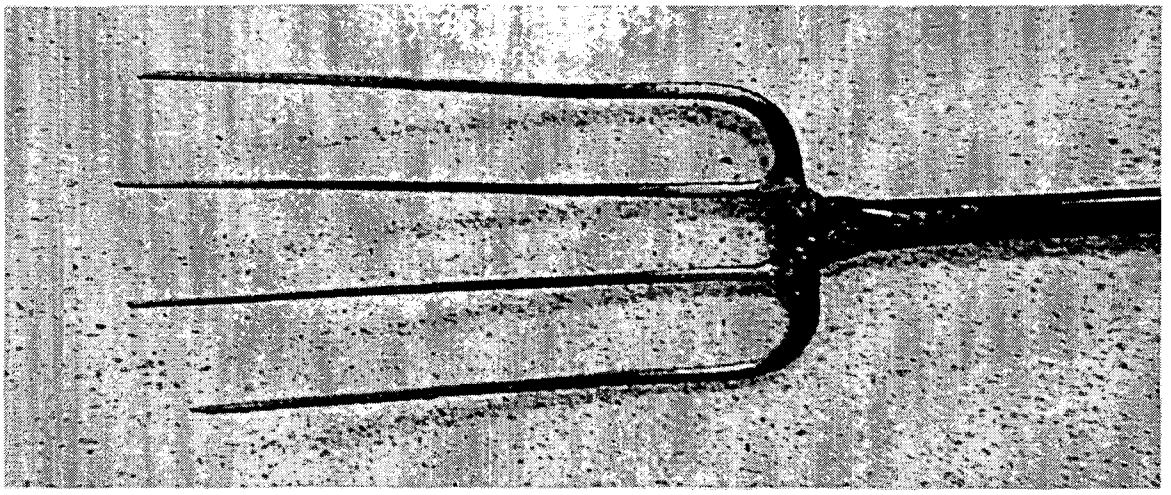

Figure 10.35 Filter fork, the business end (*Source*: Colorado Springs Utilities 2000)

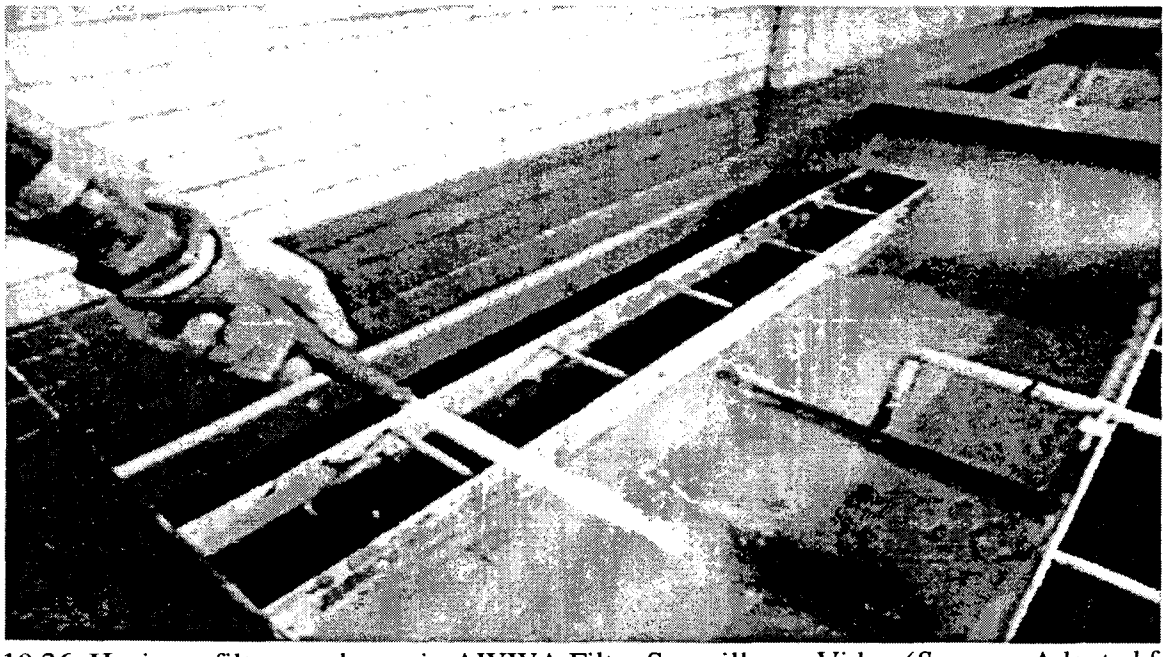

Figure 10.36 Hosing a filter, as shown in AWWA Filter Surveillance Video (*Source:* Adapted from AWWA 2000)

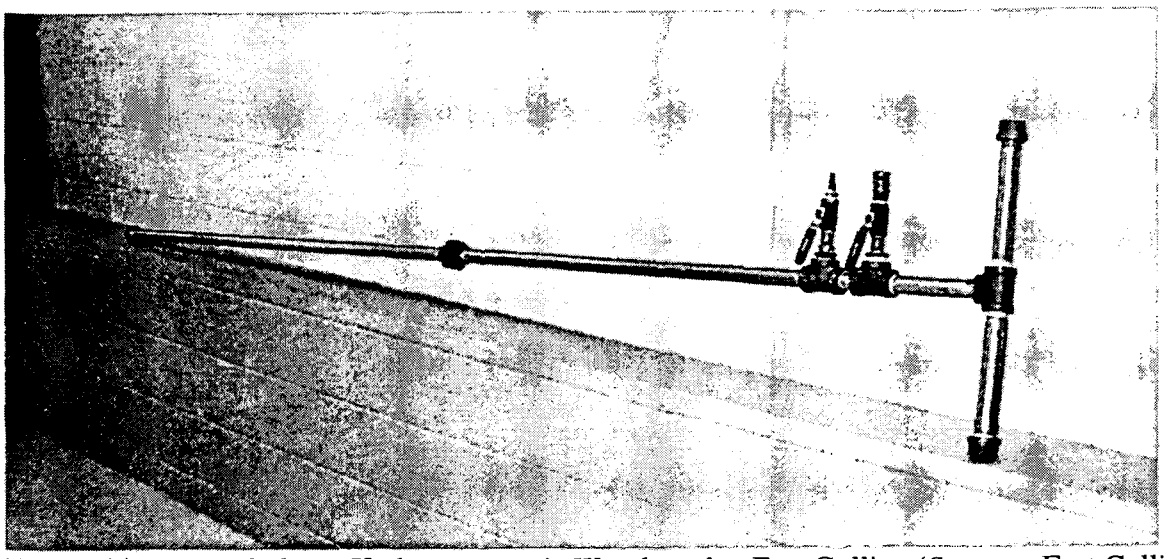

Figure 10.37 Thing-a-ma-bob, or *Hydropneumatic Wand* used at Fort Collins (*Source:* Fort Collins Utilities 2000)

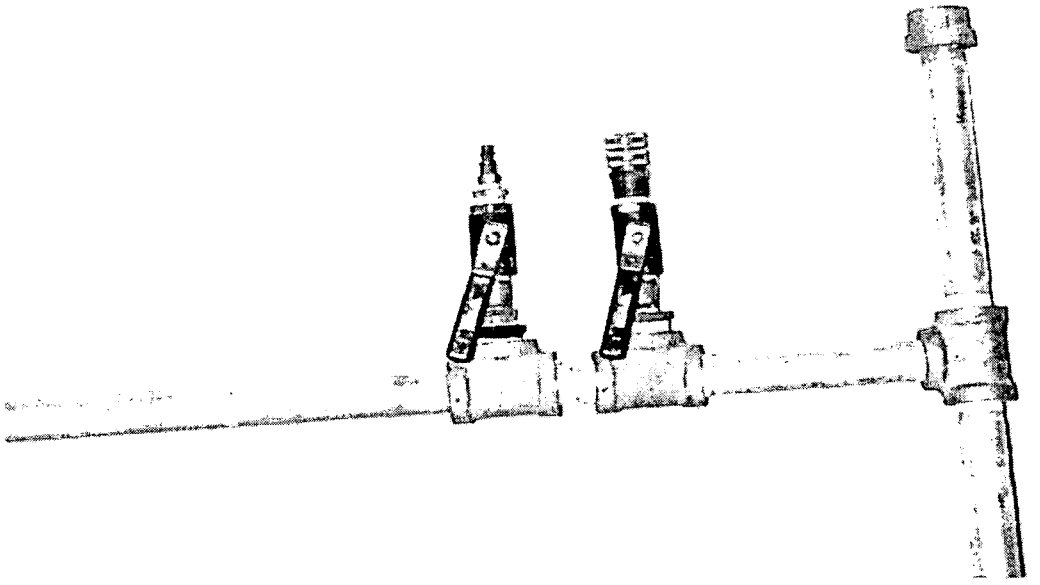

Figure 10.38 Close-up view of air and water connections and discharge end of Hydropneumatic Wand (*Source:* Fort Collins Utilities 2000)

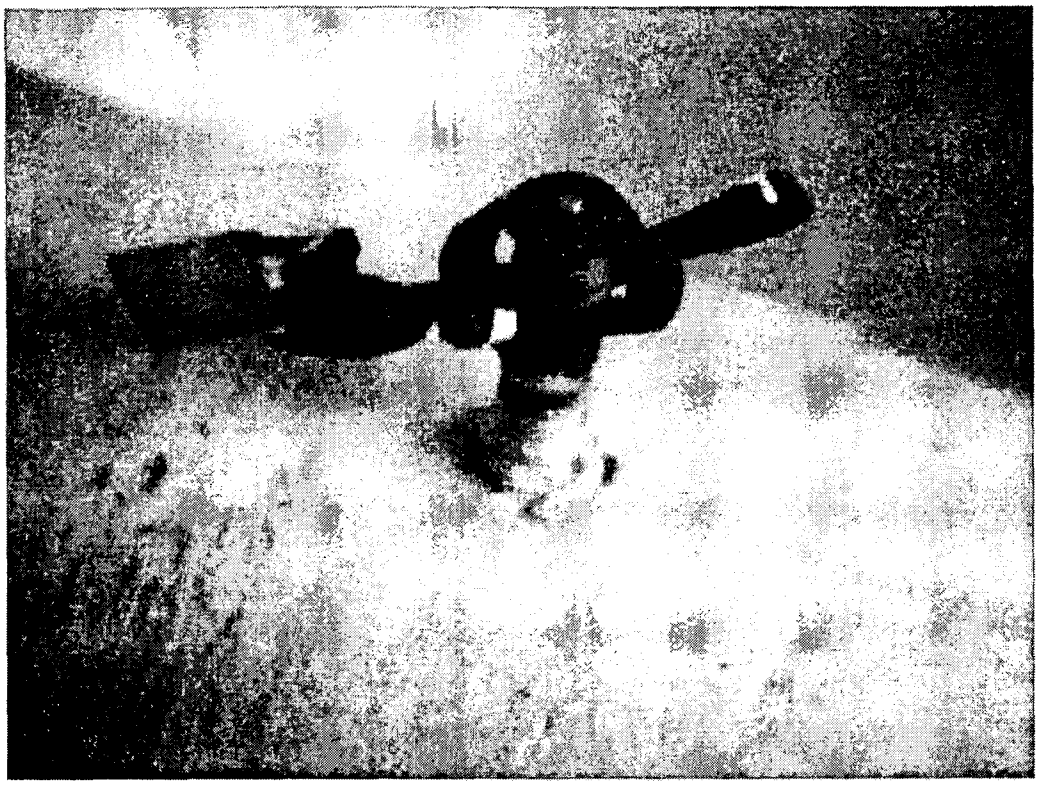

Figure 10.39 Sprinkler head mounted on surface wash pipe in filter at Grand Rapids (*Source*: Grand Rapids 2000)

Figure 10.40 Badly mounded filter medium in a lime softening plant (*Source*: Cleasby 2000)

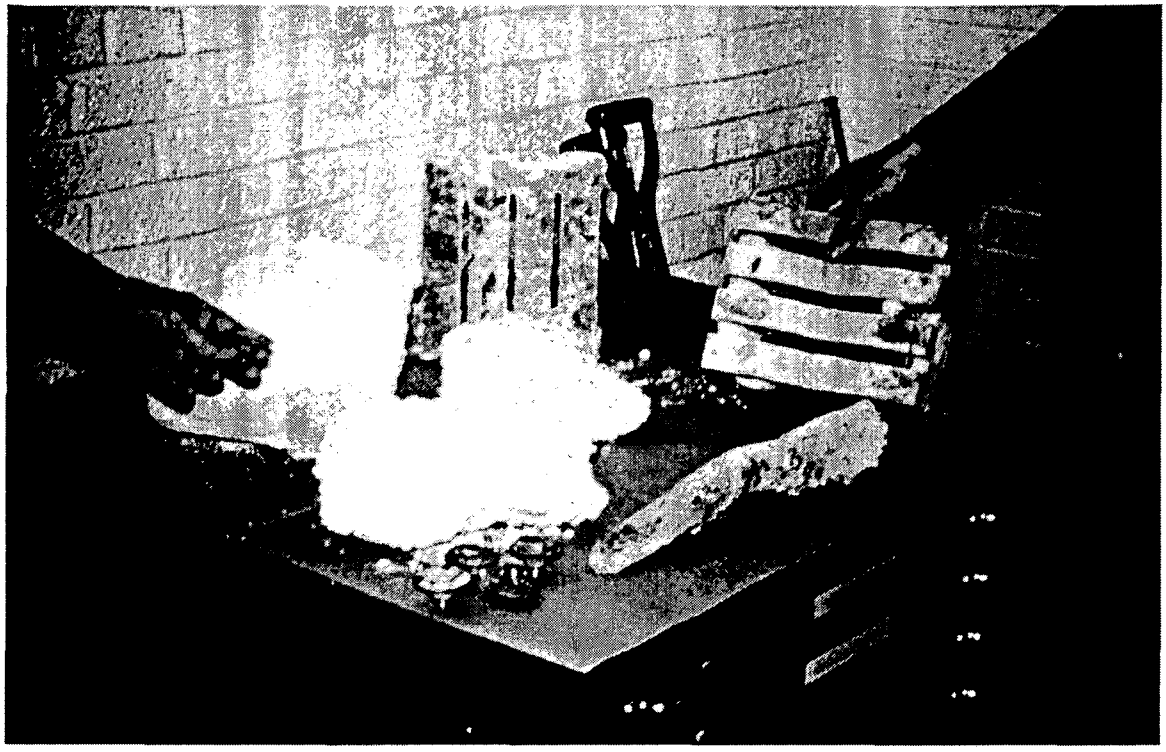

Figure 10.41 Underdrain block and cemented sand media from filter in a lime softening plant (*Source*: Cleasby 2000)

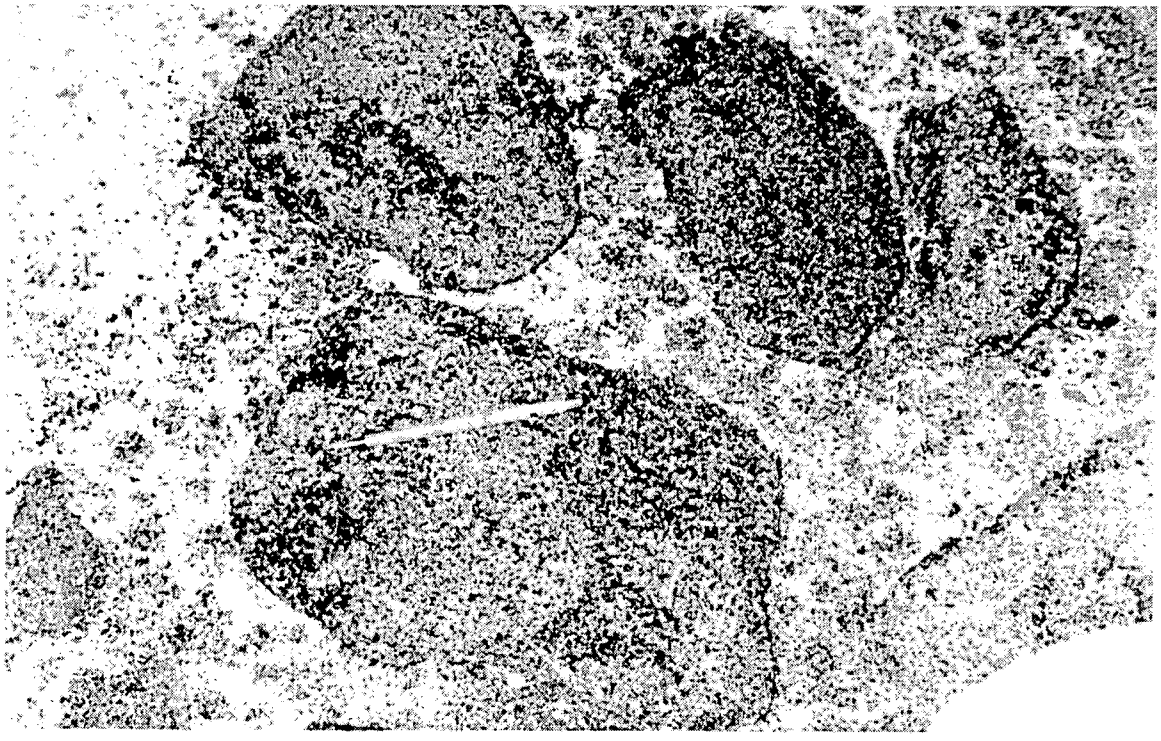

Figure 10.42 Anthracite medium bound in large lumps by polymer and $CaCO_3$ in lime softening plant (Drafter's pencil shows scale of lumps) (*Source:* Black & Veatch 2000)

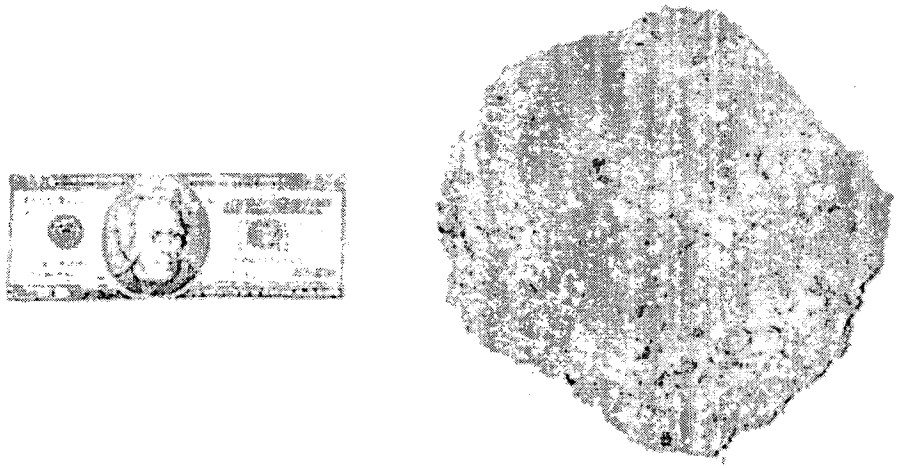

Figure 10.43 Lump of cemented sand and fine gravel taken from filter in a lime softening plant (*Source:* Black & Veatch 2000)

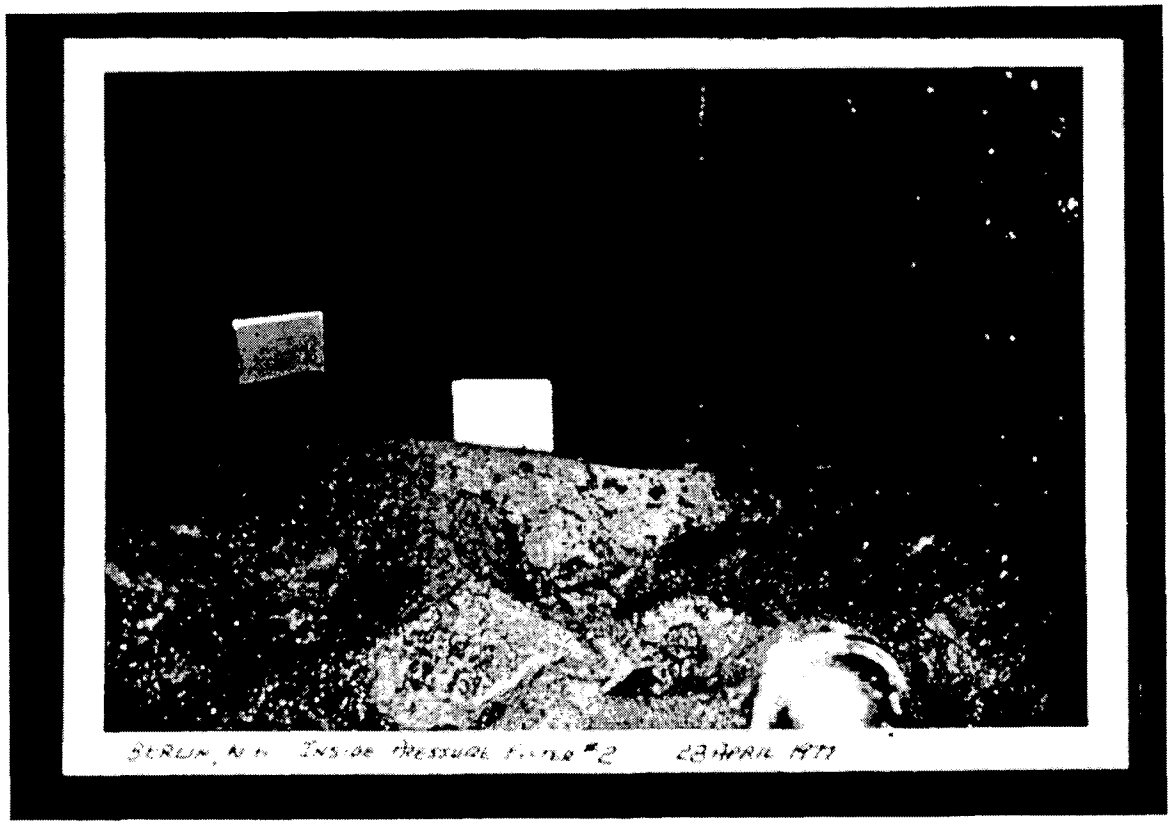

Figure 10.44 Upset media inside pressure filter (*Source:* Lippy 1978)

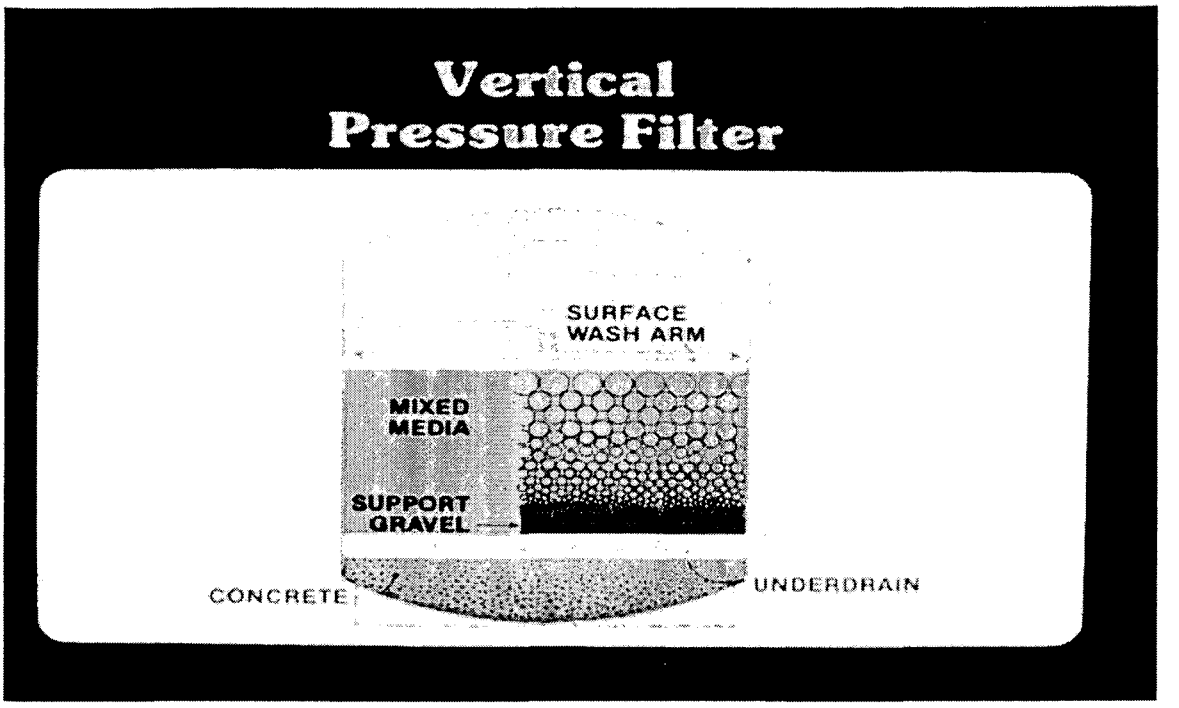

Figure 10.45 Diagram of pressure filter

Figure 10.46 Horizontal pressure filter (*Source:* Photo by E.C. Lippy)

CHAPTER 11

FILTER MEDIA CHARACTERISTICS, SELECTION, AND REPLACEMENT

INTRODUCTION

Chapter 11 contains a review of testing procedures used to evaluate the properties of filter material, such as effective size, uniformity coefficient, hardness, acid solubility, shape, and density. Filter support gravel and alternative filter media support systems are discussed. Issues related to replacement of filter media and to topping up filters are included in this chapter. Examples of test procedures are provided in detail in the appendix to this chapter.

MEDIA SELECTION

Media used in rapid gravity filters must be properly specified and managed. The full life cycle of the media from purchase, installation, filter operation and eventually replacement requires filter operators to be aware of technical terminology and practical management. Filter media may originate from a number of sources, dependent on local or national geology. The size(s) of filter media grains utilized is governed by the design of the filter plant. It is important to know the size of grains to ensure that they are retained within the filter box by the associated media retaining structures (e.g. weirs, launders, nozzles or proprietary floor designs) and so that backwash water rates are correctly specified.

Standards for specifying and testing filtering materials have been developed in the United States (ANSI/AWWA B100-96) and in the United Kingdom by British Water, the trade association for water industry companies in the private sector.

Filter Media Size and Depth Selection Overview

Filter media size is selected for its ability to produce the desired filtrate quality, given consideration of the process operating conditions and filter design. Small granules pack together to produce small void spaces, larger granules produce larger spaces. This has the effect that for a given depth of media the larger granules will produce less resistance to flow and lower starting (so called "clean") bed pressure differential (head loss). The benefits of lower clean bed head loss associated with larger filter media size must be evaluated in the context of lower particle removal efficiency attained by

larger media. Particle removal occurs when particles attach to the surfaces of filter grains. The surface area per unit bed volume is inversely proportional to grain size, so larger filter media are less effective for particle removal. To compensate for this lower capture efficiency deeper beds must be used. Dual or multiple-layer (multimedia) filters are designed with larger grains of lower density media laid over finer grains of a higher density material. This media design enables the capture of large particles in the larger pores and fine filtration in the lower layer or layers. This can increase the productivity of a filter run, that is, the total volume of water produced per unit area during the run. Capture and storage of floc and particles in large pore spaces in the upper portion of a filter bed are essential if particles are present that would rapidly blind fine filter media (e.g. some filter-clogging algae). The depth of dual media filters is often intermediate between fine sand filters and deep coarse media beds.

Media Size and Depth Selection Methods

According to the Montgomery Engineers (1985) the two means of selecting the correct media size and depth are a) pilot studies, or b) use of existing data from plants treating similar waters. Ives (1981) stated that pilot tests could be performed satisfactorily with filter beds the same depth as full scale, but with a diameter as little as 150 mm (6"). The rule of thumb is that the column diameter (D) should be greater than the grain diameter (d) by the ratio $D/d >= 50$.

Prior to setting up pilot plant trials it may be prudent to assess the comparative performance of different filter media by carrying out a bench scale filterability test with small samples of media and the water produced in jar tests. Ives (1978, 1981) provided details of the apparatus and the method to carry out such a test. Four further filterability indices were briefly described by Hess et al. (1998). Of these, one index did not include any factor related to water quality, while those that did include water quality tended to focus on solids entering and leaving the filter. Meaningful suspended solids data would be extremely difficult to get on a frequent basis, so users of these indices might be tempted to substitute turbidity data for suspended solids data. Although a rough relationship might exist between turbidity and suspended solids, changes in the nature of the turbidity or suspended solids could cause difficulties with interpretation of results.

FILTER MEDIA CHARACTERISTICS

Numerous filter media characteristics are dealt with in ANSI/AWWA B100-96 (AWWA 1996.) The first source of information for those who use AWWA standards should be B100-96. Throughout this chapter when the AWWA Standard for Filtering Material deals with the topic, this will be pointed out.

Special-Purpose Media

Some filtering materials are used for special purposes rather than general use. One such material is greensand, sometimes referred to as "manganese greensand." According to Twort, Ratnayaka, and Brandt (2000) manganese greensand is produced when greensand (the mineral glauconite, a natural zeolite) is treated with manganous sulfate followed by potassium permanganate. This process forms a manganese-coated greensand, which can remove soluble iron and manganese. When the removal capacity of the manganese greensand is exhausted, it can be restored by soaking the filter bed in potassium permanganate. In many water treatment plants, potassium permanganate is continuously fed into the influent water, so the manganese greensand can be continuously regenerated. According to Twort, Ratnayaka, and Brandt manganese greensand typically has an effective size of 0.30 to 0.35 mm, and a uniformity coefficient of 1.4 to 1.6. As a result of the relatively small effective size (as compared to typical sand or anthracite sizes), clean bed head loss at a given filtration rate will be higher for manganese greensand than for sand or anthracite when bed depths of all three filters are the same. The smaller size of the greensand may serve to limit filtration rates, as compared to rates appropriate with dual media. This filtering material tends to be applied in pressure filters, and for smaller water systems. Twort, Ratnayaka, and Brandt report that manganese greensand can be successfully regenerated by continuous dosage of free chlorine, and this is said to yield longer filter runs and lower operating costs than regeneration with potassium permanganate.

MEDIA SIZE TESTING

Sieve Media Grain Size Analysis

Sieve analysis is discussed in ANSI/AWWA B100-96, available from the American Water Works Association (AWWA 1996). Because of the complexity of performing a sieve analysis properly, many water utility personnel may prefer to have this analysis performed by a commercial analytical laboratory with extensive experience in the sieve analysis procedure. When sieve analysis is performed by competent laboratories and valid results are obtained, a review of the long-term trends of those results can reveal if abrasion is wearing down media, resulting in smaller media. Also, a review of sieve analysis results can detect growth of media size caused by calcium carbonate precipitation in lime softening plants. Media coring and sieve analysis are recommended at intervals ranging from one to five years, depending on past experience, in Chapter 10. If data accumulated over a period of years show that media size is not changing significantly, the interval between sieve analysis tests might be lengthened. On the other hand, if a serious problem of media size change is detected in a year's time, more frequent testing intervals may be called for, especially if some corrective action has been taken and utility staff need to know if media size has been stabilized by the corrective action.

Filter media grain size is defined by a sieve analysis. First, a representative sample of filter media must be taken and then dried. It should be remembered that stratification can take place in a filter bed, particularly when a fluidizing backwash is used. This means that the smallest filter grains will tend to be located at the top of the filter media layer, with the largest grains at the bottom. A representative sample should be taken by coring the filter or by excavating at known depths in the filter (see detailed section on media sampling).

New media delivered to a plant should also be properly sampled. Media can become stratified in bags during transportation or if delivered or placed by hydraulic devices.

A set of standard sieves should be used, together with a collecting dish at the bottom (the "pan") and a lid on the top. The sieves are arranged in order with the largest mesh aperture at the top and the smallest at the bottom. A representative sample of filter media is dried, weighed and placed in the topmost sieve. The weight of media used will vary with the size and manufacturer of the sieves, but 100 g or 200 g are typical. The lid is fitted and the whole assembly is placed in a mechanical shaking apparatus. After a standard period of shaking the sieve assembly is removed and the mass of grains retained on each sieve is determined by careful weighing. It is vital that all grains are removed from

each sieve without damaging the sieve mesh (many manufacturers supply suitable tools and brushes for this purpose). Note that for friable materials such as anthracite and Granular Activated Carbon (GAC), shorter dry sieving periods or wet sieving techniques should be used to minimize media damage and thus false results.

The percentage of the original total mass of media retained by each sieve is calculated and this is plotted on one of two types of graph. In case 1 the graph is plotted to show the percentage material by weight retained on a linear Y axis against the sieve aperture on a logarithmic X axis. This produces a sigmoidal (S-shaped) curve. Cleasby and Logsdon (1999) described a more appropriate method where the data are plotted on a log-probability graph that often yields an approximate straight line. The sieve opening is on the Y (log) axis and the % passing on the X (probability) axis. Either type of curve can be examined to estimate the grain size at which 10% by weight of the media is finer, i.e. a virtual sieve size that 10% of the media passes through (alternatively 90% of the media has been retained) and the grain size at which 60% by weight passes (40% retained). These sizes are termed the d_{10} and d_{60} respectively.

Filter media also may be defined by the sieve sizes where 5% passes and 95% passes. Hence a typical filter sand used in the U.K. is defined as British Sieve Size (BSS) 16-30. In this example 95% of material passes BSS 16 mesh (1.00 mm nominal apertures) and 5% passes BSS 30 mesh (0.50 mm nominal apertures). The sand is often called 16-30 sand, or 0.5-1.0 mm sand. For users of USA Standard Series Sieves, a No. 18 sieve has a 1.00-mm aperture, and a No. 35 sieve has a 0.50-mm aperture. With the USA Standard Series Sieves, this sand would be an 18–35, or 18 by 35 sand.

Differences in International Sieve Sizes

A discussion of sieves, sieve sizes, and calibration of sieves can be found in AWWA B100-96, Appendix B. This appendix recommends that an ASTM procedure should be used to calibrate sieves.

It is important to note that different countries have different national specification standards for sieve mesh apertures. There is a considerable degree of similarity in the sieve apertures that are specified when metric nominal aperture sizes are compared. It is usual to characterize filter sands with woven wire mesh sieves, but square and round perforated plates also exist. Examples of standards include International Test Sieve Standard ISO 565:1990, ISO 3310, American ASTM E11:95, Australian AS1152:1973, and British Standard BS 410:1986.

To avoid confusion it is important when describing filter media to specify carefully which standard is being used, and the sieve apertures in millimeters, in addition to the range of mesh sizes that

the sand falls between. For example in Great Britain, sand defined as BSS (BS 410: 1986) 16-30 mesh, is 1.00-0.50 mm, whereas in the United States ASTM 16-30 sand is 1.18-0.60 mm. In the US the Tyler and ASTM mesh sieve numbers for some metric aperture sizes are similar, yet for others are different.

Filter media size should be considered to be an estimate as filter sands have irregular shapes and most sieve apertures are square sections. Cleasby and Logsdon (1999) identified that it was necessary to allow a tolerance of plus or minus 10% in size measurement to enable suppliers and operators to agree that a given specification of a sample has been satisfied and to maintain economical media costs.

For further information sieve manufacturer Endecotts (1977) have produced an excellent test sieving manual.

Effective Size

Media effective size (ES) is defined (AWWA 1996) as "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." This is often stated as the d_{10} value. This is derived from the graph of percentage of media retained against sieve aperture produced from the test sieving results.

Uniformity Coefficient

Media uniformity coefficient (uc) is defined (AWWA 1996) as "A ratio calculated as the size opening that will just pass 60 percent (by dry weight) of a representative sample of the filter material divided by the size opening that will just pass 10 percent (by dry weight) of the same sample." The 60 percent size is the d_{60} size. The *uc* is the value of d_{60}/d_{10}. Typically uc values of 1.4 to 1.5 are specified for a given media type, although some utilities may specify a lower uc. Specifying a low uc avoids getting too wide a range of grain sizes with the possible risk of the large and small grains mixing together and restricting the pore spaces. While some intermixing of media types at the interface is acceptable, excessive intermixing can cause problems. If the uc is extremely low, however, the media supplier will have to sieve very large quantities of medium to obtain the needed quantities of filter material with the low uc. Thus the unit cost of filter material is likely to rise as the uc decreases.

Hydraulic Size

Stevenson (1997) stated that the hydraulic size of the media should be calculated as this represents the equivalent size of uniform filter media that would have the same hydraulic loss as the media with a uc > 1. The calculation of this value is as follows:

1) From the sieve size analysis divide the percentage weight retained by the sieve aperture (mm) for each sieve size used.
2) Sum these figures
3) Divide the sum by 100.
4) Obtain the reciprocal of this value.
5) Add 10% to adjust the retained size to the center size between one sieve mesh and the next in series.

NOTE: Step 5 applies only if the stack of sieves has apertures that increase in steps of 20%. For example Table 11.1 shows theoretical sieve sizes for increasing 20% steps (from the mid-aperture of 0.85 mm) against a set of British Standard (BS) sieves and a set of USA Standard Series sieves for 0.6 to 1.18-mm sand.

The result is the hydraulic size. Stevenson (1997) said that the hydraulic size should be used in calculating head loss with the Kozeny equation. Cleasby and Logsdon (1999) stated that in determining backwash water rates the d_{90} size of the media should be used. This size is often not quoted by media suppliers. Cleasby and Logsdon (1999) said this could be calculated from $d_{90} = d_{10}\ (10^{1.67 \log uc})$, a relationship appropriate for a linear log-probability sieve analysis fit.

Table 11.1

Examples of stacks of sieves with apertures increasing in steps of approximately 20 percent

Media size for theoretical 20% increase in sieve aperture	British Standard sieve size	USA Standard Series sieve number and designation
0.49 mm	0.5	No. 35, 500 μm
0.59 mm	0.6	No. 30, 600 μm
0.71 mm	0.71	No. 25, 710 μm
0.85 mm	0.85	No. 20, 850 μm
1.02 mm	1.00	No. 18, 1.00 mm
1.22 mm	1.18	No. 16, 1.18 mm
1.47 mm	1.41	No. 14, 1.40 mm

Hardness and Attrition

The hardness of filter grains relates to its suitability for long service life in a filter. Silica sand, ilmenite and garnet are hard materials. Anthracite and GAC are relatively soft and more easily abraded. Cleasby and Logsdon (1999) stated that anthracite filter coal specifications often require a hardness of 2.7 - 3 Mohs. For GAC, Cleasby and Logsdon (1999) referred to the standard mechanical abrasion tests given in AWWA Standard B604-74 (AWWA 1974). They stated that Graese et al. (1987) had reported in an AWWARF report that mechanical degradation of GAC due to backwashing and regeneration was not a serious problem.

Hardness testing

Hardness is estimated by trying to scratch one material with other materials of known standard hardness. The hardness scale used in geology is Mohs' Scale of Hardness. In this scale, a substance with a higher number will scratch a substance with a lower number. Minerals and their hardness ratings on the Mohs' Scale of Hardness as given by Schultz and Cleaves (1955) are:

1 talc

2 gypsum

3	calcite
4	fluorite
5	apatite
6	feldspar
7	quartz
8	topaz
9	corundum
10	diamond

According to Schultz and Cleaves, the hardness of a fingernail is about 2.5, an iron nail is about 5, glass is 5.5 to 6, a steel knife blade is about 6, and a steel file is nearly 7. According to Mohs' scale, calcite will scratch a fingernail, and a fingernail will scratch gypsum. AWWA B100-96 states that the hardness of anthracite filter material shall be greater than 2.7 on Mohs' scale, and the hardness of high-density sand shall be greater than 5. The 2.7 Mohs' hardness value was an average of hardness values of numerous individual grains of anthracite tested and found to have hardnesses of 2 or 3 or less than 4 (Walter 2001).

Rate of Attrition Testing

When the durability of a filter medium is under question it is advisable to construct a small pilot column in a laboratory, add a known mass of media of known grain size distribution, and run repeated backwashes of identical rates and durations as the main plant. After a number of backwashes the media should be removed from the column, dried, weighed and sieved. NOTE: attrition during dry sieving of soft filter materials can cause weight loss. The number of washes should be representative of the expected life of the media, say at least 300 backwashes to represent 1 to 2 years' operation. Comparison with the original data will show whether media has been lost or changed size through abrasion. If air scour or surface wash is used in the full-scale plant, they should be used in this column testing also.

A backwash test column will need retaining structures e.g. wire mesh above the expanded media volume to prevent media being washed out, or a trap to collect material abraded off the media grains or accidentally washed out.

Ives (1990) suggested that water-only washing could be used at a rate that just fluidized the media to maximize the attrition due to grain collisions. A 100-hour test could be completed in a week

and would represent 3 year's worth of backwashes. This method would be much less labor intensive as it does not include all the stops and starts associated with real backwashes. It has the potential disadvantage that it might underestimate the potential abrasion to the media as it doesn't allow for the bed to expand and collapse during each wash, but this is partly over come by not fluidizing the bed to its full expansion. Also, the method doesn't allow surface wash effects or air scour effects to be considered.

Where the backwash under test uses the collapse-pulsing combined air scour and low rate water backwashing conditions it might be possible to run this continuously and still be representative of full scale conditions. To do this, however, probably would require use of a special test apparatus. Kawamura et al. (1997) provided a diagram and description of apparatus used to evaluate GAC media loss during backwashing. Their equipment included a washwater supply tank, a recycle pump, and a bag filter that caught media that overflowed. Because the goal of an attrition study is to expose media to extended washing action, media loss must be minimized. In addition to the equipment of Kawamura et al. a media attrition test column would need to be designed to hold media loss to an absolute minimum. This might involve use of special baffles resembling a bubble trap, extra column depth, and an inverted cone-shaped or pyramid-shaped upper zone to achieve very low rise rates.

Testing of anthracite filter material for quality is an issue that was discussed in the 1980's during the time when this manual's co-author (Logsdon) was chair of the Standards Committee on Filtering Materials, and those discussions continued in the 1990's, as the issue is addressed in the Foreword of B100-96. According to the Foreword, on the basis of some water utility experiences with loss of anthracite in filters and the difficulty of accurately defining anthracite hardness by using the Mohs' scale of hardness, the Committee on Filtering Materials investigated other abrasion tests. Procedures used for testing both new and used, hard and soft, and good-performing and poor-performing anthracites were Mohs' scale of hardness, "paint shaker friability," and Hardgroves' Grindability Index, or HGI. The committee did not believe that sufficient data were available on which to base a standard when B100-96 was approved. Therefore in the Foreword, the following tests for evaluation of anthracite characteristics were listed:

ASTM D409—Standard Test Method for Grindability of Coal by the Hardgrove Machine Method
ASTM D3174—Standard Test Method for Ash in the Analysis Sample of Coal and Coke from Coal
ASTM D3175—Standard Test Method for Volatile matter in the Analysis Sample of Coal and Coke

The above tests can be used to obtain data on HGI, percent volatiles, ash percent, carbon percent, and washability characteristics. The Committee on Filtering Materials indicated that more data on anthracite characteristics would be important to the next revision of B100-96 and encouraged users of anthracite to obtain data of the kinds described above.

Recently, support gravel proposed for use in construction of slow sand filter beds was tested for durability using the Los Angeles Abrasion Test (ASTM C131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine) to assess its suitability for this purpose. For the slow sand filters, the sand and gravel would have to withstand the weight of loaded dump trucks when sand is scraped and removed from the beds. Gravel assessment was based on the percentage loss at 500 revolutions in the machine.

Acid Solubility

Acid solubility is evaluated to ensure that filter media does not comprise aggregates of finer grains cemented together, or contain excessive amounts of calcium carbonate, such as shell fragments. AWWA Standard B100-96 should be used in the United States. In the AWWA procedure, acid solubility is evaluated by immersing a known weight of dry material into 1 to 1 hydrochloric acid (a 50:50 solution of hydrochloric acid and distilled water) until the acid-soluble materials are dissolved, rinsing with distilled water, drying and weighing again to determine weight loss. Details of the procedure are presented in the Test Procedures section of B100-96, which states that the upper limit for acid solubility for media smaller than a No. 8 USA Standard Series sieve (2.36 mm) is 5%. For materials between No. 8 and 1 inch the acid solubility limit is 17.5%. For larger materials the limit is 25%.

An alternative method has been developed by Ives (1990). In this test a known dry weight of media is soaked in 20% HCl at 20° C for 24 hours. At the start of acid soaking the analyst should check for effervescence and later the release of yellow-brown color from iron deposits on the grains. After rinsing in distilled water and drying the grains should be weighed. A loss of 2% by weight is excessive according to Ives. This is much more stringent than the limits set forth in B100. A sieve analysis could also be performed if sufficient material was tested and concretion was suspected.

Filter Media Shape (Roundness and Sphericity)

Care is required with the terms roundness and sphericity as they refer to different properties of the grain, and have different definitions in geological and chemical engineering literature (Cleasby 1990). Roundness is an assessment of whether the grains have sharp edges or corners or whether these have become worn through weathering. Sphericity (ψ) is the ratio of the surface area of an equal-volume sphere to the surface area of the grain. In practice sphericity is the extent to which the grain resembles a sphere. The grain may or may not have a rounded surface.

Filter media is rarely perfectly round, although a number of fundamental filter modeling studies have been published which used spherical glass beads. Surface roughness is important in assisting filtration. Data given by Gimbel (1989) and Kau and Lawler (1995) showed that materials such as pumice or filter coke, with surface cavities and high degrees of surface roughness, were more effective filters than quartz sand, which was in turn superior to glass spheres.

The sphericity of filter media determines filter porosity according to an inverse relationship (Cleasby and Logsdon 1999). Sphericity therefore has an impact on head loss across a media bed. The porosity and media surface area / volume terms in the Kozeny equation are both affected by media grain shape (see porosity section below).

The sphericity influences the gross volume occupied by the filter media, including voids. This determines the mass of media of a given density required to achieve a given bed depth. This value is the bulk density of the media (see below).

Sphericity might also influence the fluid streamlines through the bed. Both these factors could theoretically influence filter efficiency by their effect on the transport, attachment and detachment processes that carry flocs to, and away from, the media surface.

Both round and angular filter media have been used in filters in the United States and elsewhere. Rounded sands have been used for many decades. Crushed materials such as anthracite, pumice, 'stone', ilmenite and garnet have been successfully used in numerous filter plants. Anthracite and crushed 'stone' can be used in deep coarse filter beds. Anthracite, sand, and garnet or ilmenite are used in multi-media filters. (Rounded sand grains are necessary for continuous moving bed filters).

A well-rounded and weathered sand may appear to be smooth but the electron microscope shows otherwise. Particle capture and adhesion depend more on this small-scale roughness rather than that estimated by visual (macroscopic) appearance.

In terms of shape there is the issue that all forms of silica have a conchoidal fracture whereas other minerals tend to fracture along cleavage planes. Conchoidal fractures produce a rounded shape when the mineral is struck. For this reason flint can be struck to make arrowheads that taper to a sharp edge. Silica, after weathering, tends to form rounded shapes while the other minerals will tend to form angular geometric shapes with a very rough surface.

Sphericity Testing

Sphericity may be estimated from microscopic examination of media at low power, and comparison with photographic charts. Alternatively Ives (1990) described the method and calculation for deriving the sphericity from the rate of fall of individual grains through a 1-m deep column of water.

Filter Media Material (i.e. sand, anthracite, garnet, ilmenite, crushed rock, pumice, tuff etc.)

As stated above a wide range of filter media have been used in water filtration. For locations where established media suppliers are in business and are able to provide materials meeting filter design specifications and AWWA standards, the established suppliers may be the preferred source. From an economics point of view for developing countries it may be sensible to use a locally available material, provided it meets other criteria, such as size, shape, density, hardness and cleanliness, so that it will form an effective barrier to particles for a prolonged period of operation.

Where the filter is comprised of two or more layers of media, the size and density of the media, and the backwashing conditions must be specified such that the media layers remain separated. Pilot trials are the most convenient method of determining this. Tests with small diameter columns (6 inches or 15 cm diameter, or less) can be problematic because of air becoming trapped under the bed and lifting it as a single mass. This can be counteracted by inserting a wire or similar across the surface of the bed to effectively "slice" the bed as it rises.

Specialized media such as greensand (ferruginous sandstone where the iron is present as iron (II) compounds) or polarite (sand with a manufactured coating) may be used where the catalytic removal of manganese is required. GAC may be used in some filters as a replacement for anthracite or sand. GAC provides other benefits such as removal of color, taste and odor, trace organic compounds, and in some circumstances provides a biological stage or affords some protection from pollution incidents.

Density of Filter Media

The relative density or specific gravity of individual filter grains is one of several factors important in determining the rate of water flow to achieve a certain bed expansion during backwashing at a given water temperature. It is also one of several factors that determine the rate at which media grains settle after backwashing. In systems where combined air scour and water washing takes place over a weir it determines the size of stilling zone adjacent to the weir necessary to reduce media losses.

Silica sand has a grain density of 2.65 g/cm^3. The density of anthracite coal varies from different sources but is typically 1.4 to 1.7 g/cm^3. Higher density minerals used as a lower layer in triple media filters have typical values such as garnet 3.9 g/cm^3, and ilmenite 4.2 g/cm^3.

The density of GAC and anthracite filtering materials must be determined after a suitable period of wetting (24 hours), to allow water to penetrate the microscopic pore spaces within each GAC or anthracite grain. Cleasby and Logsdon (1999) state a GAC density from 1.3 - 1.5 g/cm^3 but note that the density of GAC can rise as organic compounds and / or heavy metals become adsorbed over its working life.

As mentioned above the bulk density is the mass of filter media divided by the volume occupied in the filter, so that the combination of filter grains and voidage is measured. For silica sand a value of 1.56 g/cm^3 (1560 kg/m^3) is typical, for anthracite the figure is approximately 0.8 g/cm^3 (800 kg/m^3)

Accurate knowledge of the grain density and size is required to determine backwash rates. Appropriate grain density and size are required to ensure that the appropriate size of material is used so that dual and triple media layers do not intermix excessively.

The bulk density is required to determine the approximate weight of media required to fill a filter. If filter media are purchased by volume rather than weight it avoids concerns of paying for the weight of water adhering to the media.

Density Testing

AWWA B100-96 specifies use of ASTM C127 for determination of the specific gravity of silica gravel, with results reported as saturated-surface-dry specific gravity. AWWA B100-96 specifies use of ASTM C128 for determination of the specific gravity of high-density gravel, high-density sand, silica sand and filter anthracite with results reported as apparent specific gravity. These methods should be used in the United States and in locations where AWWA standards are used by utilities.

Another technique for measuring specific gravity is to obtain a representative sample of filter media and dry it. This should be accurately weighed. If the material has internal porosity it should be thoroughly wetted. The excess moisture then drained off and then some sort of procedure for wiping the media dry is required. Achieving a consistent saturated-surface-dry condition is difficult. The media is then placed into an accurate volumetric flask. This should then be weighed. The flask should be topped up with water to the precise volumetric mark on the flask. The water should be at the same temperature as given on the flask calibration. The volume of water should be accurately recorded. The full flask should be weighed. For saturated-surface-dry specific gravity, the saturated-surface-dry weight is used.

The volume occupied by the known mass of media is then calculated from the difference between the volumetric capacity of the flask and the actual volume of water added. The media density is the mass of media used / volume it occupies.

Porosity or Voidage

The porosity, or voidage, is the percentage of the overall filter bed volume not occupied by solid material. Porosity is an important term in the Kozeny equation for calculating head loss. A practical consideration related to porosity is that it affects the clean bed head loss of a granular media filter bed. This is important in pilot plant testing done with filter columns in which the media will not settle completely after backwashing due to the small diameter of the column. This happens in filter columns 6 inches in diameter and smaller, and might occur in slightly larger columns. When the pilot column is bumped with a rubber mallet, the media will settle further until it has been compacted to the maximum extent, after which further disturbance of the column causes no additional compaction. Failure to compact filter media to a constant porosity during pilot testing can give varied clean bed head losses when filter runs are started.

For typical rounded filter sands porosity (voidage) is approximately 40%, while for the more angular anthracite it ranges from 42% (Stevenson 1997) to 60% (Cleasby and Logsdon 1999). These values change according to the management of the media. If a test filter is backwashed and allowed to settle it will result in one depth of media. If the test column is gently tapped the media will appear to compact further, the degree of compaction depending on the size and shape of the media grains. Further compaction will occur if air is blown through the bed, for example an air 'scour'. Filter media with a uc > 1 will stratify under fluidizing backwash rates. A stratified bed will occupy a greater depth than one where the grains are randomly mixed.

Porosity is calculated by taking a known mass or weight of known grain density, placing in a transparent cylinder of known internal diameter, compacting the media gently (for example tapping the side of the cylinder gently with a pencil for 30 seconds), measuring the bed depth and calculating bed volume. The grain volume is calculated by dividing the media mass by the grain density. The voidage is (bed volume minus grain volume)/bed volume.

Ives (1990) gave the equation as $\varepsilon = 1 - (M/(\rho_s.V))$, where ε is the porosity, M is the mass of media in the filter column, ρ_s is the media grain density, and V is the bulk volume of media in the column.

Trussell et al. (1999) conducted practical trials at pilot and full scale showing how porosity influenced head loss and developed a methodology for estimating porosity on full-scale filters using a pilot column. They recommended that when pilot filter columns are used to study filtration, a reasonably consistent porosity can be attained by using a gradual termination of backwash flow rather than a rapid shutoff.

Permeability

Porous filter materials may not be sufficiently permeable if the pore spaces are so small that the pressure required to move water through them is greater than the available head. In practical terms that means avoiding specifying media with grain sizes that are too small and avoiding mixing up grains sizes in dual or multimedia filters by specifying the wrong grain sizes or losing stratification by unsatisfactory backwashing. Permeability is defined by Darcy's Law, which states that the rate of flow of water through a column of saturated porous media is directly proportional to the head loss and inversely proportional to the length (depth) of the column. For example, at a head loss of 5 feet, flow of water through a 1-foot bed of sand would be twice the flow through a 2-foot bed of sand. Permeability is not the same as porosity. Permeability depends on porosity, approximately to the fourth power.

Fluidization

In order to backwash media effectively it is often necessary to determine the velocity of water at a given temperature necessary to fluidize the media. Two flow values are required: the velocity of minimum fluidization (V_{mf}) and the velocity necessary to achieve the desired bed expansion (see backwashing section). The V_{mf} of filter media is the minimum velocity of water that just achieves an

increase in the volume of the bed (fluidization) i.e. that velocity that just starts to suspend the media grains in the rising backwash water.

Fluidization test (determination of V_{mf})

The velocity of minimum fluidization of filter media may be calculated according the example given by Cleasby and Logsdon (1999). It may be more accurate to carry out a practical measurement of fluidization behavior of any given media sample. By passing water up through a column of fully wetted and saturated media at a gradually increasing flow rate the head loss will rise until the buoyant weight of the media is just supported by the fluid drag of the water. At this point the bed starts to expand and no further increase in head loss is measured. As the flow rate increases the media grains separate and no further impediment to flow is observed. Graphs and further discussion of this subject are provided in *Water Quality & Treatment, 5th Ed.* by Cleasby and Logsdon (1999).

When conducting this test in a laboratory four points must be noted:

- The flow rate should be adjusted in small incremental (even) steps
- The head loss versus the flow rate must be recorded for the apparatus without media first and this value (the "blank" value) subtracted from the test with media.
- When head loss (minus blank) is plotted against flow rate, the V_{mf} for uniformly sized grains is determined from the inflexion point (i.e. the intersection of the rising slope and the flat slope).
- With non-spherical material the inflexion point is not easily detected because the media grains have to become "unlocked". In this case the fluidized bed head loss is just a little lower than the maximum head loss at the point of incipient fluidization.
- For graded filter material, smaller grains fluidize first at a low upflow rate and larger grains fluidize at a higher rate. The V_{mf} for the full bed occurs at the lowest velocity when the head loss becomes constant.

Media Cleanliness

New filter media should be delivered relatively clean, but there must be provision to backwash it adequately (and possibly disinfect it with sodium hypochlorite solution) before it produces water for

public supply. Once in a filter it needs to be kept reasonably clean to ensure effective filtration over its service life.

Cleanliness of filter media is addressed in AWWA B100-96 in the section on physical requirements. Cleanliness requirements are:

- Anthracite: visibly free of clay, shale, and other extraneous debris
- Silica sand: visibly free of clay, dust, and micaceous and organic matter
- High-density media: visibly free of clay, dust, and micaceous and organic matter

A maximum of 2 percent by weight less than No. 200 (0.074 mm) as removed by washing is allowed as determined by ASTM C117. An ASTM procedure is referenced in B100-96 for testing for color.

New Filter Media.

Where there is doubt, the source (mine, quarry or pit etc.) should be visited to ensure there is no contamination of filter media from unwanted fecal, pathogenic or toxic materials.

After selecting a reputable source of media the water supplier must continue to be diligent. Representative samples of filter media should be taken and subjected to microbiological examination, and tested for organic and inorganic contaminants (e.g. heavy metals).

Visual observation will provide some clues as to the condition of the media. Silica sand is likely to be dominated by clear and/or yellow-orange colored transparent or translucent grains, with occasional grains being colored black, white or brown. The darker colored grains are usually either translucent or opaque and may consist of other minerals. Silica sand has a conchoidal fracture and freshly broken surfaces should be curved with sharp edges. No cleavage planes should be visible (i.e. no obvious geometric crystal shapes).

Anthracite grains should be black with a sub-metallic luster (silvery sheen). Garnet is a term used for a group of silicate minerals differing in chemical composition and color. The common form of garnet used in water treatment is a pink or deep red color, usually translucent or opaque. It has a vitreous or silky luster and fractures unevenly or splintery (may be able to observe crystal shapes in uncrushed material).

Ilmenite (titanoferrite) is an opaque, black mineral with the composition of iron titanium oxide. It has a metallic, greasy luster and like sand and anthracite, has a conchoidal fracture. It is magnetic and therefore easily distinguished from many similar looking materials.

Chemical disinfection with chlorine or hypochlorite is also advisable. Samples of filtered water should be examined visually for appearance (clarity and color) and for odor. The filter should be run to waste or backwashed again until the water quality is suitable for public supply.

Example specifications for new supplies of filter media are given in appendices (1) and (2) at the end of this chapter.

Existing Filter Media.

The routine management of filter media in existing filters is discussed in chapter 10 and methods for examining media are given in appendices at the end of the following section.

Rubbing a small amount of media in the palm of the hand should not leave a dirty brown residue. It should not be possible to roll the media up into a ball. If mass of material retains its shape it is likely to be coated with deposits (e.g. 'mud') and it may not be possible to back-wash this off. There should not be large foreign bodies in the media for example sticks, stones, litter, detritus (e.g. leaves) or animals (including fish).

GRAVEL / SHINGLE AND ALTERNATIVE MEDIA SUPPORT SYSTEMS

Gravel/Shingle

One or more gravel or shingle (an English term referring to rounded gravel about 5 to 15 mm in diameter) layers is often necessary to prevent filter sand from passing into, or clogging, the filter floor structures, and to facilitate even distribution of air and water into the filter during backwashing. Rounded gravels (pea shingle) are preferred to prevent or reduce damage to plastic nozzles - crushed material tends to be very sharp - particularly if it's a form of silica as is usual – e.g.. think how sharp flint is!

The Foreword of AWWA B100-96 has two examples of multiple layers of support gravel for use under fine filter media (ES in the range of 0.40 mm to 0.50 mm and ES in the range of 0.50 mm to 0.60 mm.) One example was based on using four layers of gravel, while the other example employed five layers.

One application worked on by one of the authors involved retro-fitting combined air and water backwashing to a filter with 3 mm wide nozzle slots. To achieve the collapse pulsing backwashing recommended by Amirtharajah et al. (1991) it was necessary to have a double reverse-graded gravel system. The nozzles were overlaid by a layer of 10-20 mm gravel, then 5-10 mm gravel, then 1.7-4.7 mm grit, above this were 5-10 mm and 10-20 mm gravel layers. Each layer was 75 mm deep. The sand was able to penetrate to the 1.7-4.7 mm layer, but no further. Pilot trials of other gravel arrangements showed that unless it was held in place by the larger gravel layers, the fine gravel was mobilized by the backwashing process.

Gravel should be subjected to the same checks for suitability as other filter media (see above and appendix). For silica-based supplies grain density is 2.65 g/cm^3, bulk density 1.56 g/cm^3.

In older systems a progressive series of layers of stones and gravels may be present. Cleasby and Logsdon (1999) presented guidelines for the selection of gravel sizes.

ALTERNATIVE MEDIA SUPPORT SYSTEMS

As an alternative to support gravel, some manufacturers have developed plastic media support systems. One uses a porous high-density polyethylene beads that are sintered together into a thin block that can be fastened to the top surface of the underdrain. Another alternative support system is the wedge-wire screen, shaped like a portion of a wedge-wire well screen cut into an arch-shaped segment along the length of the axis of rotation of the cylindrical screen. These screens might be thought of as having the shape of a small, very long Quonset hut. Use of support gravel can be eliminated when an alternative support material is employed, and the headloss for these supports is the same as the gravel that it replaces, thereby assuring a uniform distribution of backwash water across the whole filter. By eliminating the support gravel, and the possibility of gravel upsets, loss of media into the underdrain is eliminated. The overall depth of the filter can be reduced which would provide additional freeboard and reduce media losses during backwashing or allow for deeper media depths in existing filters. This design also allows for easy and complete removal and change of media such as granular activated carbon, which must be removed and regenerated periodically.

FILTER CONDITION ASSESSMENT AND MEDIA MANAGEMENT

Filter Bed Construction

Unless a filter is designed and constructed correctly then the techniques discussed will not get a plant out of trouble. Filter floors should be reasonably level, and the underdrain devices (nozzles, block floors etc.) should be designed and installed to achieve a level structure, so that there is no fundamental reason why filtration or backwash water or air scour are not evenly distributed across the entire filter surface area. In addition, washwater troughs must be level, or else more water will flow over the troughs in the low areas, encouraging an uneven upward flow of water in the filter.

Whether a filter is new or undergoing refurbishment, good engineering practice must be adopted in the installation of filter hardware and media. The utility should ensure that reputable contractors are used and that the contract includes terms to ensure that workers adopt good hygiene practices, both personal and in terms of the equipment they use. Care should be taken at all times to avoid damaging fragile items such as filter nozzles, laterals, or block floors in transport, handling, and installation. Retaining bolts should be correctly positioned and tightened. Each and every filter nozzle or block floor should be correctly installed and checked. When filter gravel, filter media, or other filter structures are put into place after the floor has been built workers should use clean boards to spread their weight, tools or ladders should not be dropped onto floor structures or boards, and media should not be dropped into position in a way that could cause damage. When there is a possibility that damage has been caused it should be a notifiable event and the floor should be checked by a qualified engineer. Backwash water and air scour distribution should be checked after floor structures have been built but prior to the installation of any media. Media layers should be backwashed and skimmed until fines are removed for every layer used.

Examples of filter floor failure experienced by one utility include:

- In a filter floor consisting of laterals embedded in a concrete matrix with nozzles screwed into the lateral: Problem - erosion of concrete around the cap of nozzles due to backwashing, leading to media in the filter laterals. Solution - a flat plate was fitted under each nozzle cap to prevent backwash air and water by-passing the nozzle slots
- In a filter floor consisting of nozzles screwed into a lateral embedded in gravel: Problem - filter nozzles became unscrewed as the pipe thickness only allowed 2 turns of pipe thread to

hold the nozzle in place. Solution - a collar was welded to the PVC lateral pipe where each nozzle fitted to allow more pipe thread.

- In a filter floor consisting of nozzles and a plenum chamber: Problem - filter media in the plenum, investigation after excavating the entire filter showed that some of the nozzles had broken slots (cause unknown). Solution - extremely careful replacement of nozzles and media.

SAMPLING AND TESTING THE MEDIA

Procedure for Sampling Filter Media.

In the United States and in other locations where AWWA B100-96 is used, procedures for sampling filter media are given in the AWWA Standard and in ASTM D75, and those procedures should be followed. AWWA B100-96 discusses sampling from bulk shipments in rail cars and trucks, and the same rationale could be used for sampling in filter beds. The standard stipulates that 10 samples of filtering material shall be taken; one from near but not in each corner, one from the center, and five at random locations. Sampling in a filter bed would be similar if a core sample were taken near but not in each corner of the filter, one from the center, and five at random locations elsewhere in the bed. AWWA B100-96 also states that the minimum weight of material to be collected in the composite sample is 10 pounds (4.5 kg) for granular material of 9.5 mm or smaller. This size limit would cover all materials used as filtering material, but not all support materials.

Media Testing

A number of detailed test procedures for examining filter media are given in the Appendix. These procedures are listed below. They are used in the United Kingdom or elsewhere in the world and are presented in this manual as supplemental materials. In the United States, procedures presented in ANSI/AWWA B100 are recommended. Where ANSI/AWWA B100 does not have procedures comparable to those in the appendix, the appendix procedures are presented as methods that have been proven in application elsewhere.

Tests and procedures presented in the Appendix are:

Appendix 1	Example Procedure for Approval of New Supplies of Filter Sand and Shingle Support Media
Appendix 2	Example Quality Criteria for New Supplies of Filter Sand & Shingle
Appendix 3	Methodology for Quick Scanning Media Sources.
Appendix 4	Sampling Filters for Media Cleanliness
Appendix 5	Simple Method of Determining Filter Media Cleanliness
Appendix 6	Extraction of Solids from Filter Media
Appendix 7	Determination of Dry Weight Extractable Solids or "Silt" in Sand Samples
Appendix 8	Determination of Particulate Organic Carbon (POC) in Sand Samples
Appendix 9	Detection of Iron (and Copper) in Filter Media Samples
Appendix 10	Detection of Aluminum in Filter Media Samples

Replacement of Media

Reasons for Replacement, and Precautions to Observe

Filter media replacement may be done for a variety of reasons. Media loss may have become so substantial that addition of media was necessary to restore the filter bed to its original design depth. Over the years, media abrasion and wear or the accumulation of calcium carbonate deposits may have changed the physical characteristics of the filtering material so that it is now out of specification for ES (effective size) or uc (uniformity coefficient). In unusual situations involving chemical spills, contaminated water passed through the treatment plant may have tainted of filter media, necessitating replacement. An example of this kind of situation might be a spill of gasoline or other petroleum products. If media replacement were cheaper than media clean up, replacement would be the option of choice. Some water utility managers choose to replace an effective filtering material because they want to meet additional performance goals that can not be attained with the material in the filters. Examples would include replacing sand with larger ES anthracite so longer filter runs could be attained, and replacing some sand or anthracite with GAC for control of tastes and odors or other organics. An expensive reason for media replacement at some plants has been damage to the underdrain, filter floor,

or support gravel, necessitating complete removal of the filter media and reconstruction of the filter bed (and sometimes the filter floor or underdrain).

Case studies of filter rehabilitation and media replacement are presented in Chapter 13. These case studies are

- "Coring of Dual Media Leads to Identification of Cause of Media Loss,"
- "Filter Inspection and Maintenance at a Lime Softening Plant," and
- "Rehabilitation of Filters at Brick Utilities."

Many of the techniques and procedures described in this manual are "do it yourself" procedures intended to be carried out by water treatment plant operators and other staff members. Replacement of filter media is not one of these "do it yourself" procedures. Issues related to media design, specification, purchase, and installation are sufficiently complex that most water utilities should seriously consider using the services of an engineering consultant who thoroughly understands filtration and filter media. On the other hand, adding small amounts of media to an existing filter is a practice routinely and appropriately carried out by water utilities

Careful consideration to the backwash conditions is required if replacing the original media with a different medium of different density or size. Failure to evaluate suitability of a filter medium used to replace some other filtering material could result in inadequate backwash, badly intermixed media, or loss of media during backwash.

A note of caution is in order for water utilities in the United States. Many state regulatory agencies must approve media replacement projects, especially if changes in media type or specifications are planned. In the USA, check with your state regulatory agency before changing or replacing media.

Topping-up filter media

Replacing lost filter media, or topping-up media, is a maintenance task that is performed periodically by numerous water utilities. The appropriate time for replacing lost media is after a major filter inspection, as described in Chapter 10, which this manual recommends be done on an annual basis. Measurements of the filter media elevations in each bed, and probing data, will provide the numbers that can be used to determine the depth of filter media in the beds. Core samples of backwashed filter beds can be tested by sieve analysis at the utility or at a commercial laboratory to develop information on the ES and the uc of the filter materials. If the bed depth is deficient by a few inches or more, and if the

medium in the bed still meets the specifications for ES and uc, then adding more medium of the type needed is a satisfactory action. When topping up media, match the specifications (ES and uc) of the existing medium and the material being added as closely as possible. If the new and existing filtering materials do not have similar specifications, after backwashing the filter bed could have a zone of intermixed filter media where porosity was low and head loss was high. Another potential problem is that a portion of the filter bed could have media substantially different in size from the rest of the material in the bed.

When the sieve analysis results indicate that a medium no longer meets the specification under which it was purchased, carefully consider replacement of the medium. In dual and multi-media beds, obtaining a valid sieve analysis is more difficult due to the need for absolute separation of the two or three types of media before conducting the sieve analysis. If this is not done, the sieve analysis can be distorted and media may be replaced unnecessarily. Before embarking on replacement, conduct another filter inspection, and take more filter media samples for sieve analysis, following the procedures given in this manual with great care. The cost of extra materials testing in the laboratory is a tiny fraction of the cost of installing new filter media, except for the smallest of filtration plants. Perform enough careful inspection, sampling, and testing to be sure that the capital investment truly is needed before going out and spending large amounts of money on new filter media.

A special cautionary note is in order with regard to topping up filters having dual media or mixed media beds. If filter media elevations are determined and the level of anthracite in the bed seems to be dropping, a seemingly obvious solution would be to add more anthracite. This could be especially compelling if anthracite had been observed in washwater troughs following backwash, as this would be a sign that anthracite was being washed out of the bed.

Do not top up the uppermost layer of a dual media or mixed media filter, however, without obtaining core samples to verify that the lower layer or layers of filtering material (such as sand, garnet, or ilmenite) are still present per the original filter design. It is possible for sand to be washed out of a filter bed during backwashing and not observed in washwater troughs, especially if the troughs are made of concrete and the color of the troughs is similar to the color of the sand. The authors are aware of a dual media filter that was about to be topped up with anthracite when core sampling revealed that very little sand remained in the filter bed. Adding anthracite without verifying the presence of other filtering materials beneath the anthracite could ultimately result in having a filter consisting of nearly all

anthracite. For commonly-used dual media or mixed media filter depths, a monomedium anthracite bed of the same depth would not be deep enough to function as effectively as intended by the filter designer.

Replacing Filter Media Completely

Complete replacement of filter media starts with removal of existing media. Even if media replacement was all that was intended, the condition of support gravel, the media floor and nozzles, or the underdrain (or a combination of these) should be evaluated. With the media removed, these are more accessible than they will be later on when media has been put in place. Don't pass up the opportunity for a thorough inspection of the filters when media has been removed. If support gravel must be removed, its reuse generally is not feasible. To be reused, graded support gravel would have to be screened and sorted into sizes, just as was done originally by the gravel supplier. Because of the cost of labor and equipment needed for reuse, purchasing new gravel is the practical alternative.

Disposal of used sand media and support gravel should not be a problem, if contaminants have not precipitated onto the materials. If filters are backwashed before media is removed, the used sand and gravel can be used for the typical applications for which sand and gravel are purchased. Used anthracite filter material might find an application as a fuel, if a small user of coal could be located. Spent GAC in some cases can be returned to a facility that reactivates granular carbon for further use.

In the United States and elsewhere, water utilities that use AWWA B100-96 should refer first to this standard for information on physical characteristics of filter materials, sampling and testing procedures for verifying that media meets specifications, for requirements related to packing and shipping media, and for procedures to use when placing media and preparing the filter for use.

B100-96 states that each filter cell, including the underdrain plenum, shall be cleaned thoroughly before filtering materials are placed. The top elevation of each layer is to be marked by a level line on the inside of the filter cell. Detailed directions are given for placement of filter materials and for washing the gravel (if used) and for washing and skimming each layer of filtering material.

New filter media should be washed to remove fines and loosely attached coatings, and any dust or residues picked up in transportation. After several fluidizing backwashes the spent backwash water should be clear. This however does not mean the media itself is fully cleaned. Tests are required of the media itself - a simple sample, shake and a visual observation will do (see Appendix 5).

The bed should be manually skimmed using walk-boards and hand shovels to remove the finest filter media grains. B100-96 recommends removal of 3/16 inch or about 5 mm after the initial

backwash, but greater amounts are removed after the initial backwash in the U.K. Backwash and skimming cycles should be repeated until all fine material is removed, according to both B100-96 and U.K. practice. Skimming should be repeated for each media layer in turn when a dual or multimedia filter is being constructed. When a filter is skimmed, backwash and fluidize the bed. Then very gradually decrease the rise rate so stratification will be maximized as the bed settles down after backwashing. Maximizing stratification results in the greatest proportion of media fines being located at the top of the bed after backwashing, which makes the scraping more effective for removal of the fine material that has the potential to cause high clean bed head loss during filter operation.

After all work related to media placement has been concluded, the filter should be disinfected before being returned to service, according to B100-96. ANSI/AWWA C653 gives the procedure to follow for all filtering materials except granular activated carbon (GAC). For GAC refer to ANSI/AWWA B604, which was being revised when B100-96 was published.

Reusing Filter Media

Reuse of filter media is a common practice at large slow sand filter plants, where sand is periodically removed in thin layers by scraping, and then replaced as a thick layer after many thin layers have been removed. Plants where this is practiced generally have facilities for cleaning and storing used sand. Reuse of filter materials at rapid rate plants may be more complicated. When multi-media filter beds are used, removal of a single medium is very difficult, if not impossible because of the interfacial intermixing of media that occurs during backwash. To reuse filter materials with confidence, one must be able to segregate material types. The difficulty associated with this task would seem to preclude reuse of filter materials from multi-media beds. This leaves older rapid sand filters and new monomedium filters as candidates for reuse.

Reuse is appropriate only if the filter material still meets its original specifications, or if the utility is satisfied that even though the material is slightly out of specification, it is performing satisfactorily with regard to filtered water quality, head loss development, and behavior during backwash. Reusing badly performing media would be a mistake. If equipment is available for removal of a filter medium without damaging it, and if facilities are available for cleaning and storage of the medium, then reuse may be feasible. This should be considered on a case by case basis, and labor costs involved have to be included to fairly compare purchase of new filter material versus reuse of the existing material.

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APPENDICES OF THAMES WATER UTILITIES PROCEDURES

Appendix (1)	**Example Procedure for Approval of New Supplies of Filter Sand and Shingle Support Media**
Appendix (2)	**Example Quality Criteria for New Supplies of Filter Sand & Shingle**
Appendix (3)	**Methodology for Quick Scanning Media Sources.**
Appendix (4)	**Sampling Filters for Media Cleanliness**
Appendix (5)	**Simple Method of Determining Filter Media Cleanliness**
Appendix (6)	**Extraction of Solids from Filter Media**
Appendix (7)	**Determination of Dry Weight Extractable Solids or "Silt" in Sand Samples**
Appendix (8)	**Determination of Particulate Organic Carbon (POC) in Sand Samples**
Appendix (9)	**Detection of Iron (and Copper) in Filter Media Samples**
Appendix (10)	**Detection of Aluminum in Filter Media Samples**

APPENDIX 1

Example Procedure for Approval of New Supplies of Filter Sand and Shingle Support Media (From the United Kingdom)

The quality of new supplies of sand should be checked. The analyses performed will be dependent on the petrology of the source material and the conditions of extraction, storage and any processing of the material. In general, visual observations often provide the best evidence of potential contamination. Such contamination can then easily be accomplished in the laboratory.

1. All new supplies of sand and shingle must comply with the Utility's Quality Criteria. Requests for clearance by the appropriate Technical Manager to use new supplies of sand/shingle should be forwarded to .....

2. All requests for clearance of filter media shall be supported by documentation showing the specification of the material. This specification shall include values of the determinants and details of the physical criteria listed below.

   Concentrations of:

   a) Dry Weight Extractable Solids or 'silt' content.
   b) Particulate Organic Carbon (POC)
   c) Metals
   d) Carbonates

   Fecal Contamination

   a) *Escherichia coli*
   b) Faecal Streptococci
   c) *Clostridium perfringens*
   d) *Cryptosporidium & Giardia*

   Geotechnical analysis

   a) Grain Size Distribution
   b) Grain morphology and characteristics (shape)
   c) Surface Texture
   d) Color, fracture and appearance

The certificate/report shall include a description of the material, in petrological terms, with approximate percentages of each type of mineral, and details of the source(s) of the material(s).

3. If the requirements detailed in "2" are not available, they should be determined by submitting samples of the material, from the specimen sample, for testing as appropriate. The specimen sample shall consist of equal quantities of material taken from 10 different points of the stockpile: a 30kg sample is required. Samples should be submitted directly to the test house by the originator of the inquiry quoting cost code.

APPENDIX 2

Example Quality Criteria for new Supplies of Filter Sand & Shingle (From the United Kingdom)

GENERAL

Sand/Shingle supplied shall be clean river, beach or pit material, and be hard, strong and durable. It shall be entirely free from clay, earthy or organic matter and adherent coatings, and shall be washed as necessary to fulfil this condition. The sand shall consist of silica (e.g. quartz) grains (minimum 95%).

The sand/shingle grains shall be natural, there being no other artificially crushed stone or mineral present. The sand/shingle must not disintegrate or change in grading specification when shaken vigorously with water or during normal transportation and transfer operations.

The contractor shall provide contemporary test certificates corresponding to each $100m^3$ of sand/shingle delivered to site showing grain size grading within 3 days of the corresponding deliveries.

QUALITY

Sand/Shingle for use in water filters shall not be contaminated by other materials. Tests for these appear below.

Dry weight solids content.

This is expressed as the dry weight of all solid material (generally less than 0.15mm diameter) liberated from a known volume of sand/shingle by vigorous manual shaking with water

A maximum limit of 1.0 kilogram of silt per cubic meter of sand/shingle is recommended

Particulate Organic Carbon

This is an estimate of the organic solids present either adhering or otherwise trapped within the sand/shingle mass.

A maximum limit is 0.1 kilogram of POC per cubic meter of sand/shingle is recommended.

Metals

Large quantities of certain metals and their compounds are generally undesirable and limits should be placed on the concentration in sand supplies. These limits would not apply to specialized or coated media used for the catalytic removal of iron and manganese from solution. The soluble metal extractable of the metals listed below, obtained by shaking with demineralized water for 2 minutes, shall be less than 0.1% w/w.

Iron

Manganese

Aluminum

Carbonates

Carbonate minerals are usually very soft and can cause problems in terms of fine material clogging. The sand/shingle should contain less than 2% w/w of carbonates.

Fecal Contamination

Filter Sand/Shingle

There shall be no discernible evidence of faecal contamination. Representative 100 gram samples of the sand/shingle, as delivered, shall, when shaken with 500 cm^3 of sterile water, produce less than 10 colony-forming units (cfu) of *Escherichia coli* and/or faecal streptococci per 100 cm^3. No detectable spore or oocyst/cyst producing organisms (e.g. *Clostridium perfringens*, *Cryptosporidium* or *Giardia*) shall be present.

SIZE & GRADING

Rapid Filter Sand / Anthracite / Shingle

The sand, anthracite or shingle shall conform to the grain size specification produced specifically for each contract. Shingle supplied shall be the size range specified, rounded, single sized aggregate (sometimes referred to as Pea shingle)

OTHER CRITERIA

Generally, there should be no toxic materials or substances present. The sand/shingle should originate from, and be stored at, places where there are no visible signs or history of contamination by sewage, sewage solids or other pollution sources.

The vehicles used for transporting sand/shingle should be clean and have not been previously used for transporting sewage, sewage sludge or other waste/organic materials.

Sample acceptance/rejection

It is desirable that samples of media from loads arriving at water treatment works be taken, as and when required and checked against the standards used.

Samples failing any of the above criteria shall result in rejection of the entire load unless additional cleaning by the Water Utility has been authorized in the contract.

The filter sand/anthracite/shingle shall comply rigidly with this specification and the contractor should be satisfied that before submitting the Tender that the price covers the cost of all necessary screening, cleaning and all other labors.

In some instances failure to comply with the specification with respect to Dry Weight Solids may at the discretion of the Utility on advice from the Named Manager, result in the acceptance of the load provided that the supplier makes up any short fall in weight or volume of sand/anthracite/shingle due to other material and subject to compliance with the grading and quality specification.

Laboratory Analyses

All analyses and tests shall be by methods approved by the Utility, Laboratory Manager or Technical Manager as appropriate.

Access to Contractors Pit and Plant

The Utility's appointed staff shall be given every facility for the inspection of the quarry, pit or other extraction works including any screening, grading, processing and storage facilities, before the acceptance of the tender and during the extent of the contract.

APPENDIX 3

Methodology for quick scanning media sources.

Suggested quick field method.

Equipment: Hand lens or magnifying glass - need 10x power or more.
Light source (sun or lamp).
White paper.
Hand tool for crush test - steel penknife OK but something more massive is best - I use the butt-end of a scalpel handle but anything similar will do - even a coin!
Piece of planed flat wood or metal (large coin) as a hard surface.

If you can get a low power light microscope you will really be in business! Most labs should have one! Dark ground illumination is OK but you will be able to see more if the grains are illuminated FROM ABOVE (rather than below). The pictures below use normal below sample lighting and are nowhere near as good as top lighting!

Look at grains under the hand lens. Un-weathered quartz will be obvious - it has no cleavage planes and fractures conchoidally - i.e. splinters come off and leave a hollowed curved surface. For example Chalcedony (silica mineral identical to quartz in composition) was used for thousands of years as cutting tools - FLINT - fractures conchoidally and quartz should look the same under the hand lens.

Weathered quartz is much trickier to identify but there are some easy guidelines - quartz is likely to be clear or white, transparent to translucent, possibly with red-brown staining due to iron oxides (such oxides do not generally cover all the grain but are limited to fissures in the grains). Quartz is difficult to crush using steady hard hand pressure - put the grain on the block of wood or metal then place the crushing tool (coin....) on top and apply hand pressure. When it does crush the splinters will have the classic conchoidal fracture.

If you practice a bit you will get the 'feel' of the material. Softer minerals that crush easier are not likely to be durable in a filter.

Feldspars and other common minerals are more likely to be opaque - otherwise they can be classed as gemstones! These minerals with a few exceptions are going to fracture along cleavage planes (like slate). The cleavage will depend on the atomic structure and is different for each mineral. The

main point is that the mineral will fracture more easily than quartz (as a general rule) the point of weakness being the cleavage plane(s). You may be able to see the planes but crushing tends to leave a powder with no structure visible under a hand lens or low power microscope.

You can also try a chemical test - if it fizzes with vinegar then you've got a carbonate (probably calcite). We don't want carbonates in the filters - they are very very soft! Not all carbonates fizz however so the crush test is important.

APPENDIX 4

Sampling Filters for Media Cleanliness

Introduction

Sampling a filter to determine media cleanliness is complex if a high level of statistical confidence is required. The subject is too complicated to detail here but would involve a number of preliminary samples to estimate the population variance. From this starting point it would then be necessary to use statistical methods to determine the minimum number of further samples to be taken to meet the required level of significance, accuracy (mean) and variance (precision).

Such a probabilistic approach would normally require a relatively large number of samples, which would be difficult in practice to achieve. Moreover, it would require considerable laboratory and human resources.

A non-probabilistic method is therefore recommended. Whilst this limits further analysis of the results obtained, it does provide a simple estimate of media cleanliness and thus back-washing effectiveness.

The main property of filter media cleanliness is that the dirtier the filter becomes the greater the variance of the results. This contagious (over-dispersed, or clumped) dispersion of material in the filter is due to such phenomena as 'jetting' and other localized differential up-wash velocities.

Filters with an effective backwash exhibit low values of dry weight solids and particulate organic carbon (POC) with low variation. At the other extreme, filters with an ineffective backwash rapidly accumulate deposits in a highly contagious manner. With the latter, deposits are contagiously distributed both vertically through the depth column and over the whole filter bed area.

Interpretation of results can therefore be difficult. The solution is to sample the same filter under the same conditions for a period of time and note the trends in the data obtained. Low results with little variation indicate an effective backwash, whilst results with large variations and high maxima ('peaks') indicate a back-washing system that is ineffective (the degree of contagion tends to be positive correlated with the quantity of material captured and accumulated in the filter media).

The sampling and laboratory methodology is basic and provides useful operational guidance. The methods are not designed to produce results of high accuracy or high precision. Repeatability

should be within approximately 20% in any one sample. Repeatability between samples tends to be considerably worse and dependant on the dispersion of material in the filter.

Sampling

Filter media is normally sampled at various depths at several sites within a filter bed. The number of samples taken is dependent on the degree of accuracy and precision required plus the resources available. As a general rule filter media cleanliness can be estimated by taking three to five samples in a depth column at three to six different locations in the filter. For a filter depth of 62.5 cm the following depths would be a good compromise.

0.0 - 2.5 cm
10.0 - 12.5 cm
25.0 - 30.0 cm
50.0 - 62.5 cm (or bottom 12.5cm of filter media).

If five locations were chosen then this would give a total of 20 samples. Twenty samples would take a laboratory technician approximately one day to analyze for dry weight solids and POC. True random sampling is not really feasible and the variation is likely to be large in any case. Sampling locations are chosen that are reasonably evenly spaced and "representative" of the filter area (not necessarily representative of the true dispersion of accumulated material). Sampling close to the edges of a filter should be avoided as such locations are not usually representative of the filter as a whole ('edge' effects).

The samples can also be bulked e.g. all the 0-2.5 cm samples bulked together, thoroughly mixed and then sub-sampled in the laboratory (in the above example this would yield four [depth] samples per filter however many locations were sampled).

It is not recommended to bulk all the depth column samples together as it will then be difficult to determine depth effects and the integration will not be calculable. If it is desired to determine the dispersion of material in the filter then a large number of samples will need to be taken and analyzed separately. Such a sampling program could be set up by use of a grid within the filter bed. Depth

samples would then be taken at each intersection of the grid. Random sampling in this case would be inappropriate as the objective would be to map any gradient found.

Filter media may be sampled using coring devices although difficulties are likely to be experienced with clean filter media (clean rounded filter media does not hold well in a coring tube). Coring devices may also compress the media and it may then be difficult to determine the true depth from which the sample was obtained. Alternatively, a small trench may be dug and a trowel or flat plate can then be inserted into the vertical face of the trench and samples from measured depths obtained.

Sampling itself often provides a good indication of the media cleanliness. Holes dug in clean filter media usually collapse rapidly and larger pits need to be excavated. Dirty filter media grains adhere together and sampling holes do not readily collapse.

The surface of the media should also be observed. Large, irregular dispersed 'boils' and cracks in the media are indicative of dirty filter media and an ineffective backwash.

'Mud balls' are concretions of organic and inorganic constituents that are indicative of very dirty filter media. In extreme cases a compacted layer across most of the filter area may form at depth.

Materials and Equipment Required

Equipment is basically crude and may be obtained easily. A garden spade or shovel, a garden trowel, a ruler (plastic is preferable) and some re-sealable plastic bags is all that is required. If a coring device is required, this can simply be made from a length of perspex tube. If a flat plate is preferred to a garden trowel then this may be made from a rectangle of mild steel, but protected along one edge with a custom made handle to prevent damage to the hands.

Stout rubber boots are recommended; preferably with steel reinforced toecaps for safety reasons. A safety helmet may be required by regulations or if there are any projecting structures in the filter shell.

Sodium hypochlorite solution should be available so that boots and equipment can be chemically disinfected. A 1% solution should be adequate.

A ladder and rope are essential.

Equipment, including boots, should be washed and dried after use and stored for filter sampling only.

Preparation

Sampling should be performed just after a backwash. If the backwash is effective then the filter media will not accumulate deposits. Conversely if the filter backwash is ineffective then a recent backwash will not significantly affect the results. For the filter media to be sampled the filter must be drained and this is most easily and quickly accomplished immediately after backwashing.

It is important to drain the water from the whole media depth column else sampling will be difficult, if not impossible. Pools of water in the bed, at the surface or at depth, will result in some of the deposits being washed away from the samples.

All automatic valves should be locked off before entry to the filter to prevent accidental operation and the dangers from drowning. Operation of backwash valves or inlet valve is likely to result in 'quick-sand' like conditions in the filter and egress may not be possible.

All sampling items and boots etc. should be thoroughly cleaned, washed in sodium hypochlorite solution and rinsed with potable water before entry into a filter shell. Hygiene is paramount and care should be taken such as washing hands etc. before entry into the filter. Ladders should be made secure by pushing firmly into the media and tying to suitable hand railing or other suitable permanent structure.

Sampling Method

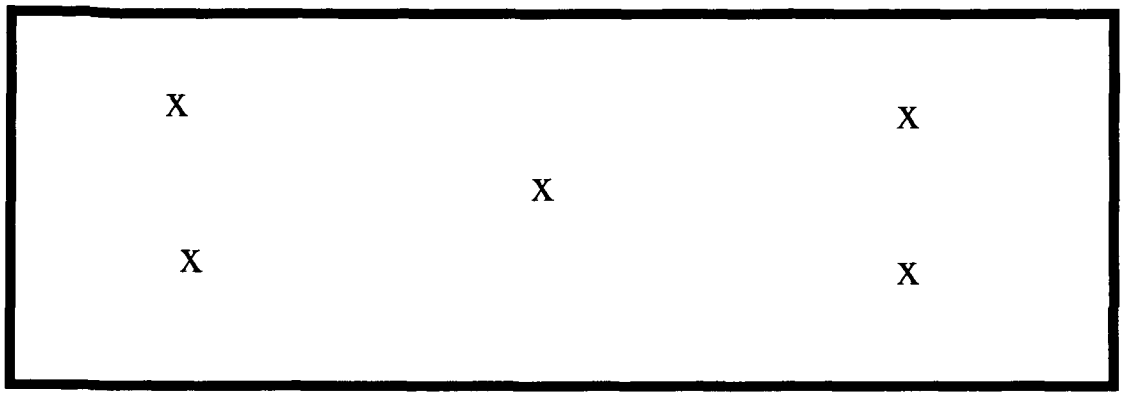
The simplest sampling method is to manually dig a small trench or hole down to the support layers (usually gravel). A side of the hole should be a vertical flat 'face'. A trowel or plate can be inserted into this face at designated depths. The media sample is then transferred to a labeled resealable plastic bag.

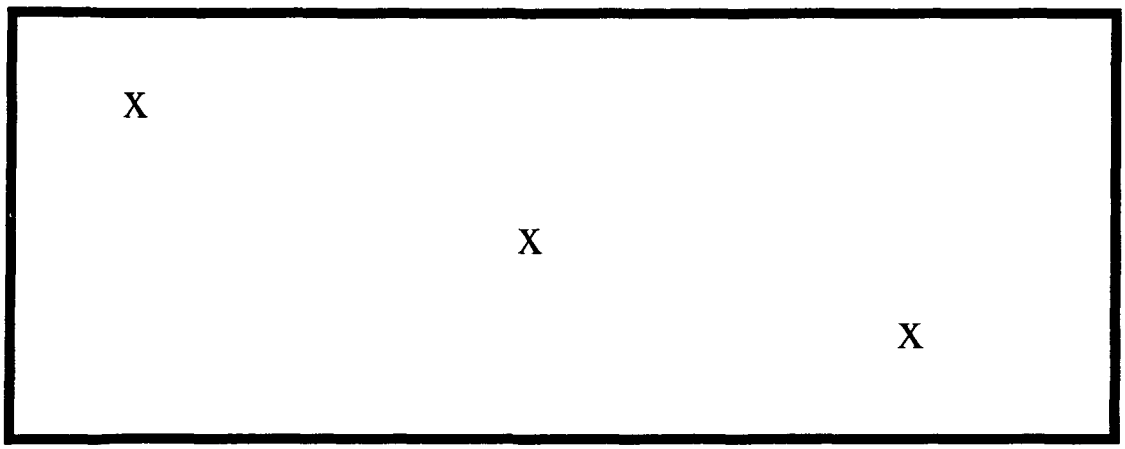
Using a simple coring device [tube] it is only necessary to push the tube into the media, cover the open end with the palm of the hand and pull the tube out again. It is unlikely that depths greater than approximately 30 cm will be obtainable due to the force necessary to insert the tube. It may therefore be necessary to dig a trench to sample near the bottom layers of the media.

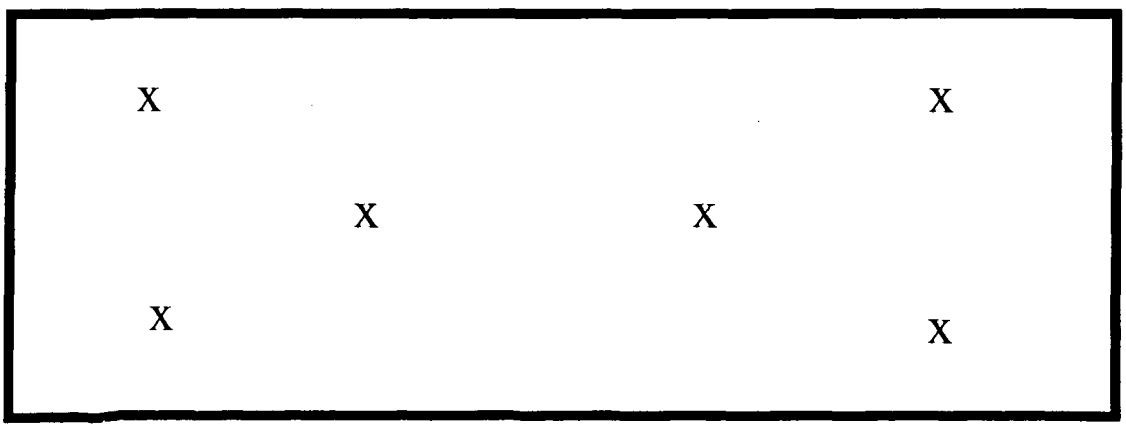
When digging holes and trenches it is important not to disturb any gravel support layers or damage any structures, particularly plastic type nozzles. A small amount of damage to a plastic nozzle may result in media loss through the bed and subsequent further erosion of nozzles during backwashing

(the media being pushed upwards again). Under these conditions an entire bed may have to be fitted with new nozzles and the pipe-work/plenums cleaned out.

Sampling sites may vary with the area and linear dimensions of a filter. Suggested site patterns are given below (rectangular filters) looking down at the filter media surface (plan view).







The 'X' denotes a sampling site, i.e. a depth profile taken at site marked.

If the dispersion of material is to be determined then a grid is required, sampling taking place at each grid intersection (node). A grid of 60 or so equally spaced nodes should be sufficient to estimate the gross dispersion of material. A 'contour' type map of the filter media at different depths may then be obtained. This is unlikely to be a common requirement due to the large number of samples generated and the dynamic nature of any deposits in the filter.

Interpretation of Results

Values for filter media cleanliness are given for each laboratory method. The absolute values are not always critical and trends over at least three months of weekly sampling tend to be of more use. Overall, the effects on filtered water quality and starting head-loss are the over-riding factors. Experience with local results is often more useful than a set figure based on any one set of filters.

Operators should thus set dry weight solids and POC criteria based on local experience. Long term trends offer more in terms of bed management strategies.

The Dry Weight:POC ratio is important in understanding results. A ratio of less than 4:1 is indicative of a significant biogenic component (e.g. algae, detritus etc.) whilst a ratio in excess of 6:1 indicates a predominance of inorganic particles (either clay and silt derived from the water, excess precipitated coagulant or 'fines' in the filter media).

APPENDIX 5

Simple Method of Determining Filter Media Cleanliness

Introduction

Filter media may be analyzed using a number of methodologies. The simplest technique is to extract filtered material from the filter media and measure the relative volumes after settlement.

The method here identifies the steps necessary to separate the captured particulate matter from the filter media. The technique is fairly violent and is thus suitable for sands and fine gravel. There is a limited application for softer materials such as anthracite and granular activated carbon (these materials are abraded by the extraction method). Other strong, durable filter media may be analyzed e.g. garnet, ilmenite.

Materials and equipment required

250 cm^3 measuring cylinders with plastic (sealing) stoppers. Glass cylinders are preferred but plastic materials may be used if sufficiently strong, abrasion resistant and transparent.
Heavy-duty gloves (the thick 'glass blower/worker' soft leather type are ideal).
Eye protection.

Preparation

When shaking the cylinder as detailed below take all necessary safety precautions. Glass cylinders have been used successfully but breakage can occur, particularly when larger stones/shingle is present in the filter media. Face and eye protection are required in addition to safety gloves for prevention of cuts from broken glass. The most common accident is for stones to break the glass at the base of the measuring cylinder and so thick leather gloves are mandatory.

It requires stamina to extract a large number of samples and adequate preparation of time is advised. The media samples must be shaken for considerable periods (1-2 minutes each) with as equal a force as possible.

Ultrasonics and automatic shaking methods have been tried but were generally inferior to manual shaking.

Extraction process

Place approximately 100 cm^3 of filter media in a 250 cm^3 measuring cylinder. Add clean tap water to the 200 cm^3 mark. There is no requirement to use purified water.

Stopper tightly and hold the cylinder horizontally in both hands, one hand on the base and the other hand on the stopper. Shake by using an oscillating sideways motion in a vigorous manner for at least one minute. The 'swing' of the cylinder should cover at least 20 cm, the filter media being violently transferred from one end of the cylinder to the other on each swing. Continue shaking for at least one minute. This action dislodges deposits on the media and degrades larger masses.

It is likely that the glass cylinder will break from time to time. As mentioned above the usual cause is larger stones, but occasionally a break may result from hand pressure. Hence, gloves and spectacles (or similar eye protection) that are resistant to broken glass should be worn at all times.

Stand cylinder vertically [on its base] on a level surface for long enough to ensure that the filter media has settled. Top up with the same media sample so that the level of media (excluding any fine material) reaches the 100 cm^3 mark. Shake the cylinder again for a few seconds. Top up the cylinder with water to the 250 cm^3 mark. Shake the cylinder violently again for at least one minute. Stand cylinder vertically again and tap gently with the gloved hand to ensure the filter media forms a level surface. Allow the contents to settle. The time taken for settlement will vary according to the cleanliness of the media and the nature of the material. Generally, 20 to 30 minutes is adequate. Settlement time is determined experimentally by trial and error and should then be kept as a standard for the particular water treatment works. It is inadvisable to use long settlement times as denitrification can occur in some samples, the nitrogen gas released disturbing the sediments. The objective is to achieve a fairly clear supernatant. Record the volume of sediment (above the filter media grains) as V_c.

There are no standard values of V_c, rather the values are comparative between samples. The value can be used for trending although care should be taken as small changes are likely to be due to errors in measurement.

Anthracite (coal) media

Anthracite or other coal-based media are likely to be significantly abraded by the extraction method. A gentler action is needed with this material, i.e. gentle turning of the cylinder end over end. The extraction is much less effective than shaking. Ultrasound may prove effective but there is always the risk of media grain fracture.

Granular Activated Carbon

Occasionally a filter utilizes this medium. The extraction method, even using gentle action, is not suitable due to the friability of this material.

APPENDIX 6

Extraction of Solids from Filter Media

Introduction

Filter media may be analyzed using a number of methodologies. Media state may be judged using two simple laboratory methods. The methods are:

- Dry Weight Solids and
- Particulate Organic Carbon (POC).

The methods estimate filter media cleanliness and therefore the effectiveness of backwashing.

The methods may be used in conjunction with sieve-sizing techniques and the use of filtration rate and head-loss measurements.

The method here identifies the steps necessary to separate the captured particulate matter from the filter media. The technique is fairly violent and is thus suitable for sands and fine gravel. There is a limited application for softer materials such as anthracite and granular activated carbon (these materials are abraded by the laboratory extraction method). Other strong, durable filter media may be analyzed e.g. garnet, ilmenite.

Where the filter material is derived from crushed stone, an examination should be made of the mineral constituents. Soft minerals, such as the mica group and feldspar group may be significantly abraded by the extraction method and lead to falsely high results (testing fresh, washed and clean media will determine this).

Materials and equipment required

250 cm^3 measuring cylinders with plastic (sealing) stoppers. Glass cylinders are preferred but plastic materials may be used if sufficiently strong, abrasion resistant and transparent.
Small flasks (100 cm^3 round or conical are ideal) and stoppers.
Heavy-duty gloves (the thick 'glass blower/worker' soft leather type are ideal).
Eye protection.

Preparation

When shaking the cylinder as detailed below take all necessary safety precautions. Glass cylinders have been used successfully but breakage can occur, particularly when larger stones/shingle is present in the filter media. Face and eye protection are required in addition to safety gloves for prevention of cuts from broken glass. The most common accident is for stones to break the glass at the base of the measuring cylinder and so thick leather gloves are mandatory.

It requires stamina to extract a large number of samples and adequate preparation of time is advised. The media samples must be shaken for considerable periods (1-2 minutes each) with as equal a force as possible.

Ultrasonics and automatic shaking methods have been tried but were generally inferior to manual shaking.

Extraction process

Place approximately 100 cm^3 of filter media in a 250 cm^3 measuring cylinder. Add clean tap water to the 250 cm^3 mark. There is no requirement to use purified water for this stage.

Stopper tightly and hold the cylinder horizontally in both hands, one hand on the base and the other hand on the stopper. Shake by using an oscillating sideways motion in a vigorous manner for at least one minute. The 'swing' of the cylinder should cover at least 20 cm, the filter media being violently transferred from one end of the cylinder to the other on each swing. Continue shaking for at least one minute. This action dislodges deposits on the media and degrades larger masses.

It is likely that the glass cylinder will break from time to time. As mentioned above the usual cause is larger stones, but occasionally a break may result from hand pressure. Hence, gloves and spectacles (or similar eye protection) that are resistant to broken glass should be worn at all times.

Stand cylinder vertically [on its base] on a level surface for long enough to ensure that the filter media has settled. Tap the cylinder gently with the gloved hand to ensure the filter media forms a level surface. Record the volume of filter media (ignoring fine silt and other matter) in cm^3 as V_s. Record the total volume [filter media, water etc.] in cm^3 as V_t.

Shake the cylinder again in the manner above for a few seconds, remove the stopper and rapidly pour off the supernatant suspension into a flask. The objective is to decant the fine material and

organics etc. but to leave the filter media in the cylinder. Discard the filter media and remaining supernatant from the cylinder.

Calculation

There are no calculations at this stage although it is necessary to calculate the dry weight solids and/or POC relative to the volume of filter media. To achieve this the following factor is calculated:

Volume of filter media = V_s

Total volume of media and water etc. = V_t

We need the volume of water which will be the difference between the two values above plus the volume contained within the voids between media grains. A porosity of 30% is assumed for this. Different porosities could be measured for each media type, size and shape although the range is likely to lie between 25 and 40%. Porosity of dirty media is likely to be small and difficult to measure, hence the assumed 30% porosity to estimate all media.

Volume of water = $(V_t - V_S) + 0.3V_s$

To relate this back to each cm^3 of sand and provide a factor for later calculations, the above equation is divided by the volume of media i.e.

$$\frac{(V_t - V_s) + 0.3V_s}{V_s} = \frac{V_t}{V_s} - \frac{V_s}{V_s} + 0.3\frac{V_s}{V_s} = \frac{V_t}{V_s} - 1 + 0.3 = \left(\frac{V_t}{V_s}\right) - 0.7$$

The latter term in the equation above is the simplified factor used for the calculations in the dry weight solids and POC methods.

Anthracite (coal) media

Anthracite or other coal-based media are likely to be significantly abraded by the extraction method. A gentler action is needed with this material, i.e. gentle turning of the cylinder end over end. The extraction is much less effective than shaking. Ultrasound may prove effective but there is always the risk of media grain fracture. The dry weight solids method may be used subsequently provided that any obvious media grains are removed from the circles (see method). The POC method will be grossly contaminated with only a few microscopic grains of coal and it is not recommended.

Granular Activated Carbon

Occasionally a filter utilizes this medium. The extraction method, even using gentle action, is not suitable due to the friability of this material. It is possible however to use a gentle method for the purposes of subsequent straining of the invertebrates colonizing the bed for taxonomic identification and enumeration via microscopy.

APPENDIX 7

Determination of Dry Weight Extractable Solids or "Silt" in Sand Samples

The sampling and extraction methodologies are given elsewhere.

Introduction

The method is often referred to as 'silt' analysis but this terminology is not strictly correct, silt having a precise geological [inorganic] definition in terms of particle size. This analysis includes all mineral material between approximately 1 μm to 0.5 mm in diameter and all organic material including small invertebrates, algae and detritus.

The method is suitable for sands and gravels. There is a limited application for softer materials such as anthracite and granular activated carbon (these materials tend to be abraded by the laboratory extraction method).

Materials and equipment required

Oven with removable sliding shelf (set to 60°C). The oven should be regulated to temperature of 60^0 Celsius. Temperature control is not critical and a range of 55°C to 65°C is acceptable.
Analytical balance capable of reading to 0.1 mg (0.0001 g or 100 μg).
Forceps.
Glass fiber circles (e.g. Whatman™ GF/C grade or equivalent).
Vacuum filtration equipment.
Pipettes - large bore, graduated. 1 cm^3, 10 cm^3 and 25 cm^3 capacity.
Low volume measuring cylinders. Selection from 25 cm^3 to 100 cm^3.
Heat proof gloves.

Dry Weight determination

A number of glass fiber circles should be pre-dried overnight in the oven. Alternatively, dry until constant weight is achieved.

Remove a pre-dried glass fiber circle from the oven and mark it so that it is identifiable with the sand sample taken. Pencil marks or small clips taken out of the outer edge of the circle are acceptable but ink should be avoided (volatile components).

After marking, weigh the glass fiber circle using an analytical balance. Record this weight in milligrams (mg) as W_P.

Place weighed pad on the vacuum filtration unit. Violently agitate the extracted suspension in the flask until the contents are well mixed and filter an aliquot through the pad. The objective is to filter as much suspension as possible so that a significant weight of material can be detected on the balance after drying. It is better to use multiple small aliquots to avoid filter blockage.

Record the <u>total</u> volume of aliquot(s) in cm^3 used as V_a.

Observe pad. There should be no media (normally sand) grains present. Pick any media grains off the pad with fine forceps being careful not to disturb or remove other material.

Place pad in the oven and leave overnight to dry. A shorter time may be used provided the pad is re-weighed until no further weight loss is recorded. When removing the oven tray be very careful as the slightest draft will send the circles airborne.

Weigh pad again and record weight in milligrams as W_{P+S}.

<u>Calculation</u>

$$Dry\,Weight\,Solids\,mg.cm^{-3}_{media} = S$$

$$S = \left\{\left[\frac{V_t}{V_s}\right] - 0.7\right\}\frac{\left(W_{p+s} - W_p\right)}{V_a}$$

V_t and V_s are obtained during the extraction method.

A trapezoidal integration (with respect to depth) can then be performed on the results if required. Integrate the depth-related results to give a value in mg $\cdot$ cm^{-2} and then add the surface result. Multiply this result by 10 to convert to grams dry weight per square meter of bed.

INTEGRATION

$$Dry\,Weight\ Solids\ mg.cm^{-2}_{filter} = 10\left[\sum_{i=1}^{n}\left\{\frac{(Z_{i+1}-Z_i)(S_{Zi+1}+S_{Zi})}{2}\right\}\right]$$

Where:

Z_i	=	Depths in cm.
S_{Zi}	=	Depth dry weight results in $mg \cdot cm^{-3}$.
10	=	conversion factor for $mg \cdot cm^{-2}$ to $g \cdot m^{-2}$ ($10^4/10^3$).

Interpretation of results

A dry weight (depth) result of greater than 2 $mg \cdot cm^{-3}$ would indicate fairly dirty sand or considerable media 'fines' in the filter. An integral value of 1500 $g \cdot m^{-2}$ would suggest similar.

APPENDIX 8

Determination of Particulate Organic Carbon (POC) in Sand Samples

The sampling and extraction methodologies are given elsewhere.

Introduction

The principal of the method is that organic matter is oxidized to its original inorganic constituents. The quantity of carbon can be calculated from the quantity of oxygen utilized in the reaction:

$$C_xH_{2y}O_z + \left(x + \frac{[y-z]}{2}\right)O_2 \rightarrow xCO_2 + yH_2O$$

To determine the values of x, y and z, it is necessary to know the composition of the organic matter. In most cases this is not known but it is usually assumed as an empirical monosaccharide formula thus:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + yH_2O$$

or more simply:

$$C + O_2 \rightarrow CO_2$$

Therefore 2 moles of oxygen are required to oxidize 1 mole of carbon.

The oxidant used in the reaction is potassium dichromate.

This method is suitable for sand filtration media and similar inert inorganic minerals. It is not suitable for granular activated carbon or anthracite (coal). The latter two materials are rapidly oxidized and even a trace affects the results. Filters using the dual media combination of sand and anthracite cannot easily be tested with this method unless measures to exclude all the anthracite (large grains and 'fines') are successfully undertaken.

Reaction

The organic matter is heated with excess potassium dichromate in the presence of sulfuric acid and using a silver sulfate catalyst. The dichromate remaining unreduced at the completion of the reaction is determined by titrating with iron(II) ammonium sulfate to an end point located by a redox indicator color change.

$$K_2Cr_2O_7 + 4H_2SO_4 \rightarrow K_2SO_4 + Cr_2(SO_4)_3 + 4H_2O + 3[O]$$

Potassium dichromate reacted with sulfuric acid yields potassium sulfate and chromium (III) sulfate, water and oxygen

$$C + 2[O] \rightarrow CO_2$$

Carbon reacted with oxygen yields carbon dioxide.

$$K_2Cr_2O_7 + 7H_2SO_4 + 6\,FeSO_4 \rightarrow K_2SO_4 + Cr_2(SO_4)_3 \ldots + 3Fe_2(SO_4)_3 + 7H_2O$$

Iron(II) sulfate ($FeSO_4$) is used in the above equation in place of iron(II) ammonium sulfate as the ammonium sulfate does not take part in the reaction. The iron(II) sulfate is oxidized to iron(III) sulfate [$Fe_2(SO_4)_3$].

Interferences

The filtration media may contain substances that are oxidized by the reaction and thus give falsely high results. Anthracite (coal) and activated carbon are extreme examples. Quartz/silica sand does not interfere. Some other minerals used in filtration, or some common mineral 'contaminants', may also interfere. Samples of laboratory-cleaned media (or cleaned new supplies) can be used to determine such effects.

High concentrations of chloride ions cause the final POC to be overestimated. Soluble chlorides are best removed by washing with de-ionized/pure water (see method). Limited success can also be achieved using mercuric sulfate. For drinking water production, chloride concentration should not normally be an issue.

Iron(II) and iron(III) compounds interfere and cause the POC to be overestimated. The role of iron(III) compounds is unclear but may be catalytic in nature. Not all media samples may be affected by the presence of iron(III) compounds. Media used to filter water treated with iron coagulants may thus give erroneously high results. In practice tests should be performed on clean media with and without iron coagulants to determine any effects.

Any other reducing agents will interfere and should be removed prior to the test e.g. sulfides, nitrites and bisulfites. Hypochlorite, when used prior to filtration or coagulation may also interfere.

Reagents (all analytical grade)

Potassium dichromate, anhydrous.

Iron(II) ammonium sulfate, hexahydrate. Also known as (di-)ammonium iron(II) sulfate hexahydrate, ferrous ammonium sulfate hexahydrate and (di-)ammonium ferrous sulfate hexahydrate.

Silver sulfate.

Sulfuric acid (concentrated), Specific Gravity 1.84.

De-ionized or similar purified water.

Redox indicator: 1,10-phenanthroline iron(II) sulfate complex solution (0.025 M).

Safety Equipment

Fume cupboard with appropriate extraction.

Neoprene or similar acid-proof gloves.

Thick gloves.

Face shield.

Protective glasses.

Laboratory coat (acid proof or acid resistant).

Apparatus

Burette 25 cm^3 capacity, preferably auto-zero type.

Thermostatic hotplate - set to 105°C.

Erlenmeyer flasks 100 cm^3 capacity.

Watch glasses, 50 mm diameter.

Auto-dispenser (liquid), acid proof and set for delivery of 7.0 cm^3.

Stainless steel forceps, smooth flat blades.

Muffle furnace, thermostatic - set to 500°C.

Glass fiber filter circles, 47 mm diameter (1-5 μm particle capture).

Vacuum filter equipment for 47 mm diameter filters.

Volumetric flasks, 1 liter and 2 liter.

Measuring cylinders, range of capacities from 25 cm^3 to 100 cm^3.

Measuring cylinder, 1 liter, glass with pouring spout.

Heat resistant ('Pyrex') beaker, 2 liter capacity.

Large stirrer (acid and oxidant resistant).

Analytical balance (precision to 100 μg).

Pipette, 10 cm^3. Bulb type.

Pipette filler (safety)

Pipettes, 1 cm^3, 10 cm^3 and 25 cm^3, graduated and wide bore.

Drying oven set to 60°C.

Tongs for use with the muffle furnace.

Reagent solutions to be prepared.

1. Standard potassium dichromate 4.17 mM (0.025 N).

   Dissolve 2.4515 g of dried (60°C) potassium dichromate (anhydrous) in pure water in a volumetric flask. When dissolved, make up the volume to 2 liters using pure water.

   Store in the dark.

2. Stock potassium dichromate solution 208 mM (1.25 N).

   Dissolve 61.2875 g potassium dichromate (anhydrous) in pure water in a volumetric flask. When dissolved, make up the volume to 1 liter using pure water.

   Store in the dark.

3. Stock titrant solution 255 mM.

   Dissolve 100 g iron(II) ammonium sulfate in approximately 500 cm^3 of pure water. Carefully add, whilst stirring, 50 cm^3 of concentrated sulfuric acid. Make up to 1 liter with pure water in a volumetric flask. The acid is required to increase the stability of the reagent (prevents precipitation of iron hydroxides).

   Safety note: Always wear protective glasses or face shield when adding the acid.

   Store in the dark. Discard this solution if it becomes a deep yellow color [Iron(II) oxidized to iron(III)].

4. Working titrant solution 33 mM (0.033 N).

   Add 131 cm^3 (a measuring cylinder may be used) of stock titrant to a volumetric flask and make up the volume to 1 liter with pure water.

   Use within 14 days.

5. Digestant.

   The preparation of the digestant involves adding concentrated sulfuric acid to a small volume of aqueous solution. Considerable heat is generated and the mixture may boil, particularly in the early stages of acid addition. If the mixture is not stirred and boiling occurs then hot concentrated acid and dichromate may be ejected from the beaker. Experience of diluting

concentrated sulfuric acid is required. The procedure should be performed in a fume cupboard equipped with a front lip to prevent spillage. Protective acid proof gloves, laboratory coat and face shield must be worn. The provision of a cold water shower nearby is recommended. Alternatively a chemical supplier may be able to manufacture the reagent on request.

Add 5 g of silver sulfate to a 2 liter heat proof glass beaker.

Add 93 cm^3 of the stock potassium dichromate solution (a 100 cm^3 measuring cylinder may be used).

Add 187 cm^3 of pure water (a measuring cylinder may be used).

Mix thoroughly by swirling.

Carefully and slowly add 700 cm^3 of concentrated sulfuric acid, stirring constantly. Note the safety advice above.

Place a glass or other acid proof cover over the beaker (but do not allow a seal to form) and allow the contents to cool to room temperature. Decant digestant to a sealed bottle or dispenser and store in the dark.

Method

Take some glass fiber circles and ignite in the muffle furnace at 500°C for 1 hour. This will remove any organic contaminants. After ignition the circles should only be handled with clean forceps. Place the ignited circles in a petri dish and cover. On no account should the circles be handled as oils and other organic compounds from the skin will contaminate them.

Take the extract prepared earlier (see extraction method) and mix violently. Measure an aliquot of this extract, using a graduated wide bore pipette and filter through an ignited circle using the vacuum filter apparatus. The objective is to filter enough extract to give approximately 1mg carbon on the circle. This objective becomes easier with experience. As a guide, if the extract is very heavily loaded with solids and no light will penetrate through the flask then filter 1-2 cm^3 of the extract. If the extract is pale in color and light is transmitted then use approximately 10 cm^3 or less if the filter clogs. Record the volume of extract filtered in cubic centimeters as V_a.

The circle and deposits may now be washed, whilst maintaining vacuum filtration, with pure water to remove soluble chlorides and other soluble interfering compounds if necessary.

Transfer the circle to an Erlenmeyer flask (100 cm^3 capacity). The circle should fit exactly in the bottom of the flask and preferably with the filtered deposits facing upwards.

Set up three blank flasks using ignited circles only.

Add 7.0 cm^3 of digestant (to each sample and each blank) and place on the thermostatic hotplate set at 105°C. The hotplate should be permanently placed in the fume cupboard. Leave for 1 hour, occasionally checking the color of the digestant. If the digestant color turns green or even blue add another 7.0 cm^3 of digestant. Repeat as necessary. If it is necessary to add more digestant ensure that the flask remains on the hot plate for at least 15 minutes. Record the number of 7.0 cm^3 aliquots of digestant used as n_a.

During the digestion a watch glass should be placed over the top of each flask to minimize loss of water (via evaporation).

Remove from the hotplate and allow to cool for 10-15 minutes.

Remove watch glass and add approximately 20-30 cm^3 of pure water (wear glasses and acid proof gloves. Swirl each flask to thoroughly mix the contents.

Add 1 drop of the redox indicator to a flask and titrate using the working titrant solution. Add titrant slowly whilst swirling the flask continuously. The end point is when the color changes to red (various other color changes may take place - e.g. from yellow to green to blue but the change to red is sudden). Record the titrant volume used for the blanks as B_i. Record the volume of titrant used for each sample as T.

Take a flask that has been titrated and is just at the end point. Add to this flask and its contents 20 cm^3 of the standard potassium dichromate solution using an accurate bulb type pipette (use a 10 cm^3 bulb pipette twice).

Add another drop of redox indicator and titrate as normal. Record the volume of titrant used, S.

Calculations

For each sample:

$$mgPOC.cm^{-3}_{sand} = \left[\left(\frac{V_t}{V_s}\right) - 0.7\right] \cdot \frac{\left[\left(n_a \cdot \frac{\sum_{i=1}^{n_b} B_i}{n_b}\right) - T\right] \cdot 1.5}{S \cdot V_a}$$

where n_b is the number of blanks set up.

V_t and V_s are obtained during the extraction method.

$\frac{\sum_{i=1}^{n_b} B_i}{n_b}$ is the average blank.

All units for each variable are in cm^3.

The individual results for the depth samples may be integrated thus (trapezoidal):

$$gPOC.m^{-2}_{filter} = 10\left[\sum_{i=1}^{n}\left\{\frac{(Z_{i+1} - Z_i)(POC_{Zi+1} + POC_{Zi})}{2}\right\}\right]$$

Where:

Z_i	=	Sample depths in cm.
POC_{Zi}	=	Depth POC results in mg · cm^{-3}.
10	=	conversion factor for mg · cm^{-2} to g · m^{-2} ($10^4/10^3$).

Sand media is normally judged to be 'dirty' if individual sample results exceed 0.4 mg POC · cm^{-3} or if the integral exceeds 250 g POC · m^{-2}.

Environmental Note: Spent reagent disposal

Discard all spent reagents safely. The sulfuric acid, chromium, iron and silver content may be subject to local disposal laws and these should be checked beforehand.

It is possible to recover the silver used although the economics may not justify this. The silver may be precipitated from solution by the addition of a small volume of concentrated hydrochloric acid. After a few days settlement, the supernatant liquor can be discarded [still containing acids, iron(III) and chromium(III)] and the silver chloride filtered, washed and dried. The silver chloride is then best returned to a recycling facility as it is generally too expensive and complicated to recycle to analytical grade silver sulfate in the laboratory. If the silver is to be recycled in the laboratory then the chloride needs to be washed several times with pure water, reduced to the oxide in boiling sodium hydroxide solution, filtered, washed and then dissolved in nitric acid. The sulfate can then be precipitated with excess dilute sulfuric acid. The silver sulfate produced must then be washed thoroughly to remove any nitric acid, nitrates and soluble sulfates.

If it is necessary to remove chromium [chromium(III) sulfate] and iron remaining in the spent reagent this may be partially removed by precipitation with sodium phosphate (after removal of silver chloride).

The remaining acid may be neutralized if necessary with any convenient base, although great care should be taken with alkali metal hydroxides as heat will be generated. If this step is undertaken then all chromium(III) and iron compounds will be precipitated (as complex hydroxides) and can be separated by settlement and filtration. Ammonia solution should not be used to neutralize the acid as the chromium may be held in solution as a complex. Ground chalk or limestone may also be used but will generate copious quantities of carbon dioxide gas and leave a large amount of solid calcium sulfate contaminated with chromium and iron compounds.

Examples

1. Carbon digestion

Blank titrations:	22.8, 23.1, 22.9 cm^3
Standard titration:	18.2 cm^3
Sample titration:	11.6 cm^3
Volume of extract filtered:	3.0 cm^3
Number of 7.0 cm^3 aliquots of digestant:	2
From extraction method:	

Volume of sand:	86 cm^3
Total volume:	243 cm^3

Then:

$$mgPOC.cm^{-3}_{sand} = \left[\left(\frac{243}{86}\right) - 0.7\right] \cdot \frac{\left[\left(2 \cdot \frac{(22.8 + 23.1 + 22.9)}{3}\right) - 11.6\right] \cdot 1.5}{18.2 \cdot 3}$$

$$mgPOC.cm^{-3}_{sand} = 2.13 \cdot \frac{[(2 \cdot 22.93) - 11.6] \cdot 1.5}{54.6}$$

$$mgPOC.cm^{-3}_{sand} = 2.00$$

2. *Integration*

Samples taken from a single location in the filter from 4 different depth regions.

Depth region (from surface downwards) cm	P.O.C. $mg \cdot cm^{-3}$
0 to 5	0.38
10 to 12	0.49
25 to 30	0.16
50 to 60	0.18

Applying the trapezoidal formula:

$$gPOC.m^{-2}_{filter} = 10\left[\begin{array}{l}\frac{5\cdot 0.38}{2}+\frac{(10-5)(0.38+0.49)}{2}+\ldots \\ \ldots\frac{(12-10)0.49}{2}+\frac{(25-12)(0.49+0.16)}{2}+ \\ \frac{(30-25)0.16}{2}+\frac{(50-30)(0.16+0.18)}{2}+ \\ \frac{(60-50)0.18}{2}\end{array}\right]$$

$$gPOC.m^{-2}_{filter} = 10[0.95+2.175+0.49+4.225+0.4+3.4+0.9]$$

$$gPOC.m^{-2}_{filter} = 125$$

APPENDIX 9

Detection of Iron (and Copper) in Filter Media Samples

Fresh samples of filter media may be easily tested for iron compounds by the following method. The method is qualitative.

Introduction

Fresh supplies of media may contain considerable quantities of Iron compounds. Whilst small amounts of iron oxides are unlikely to degrade filter performance, excessive quantities may cause the filtrate turbidity to rise and/or result in rapid head-loss increases (fine particles). There may also be Regulatory standards issues.

Equipment and Chemicals

Microscope, low power.
Plastic or glass dishes (small Petri type ideal).
Membrane filtration apparatus.
Membranes (glass fiber circles, e.g. Whatman GF/C).
1 cm^3 pipette.
Pipette filler.
100 cm^3 measuring cylinder.
250 cm^3 clean glass beaker.
Glass dropper bottles (clean).
De-ionized water.
Hydrochloric acid (Analytical grade) 'concentrated'.
Potassium Iron(II) cyanide (also known as potassium ferrocyanide). Analytical grade.
Plastic forceps.
Safety spectacles.
Protective gloves.
Fume cupboard.

Methods

Wear gloves and eye protection when preparing the solutions. Solution 2 should be prepared in a fume cupboard. Always use a pipette filling device and never 'mouth pipette'.

Solution 1: Weigh 2 grams of potassium iron(II) cyanide and dissolve in 100 cm^3 of de-ionized water. Filter this solution through a membrane pad and store in a dropper bottle.

Solution 2: Add 2 cm^2 of concentrated hydrochloric acid to 98 cm^3 of deionized water. Filter this solution through a membrane pad and store in a dropper bottle.

Both solutions will keep indefinitely provided no cross contamination occurs.

Solution 1 should always appear to be a faint yellow color, and solution 2 should be clear. Discard solutions if turbid or colored differently.

Add a small sample of media grains to a small petri dish. Pour off any water present carefully. Add sufficient solution 2 to just cover the grains, then add an equal volume of solution 1. Mix using plastic forceps.

Examine the petri dish contents under the low power microscope. Iron compounds stain deep (Prussian) blue within 30 seconds.

Any copper compounds stain a rich chocolate brown within 90 seconds.

APPENDIX 10

Detection of Aluminum in Filter Media Samples

Fresh samples of filter media may be easily tested for aluminum compounds by the following method, modified from Walker (1983).

The method is qualitative.

Introduction

Old filter media may have quantities of Aluminum flocs attached. Whilst small amounts are unlikely to degrade filter performance, excessive quantities may cause the filtrate turbidity to rise and/or result in rapid head-loss increases (fine particles). There may also be Regulatory Standards issues.

Equipment and Chemicals

Microscope, low power.
Plastic or glass dishes (small Petri type ideal).
Membrane filtration apparatus.
Membranes (glass fiber circles, e.g. Whatman GF/C).
1 cm^3 pipette.
Pipette filler.
100 cm^3 measuring cylinder.
250 cm^3 clean glass beaker.
Glass dropper bottles (clean).
De-ionized water.
Hexamine
Ammonia solution 0.880
Pyrocatechol violet
Plastic forceps.

Safety spectacles.

Protective gloves.

Fume cupboard.

Methods

Wear gloves and eye protection when preparing the solutions. Solution 1 should be prepared in a fume cupboard. Always use a pipette filling device and never 'mouth pipette'.

Solution 1: Hexamine Buffer: Weigh 15 grams of Hexamine and dissolve in 100 cm^3 of de-ionized water. Add 1.3 cm^3 Ammonia, 0.880.

Solution 2: PCV Stain: Add 0.094 grams of Pyrocatechol Violet to 250 cm^3 of de-ionized water.

Add a small sample of media grains to a small Petri dish. Pour off any water present carefully. Fill the Petri dish with sufficient of solution 1 to just cover the grains and allow to stand for 10 minutes. This chelates and iron and prevents interference from ferric ions.

Flood the Petri dish with PCV stain, and allow to develop for 5 minutes. Examine the Petri dish contents under the low power microscope. Particles rich in aluminum stain sky-blue.

It is essential that particles to be examined are not allowed to dry, since it has been found that unavailable Al, such as in aluminum oxide, does not react with the stain.

CHAPTER 12
QUALITY CONTROL AND INSTRUMENTATION ISSUES

INTRODUCTION

More and more reliance is being placed on instrumentation and electronics in the monitoring and operation of water filtration plants. Decisions on water treatment are being made on the basis of instrument read-outs or electrical signals transmitted from a remote sensor to a computer screen or data panel in the control room or a similar place in the treatment plant. For the purpose of providing water that is safe to drink as well as for the purpose of regulatory compliance in some instances, monitoring data must be accurate. Making decisions and operating a plant on the basis of inaccurate data about pH, turbidity, coagulation, water flow, or head loss could result in bad treatment decisions, economically wasteful treatment practices, unsafe drinking water, or a combination of these undesirable outcomes. Carrying out an effective quality control program is the key to being able to trust the instruments and the information they are providing.

This chapter reviews information on quality assurance and maintenance procedures for on-line turbidimeters, on-line particle counters, streaming current instruments, on-line pH meters, flow meters for filters, and head loss instrumentation.

SOURCES OF INFORMATION

Standard Methods

Standard Methods for the Examination of Water and Wastewater (APHA 1995) contains an extensive discussion of statistics, quality assurance and data quality in Part 1000, INTRODUCTION. Check the current edition of *Standard Methods* for information on those topics.

MANUFACTURERS' INFORMATION

The guidance presented in this manual is not intended to supercede or replace the recommendations, guidelines, or specified procedures provided by manufacturers of monitoring devices and instruments addressed in this manual.

For specific procedures on inspection, cleaning, maintenance, and calibration of instruments and measuring devices, consult the manual provided by the manufacturer. The details of such procedures found in manufacturer's bulletins, operating manuals, or instruction manuals are not reproduced in this guidance manual, as they are subject to change.

Regulatory Guidance

The California Department of Health Services has developed guidelines for turbidity monitoring and for particle counting. Other States also may have done this. Check with your State or Provincial drinking water program representatives about whether guidelines may be available in your state or province.

WATER QUALITY INSTRUMENTATION

Advice for Small Systems

The need for quality control is not diminished because a water system is classified as a small. Data must be accurate, regardless of system size. One utility participating in this project reported using a contract service for quarterly calibration of pH meters and turbidimeters. The information provided indicated that the service of an outside technician was quite satisfactory. This option should be given serious consideration if water treatment plant staff do not feel confident of their ability to conduct the quality control procedures needed at a plant or if time is not available for quality control activities such as turbidimeter calibration.

Testing Apparatus and Dilution Water

The availability of easily used testing equipment and a plentiful supply of low-turbidity water or "particle-free" water will make the task of calibrating turbidimeters and checking performance of particle counters much easier when these activities are performed by treatment plant staff . Information on water preparation is presented in *Standard Methods* (APHA 1995) in Method 2310, Turbidity, and Method 2560, Particle Counting and Size Distribution. Hargesheimer and Lewis (1995) prepared quantities of up to about 1 liter at a time by pumping high quality water through a cartridge filter. They used a peristaltic pump with a Masterflex Model 7019 pump head, 9 mm ID silicone tubing, and a 0.22 µm pore size cartridge filter (Sterivex-type from Millipore). The water was pumped directly into the

clean bottle or container in which it was to be analyzed. The quantities of water needed for quality assurance procedures involving turbidimeters and particle counters will depend on the number of these devices in use at a particular plant. The person responsible for water quality should review the situation at the plant and determine the most appropriate means of producing the needed quantities of water for dilution or testing.

Dedicated equipment may be needed when multiple instruments are to be inspected, maintained, or calibrated in an efficient and cost-effective manner. Use of a stainless steel laboratory cart equipped with all of the supplies, expendable items, and apparatus needed for cleaning and/or calibrating turbidimeters and particle counters would save staff time during the performance of the actual QC procedures. At treatment plants that are not large enough to have an elevator servicing the pipe gallery, a cart could be purchased and left in the pipe gallery for the QC work. Check *Standard Methods* and the operating manuals of the instrument manufacturers for specifics on how to properly equip a turbidimeter and particle counter QC cart. Figures 12.1 and 12.2 show two views of a cart equipped for particle counter calibration.

On-line Turbidimeters

Background

The Interim Enhanced Surface Water Treatment Rule (IESWTR), effective January 1, 2002, requires continuous monitoring of turbidity for each individual filter using an approved method (USEPA 1998). Turbidity monitoring results must be recorded every 15 minutes. The provisions of the IESWTR apply to water utilities serving 10,000 persons or more, but the concept of monitoring the turbidity of filtered water from each filter with an on-line turbidimeter is equally important for any granular media filtration plant treating surface water, regardless of size. Monitoring filter performance provides operators with the basis for understanding what the filter is doing. An effective quality control (QC) program for turbidity measurement is absolutely necessary. Burlingame et al. (1998) described the practical application of turbidity monitoring in water treatment. They presented a comprehensive discussion of issues related to turbidimeter calibration and quality control. Manual users who want a more detailed explanation of calibration issues than that presented herein are referred to this paper.

Installation

On-line turbidimeters must be installed in a manner that enables them to measure water samples that are representative of the full flow of the water being sampled. For accurate turbidity measurement, the sample line from the source to the turbidimeter must be a material that will not corrode or otherwise contribute to the turbidity of the water being transported to the turbidimeter. Burlingame et al. (1998) noted that corrosion from sampling taps and plumbing can cause turbidity readings to be erroneously high.

Some recommendations regarding installation of on-line turbidimeters for measurement of raw water turbidity and settled water turbidity are different from recommendations for filtered water turbidimeters. Ideally the raw water turbidity would be measured before any chemicals such as potassium permanganate, metal coagulant, or polymer are added to the water so the data recorded would accurately indicate the turbidity of the raw water. This may not be possible at plants where chemicals are added at the intake to control zebra mussels. This becomes a matter of deciding what turbidity data are needed, the purpose for which the data will be used, and whether changes in quality are so significant that an effort has to be made to obtain raw water before any chemicals are added.

Treatment plants having preliminary sedimentation basins ahead of the treatment works need to have an on-line turbidimeter installed at the discharge point from such a basin or just ahead of the first chemical addition point where adding the chemical could influence the turbidity of the water. If particle counting is also used, this sampling point must be consistent with good practices for sampling for particle counters, as common sample streams are advisable when turbidity and particle count both are measured.

Excellent sources of guidance for filtered water turbidimeter and particle counter installation are the manufacturers' manuals; *EPA Guidance Manual, Turbidity Provisions* (EPA 1999); and *A Practical Guide to Particle Counting* (Hargesheimer and Lewis 1995). The latter is an important source of information for two reasons. First, particle counters are more sensitive than turbidimeters so some of their requirements are more stringent. Second, the number of utilities installing particle counters is increasing, and if turbidity data and particle count data are to be compared, common water samples should be analyzed. To do this, a flow stream from one sample tap would need to be split and routed to a turbidimeter and to a particle counter, or the two sample streams would need to be extracted in close proximity, using similar sample taps.

Place the tap for the sample line for filtered water in the effluent pipe coming from the filter box, as far upstream from bends or flow control valves as practical. If water is to be sampled for both filter to the clearwell and filter to waste measurement, the sample tap must precede the split of these two flows. Hargesheimer and Lewis did not detect any difference in particle counts for sample tubes mounted on the top, side, or bottom of the pipe, but turbidimeter manufacturers do make specific recommendations. Hach manuals (Hach 1997 and Hach 1999) recommend installation of the sample tap in the side of the effluent pipe, at the midpoint between top and bottom, or in the top, with the sample line protruding to the middle of the pipe. The latter is indicated in the manuals as the preferred location. GLI International (1999) recommends a sample tap installed at mid-depth in the side of the pipe and flush with the pipe wall as a good location, but the best location is to have a tap at the same place but extend the sample tube into the middle of the pipe.

An improperly located sample tap can cause problems. One participating utility reported that turbidity sample taps were located at the top of the effluent piping, and when air binding occurred, the water stream would pull away from the top of the pipe, interrupting flow to the on-line turbidimeter. To remedy this sampling difficulty, sample lines for turbidity monitoring were extended into the centerline of the pipe. Hach (1999) notes that sample taps that draw water from the top or bottom of a pipe may cause interference from air bubbles or bottom sediments. Figure 12.1 shows two views of a header penetrated by a sample tap. In this figure the sample line penetrates to the middle of the pipe and is curved so the orifice of the sample tube points upstream, as recommended in the particle counting procedure (Method 2560) in *Standard Methods* (APHA 1995).

After a tentative location has been selected for a sample tap, evaluate the practicality of this location before tapping into the effluent pipe. Flow from the tap must travel to the turbidimeter under the forces of water pressure within the pipe, or gravity, or a combination of those. Pumping filter effluent samples will break up particles and may change the turbidity. Do not pump these samples. (Finished water sample flows, analyzed for regulatory purposes, are likely to be pumped in most filtration plants. They represent water sent to the distribution system, not water from individual filters.) Preventing air from entering the sample line to the on-line turbidimeter is important, as air bubbles can cause false high turbidity readings. A bubble trap may be needed to avoid problems caused by air bubbles.

Filtered water turbidimeters are placed in the pipe gallery, close to the sample tap. In selecting a location be sure that the instrument will be easy to service when routine maintenance and calibration are necessary. Hach (1997) recommends use of ¼ inch (6 mm) rigid or semi-rigid tubing, routed as directly

as possible from the sample point to the turbidimeter. Use of long tubing causes a long lag time between the extraction of the sample from the plant's piping and the analysis of that sample. Hargesheimer and Lewis (1995) found no influence on particle count for tubing lengths of up to 10 feet (3 m), and they also recommended that the length of sample tubing be as short as possible. Apply this concept to turbidimeter installations. The flow through an on-line turbidimeter is small compared to flow from a filter. The recommendation of this manual is that the flow be wasted after analysis. Design the waste line to facilitate easily checking the rate of flow through the on-line turbidimeter, because this is one of the operating and quality control checks that operators must perform periodically. Also be sure that the on-line turbidimeter and the waste line are installed so water flowing to waste from the turbidimeter is readily visible as an operator passes by the turbidimeter. This will enable the operator to easily observe an interruption in flow to a turbidimeter if such an interruption should happen.

Inspection and Performance Checks

Inspection and performance checks should be performed on a frequent basis for comparison of on-line turbidimeter and bench turbidimeter results, rate of flow, and condition of tubing. California DOHS draft turbidity monitoring guidelines recommend a weekly inspection interval, and note that raw water turbidimeters may need to be cleaned more frequently than filtered water turbidimeters, especially when raw water turbidity exceeds 20 ntu.

On-line turbidimeters should be checked about once per week to once per month to verify that the rate of flow through the instrument is within the range specified by the manufacturer. Flow from a filter is dependent on the head available, and at many plants the head at the sample tap will vary according to the head loss occurring within the filter at that time. Therefore when the flow check is made, note the head loss on the filter and take this into account. Flow will be highest when head loss is lowest and lowest as head loss nears the terminal value. After the flow check is made, record the result.

If transparent sample tubing is used for the sample line, the condition of the tubing should be checked. Some types of tubing can permit growth of biofilms on the tubing wall, and this could lead to erroneous readings. Burlingame et al. (1998) noted that sample tubing needs to be changed on a periodic basis.

Turbidimeter calibration checks fall into two categories: those made with primary standards and those made with secondary standards. Primary standards are those that are prepared in a reproducible manner from traceable raw materials, under controlled environmental conditions (California DOHS

1998). Secondary standards are standards that are traced to a primary standard. Secondary standards can be used to verify calibration and to monitor an instrument's drift from calibration, but they are not to be used for performance of a primary calibration (California DOHS 1998).

On a daily basis or weekly basis, the reading of an on-line turbidimeter should be checked to learn whether the instrument's calibration has drifted. California DOHS guidelines for turbidity monitoring recommend that the calibration be reviewed on a weekly basis by using primary standards, designated primary standards, secondary standards, or by comparison to turbidity as determined by a bench turbidimeter. According to the California guidelines, the on-line versus bench turbidimeter is the least desirable because sample collection and handling may introduce error. On the other hand, this may be the easiest and most practical approach for many utilities. California recommends performing a calibration with a primary standard or a designated primary standard if the calibration check shows a difference of more than 10% in the two turbidity values.

When comparing filtered water turbidity as measured by on-line and bench turbidimeters, collect the filtered water sample at the on-line turbidimeter and note the reading of the on-line instrument. Compare that reading to the value determined on a bench model that has first been subjected to a secondary standard check. If the two readings fall outside the expected range of differences usually noted for the on-line turbidimeter versus the bench turbidimeter, recheck. If the difference continues to be observed, the on-line turbidimeter should be recalibrated. Do not merely adjust the reading of the on-line turbidimeter to coincide with the reading of the bench turbidimeter. The comparison of bench and on-line turbidity readings is done to learn if the on-line turbidimeter is still reading within an accepted range as compared to the bench model, not to serve as the actual calibration of the on-line turbidimeter. Record the results after the comparison is made.

As performed by one utility participating inthis project, the procedure for comparing readings from an on-line turbidimeter and a bench turbidimeter is as follows:

1. Apparatus and Instruments
    a. Glass grab sample collection containers (plastic OK for higher turbidity water)
    b. Timer
    c. Graduated cylinder
    d. Beaker
    e. Bench top turbidimeter and related accessories

(Items a. through d. would be put on the QA cart and taken from instrument to instrument in the

pipe gallery. The turbidimeter remains in the laboratory.)

2. Procedure
    a. Check the flow using a timer and a graduated cylinder. A beaker may be necessary to collect the flow on some turbidimeters. The flow for each turbidimeter must be within the range specified by the manufacturer (record the value for each turbidimeter).
    b. Using a clean sample bottle, collect a sample from the bypass or effluent of each turbidimeter to be checked. Record the instrument reading at the time of sample collection. Surface scatter turbidimeters, if checked in this procedure, will benefit from a flushing and cleaning prior to sample collection. Allow enough time for the reading to stabilize after cleaning before the check sample is collected.
    c. Record the SCADA reading for each turbidimeter to be checked.
    d. Using established laboratory procedures, check the turbidity of each sample in the laboratory using the bench top turbidimeter. This instrument is calibrated every three months with a primary standard and is checked with secondary standards twice daily.
    e. Enter the data on a spreadsheet program. There are allowable deviations, which will automatically be calculated on the spreadsheet. For turbidities < 0.5 ntu, the deviation must be < +/- 10%. When comparing the instrument reading to the SCADA reading, the deviation must be < +/- 10% for turbidities > 0.3 ntu and within +/- 0.03 ntu for turbidities < 0.3 ntu.
    f. If any of the turbidimeters does not meet the standards, clean, flush and recheck the unit. Recalibration with a primary standard may be necessary if the turbidimeter still does not fall within an acceptable range.
3. Notes
    a. Due to the nature of grab samples, the bench top readings will likely be higher than the on-line readings due to entrapped air, contamination, etc. Clean bottles and gentle handling of the samples will help obtain a good reading.
    b. Notify maintenance if any of the turbidimeters does not meet standards. Recalibration or a check of the electronics of the turbidimeter may be necessary.
    c. Special washing procedures are needed for sample bottles if they are reused.

Another option for checking the status of an on-line turbidimeter is to use a secondary standard provided by the instrument manufacturer. One participating utility reported changing from checking on-line turbidimeters by the bench turbidimeter comparison method to checking the on-line instruments by using secondary standards sold by the manufacturer, and the latter technique was favored by the utility. Purchase of secondary standards for on-line turbidimeters does involve an initial expense, but the savings of time and labor derived from using the secondary standards instead of doing an on-line versus bench turbidimeter check may result in cost savings in the long run.

Turbidimeters used for analysis of raw water or settled water may need to be cleaned on a weekly or monthly basis. Filtered water turbidimeters, used to measure much lower levels of turbidity than instruments used to monitor turbidity in pretreatment, are more sensitive to problems caused by accumulated biofilms, floc deposits, rust, and other particulate matter. The turbidimeter body, bubble trap, and photocell window may need to be cleaned from time to time. One utility participating in this study reported use of a tubing cleaning technique that involved forcing a wad of laboratory wiping tissue through a sample line by means of water pressure. This would act like a mini-pig to wipe deposits from the sample line. After wiping, the tubing would require a thorough flush to remove any loose particulate matter. Manuals of the Hach Company and GLI International listed below in *References* did not specify an appropriate time interval for inspection and cleaning. This is likely to vary according to the characteristics of the water being analyzed, with filtered water turbidimeters having longer time intervals before cleaning is needed. Be sure to document any cleaning event.

Calibration

Calibration of on-line turbidimeters is addressed in the IESWTR. The Rule says, "In addition to monitoring required by § 141.74, a public water system subject to the requirements of this subpart that provides conventional filtration treatment or direct filtration must conduct continuous monitoring of turbidity for each individual filter using an approved method in § 141.74(a) and must calibrate turbidimeters using the procedure specified by the manufacturer." The requirements for calibration will differ from manufacturer to manufacturer. Be sure to obtain and use the appropriate instrument manual for your on-line turbidimeters as the guide to calibration requirements and procedures. The EPA Guidance Manual (US EPA 1999) and California DOHS draft guidance (California DOHS 1998) both recommend that on-line turbidimeters should be cleaned and calibrated with primary standards

(alternatively with a designated primary standard in the case of California) at least every three months.

At some filtration plants, staff have concluded that they will calibrate on-line turbidimeters more frequently than recommended by manufacturer. Some plants perform calibration of on-line turbidimeters with a primary standard on a monthly basis. Consider the manufacturer's recommendation for the time interval between calibrations to be the maximum time to use a turbidimeter without calibration. If the periodic checks of the on-line turbidimeter reading versus a bench turbidimeter reading indicate that the on-line instrument is drifting excessively before the calibration interval, reducing the time interval between calibrations may be appropriate.

Whenever an on-line turbidimeter is calibrated the turbidimeter body must be cleaned and flushed. Also, flush the sample line supplying water to the turbidimeter. Always document all procedures carried out for cleaning or calibrating the turbidimeter.

Bench-top Turbidimeters

Procedures for secondary standard check, calibration, and maintenance can be found in Standard Methods, Method 2310, and in the instrument manuals provided by the manufacturers of turbidimeters. Follow these procedures for bench-top turbidimeters.

On-Line Particle Counters

A few water utilities began to use particle counters for water quality monitoring in the 1970's, and since then great strides have been made in the application of particle counting to water treatment. Sensors have improved, and personal computers are now used to record, store, and analyze data. Software for these purposes has been developed by manufacturers of the instruments.

AwwaRF has sponsored projects that have led to a better understanding of how particle counters can be applied in water treatment. One of these projects developed the report, *A Practical Guide to Particle Counting* (Hargesheimer and Lewis 1995). The information in that report is the basis for much of the information on particle counters in this manual. *Fundamentals of Drinking Water Particle Counting* (Hargesheimer, McTigue, and Lewis 2000) describes how particle counters work and discusses installation and calibration of the instruments and collection and interpretation of particle counter data. This AwwaRF report contains detailed methods for instrument set-up and performance validation, written in a style that will enable operators and water quality personnel to readily adapt them for use on-site. According to Hargesheimer, McTigue, and Lewis (2000) suspensions of polystyrene

latex spheres can be obtained with known particle counts, so both the sizing and the counting capability of particle counters can now be checked.

Another source of information is *A Practical Guide to Particle Counting for Drinking Water Treatment* (Broadwell 2001). This book contains a chapter on installation, operation, and maintenance of particle counters; in addition to chapters on fundamentals of particle counting, data collection, and applications to drinking water treatment.

For additional information beyond that developed by the sources cited above, refer to *Standard Methods*, Method 2560.

Installation

Hargesheimer and Lewis (1995) evaluated a variety of factors related to installation of on-line particle counters in a water filtration plant. They recommended use of particle counting only for raw water and filtered water, but not for settled water. They studied the effect of location of sample line, type of material used for the sample line, and length of sample line for on-line counters.

Installation for raw water monitoring. The sample location point for raw water is an issue that is subject to a variety of opinions. The authors of this manual believe the raw water sample should be extracted as close to the treatment plant as possible but before any potassium permanganate, coagulant chemical, or polymers are added to the water. This may be impossible at plants where certain chemicals are used for zebra mussel control at the intakes. Sampling should be ahead of coagulant and polymer addition because that is the start of coagulation and pretreatment. Potassium permanganate may form particles as it oxidizes substances in the water, and it might coat the particle counting sensor with the passage of time. Otherwise, obtaining a sample of water close to the coagulant chemical addition point gives information on the nature of the particles that are going to be treated in the plant. Another advantage of having a raw water particle counter close to the plant, or at least having the sensor close to the plant, is that a coarse filter may need to be installed to prevent blockage of the sensor. If this is done, the filter should be readily accessible to the plant operators so they can easily maintain it.

Hargesheimer and Lewis (1995) recommended that the raw water sample location be as close to the source as possible, explaining that changes to particles may occur as a result of pumping and turbulence in a pipeline. Changes in particle size and number may occur as a result of pumping water from a source to a treatment plant, but the changed particles in the raw water line are the ones that will have to be treated. Hargesheimer and Lewis noted that depending on source water quality, a mesh

prefilter may be required on the sample line upstream of the particle counter so large particles do not block the sensor. They also pointed out that if the prefilter became clogged it might alter the particle size distribution of the particles that did reach the sensor, and recommended daily cleaning of the prefilter. This is a good recommendation, but from an operator's perspective, the burden of daily cleaning of the prefilter for a raw water particle counter would be minimized if the prefilter and counter were located in the plant rather than at a distant intake site. The maintenance aspect of counting particles in raw water may be a significant factor in selecting the location for that counter in some plants.

The final decision on where to sample and count particles in raw water becomes a site-specific decision. The relationship of intake location to the plant has to be considered. If the intake is a very long distance from the plant and intake facilities are not inspected once per shift or once per day, locating a particle counter at the intake could result in the instrument's suffering from neglect. On the other hand, locating a particle counter at the plant may result in pumping raw water a great distance before sampling or counting particles in water that has been treated by chemicals to control taste and odor, with possible changes in particle count. The authors of this manual believe that valid particle count data even after pumping or addition of some chemicals would be more valuable than invalid data on raw water, so greater weight is given to locating the raw water particle counter at a place where it will be properly serviced and maintained.

Installation for filtered water monitoring. Hargesheimer and Lewis (1995) gave extensive advice on installation of particle counters for monitoring filtered water. The guidance in this manual is based primarily on their findings. The sample point for filtered water should be from an effluent pipe with as few turbulence-creating devices as possible upstream. This includes valves and venturis. The sample tap ideally should be designed so the sample tube penetrates to the mid-point of the pipe. Do not withdraw a sample from the top of the pipe because of the potential for encountering air bubbles. Avoid the pipe bottom as particles such as fine sand might settle out and clog the sensor. Minimize the distance from the sample extraction point to the sensor, and use the same length of sample line for each particle counter. Select a dry location where the sensor can be mounted, out of the way of workers so it will not be accidentally damaged, but readily accessible for inspection and maintenance. The sensor should be located near a drain. If a floor drain is not nearby, plastic pipe used for building plumbing can be used to convey flow to a drain.

Standard Methods recommends that samples be withdrawn at a sampling point that is representative, and away from the pipe wall. The sample line should point upstream, into the direction

of flow. *Standard Methods* has one recommendation that is impractical for most water filtration plants, suggesting that the velocity of water in the opening of the sample line should be nearly the same as the surrounding flow. This should be interpreted loosely, as on-line particle counters require a constant rate of flow, but most filters are operated over a range of flows throughout the year or even over a day's time or week's time. One approach would be to size the sample tube to match the typical velocity in the pipe from which the sample is taken. *Standard Methods* also recommends use of curved sample lines rather than 90° bends and avoidance of horizontal lines. Flow-modifying devices such as pumps, fittings with irregular surfaces, sharp angle changes, and flow controllers are not to be used between sample extraction and the particle counting sensor.

When flow through the sample line to the sensor is driven by the pressure in the pipe being sampled, the head in the pipe (upstream of the rate controller) will decline as the head loss increases in the filter. This will result in gradually declining sample flow as the filter run progresses. For this reason the advice in *Standard Methods* with regard to pacing sample flow with the rate of flow through the pipe seems impractical for filter effluent sampling.

Samples for particle counting and turbidity measurement can be withdrawn from the same tap and split using a brass Y-shaped fitting of the type used by Hargesheimer and Lewis, or the turbidity sample tap can be located a few inches downstream from the particle sample tap. Particle counting is more sensitive then nephelometric turbidity measurement, but if particle count data are to be used in conjunction with turbidity data for plant operation, it is important to be analyzing the same stream of water by both methods. This is best done by splitting the sample flow, or can be very closely approximated by locating the two sample taps close to each other. The discharge line from the particle counter must be installed in a manner to provide for periodic flow measurement using a graduated cylinder and stopwatch. Water flowing from the particle counter is wasted to a drain.

Establishing a means to attain a constant rate of flow for the particle counter is a critical aspect of installation of on-line counters. One of the more successful flow control devices evaluated by Hargesheimer and Lewis was an overflow device that functioned like a hydraulic weir. Water flow to the controlling device must exceed the flow requirement of the sensor, so some water can be wasted over the weir. As long as this condition can be met and deposits do not build up in the line between the overflow weir and the particle counter's sensor, flow through the sensor should remain constant. The sample is withdrawn on the upstream side of the weir, and the head available is constant regardless of filter head loss. Hargesheimer and Lewis noted that the overflow weir device functioned well when the flow to the sensor was greater than 50 mL per minute. The overflow weir works by gravity. For this

device to be used, sufficient head must be available to drive water through the particle counter's sensor at the required rate of flow. Check with the manufacturer to be sure this approach will work at the location where water would be sampled for particle counting before making a commitment to use this flow control method.

Hargesheimer and Lewis (1995) tried a variety of flow control devices that were found to be less successful than the overflow weir for controlling the flow in the required range. Downstream devices evaluated included a needle valve, a venturi, a peristaltic pump, and a positive displacement micropump. A peristaltic pump upstream of the sensor also was evaluated. None of these devices worked as well as the overflow weir.

Typically a sample tap and line to supply filtered water to a particle counter would be equipped with a valve to shut off flow when maintenance on the sample line and particle counter are performed. Broadwell (2001) recommends use of ball valves for particle counter sample lines, as they are "..... less prone to particle shedding than other types because of their smooth, rounded surfaces."

Inspection and Operational Check

A necessary operational check is the verification of a satisfactory rate of flow through the sensor. Hargesheimer and Lewis (1995) recommend that confirmation of the sensor flow rate using a stopwatch and graduated cylinder be made on a daily basis. More recently Hargesheimer, McTigue, and Lewis (2000) recommended that a manual flow check be performed weekly for instruments used to monitor particle counts in filtered water. Flow must be controlled within a specified range if the particle counter output is to be valid, and the particle concentration, expressed as particles/mL, can not be calculated correctly unless the true rate of flow through the sensor is known. If flow decreases, clean and flush sample lines after disconnecting the sensor from the sample line. One utility reported that a swab is forced through the sample line by water pressure as a means of cleaning the line. Always rinse a sample line thoroughly after it has been cleaned, before reconnecting to the sensor and resuming particle counting. Record the flow and the check date and document the cleaning and flushing of sample lines whenever this is done.

Particle count sensors analyzing raw water samples may require more attention than sensors for filtered water. Inthis project, one utility reported that screens on sample lines were cleaned daily. Others clean screens on raw water line twice per week. Inspection of particle counters once per shift and once per day were reported. Hargesheimer, McTigue, and Lewis (2000) recommended that flow be

checked one or more times daily, and that the sensor should be cleaned daily with a brush. Both chemical cleaning and replacing the sample tubing were recommended as monthly activities, or to be done as needed based on visual inspection.

Calibration

Calibration of particle counters on an annual basis or once every other year was reported by utilities in this project. Generally calibrations are carried out by the instrument manufacturer. Save all papers and documents from the manufacturer whenever calibrations are done.

Maintenance

Depending on water quality being analyzed, particle count sensors will need to be cleaned periodically. Cleaning of sensors is addressed in the operations manual of Chemtrac Systems, Inc. (1999). The Chemtrac manual recommends that a small mesh strainer be placed in the sample line before the sensor to catch debris that might be present in raw water. Among the methods recommended for cleaning a flow cell are compressed air and chemical cleaning.

A small can of compressed air (available at radio and electronic supply stores or hardware stores) can be used to blow air through the flow cell in the direction opposite to the direction of water flow. This may enable the maintenance person to unplug a sensor blocked by a large particle. After the sensor is unplugged, light is visible when looking through the sensor. When a plugged sensor is cleaned out, the sample line should be flushed thoroughly to remove other particles that may be present.

If a sensor has been coated by chemical deposits, chemical cleaning is the appropriate cleaning method. Iron or manganese in water can cause chemical build-up. Vinegar or some other slightly acidic liquid can be used for these deposits. Hargesheimer, McTigue, and Lewis (2000) recommend using Rover® for iron deposits and a combination of acetic acid and hydrogen peroxide for manganese deposits. Calcium carbonate deposits would be removed in the same way. To remove chemical deposits, fill a large syringe with the cleaning solution (diluted to 1% or 2% with deionized water) and attach the syringe to the sensor with a short piece of tubing. Force the cleaner through the cell. If a cleaning brush was supplied with the particle counter, apply a couple of drops of diluted cleaning solution to the brush and insert into the sensor. Turn the brush a couple of times and remove. NOTE: this procedure is an example of the cleaning method recommended for Chemtrac particle counters. For

other brands, consult the instrument manufacturer's manual. For cells that are dirty, Hargesheimer, McTigue, and Lewis (2000) recommend using detergent solution. They suggest using isopropyl alcohol to clean off microbiological growth.

Particle counters at Fort Collins, Colorado are given routine maintenance, including cleaning on a frequency averaging once per week (Engelhardt and Gertig 1998). Those authors noted that once per month is a typical frequency for cleaning filtered water particle counter sensors in the water industry.

Hargesheimer, McTigue, and Lewis (2000) included a table of recommended frequencies for particle counter maintenance tasks. Sensor cleaning with a brush is a recommended monthly task. Sensor cleaning with chemicals is suggested as a monthly task, or as needed. They recommend changing tubing quarterly or when needed based on visual inspection of the tubing.

Document all particle counter maintenance activities for future reference.

Streaming Current Instruments

Use of streaming current instruments (called streaming current detectors or streaming current monitors, depending on the manufacturer) has increased dramatically since the mid-1980s, when the AWWA Research Foundation sponsored a research project on the use of these instruments in the water industry (Dentel and Kingery 1988). The AwwaRF report was summarized in a *Journal AWWA* paper (Dentel and Kingery 1989). Even though streaming current instruments have been evaluated in a research project, their application is both a science and an art. Determination of the set point value is a trial and error procedure. Their use has been helpful at many water utilities, so when appropriately applied, these instruments can be beneficial. Streaming current instruments may be unreliable for mineralized waters (conductivity > 600 μS/cm.)

Installation

Installation of streaming current instruments is described in manuals by the manufacturers (Chemtrac Systems, Inc. 1999 and Milton Roy Company 1993). The sensor for the streaming current instrument should be mounted as close as possible to the sample extraction point. This minimizes the delay time from sample extraction to read-out and allows a faster response to process changes. The sensor should be protected from rain, snow, spills and direct sunlight. Of course, since water is involved, the sensor has to be mounted in a location where it will not freeze, and the sample line to the sensor must be protected from freezing, if sub-freezing temperatures are encountered in winter.

Selecting the proper location for obtaining the water sample is very important. According to the Milton Roy Company, four requirements are:

- The water sampled must be representative of the process being monitored or controlled
- The sample must be free of foreign matter that can damage the probe or block sample flow
- Sampling must be continuous when the streaming current instrument is operating
- The location sampled must be selected to provide appropriate system delay times

Streaming current instruments are used to monitor the electrical charge on the surface of particles in coagulated water. Therefore the sample line must be installed at a point downstream of the coagulant application point.

Thorough mixing is essential for obtaining a representative sample of coagulated water. If the water is not completely mixed with coagulant before it is sampled, the streaming current value may fluctuate over time, even if the chemical dosage and raw water properties have not changed. A pipeline or flume between the rapid mixer and flocculator could be sampled. Depending on the distance from the rapid mixer, such a sample point will increase the delay time for response to coagulation changes. Sampling in the flocculation basin usually is not recommended because of the long response times and poor sensitivity (Milton Roy Company 1993). According to the operations manuals, pumping the sample to the sensor is accepted practice. Provide a free-draining line to carry away the coagulated water that has passed through the sensor.

The water to be analyzed by streaming current instruments is coagulated but not clarified. Depending on the source water, small amounts of sand, grit, silt, or other particulate matter may be found in the sample stream. Gritty materials can damage the sensor, causing rapid wear and erratic streaming current readings. To remove fine gritty material, a cyclone separator or a small pressurized settling chamber can be used. A filter to strain out leaves and debris that clogged a streaming current instrument was built and then described in *Opflow* (Saulmon 1997).

A sampling location that provides a delay time of about two minutes after coagulation is recommended (Milton Roy Company 1993). Sampling when the detention time is less than 30 seconds from the time of coagulation is not recommended, nor are delay times longer than three minutes recommended if streaming current data are used to control coagulant dosage.

Be sure to include the transit time in the sample line when calculating the delay time between coagulation and measurement of streaming current.

Dentel and Kingery (1989) made some recommendations with regard to clogging of sample lines. They suggested considering relocation of the sample line to reduce the entry of silt into the line, use of clear sample lines so operators could see if clogging was occurring when they check the instrument, and use of solids separation devices ahead of the sensor. They suggested that periodic cleaning of sample lines could be accomplished by backflushing.

Inspection

The quality of water analyzed by streaming current instruments varies widely from utility to utility, and practices for inspection vary just as much. Some utilities inspect these instruments on a daily basis, while others do it weekly. One utility that treats a river with a turbidity range of 1 to 2000 ntu reported that the instrument is cleaned on the basis of the raw water turbidity. Inspections should be done as needed, based on experience with the type of water being analyzed at the time.

Maintenance

Maintenance practices reported included flushing, cleaning the instrument, and changing probes. Flushing is done more often than cleaning. Some utilities flush the streaming current sensors on a daily basis. Cleaning on a weekly and monthly frequency was reported. At some plants with high quality reservoir water, the interval was three months.

Cleaning the sensor is an appropriate maintenance procedure to perform when periodic signal fluctuations are noted or when the sensitivity of the unit has decreased. The sensor has to be clean to work properly. Dentel and Kingery (1989) recommended that cleaning solutions be prepared in very dilute form and the concentration increased if the cleaning action is not satisfactory. They cautioned against the use of cleaning agents containing surfactants (detergents) because many hours of flow through the sensor may be required to remove traces of the surfactant from the sensor.

Procedures for cleaning are described in the operation manuals of both manufacturers. Debris such as particulate matter can be removed by scrubbing with a test tube brush or a bottle brush and thoroughly flushing. When chemical deposits have formed on the sensor, more vigorous cleaning procedures are needed. Some organic and chemical coatings, including alum precipitates, can be

removed with household bleach diluted to 10% of its strength. If iron or manganese deposits have formed, the sensor can be cleaned with a solution of RoVer™ Rust Remover, available from the Hach Company in Loveland, Colorado. A solution strength of 30 grams per liter (about 1 tablespoon per quart) is recommended (Milton Roy Company 1993). Weekly cleaning may be needed when metal coagulants are used. Never use any soap or detergent to clean a sensor. Surface active agents linger for a very long time on the sensor and cause false readings. After cleaning the sensor, flush and rinse very thoroughly. Document all maintenance activities.

Periodic Determination of Set Point

Set point determination, as explained in the manufacturers' manuals, is more like an art than a science. Milton Roy Company (1993) recommends three approaches. One is to observe the streaming current reading over a period of time and study the plant operating data when plant performance is optimized. Another procedure involves use of jar tests (refer to the manufacturer's manual for details). Still another approach, for water utilities that have an instrument for measuring zeta potential, is to find the optimum coagulant dosage by zeta potential measurements, verify that dosage by using it in the plant and confirming that performance is optimized, and then read the streaming current value of coagulated water sampled in the plant. Chemtrac Systems, Inc. (1999) suggests that treatment optimization be done slowly and stepwise. After streaming current and treated water quality data have been recorded, they recommend decreasing the coagulant dosage by 10%. Then wait to see if this dosage reduction causes a change in treated water quality. If water quality is not affected adversely, the larger dosage may have been too high. If filtered water turbidity increased as a result of the dosage decrease, the prior dosage and set point may have been optimum. The full-scale dosage reduction strategy for finding the set point should be considered in the context of treatment plant practice. At plants where operators have generally overdosed coagulant to have a margin of safety, this may be a good approach. At a plant where operators are confident that coagulation is optimized and the dosage should not be lowered, full-scale changes in coagulation dosage in search of the set point are not recommended.

Document the date and results of each set point determination, as well as the complete information on water temperature and coagulation practice at the time, including pH, alkalinity, coagulant used and the dosage applied.

pH Instrumentation

Control of pH is necessary for optimization of filtration performance at plants that practice coagulation. At lime softening plants, pH control is critical to effective softening. Monitoring and controlling pH also must be done to protection of filter beds and water mains when recarbonation is practiced and polyphosphate addition is not used to prevent calcium carbonate precipitation. Deposition of calcium carbonate can increase the size of filter media, and in extreme cases can cement the media into a limestone conglomerate, forming large hard lumps of stone-like material in the filter bed or even cementing the entire bed into a solid mass. Problems like this can be avoided by monitoring pH and maintaining the pH value that is appropriate for the process in question.

Measurement of pH is described in *Standard Methods* (APHA 1995), which explains that the pH of a water sample is related to the electrode potential. Figure 4500-H^+:2 (found in *Standard Methods* but NOT presented in this manual) shows how pH varies with electrode potential at different temperatures. Performing a pH measurement with an on-line instrument and then adjusting the on-line meter based on a pH measurement made using a calibrated bench model is a one-point calibration. Because the lines relating the electrode potential and pH in Figure 4500-H^+:2 are sloped, a one-point calibration is valid only at the pH that was measured. To calibrate an on-line pH meter over a pH range, a pH buffer at each end of the range would have to be used. If a one-point calibration is made and the pH of the water changes, the readout from the on-line meter may or may not be valid.

Both the two-point and the one-point calibration of on-line pH meters are described in the Hach Company's manual (Hach Company 1997). The two-point calibration is recommended for new electrodes before they are put into service, and for periodic calibration thereafter. A frequency is not specified but is ".... determined by the accuracy desired and the application in which the electrode is used." The electrode must be removed from service when the two-point calibration is used. Hach recommends that the one-point calibration be performed periodically in the intervals between two-point calibrations. Doing this would enable plant operators to learn whether the pH meter had remained in calibration during the time between calibrations. If the pH reading is not within the desired limits, a two-point calibration would be needed. Any calibration activity must be recorded.

Water utility practice for pH meter calibration, as reported forthis project, is varied. The wide range of responses was caused in part by the wording of the question on pH meter calibration, as two-point calibration was not specified. Responses could refer to either one-point or two-point calibration. Calibration intervals of daily, three times per week, and weekly may have referred to one-point

calibrations, whereas intervals of one, two, three, or six months, or one year may have referred to two-point calibrations. One utility replied "verify daily, calibrate monthly," which strongly suggests a one-point check on a daily basis and a two-point calibration on a monthly basis. Another plant, using coagulation and filtration, reported that their instrument was calibrated when the drift exceeded 0.2 pH unit. At the Elm Fork Water Treatment Plant in Dallas, on-line pH meters are calibrated monthly using two different pH standard solutions. The laboratory pH meters are calibrated daily using three different pH standards. The Elm Fork plant is a lime softening plant, so pH data must be accurate. Monthly two-point calibration with a daily check of on-line readout versus the laboratory pH meter reading is recommended. Document all checks and calibrations.

As with other on-line instruments, the pH probe must be placed where a representative sample of water is analyzed, or if water is pumped to the probe, the sample being pumped must be representative of the quality of the passing the sampling point. If chemicals have been added to the water being sampled, they must be thoroughly mixed before pH samples are taken. When the alkalinity of the water being treated is very low, addition of chlorine or fluoride can lower pH. Be careful to obtain thoroughly mixed water that is representative of all of the water passing the sampling or measuring point, in these situations.

Consult the instrument manufacturer's manual for explicit information on calibration of pH meters, handling of pH probes, and other instrument-specific instructions.

FLOW MEASUREMENT INSTRUMENTATION CHECK AND CALIBRATION

Accurate flow measurement is the basis on which many decisions are made at a water treatment plant. Having accurate flow data can be as important as having accurate chemical measurements. For example, if the alum dosage for coagulation should be 10 mg/L on the basis of jar tests, to attain that dosage in a plant where liquid alum is fed, calculations would be based on the chemical strength of the liquid alum in the chemical tank, the feed rate of alum in gallons per hour or liters per hour, and the raw water flow in gallons per hour (mgd/24 hr/d) or million liters per day divided by 24 hr/d. If the chemical analysis of the alum is incorrect, the dosage will not be correct. Likewise, if either the flow of alum solution or the flow of raw water is incorrect, the dosage will not be correct.

The fundamental technique for measuring flow, taught in hydraulics laboratories in engineering schools, is the "bucket and stopwatch" method. Using a calibrated container to hold the liquid, or a container whose dimensions are known so the volume can be calculated, the change in liquid volume

over a defined time is determined. From this the flow rate can be calculated and expressed in any desired units, whether customary foot-pound-second units or metric units. Measuring the change in liquid volume over a defined time is a concept that can be used in numerous ways at a water treatment plant. Generally the tasks of watching the time, measuring the water surface level, and collecting flow meter readings are sufficiently complex that two or three persons may be needed to obtain all of the needed data when large flows are involved.

Chemical Feed Pumps

Chemical feed pumps often are equipped with piping and valves so the chemical being pumped can be filled into a graduated cylinder, and then the feed pump can draw liquid from the cylinder. This method of flow calibration takes only a few minutes, when the graduated cylinder is properly sized. If this kind of flow calibration equipment has not been provided for chemical feed pumps, adding calibration cylinders is a task that should not be too difficult for a talented maintenance crew.

Filtered Water Flow Meters

The accuracy of the flow meter for a filter can be determined by draining a filter box while checking water elevations versus time and the flow rate. At least two operators are needed to do this because of the complexities of measurement and data recording. A timer or stopwatch and surveying rod or tape measure are needed. The steps are:

- Fill a filter with water and then shut off all influent water.
- Measure the initial elevation of the water surface.
- Open the filter effluent valve to the desired rate of flow
- Determine the rate of flow as water passes through the filter by observing periodic measurements of the elevation of the water surface. Measuring the water elevation at 30-second intervals is recommended. If determining the water surface elevation at precise times is too difficult, then determine the exact surface elevation about every 30 seconds, and note precisely the time when each elevation is called out. Either call out the exact 30-second time and note the water elevation at that moment, or call out a water elevation at intervals of approximately 30 seconds, and note the exact time when the elevation was observed. Record both elevation and time.

- Every time an elevation is recorded, also record the flow meter reading. Don't continue this after the water surface goes below the top of the washwater trough or washwater gullet, as calculations would have to be made to compensate for the volume of water in the trough or gullet, and this might be complex.

When the flow measurement data are obtained, graph the data with water surface elevations on the vertical axis and time on the horizontal axis. An example graph is shown in Figure 12.4, which shows hypothetical data for a linear drop in elevation with time (constant rate of flow) and for a gradually slowing drop with time (declining rate of flow). The graph may show that the water surface was dropping faster at first, with the rate of flow slowly declining as time passed. If so, draw a line tangent to the curve at a data point on the graph where an elevation was measured and flow meter data are available. From the slope of the straight line, calculate the rate of flow and convert to the same units in which flow meter data are available. Check this by drawing another tangent line at a different data point on the graph. Check the manual provided by the flow meter manufacturer if the calculated flow rate and the flow meter reading do not agree. Document and save the results.

Perform this check annually or more frequently. Typical time intervals reported for this procedure were quarterly to annually.

Backwash Water Flow Meters

A calibration check for a backwash water flow meter would be done in a manner similar to that for the filtered water flow meter. Again this requires two persons, a timer or stopwatch, and a surveying rod or tape measure. The procedure is:

- First, terminate the filter run and draw the water level down to just above the surface of the filter media.
- Measure the elevation of the water level in the filter box.
- Then turn on the backwash water flow and note the rate of flow each time the water level and time are recorded.
- Get at least five measurements. If this can not be done before the water level reaches the bottom of the washwater troughs, wait until the water passes the top of the trough and fills the trough, and then resume data collection. The groups of data collected before the water reaches the trough bottom and after the trough has been filled must be analyzed separately.

If the level goes above the top of the gullet wall, the increased area of the filter plus gullet must be introduced into the calculation.

Graph the data as described above in the procedure for filtered water flow meter. If the plot of water surface elevation versus time is a straight, sloped line, then the flow rate was constant. The slope of the line through all of the data points can be used to calculate the rate of flow in this case. If the graph of the data is a curved line, analyze the data as explained above in the section on filtered water flow meters. Document and save the results.

Perform this check annually or more frequently. Typical reported time intervals for this procedure were quarterly to annually.

Surface Wash Water Flow Meters

Surface wash flow meters can be checked in a technique like that described above for backwash flow meters. Draw the water level in the filter down to a point where it is just over the top of the media and measure the level. Then turn on the surface wash, noting the time when this was done. At periodic intervals, measure the elevation of the water in the filter box and the flow rate. Analyze the data as explained above for backwash flow rate. Document and save the results.

Perform this check whenever the backwash flow meter is checked.

Measurement of Air Flow for Air Scour

Checking the air flow rate is very difficult. In plants equipped with orifice air meters, operators seem to accept the original calibration of the orifice, and merely check the change in pressure with a manometer kit to see if the output agrees with the change in pressure determined from the manufacturer's formula and the operational conditions. One approach to checking air flow meters would be to remove a meter from service, and replace it with another, on a periodic basis. Then take the meter that was removed and have its calibration checked in a testing shop/laboratory by measuring water displacement in a measuring vessel.

FILTER 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, drain the filter to the top of the media and measure the water surface elevation. Hold for 24 hours. Watch to see if water leaks into the filter box. To check the effluent valve to the clearwell (and to filter to waste, if present), fill the filter until the water surface is at the usual high level, and shut off all valves. Measure the water surface and wait 24 hours. Determine if the water surface drops in that time. To check the valve controlling the flow of backwash water into the filter drain the filter down until the water is at the top of the filter media. Watch for the water to slowly rise above the media surface while other filters are backwashed. If filter to waste facilities are provided at the plant, check to be sure that the filter waste flow is zero while filtered water is being discharged to the clearwell. Perform this check on an annual basis when the filter inspection procedures are carried out.

HEAD LOSS INSTRUMENTATION CHECK

Head loss data give an indication of the degree of clogging in a filter. The data are quite useful, even if not extremely precise. In the survey of water utility practices, utilities reported cleaning head loss instrumentation on a monthly or quarterly basis. Calibration frequency generally was annually or quarterly, with a few doing this on a monthly basis. The zero value of a head loss gauge can be checked by stopping the flow through the filter. When flow is zero, head loss is also zero. If the head loss gauge indicates a value other than zero under a no-flow condition, that value is erroneous. Depending on the layout of the plant and pipe gallery in particular, if a clear plastic tube can be raised up from the discharge pipe from the filter to the level of the water surface of the filter or higher, then the drop in the water level from the static condition to the flowing condition indicates the head loss. This kind of tube is a piezometer tube, and these are commonly used to measure head loss in pilot plant filters. When piezometer tubes are used, the head loss is the measured difference between the level of water in the piezometer tube and the level of the water in the filter. This is a simple physical measurement and it can be considered absolute, as long as the elevations are accurate and no air bubbles are present in the piezometer line.

MISCELLANEOUS

Mudlegs and Sensing Lines

Mudlegs (the deliberate low spots in instrument piping systems for collection of debris and sediment) and sensing lines should be inspected and cleaned periodically to ensure that instruments respond properly. Based on the survey of utility practices, typical time intervals for this maintenance activity range from weekly to monthly to quarterly.

Sample Lines

Sample lines are inspected and cleaned frequently by many of the utilities participating inthis project. The most frequently reported interval was weekly. A smaller number reported doing this on a monthly, and still fewer utilities inspect and clean sample lines on a quarterly basis. One utility reported that lines are cleaned every three months and replaced every three years.

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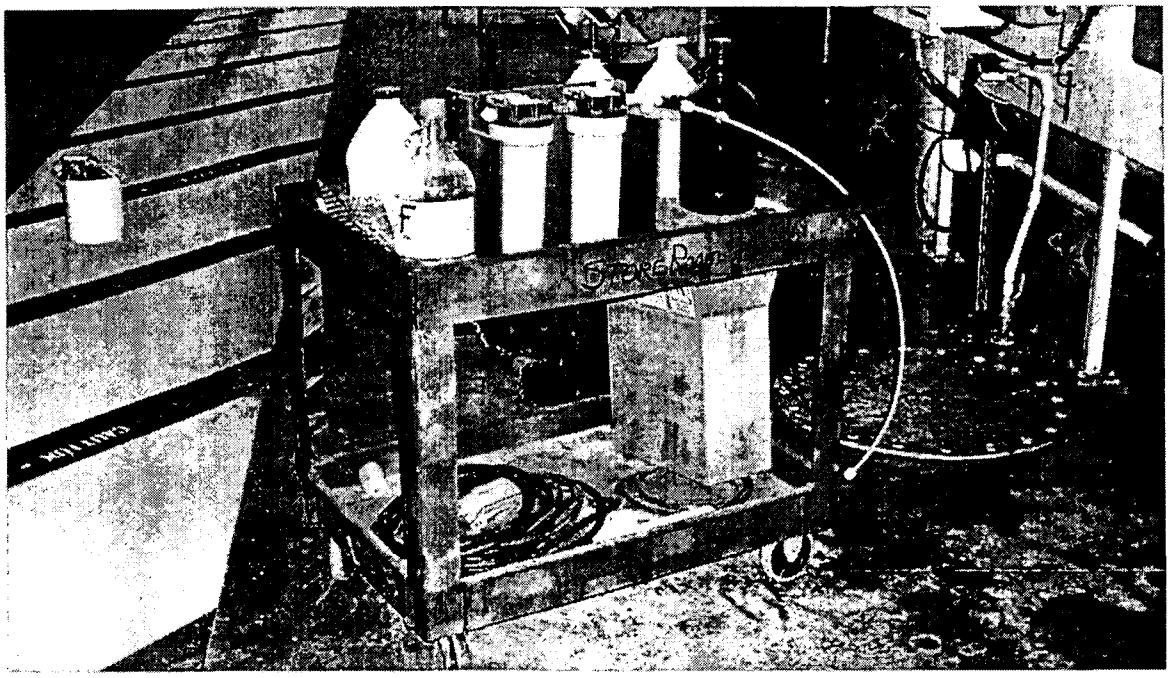

Figure 12.1 Particle counter calibration cart (*Source:* Southern Nevada Water Authority 2000)

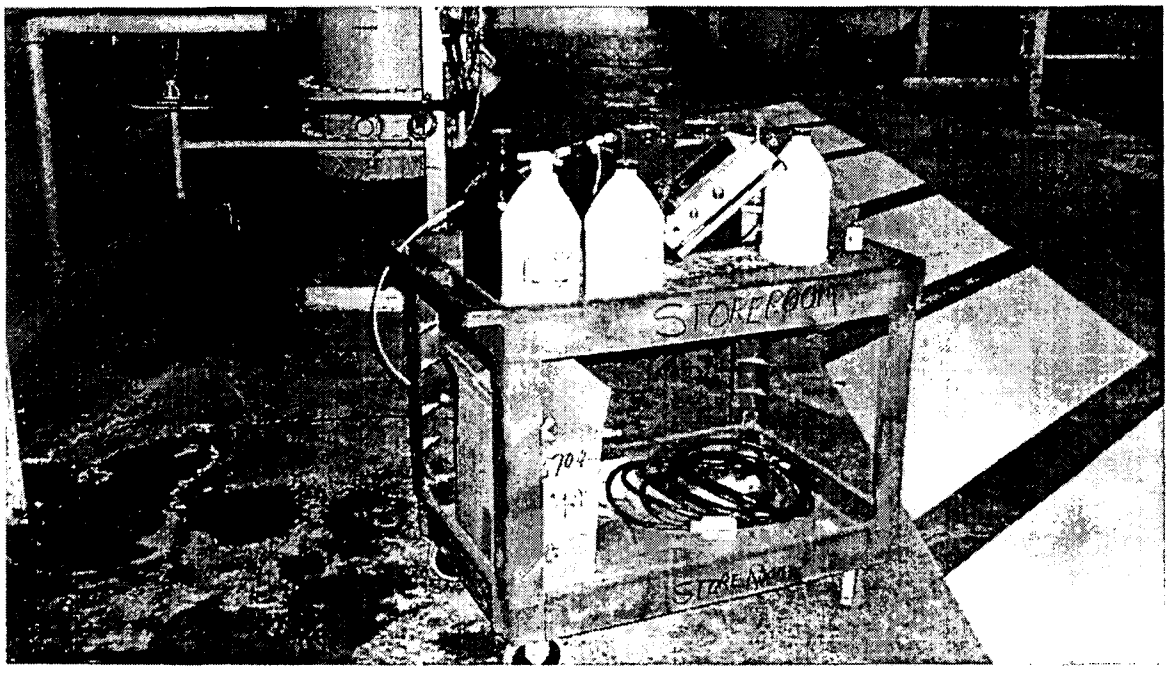

Figure 12.2 Particle counter calibration cart (*Source:* Southern Nevada Water Authority 2000)

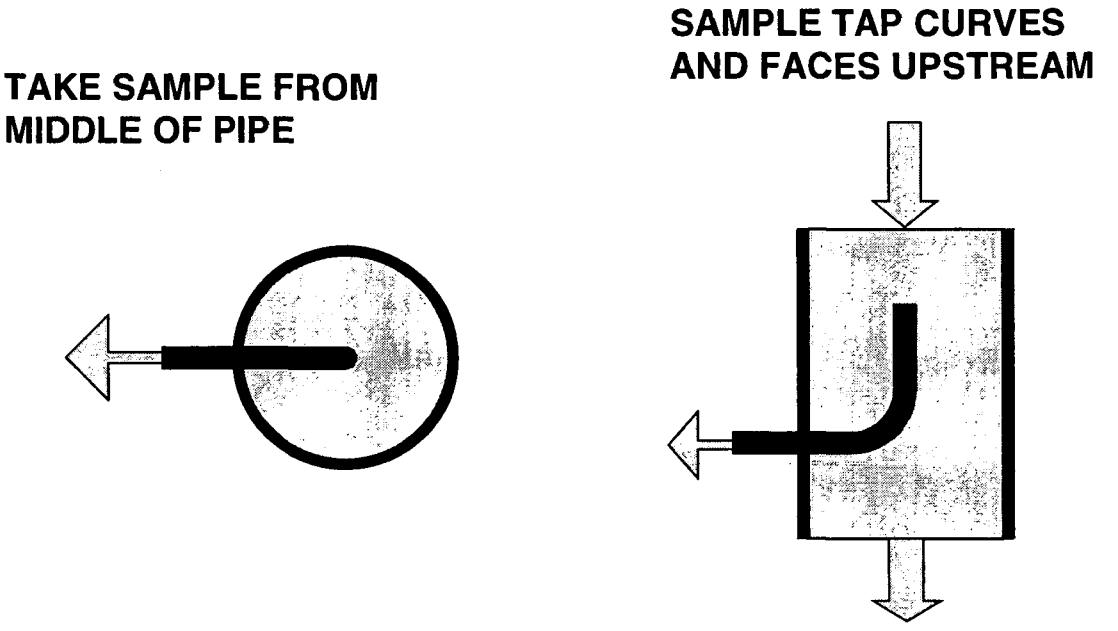

Figure 12.3 Installation of sample tap in header for in-line turbidimeter or particle counter

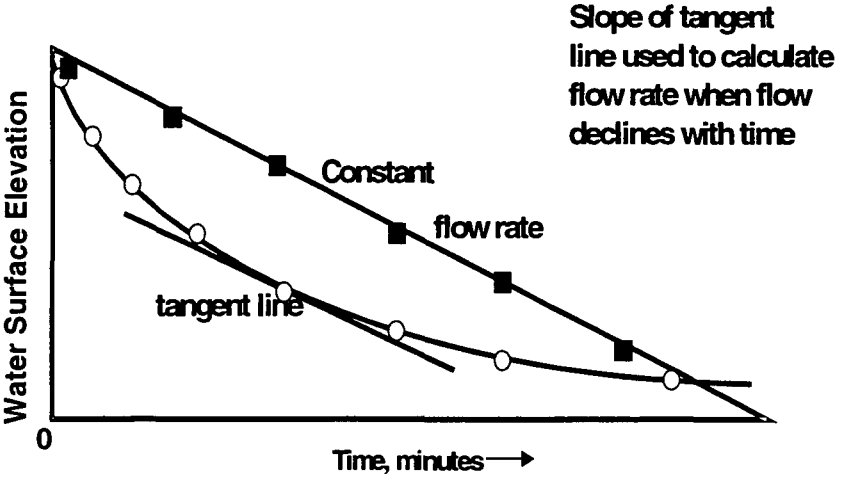

Figure 12.4 Example graph showing decline of water surface elevation with time, used for calculation of flow rate to check calibration of flow meter for filter

CHAPTER 13
CASE STUDIES

INTRODUCTION

This chapter presents case studies related to the maintenance and operation of water filters and pretreatment. Some are drawn from information reported by participating water utilities. Others are based on experiences of the members and associates of the project team who developed this manual, while some are based on case studies reported in the literature.

The following case studies are included in this chapter:

- Addition of Alum to Settled Water Flowing into Filter Box: summarizes Greenville Water System's engineering study for reducing the initial turbidity spike.
- Determining Profiles and Contours of Filter Media and Support Materials in Filter Beds: describes procedures used and data collected at Austin, Texas; Calgary, Alberta; Modesto Irrigation District, California; and Southern Nevada Water Authority, Nevada.
- Monitoring Water Quality within the Filter Bed: presents data on monitoring turbidity within the filter bed to provide early warning for impending turbidity breakthrough at Swift Creek Water Treatment Plant and the Modesto Irrigation District.
- Filter Inspection and Maintenance at a Partial Lime Softening Plant: reviews filter rehabilitation work and maintenance procedures used the Elm Fork Water Treatment Plant operated by Dallas Water Utilities.
- Monitoring and Review of Rapid Gravity Filter Performance Using On-line Particle Counters at Hope Valley Water Treatment Plant, Adelaide, South Australia: this study demonstrated that prechlorination resulted in lower filtered water particle counts.
- Implementing Optimization at Filtration Plants: optimization programs are described, and results are presented for the Elm Fork Water Treatment Plant at Dallas, Texas; a 2.0 mgd (7.6 ML/d) direct filtration plant at Leavenworth, Washington; and the conventional filtration plant at Fort Collins, Colorado.
- Chemical Cleaning of Filter Media: reviews technique used to clean filter media at a lime softening plant at Chanute, Kansas.

- Application of Streaming Current Instruments at Philadelphia: experiences, both positive and negative, with use of streaming current instruments at Philadelphia's Samual S. Baxter Water Treatment Plant are described.
- Rehabilitation of Filters at Brick Utilities: experience with a filter rehabilitation program is reviewed.
- Case Study of Modifications to Air Scour System: operational difficulties led to improvements in filters equipped with air scour.
- Improved Filtered Water Turbidity by Continuous Dosing of Supplementary Coagulant at Thames Water Utilities: supplemental dosing of ferric chloride at the weir where clarified water was discharged to the filter flume improved filtered water turbidity at the Shalford Works.
- Shortening Filter Ripening Time by Short Term Additional Coagulant Dosing: initial turbidity spike can be reduced by adding ferric chloride when the filter box is refilled, in full-scale study at Thames Water Utilities' Shalford Works.
- Coring of Dual Media Leads to Identification of Cause of Media Loss: apparent loss of filter media from beds was revealed instead to be a failure to place all of required media during construction.

ADDITION OF ALUM TO SETTLED WATER FLOWING INTO FILTER BOX

Introduction

During the survey of water treatment plant practices carried out as a part of this project during 1999, the Grand Rapids Water System reported that alum was added to settled water when the filter box was refilled after a filter backwash at their Lake Michigan Filtration Plant, a conventional plant using alum as the primary coagulant. This approach to reducing the initial turbidity spike at the start of a filter run was discussed in Chapter 7 of this manual.

Setting for Study

While preparation of this manual was under way, the Greenville Water System (GWS) in South Carolina was interested in controlling the turbidity spike at the beginning of filter runs at its Adkins Plant. This plant is a 30-mgd (114 ML/day) conventional plant that treats high quality surface water

from Lake Keowee, using alum as the coagulant chemical. The source water turbidity ranges from 1 to 2 ntu and alkalinity is low. The present filtration rate is 4 gpm/sf (10 m/h). Filter media consists of 18 inches (46 cm) of anthracite over 12 inches (30 cm) of sand.

The concept of adding alum to influent settled water at the start of a filter run while the filter was being refilled after backwash was discussed with Greenville, and recommendations were made for testing. Subsequently 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/sf (6 to 10 m/h). The water temperature range for the testing was 72° to 82° F (22° to 28° C). During this study, Filters 2 and 3 were utilized for the testing. Filters were operated alternately with alum added and without addition of any alum so the comparison of plant performance would not be influenced by changes in source water quality during the evaluation period. When alum was added, about 1200 mL of liquid alum was poured out over approximately 45 seconds 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 water was about 3.2 mg/L (based on the volume of water in the filter box, from the top of the media to the water surface). The dosage used was based on information reported by Grand Rapids.

Results

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 help to lower the initial turbidity spike when filters were placed into operation. 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. Data on turbidity peaks are summarized in Table 13.1.

The average time for turbidity to return to 0.10 ntu after filter start-up was 17.9 minutes for filters started without adding alum to the settled water, contrasted to 4.1 minutes for filters started after alum was added to the influent settled water. The rates of decline of filtered water turbidity were not statistically different for filters with and without added alum, but because the turbidity peak was so much lower when alum was added, filtered water reached 0.10 ntu much more quickly when alum was added. Data on times to reach 0.10 ntu after filter runs started are presented in Table 13.2. The reduction in average time to 0.10 ntu is a valuable improvement in performance.

Table 13.1

Comparisons of turbidity peaks during filter starts with and without added alum

	Peak turbidity during starts without added alum	Peak turbidity during starts with added alum
Number of starts	28	29
Smallest peak	0.07 ntu	0.07 ntu
Lower quartile	0.145 ntu	0.09 ntu
Median	0.195 ntu	0.11 ntu
Upper quartile	0.27 ntu	0.14 ntu
Largest peak	0.64 ntu	0.32 ntu

Table 13.2

Comparisons of time for filtered water turbidity to decrease to 0.10 ntu during filter starts with and without added alum

	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 minutes	0 minutes
Lower quartile	7.5 minutes	0 minutes
Median time	16.5 minutes	1 minute
Upper quartile	27.5 minutes	7 minutes
Longest time	45 minutes	26 minutes

Discussion

When filter-to-waste is used, as at Greenville's Adkins Plant, as soon as the utility's filtered water turbidity goal is met, the filter-to-waste procedure can be ended. Reducing the time needed for filter-to-waste improves the productivity of a filtration plant and reduces the volume of water from filter-to-waste that has to be handled as a residual flow stream. The work done at Greenville illustrates

that filter-to-waste ought to be managed on the basis of filtered turbidity, rather than operated for a fixed amount of time regardless of the quality of the water produced by the filter.

This controlled full-scale evaluation of adding alum to influent settled water showed that the practice was beneficial at the Greenville Water System's Adkins Plant. This practice has been used at other treatment plants, but the Greenville experience is thought to be the first documented, statistically tested evaluation of the procedure.

Treatment plant operators are cautioned that even though this procedure successfully reduced the magnitude of the initial turbidity spike and the time to attain 0.10 ntu after filter start-up, the results attained at this plant may differ from results at other facilities. Furthermore, trial and error testing is needed to determine the appropriate dosage of coagulant to add to the water flowing in to the filter box.

When extra alum is added during refilling of the filter following backwash, measuring total aluminum in finished water is recommended. In cold water, some aluminum might not precipitate and react with particulate matter in time to be trapped in the filter, and elevated aluminum concentrations in finished water might be observed. Collecting a sample of filtered water shortly after the filter is returned to service, and analyzing for aluminum would be a good idea. If this is done, be sure to calculate the time required for the water on top of the filter media to pass through the filter media and underdrain, and do not collect the sample until the water treated with extra alum is passing out of the filter.

DETERMINING PROFILES AND CONTOURS OF FILTER MEDIA AND SUPPORT MATERIAL IN FILTER BEDS

Introduction

Measuring the depth of filter media and of support materials provides insights into the condition of a filter bed. The extent of the information developed on a filter bed is related to the amount of data collected. As more measurements are made, chances of finding a smaller area containing a gravel mound or depression are increased. Making more measurements on a systematic basis is the best way to collect data efficiently. This case study includes information on the use of a grid pattern for determining the thickness of layers of media and support gravel, as practiced at four water utilities.

Austin, Texas

Operators at the City of Austin, Texas use a steel rod to take measurements to the top of the media from the lip of the washwater trough, and they also probe the gravel layer with the rod. This enables them to determine the elevation of both the media and the gravel. With these data they can create profiles of media through the bed. These profiles are useful in assessing the general condition of the media bed. Occasionally, more complete coverage of the media bed may be required. In these cases, plant staff take additional profile data between troughs by laying a straight 2" x 10" board across two troughs, and then obtain probing data at 1-foot (0.3 m) intervals between the troughs. This procedure provides sufficient data to permit development of topographic maps of the media surface and the media-gravel interface, such as those shown in Figures 13.1 and 13.2. The contour maps are helpful in identifying depressions or mounding of filter media or gravel. These maps can be plotted as surface charts in the Excel spreadsheet program. Figure 13.2 shows examples of gravel mounding (black color) and gravel depressions (white). Tables of probing data can be used to give information on the depth of the filtering material. Tables 13.3 and 13.4, provided by the City of Austin, are examples of such data, and these were used to prepare topographic surface charts that show media layer thickness.

When probing data at Austin reveals an unusual or out-of-specification circumstance, the filter is drained and media is excavated using either a 10-inch (25-cm) diameter PVC pipe or a 2-foot (0.6-m) square plexiglass box. Materials removed during excavation are carefully separated and stored for replacement after the inspection has been completed. If a filter is found to have significant problems in media and gravel depths, it is taken off-line permanently and given a higher priority for media replacement when possible.

Table 13.3

Total filter media depth

Area between washwater troughs 5 and 7 (Austin, Tx)

Distance from left filter wall along Trough 5 (feet)	Distance from Collection Trough 5 (feet)								
	0	1	2	3	4	5	6	7	8
	Total Filter Media Depth in Inches								
0.5	32.5	32.5	32.5	32.5	32.5	32	34	34.5	33
1.5	32.5	32.5	32.5	32.5	32.5	32	32	32	32
2.5	32	32.5	33	33.5	33.5	33	33	32.5	32.5
3.5	32	32	33	34	34	34	34.5	33.5	33.5
4.5	32	32	33	34	34	34.5	35	33.5	33
5.5	32	32	32	33	32.5	33	33	32.5	32
6.5	32	32	32	32	32.5	32	33	32	32
7.5	32	32	32	32	32	32	32	32	32
8.5	32	32	31.5	31.5	32	32	32	32	32
9.5	32	32	32	32	32	32	31.5	31.5	32
10.5	32	32	32	32	33	33	33	32	31.5
11.5	32	32.5	32	32	32.5	33	33	32	32
12.5	32.5	32	33	33.5	33	32	32	32	32.5
13.5	33	32.5	32.5	32.5	33	33.5	33	32.5	32

Table 13.4

Total depth of gravel

Area between washwater troughs 5 and 7 (Austin, Tx)

Distance from left filter wall along Trough 5 (feet)	Distance from Collection Trough 5 (feet)								
	0	1	2	3	4	5	6	7	8
	Total Depth of Gravel in Inches								
0.5	7.5	8.5	8.5	8	8.5	9.5	8.5	10	8
1.5	8	8.5	7	7	6.5	8	8	7.5	7.5
2.5	7	8.5	6	6.5	5.5	6	8	7.5	8
3.5	8	7.5	6	6	3.5	3.5	6.5	4.5	5.5
4.5	6	4	5.5	4	3.5	6.5	9	9.5	9.5
5.5	6.5	5.5	7	6.5	6	7	9.5	8.5	8
6.5	8	8	8.5	9	10	9	10	9	9
7.5	9	9	9	9	9	9.5	9	8.5	8
8.5	9	9.5	9	9.5	9.5	9.5	9	9	8.5
9.5	8	8	8.5	9.5	10	10.5	9.5	8.5	8.5
10.5	8	8	8.5	10	8.5	6.5	7.5	9	9
11.5	7	8.5	7	9	5.5	3	4.5	9	10
12.5	7	7	8.5	10.5	4	0	3	8	9.5
13.5	7.5	7.5	7.5	9	7	6	4.5	8.5	7.5

Calgary, Alberta

The City of Calgary carries out an extensive filter maintenance program (Limacher et al. 1998) which was initiated after an underdrain failure resulted in mounded gravel at one end of the filters. To obtain data for filter media profiles, staff at Calgary's filtration plants performed filter coring in a systematic manner, using a grid pattern of 1 m x 1 m (3.3 ft x 3.3 ft) for core samples. A 25-mm (1-inch) PVC tube was used for obtaining core samples. The complete coring for one filter bed was reported to require about three hours' work for two staff members. Based on figures contained in the

paper presented by Limacher et al. (1998) showing the thickness of various layers of filtering material and support gravel, the number of core samples taken for a complete coring of a single filter bed ranged from about 50 to 80. Use of a grid pattern and collection of a large amount of data facilitate plotting of the results. The graphs presented by Limacher et al. are Excel Surface Charts or something similar. These graphs show the surface of each layer of material in a 3-dimensional manner on flat paper.

Subsequent to publication of the paper by Limacher et al. changes were made in the core sampling procedures at Calgary. As of the year 2000, staff takes core samples at only four locations between troughs or between a trough and the wall. This results in collection of 28 cores. A small hole is excavated at either end of the filter to confirm core measurements and to determine the location of the interface. Freeboard measurements also are taken, in a pattern similar to that used for core sampling. A team of three persons can accomplish collection of 28 cores, excavation of the holes at either end of the filter, and freeboard measurements in about one hour. The purposes for the coring are to measure anthracite depth and to probe the gravel.

Modesto Irrigation District, California

The Modesto Irrigation District measures media loss on each 6-foot (1.8 m) deep monomedium filter annually by measuring the distance to the surface of the media from the top of the parapet wall, taking five readings for each filter along the top of one wall and averaging the data. Staff uses the average surface elevation to determine the extent of media loss in each filter. The profile of the support gravel is measured with the aid of a surveyor's transit, a measuring rod, and scaffolding. This utilizes a precise method of determining elevations and enables staff to avoid going into the filter bed, thus avoiding questions of a confined space entry. The person using the rod works on a scaffold that spans the filter, and the transit is set up on the deck near the filter. The rod is pushed down through the anthracite to the top of the gravel, easily determined by a firm "stop" when the rod reaches the gravel. Gravel elevation data are collected at 8 locations across the width of the filter, at each of 17 positions along the length of the filter bed. This results in 136 measurements, which are put into a spreadsheet and graphed as a 3-dimensional bar graph. Based on filter bed dimensions, the measurement locations are 2.0 feet apart (0.61 m) across the width of the bed and 2.6 ft (0.79 m) apart along the length of the bed. A plot of a portion of the MID data is presented in Figure 13.3. The bars extending above or below the zero line depict the deviation of gravel depth above or below the average depth. This kind of chart is easier to view and understand when it is presented in color, as it was provided to this project by

MID. The legend in Figure 13.3 identifies rows of measurements that were taken at 2.0-ft intervals. Each row shows 17 observations that were made along the length of the filter.

Southern Nevada Water Authority, Nevada

The Southern Nevada Water Authority's Alfred Merritt Smith Water Treatment Facility (AMSWTF) has 26 filters. Each filter is divided into two halves. Filter dimensions for each half are 16 ft (4.9 m) wide and either 87.5 or 90 ft (26.7 or 27.4 m) long. Filter inspections revealed that some media migration was occurring when filters were filled after backwash. The migration appeared to be caused by the energy associated with refilling the filters after backwash, when refill water flowed down the influent gullet and carried media from the rear to the front of each filter. Studies were undertaken to document the extent of media migration.

Two methods of obtaining media elevation data have been used at the AMSWTF. The first approach was to use a level rod and surveying instrument to obtain elevations at 20 locations around the periphery of the filter beds. This method did not provide sufficient data on the elevation of the media away from the edges of the filter so a grid system was developed. For media elevation studies, a filter was divided into four quadrants, or two quadrants per each half. Initially elevation readings were taken on a grid of about 3.5 x 4 ft (1.1 x 1.2 m), resulting in 48 elevations per quadrant or 192 elevations per filter. This was deemed to require too much labor, so the grid dimensions were increased to about 5.3 x 7.2 ft (1.6 x 2.2 m), resulting in 21 readings per quadrant, or 84 readings per filter. The larger quadrants provide a satisfactory amount of data, and media gain or loss in a filter can be determined to within +/- 1 inch (2.5 cm).

After the filter media profiles had been determined, and media migration was documented, the filter backwash program was changed to modulate the filter influent valve and reduce the energy of the influent water. This cured the media migration problem.

Discussion

Two aspects of quality control are important for obtaining filter profile data. The usefulness of filter profile data is in part dependent on the amount of data obtained for a filter bed. When a grid pattern is used, plotting the data is much easier than if data were collected from random sampling points within a filter. As the number of sample points increases, the definition of the surface elevations of each layer can be improved, and the true contours of layers beneath the media surface are described with

better precision. As the distances in the sampling grid are decreased, the number of samples and thus the hours of labor needed to profile a filter will increase. The danger in using a widely spaced grid pattern is that a small area of serious disruption could be missed, if it fell entirely within the area of one grid square or rectangle. A tradeoff exists between labor requirements for a really thorough measuring program and the chances of missing a trouble spot within a filter if sampling points are not sufficient in number. One approach for reducing the number of probings or core samples done on a filter is to carefully watch the backwashing of a filter several times before a major filter profile study is undertaken, to identify locations within the filter bed where backwashing action has a different appearance from the rest of the bed. Areas with boils or dead zones are candidates for a more intensive sampling (i.e. closer spacing for sample sites, with distances of one half or one third of the usual) than the sampling done in the grid for the whole filter.

Another factor related to quality control is the accuracy and precision of the sample positions and the depth determinations. Sample location can be determined accurately when reasonable care is taken in selecting the sample location, as this would typically be done with a steel tape of the kind used in construction trades. Media profile data may be more difficult to obtain with desired precision and accuracy. Before profile data are obtained, the person doing this work should perform a group of probings or core samplings in a small area, perhaps that defined by a circle of 2 feet or 0.6 m in diameter. The average and standard deviation of the data can be calculated. If the location selected for the quality control check on the measuring method is not located over a mound or depression, results should be similar for all probe or core sample data. This check on technique is recommended when someone is probing or coring for the first time. After an operator has experience with the methods used, he or she will have an understanding of the amount of variability involved in the data being collected and can then evaluate the results in the context of the variation that would occur at random.

MONITORING WATER QUALITY WITHIN THE FILTER BED

Introduction

Traditionally at water filtration plants the quality of water produced by filters has been monitored after the water has exited from the filter. Some filtration researchers have monitored the quality of water within filter beds, but this has seldom been done at full-scale plants, even though this practice was advocated in the early 1970s (Harris 1972). Harris described a trial-and-error procedure for evaluating filter aid dosage when using dual media filters, based on measurement of turbidity at the interface of

anthracite and sand media in a dual media filter. This was described in more detail in this Manual in Chapter 8.

Harris explained how a sample extraction pipe and screen could be built into a dual media filter at the elevation within the bed where the interface of the coal and sand was located. When the interface turbidity measurement concept was presented, it may have been patented. Furthermore, the concept was suggested to be appropriate for filters having a clearly defined interface between coal and sand, rather than an interface in which the two media types were intermixed. Whatever the reason or reasons may be, interface turbidity measurement did not become a widely-accepted practice in the drinking water industry, and an early warning technique that can enable plant operators to anticipate turbidity breakthrough remained generally unused.

Chesterfield County Utilities Department, Virginia

The Swift Creek Water Treatment Plant of the Chesterfield County Utilities Department has dual media filters equipped with interface water quality monitoring capability. Interface turbidity data provide operators with a tool for evaluating floc strength (a function of pretreatment) and filter performance and these data enable operators to anticipate and thus avoid turbidity breakthrough episodes. Turbidity data from one filter run at this plant are presented in Figure 13.4. Note that for 11 hours of filter operation the interface turbidity data changed only slightly, but then at hour 12, interface turbidity jumped by 0.08 ntu to 0.18 ntu and then to 0.26 ntu in the next hour. This change in turbidity at the interface between the anthracite and sand layers is a signal to plant staff that effluent turbidity will be rising in the future. In fact, between hour 12 and hour 14, effluent turbidity rose from 0.04 ntu to 0.06 ntu. The run continued past 25 hours, at which time the interface turbidity had risen to 0.34 ntu and the filter effluent reached 0.10 ntu.

Modesto Irrigation District, California

Measurement of filtered water turbidity within the filter bed is practiced at the Modesto Irrigation District, where one of the six anthracite monomedium deep-bed filters is equipped with sample taps through the filter box at 1-foot (0.3-m) intervals. These taps supply water to continuous turbidimeters and help the operators understand what is happening within the filter bed. An example of the data obtained from this filter is presented in Figure 13.5. The value of within-filter turbidity data lies in the added knowledge available to plant operators on the status of their filter beds, and how well

they are functioning. A monomedium filter such as the one at Modesto has no interface, but the data from within the filter are helpful in showing the extent of penetration of turbidity within the bed.

An example of the design of a within-filter sampling device is shown in Figure 13.6, which was the design provided by Black & Veatch for the within-filter sampling system used at Modesto. In this case, 20 mesh stainless steel screen was placed between a ½ inch x 1 ½ inch increaser and a 1 ½ inch flange to provide the point of entry for the water to flow to each turbidimeter.

Discussion

The possible drawbacks to the use interface turbidity measurement should be reconsidered. If in fact a patent did exist in 1972, by the year 2001 it would have expired. Unless some variation on the concept was patented within the last 17 years, engineers should be able to use interface turbidity sampling and measuring concepts at filtration plants without patent infringement, just as mixed media filters now can be used without patent infringement. The idea that within-filter turbidity measurement is especially appropriate for a dual media filter having clearly defined interface between the anthracite and sand layers is no longer justified, as this concept has been extended to deep bed monomedium filters as well.

Within-filter turbidity measurement is appropriate for both monomedium and multi-media filters. A clearly defined interface in media layers is not needed for this technique to provide valuable information on the status of a filter. The early warning related to the possibility of future turbidity breakthrough can give operators extra time to plan for and schedule filter backwashes in a way that fits well with water production needs and staffing schedules

Some precautions on use of within-filter sampling are appropriate. Some filters are equipped with mixed media, which typically consists of anthracite and sand over a bottom layer of fine garnet or ilmenite. The effective size of the fine garnet or ilmenite may be about 0.3 mm, or perhaps smaller. The effective size is not the smallest size of the material, and 10 percent by weight will be smaller than the ES. Within-filter sampling devices must be designed with orifices sized appropriately to screen out fine filter material, which will be a greater challenge when a mixed media bed is involved. In addition, the velocity of the water flowing through the area of the sampling probe (e.g. the area of slots on a fine filter nozzle) should be similar to the interstitial velocity of water flowing through the filter bed. Ideally, these velocities should be the same, but filtration rates change from time to time, and adjusting the sample flow rate every time the filtration rate changed could be burdensome to the operating staff. As a

compromise, the sampling probe can be designed so the interstitial velocity is similar to the velocity within the filter bed at the average filtration rate.

FILTER INSPECTION AND MAINTENANCE AT A LIME SOFTENING PLANT

Introduction

Filter inspection and maintenance are important activities at all granular media filtration plants, but these activities can be especially important at lime softening plants, where the filtering materials are subject to accumulations of calcium carbonate caused by inadequate stabilization of softened water before filtration. The Elm Fork Water Treatment Plant operated by Dallas Water Utilities is a 330-mgd (1250 ML/day) facility with a treatment train consisting of preozonation, two stages of coagulation and sedimentation, filtration and final disinfection. Ferric sulfate and polymer are used for coagulation and flocculation. Partial lime softening is used, with addition of carbon dioxide for pH adjustment.

In 1992, the plant was rehabilitated. Filter boxes were rebuilt. Wash water troughs, the surface wash equipment, and underdrains were removed. Gullet walls were raised and designed to act as weirs for spent backwash water overflow. Air scour was installed. Filter medium consisting of 44 inches (112 cm) of 1.0 mmES anthracite was placed over 6 inches (15 cm) of support gravel.

The plant has an on-line turbidimeter for each filter, and an on-line particle counter has been installed to monitor combined filter effluent. Raw and settled turbidity are measured by grab samples taken six times per day. At this lime softening plant the pH of settled water is monitored continuously.

At the Elm Fork Plant a normal filter run has filtered water turbidity less than 0.10 ntu. Particle counts in finished water typically range from 2 to 5 particles per mL in the 2 μm to 50 μm size range. During the month of July, 1999 a total of 64,775 filtered water turbidity readings resulted in 99.9% of the data equal to or less than 0.1 ntu. The maximum turbidity was 0.18 ntu. Post-backwash turbidity was between 0.05 and 0.10 ntu at 15 minutes into new filter runs.

Inspection and Maintenance Activities at Dallas Water Utilities' Elm Fork Plant

A program of regular, scheduled maintenance has been established at the Elm Fork Plant. Basins and flocculation equipment are drained and inspected semi-annually, a procedure that usually takes 3 to 5 days of time. Basins and equipment are checked for integrity and physical appearance. Instruments are calibrated and adjustments are made as needed. Chemical feed pumps are calibrated by volumetric

measurements on a quarterly basis. Volumetric feeders are calibrated according to manufacturer's instructions. Records of maintenance requests and maintenance reports are kept. Maintaining correct pH during treatment is very important at lime softening plants, so pH instrumentation is calibrated on a monthly basis using buffer standards.

A filter inspection is conducted once per year. This inspection includes probing support gravel and coring media. Sieve analysis is done on an annual basis, and acid solubility testing is done for at least two representative filters annually. Evaluation for accumulated floc and dirt deposits is also done on an annual basis. Filter media maintenance also includes annual disinfection with 50 mg/L free chlorine for at least 6 hours. On a quarterly basis, elevation of the filter medium is checked to determine if a loss or growth has occurred. Media loss is reported to be about one inch (two to three cm) per year.

Rehabilitation of the plant has enabled staff to improve filtered water turbidity from an average of 0.30 ntu before rehabilitation to 0.07 ntu afterwards. Plant capacity was increased, and use of monomedium anthracite with air scour resulted in a reduction of the backwash rate. Filter backwash does last longer, however, as a result of removal of the washwater troughs. Now all spent washwater must flow over weirs into gullets and this arrangement requires a longer time for washwater to clear.

Discussion

The Elm Fork Water Treatment Plant is a participant in the Partnership for Safe Water, and this plant has been recognized as an optimized plant by the State of Texas. Achieving this level of performance would be difficult or perhaps not possible without an effective program of inspection and maintenance. This case study provides an example of the type and frequency of inspection and maintenance activities that may be appropriate at other lime softening plants.

Pretreatment facilities in lime softening plants are exposed to unstable water in which calcium carbonate is supersaturated. Calcium carbonate can precipitate on mixer blades and shafts, on flocculators, on sludge removal equipment, on baffles, on process equipment such as clarifier cones, and on basin walls in pretreatment facilities. Periodic inspections of pretreatment facilities and equipment must be carried out to ensure that equipment remains operable and capable of functioning as originally intended.

Filter media at lime softening plants are susceptible to media loss, as at other granular media filter plants. At these plants, media also are susceptible to accumulation of deposits of calcium carbonate when lime-softened water that is not stable is filtered. Calcium carbonate deposition can

result in filter media growth, manifested in an increase in the size of the filtering material as determined by sieve analysis and by an increase in the acid solubility of the filtering material. In extreme cases, filter media cementation can occur, resulting in a solid mass of filter media and calcium carbonate. Filter bed acidification or physical removal by jackhammers might be needed when cementation occurs. Therefore regular inspection, testing, and maintenance are necessary at lime softening plants.

The appropriate frequency for inspection and maintenance activities at lime softening plants should be related to the chemical stability of the water in the processes or basins being inspected. At Dallas, pretreatment facilities (in which water is chemically unstable) are subjected to quarterly inspection, whereas filters that receive stable water are inspected annually. Frequency of inspection should be tailored to the conditions at each plant. If serious and detrimental changes have occurred since the last inspection at a plant, this could signal the need for a shorter interval between inspections. Needs may vary from plant to plant, so operators ought to be alert to whether or not their inspections are being done at an adequate frequency.

MONITORING AND REVIEW OF RAPID GRAVITY FILTER PERFORMANCE USING ON-LINE PARTICLE COUNTERS AT HOPE VALLEY WATER TREATMENT PLANT, ADELAIDE, SOUTH AUSTRALIA

Introduction

This case study was prepared by Elizabeth Roder and is based on a paper by Roder, Holmes, and Chipps (2000).

Water treatment at the Hope Valley water treatment plant (273 ML/day or 72 mgd capacity) includes catchment (watershed) protection and monitoring, screening, coagulation, flocculation, sedimentation, filter prechlorination (chlorine dosed into the settled water duct), filtration (12 open, rapid gravity, dual media filters), and post chlorination. Chemical dosing at the plant is flow paced. The flow into the head of plant varies according to demand, and is controlled through the operation of six pumps of various sizes.

The need to avoid or limit the production of THMs has caused many utilities to reduce or abandon prechlorination ahead of chemical treatment and clarification. This has impacted on the appearance of clarifiers, permitting algal growth, and potentially causes poorer clarifier and filter performance. One means of regaining some of the benefits of prechlorination may be to dose after the

removal of TOC by enhanced coagulation in the stream between the clarifier outlet and the filter inlet. This results in the chlorine meeting a lower organic load for a shorter period of time. Previous experience had shown little benefit of filter chlorination on filtered water turbidity values, although low filtered water turbidity values (approximately 0.1 ntu) were consistently obtained during the study. However, it has been reported by many researchers that, at low turbidity values, particle counter data can show that filtration performance can be further improved by changes to operational practices, despite little or no apparent improvement in filtered water turbidity.

Testing Program

Between December 1998 and February 2000 a study was undertaken into the operation and performance of full scale rapid gravity filters at the Hope Valley water treatment plant in Adelaide, South Australia, operated by United Water International. During the study, Met One particle counters were installed on-line on the outlets of rapid gravity filters, and were used to assess a number of standard and modified filter activities for the optimization of particle removal.

Standard operation of the rapid gravity filters at the Hope Valley WTP at the time of the study included filter prechlorination, achieved through dosing chlorine into the settled water duct. Typical chlorine doses applied were between approximately 1-2 mg/L, resulting in free chlorine residuals of approximately 0.5 mg/L and 0.3 mg/L at the surfaces and outlets of the filters respectively.

During the study, several filters were operated without prechlorination for periods of up to 5 months. Other filters were operated without prechlorination for up to 3 weeks. Additional short-term trials were performed on these filters to confirm the results for filters for which longer-term effects were reviewed. The short-term trials involved operation of a number of filters without filter prechlorination for periods of up to 24 hours. Filtered water particle counts were then reviewed for the conditions before, during and after the trial. Further details and results were published by Roder et al. (2000).

Results

An example of the impact of filter prechlorination on filtered water particle counts is given for two particle size ranges in Figure 13.7. It shows that particle counts decreased rapidly and dramatically when prechlorination was returned on 1 February 2000, and increased just as quickly and significantly when the prechlorination was turned off again on 2 February 2000.

Results from the study clearly demonstrated that filter prechlorination yielded benefits, in terms of reduced particle breakthrough. Review of the results consistently showed the filtered water particle counts increased significantly when the filter prechlorination was turned off, and decreased significantly when filter prechlorination was returned.

Discussion

Numerous references in the literature have suggested that preoxidation can cause "micro-flocculation", enhancing the performance of filters and improving the level of particle and turbidity removal achieved. The effectiveness of ozone as a preoxidant has been widely documented (Chipps 1998). A number of suggestions have been made in the literature as to how preoxidation (via ozonation) could enable "micro-flocculation":

- changes in the surface charges of colloidal particles;
- formation of colloidal particles from organic matter; and
- formation of larger particles, including the agglomeration of algae.

The potential benefits of chlorine as an effective preoxidant are less widely documented. The effectiveness of chlorine in its ability to remove turbidity has been shown in some reports, although other work has demonstrated no benefit of prechlorination on dual media filtration. However, based on the well-demonstrated effectiveness of preoxidation via ozonation, it is considered likely that the same mechanisms and benefits of "micro-flocculation" may also be applicable to preoxidation using chlorine.

IMPLEMENTING OPTIMIZATION AT FILTRATION PLANTS

Introduction

When improved water treatment plant performance is desired, some water utilities undertake formalized optimization programs. This portion of Chapter 13 is based on two published reports of optimization activities and on one report submitted by a water utility participating in this project. The cases reported herein show that optimization can be undertaken successfully at water treatment plants covering a wide range of sizes.

Elm Fork Water Treatment Plant at Dallas, Texas

Background

Optimization of the Elm Fork Water Treatment Plant was described by Kilpatrick, Smith, and Guzman (1998). This plant is a 300 mgd (1250 ML/day) plant having a treatment train consisting of two stages of coagulation, flocculation, and sedimentation followed by filtration through deep beds of monomedium anthracite. Ozone is used for primary disinfection. Three man-made reservoirs and a river are water sources. Turbidity of source water can be as high as 3500 ntu. Major process improvements were made in the early 1990's, but after the cryptosporidiosis outbreak in Milwaukee in 1993, utility personnel recognized the need for minimizing filtered water turbidity. Subsequently the Elm Fork Water Treatment Plant was brought into the Partnership for Safe Water and became a participant in the Texas Optimization Program.

Kilpatrick, Smith and Guzman (1998) described both programs in detail in their paper. The Partnership goals adopted by Dallas Water Utilities were:

- individual filtered water turbidities ≤ 0.1 ntu
- settled water turbidities ≤ 2.0 ntu
- turbidity spike after backwash ≤ 0.3 ntu
- turbidity within 15 minutes in new run ≤ 0.1 ntu

The Texas Optimization Recognition Program was described and those goals, which differ somewhat from the Partnership goals, were:

- 90% of each individual filter's turbidity readings ≤ 0.1 ntu
- 95% of all individual filter turbidity readings ≤ 0.1 ntu
- 100% of all individual filters readings ≤ 0.5 ntu
- turbidity spike after backwash ≤ 0.3 ntu
- turbidity within 30 minutes in new run ≤ 0.1 ntu

Changes Made

Major improvements had been made to the plant in the early 1990's so the focus on optimization was on staff training and communications and on fine-tuning the facility so consistently excellent performance could be attained. Communicating the reasons for optimization and how it would be carried out was very important and required considerable effort. Physical and operational changes were not major, because of the prior improvements. Changes made include:

- Relocation of ferric sulfate feed point to rapid mixer basin to obtain better floc formation.
- Subsequent use of hydraulic mixing in the rapid mix basin, which was as effective as mechanical mixing but eliminated the problem of lime scale building up on rapid mixer blades.
- Increasing dosages of ferric sulfate from 12 mg/L to 30 mg/L for primary treatment and from 6 mg/L to 9 mg/L for secondary treatment. Together with usual lime dosages of 42 mg/L to 48 mg/L, this resulted in applied turbidities of 2 to 4 ntu.
- Use of 0.1 to 0.5 mg/L dosage of medium molecular weight cationic polymer in the secondary basins to increase floc size and reduce applied water turbidity.
- Program filter controls to backwash a filter when turbidity reached 0.1 ntu.
- Add low molecular weight cationic polymer as a filter aid in dosages of 0.01 to 0.02 mg/L to help keep individual filter turbidities $\leq$ 0.1 ntu. This action did cause a higher rate of head loss increase, and shorter filter runs.
- Application of low molecular weight cationic polymer for 10 to 12 minutes during filter backwash, to condition the media and reduce turbidity spikes upon filter startup.
- Resting filters after backwash, and ramping the flow controller to the desired filtration rate to reduce turbidity spikes.
- Performing monthly filter inspections and freeboard measurements.
- Topping up anthracite filters to the original design depth.

The above list of changes does not include large capital cost items. The optimization was accomplished through the effective use of existing facilities, without large expenditures of funds for new equipment or process facilities.

Results

Results of the optimization activities were positive. The finished water turbidity produced by the Elm Fork Water Treatment Plant consistently averaged about 0.05 ntu during the years 1996 through 1998. The Partnership's filtered water goals were met over 99% of the time in spite of treating a source water with a highly variable turbidity. The Elm Fork Water Treatment Plant was recognized for completion of Phase III of the Partnership for Safe Water program in 1998. During the period of February through July, 1998, more than 120,000 individual filtered water turbidity measurements were made, and over 99.6% of these were $\leq$ 0.1 ntu. The plant also successfully completed the Texas Optimization Recognition Program.

Leavenworth, Washington

Background

A description of treatment problems encountered in Leavenworth, Washington and the approach to optimizing treatment was presented in *Opflow* (Hegg et al. 2000), and the Leavenworth experience described in this chapter is based on that reference. Leavenworth is a small community located in the Cascade Mountains. The source water, Icicle Creek, had an average turbidity of 0.61 ntu in 1998. As the name implies, the source water can be very cold. The 2.0 mgd (7.6 ML/d) direct filtration plant could not meet the Washington Department of Health requirements for filtered water turbidity. In the State of Washington, when source water turbidity is less than 2.5 ntu, plants that use coagulation and filtration must attain at least 80% average turbidity removal, or the 95th percentile turbidity must be equal to or less than 0.1 ntu. Filtered water turbidity at Leavenworth's plant tended to increase when raw water turbidity increased, indicating that treatment was not optimized.

Improvements Made

Before the optimization program led by engineers from Process Applications, Inc. was started, plant staff had taken a number of actions, including:

- install an alarm system to alert operators to high raw or filtered water turbidity
- improve coagulant feed system so both coagulant and filter aid could be fed, and install a streaming current monitor
- implement procedures to maintain constant rate of flow through treatment plant

A review of the plant and procedures by the consultant revealed a number of obstacles to optimization. These included:

- lack of calibration curves for chemical feed pumps
- procedures for selecting chemical dosages were not documented
- filter media depth not maintained at design value
- coagulant chemical (ferric chloride) dosage not adjusted for variation in source water quality
- direct filtration plant not staffed during all hours of operation
- filtration rate for filters remaining in service surged when one filter removed for backwash

The consultants worked with Leavenworth plant staff and city administrators to achieve changes and improvements. A utility worker who had been assigned multiple tasks was reassigned to work mostly on water treatment, improving the staffing pattern at the direct filtration plant. Jar tests showed that the higher ferric chloride dosages needed to attain effective coagulation depleted the alkalinity and caused high turbidity, so coagulation practice was changed. Polyaluminum chloride was substituted for ferric chloride, because polyaluminum chloride did not depress the pH in the low-alkalinity water from Icicle Creek. Other changes included repair of surface wash mechanisms, adding anthracite media to the filters, adding flow measuring equipment, and obtaining chemical feed pumps with greater capacity. Operator training and strengthening of skills of the plant operators were key aspects to the optimization.

Results of the Optimization Program

The results of this improvement program were excellent, and are shown in Figures 13.8 and 13.9, which depict raw water turbidity and filtered water turbidity at the plant from January, 1996 through February, 1999. Filtered water turbidity was influenced by raw water turbidity and ranged from 0.05 ntu to 0.5 ntu in 1996 and the first half of 1997 before optimization. Beginning in January 1998, following optimization, the maximum finished water turbidity did not exceed 0.1 ntu even when raw water quality varied. The State of Washington recognized the improvements in May, 1998 and noted that the improvement in water quality was accomplished without major new capital facilities. The chief operator of the Leavenworth utility was recognized as the Operator of the Year for 1998 by the Evergreen Rural Water Association.

Fort Collins Water Treatment Facility

The Fort Collins Water Treatment Facility is a conventional filtration plant with four treatment trains having a total capacity of 74 mgd (280 ML/d). Water sources are the Cache La Poudre River and Horsetooth Reservoir, which generally have low turbidity, ranging from less than 1 ntu to 4 ntu, but runoff from snowmelt in mid- to late-spring can cause turbidity to reach 100 ntu. Rapid changes in source water quality present a challenge to the plant operators, so treatment practice has been developed to cope with these changes. The text for this case study is based on information on means of attaining optimized performance, as reported by Fort Collins Utilities personnel.

Means of Attaining Optimized Performance

Optimized performance at the Fort Collins Water Treatment Facility (FCWTF) is generally achieved through proper optimization of the coagulation, settling, and filtration processes. The FCWTF operators have many tools available to them to help them make the correct process control decisions. All operators use documented unit process performance targets and finished water targets to control plant performance. The FCWTF plant performance goals are summarized below:

- settled water turbidity ≤ 1.0 ntu
- individual filter turbidity ≤ 0.1 ntu
- individual filter particle counts ≤ 10 per mL above 2 μm

- post-backwash turbidity spike $\leq$ 0.3 ntu
- individual filter turbidity within 15 minutes of returning to service after backwash $\leq$ 0.1 ntu
- individual filter particle counts within 15 minutes of returning to service after backwash $\leq$ 10 per mL above 2 μm

Optimization of Coagulation

Liquid aluminum sulfate (alum) is the primary coagulant used at the FCWTF. The typical alum dose ranges from approximately 20 mg/L in the winter to 40 mg/L during the Cache La Poudre River spring runoff period. The operators use a number of indicators to determine if a change in alum dose is required. Process monitoring of raw water turbidity, settled water turbidity, filtered water turbidity, zeta potential, temperature, pH, color, and filter particle counts may all be used to initiate an alum dose change. Settling characteristics of the floc carryover into the filters is also considered. Filter run times may also be used as an indicator that an alum dose change is required.

Rapidly changing water quality and elevated turbidity are the circumstances when the greatest effort is needed for determining correct coagulation conditions. Snowmelt occurring in the spring causes large changes in source water quality. At this time a laboratory technician retrains operators on the procedures used for testing to determine chemical dosages. Once it has been determined that an alum dose change is required, the operators use jar tests, a zeta meter, and streaming current monitors to assist in determining and maintaining the correct alum dose. Frequently the operators will make alum dose changes of 0.5 to 2 mg/L based on their prior experience (the ten Class A Operators at the FCWTF average 10 years of ADD (experience) at the FCWTF, with a range of 3 to 30 years). The response to a change in alum dose is monitored by the operators using the Supervisory Control and Data Acquisition System (SCADA) trend charts for pH, settled turbidity, filtered water turbidity, and particle counts. Operators also determine the zeta potential on grab samples to monitor the response to a dose change.

All operators are experienced in performing jar tests. However, they do not perform them very frequently because the tests take a significant amount of time. Jar tests are performed most often by the operators during the spring runoff period when the turbidity, color and total organic carbon are undergoing significant changes and the water presents the greatest treatment challenges. The FCWTF Water Treatment Quality Coordinator often performs jar tests for the operators during this time. The

Water Treatment Quality Coordinator also uses the FCWTF pilot plant in combination with the jar tests during the runoff period to optimize both the alum and flocculant aid doses.

Once an alum dose is selected by the operator and entered in the SCADA system, the alum feed pumps are flow-paced to assure a steady dose. The operators verify the alum feed rate by conducting 15-second drawdown measurements using the alum sight tube associated with the alum feed system. A 15-second drawdown is conducted once per shift to verify the current alum dose. A 15-second drawdown is also conducted whenever an alum dose change is made.

Streaming current monitors are present for each process train to determine the particle charge of the water after alum addition. The operators generally use the streaming current monitors as an early alarm for the loss of alum feed or some other unexpected deviation in the alum feed rate. They have been found to be useful on a year-round basis, but at Fort Collins, the instruments need to be backflushed on a daily basis.

Zeta potential testing is done frequently during the runoff season, as the test takes only a few minutes. Operators use this test for fine-tuning the coagulant dosage, as the time required for zeta potential is less than that needed for jar testing.

Optimization of the Settling Process

The operators generally strive for a settled water turbidity goal of $\leq$ 1.0 ntu, although it depends on the water quality and the floc characteristics. From the operator's perspective, the most important factor to be considered is how the settled turbidity affects behavior of the filters. In some cases, the filters perform better when the settled turbidity is greater than 1.0. In order to achieve the settled turbidity goal, or to otherwise optimize the settling process, the operators can change the following:

- alum dose
- flocculant aid dose
- application points of the flocculant aid
- flow within the treatment train
- blend of the raw water (the proportions obtained from the river and the reservoir)

Optimization of Filter Performance

Operational practices. Filter optimization for particle removal and production efficiency is a high priority for the FCWTF. Filter performance is continuously evaluated with respect to the individual filter turbidity goals. The individual filter turbidity goal of ≤ 0.10 ntu is strictly adhered to by the operators. If the individual filter turbidity is greater than 0.10 ntu after the first fifteen minutes of the filter run, an alarm will go off through the FCWTF's SCADA system. A filter backwash will also be initiated at that point. However, it should be noted that the other backwash criteria (flow, water level, or run time) are generally met before turbidity or particle breakthrough are observed. The particle count goal of ≤ 10 particles per mL above 2 μm used by the operators as a guide on process performance and is also alarmed to the SCADA system. The particle counters are more sensitive than the turbidimeters and, therefore, have the ability to detect small changes in the process that the turbidimeters might not detect.

A backwash report is automatically generated at midnight every day by the FCWTF SCADA system. This report summarizes all the backwashes that were conducted during the previous 24-hour period and includes the reason for backwashing, the terminal conditions, filter run time, backwash flow, unit filter run volume, and production efficiency. Data on filter restarts, including filtered turbidity and particle counts, and the duration of ripening, are also kept. If a filter exceeds set points for turbidity or particle counts this is noted for future reference. This information is used to track filtration performance and to help determine if process changes are required. For example, if the filter run time or production efficiency is decreasing, changes in alum dose or filter washing may be required.

Filter optimization study. As part of a Master Planning effort, a comprehensive filter optimization study was conducted by the FCWTF and its consultant from January 1996 to September 1997 to develop recommended filter improvements. The filter optimization study included:

- Analysis of particle count data collected individually from each of the 23 filters during various times from September 1996 to August 1997.
- Analysis of average run times, loading rates, and unit filter run volumes for each filter.
- Analysis of the hydraulic capacity of the filters including the clean bed head loss and the filter hydraulic driving head.

- Analysis of filter backwash operations to determine if the current operations can be optimized of new features added to enhance the backwash process.
- A filter inspection that included a video inspection of each of the 23 filters conducted in the summer of 1997, and the collection of media samples from six of the mixed-media filters for sieve analysis, effective size and uniformity coefficient. This inspection was performed using the borescope, which was described in Chapter 10.
- Discussions with plant staff to identify filter operation and maintenance problems.

The results of the filter optimization study showed that several of the oldest declining rate filters produced filtered water of poorer quality than the newer filters. While still exceeding water quality requirements, the higher particle counts from these filters indicated diminished performance of the filter media. The existing mixed media (consisting of 16.5 inches (42 cm) of anthracite coal, 9 inches (23 cm) of silica sand, and 4.5 inches 11 cm) of high-density sand (garnet), and underlain by 10 inches (25 cm) of support gravel) were poorly matched and the anthracite layer was not sufficiently fluidized during normal backwashing. Video inspection of the media indicated significant loss of garnet and over-mixing of the media. For these reasons, replacement of the mixed media in all 15 declining rate filters (Filters 9-23) was recommended.

The recommend upgrade included removing the mixed media, support gravel, and underdrains and replacing them with deep-bed dual media (30 inches of anthracite over 12 inches of sand), an IMS® cap, and a new underdrain system. An air scour system was also installed for these filters to provide for air/water backwashing. The filter upgrades were based on the results of both the filter optimization study and a pilot plant filtration study conducted in the summer of 1998.

Summary

Optimization activities at Dallas, Leavenworth, and Fort Collins illustrate some important concepts about water filtration plant optimization.

- Communication involving operators and utility management is important, as everyone needs to buy into the concept of optimization and support it.

- Training and education are important and this is not limited to operators. Optimization requires management understanding of the purposes of optimization and what an optimization program entails.
- Optimization to achieve the best practically attainable quality of water from a plant does not have to be accompanied by a big capital investment program. Evaluating existing facilities and figuring out how to get the best performance of the plant as it exists, and perhaps making slight modifications, is an approach that can yield substantial improvements in filtered water quality.
- Operators may need to use multiple techniques to assess filtration plant performance and to ensure that pretreatment is effective so that optimized filtration performance can be achieved under a wide range of raw water quality conditions.
- Water filtration plant size is not a factor that directly limits the ability to optimize a plant. The attitudes of management towards optimization, the availability of sufficient staff to effectively operate a plant, and the provision of training and guidance for utility personnel are key factors to attaining optimization, regardless of plant size.
- An organized and systematic approach to plant optimization is needed, so all aspects of the management and operation of the plant will be considered. The EPA's publication *Optimizing Water Treatment Plant Performance Using the Composite Correction Program, 1998 Edition* (Hegg et al. 1998) is an excellent source of information on optimization.

CHEMICAL CLEANING OF FILTER MEDIA

Introduction

The circumstances that led to cleaning filter media at the water treatment plant at Chanute, Kansas were described in an article in *Opflow* (Adkinson and Schnieders 2000). The 6 mgd (23 ML/day) treatment plant at Chanute employs presedimentation of river water treated with cationic polymer and potassium permanganate, coagulation, lime softening, clarification and secondary settling, recarbonation, polyphosphate feed, and filtration through anthracite filters or through sand filters. During the summer of 1998 filtered water turbidity fluctuated and in some cases was unacceptable. Backwashing the filters more frequently did not help.

Action Taken

As a result of the problems encountered, filter media samples were examined. Media was found to be coated with both inorganic materials and with biofilm. The coatings on the media caused some media grains to be cemented together. Media samples were taken from two of the filters at the plant, at the surface and below the surface. Chemical cleaning removed surface deposits ranging from 7.5 to 19.3 percent by weight. Further testing indicated about one half of the deposits (by weight) were organic matter. Cleaning chemicals were evaluated by testing their effect on media samples. Chemicals tested included hydrochloric acid, acetic acid, hydroxyacetic acid, phosphoric acid, and potassium hydroxide. The acids were tested alone and in conjunction with a biodispersant, which would aid in breaking up the biofilm. The dispersant was found to be helpful. The authors (Adkinson and Schnieders) noted that NSF International is the source of information on biodispersant products for use in cleaning filters.

After testing showed that the most effective combination of chemicals was a 3 percent solution of food grade phosphoric acid plus a 1 percent solution of biodispersant, this combination was used to clean filters. When filters were cleaned, the chemicals were added to the water over the filter and then the water-chemical solution was mixed by using high-pressure hoses to stir the water. Adding the chemicals to the water resulted in a release of carbon dioxide, caused by dissolution of calcium carbonate. Following the release of carbon dioxide, a black scum was observed, and this was later found to be organic matter. After the filters were chemically treated, repeated cycles of backwashing were needed to fully clean the media and eliminate a cloudy or hazy appearance in the filters during backwash.

Results

Adkinson and Schnieders reported that chemical cleaning of a single filter required about 24 hours. The cost for chemical cleaning of a filter was about one fourth of the cost of media replacement. Photographs of the media before cleaning and after cleaning were presented by Adkinson and Schnieders in the *Opflow* article, and substantial differences in the "before" and "after" photographs were apparent. The anthracite (Figure 13.10) and sand (Figure 13.11) were much cleaner (by visual appearance) after the chemical cleaning procedure.

APPLICATION OF STREAMING CURRENT INSTRUMENTS AT PHILADELPHIA

Introduction

Use of streaming current instruments at the Samuel S. Baxter Water Treatment Plant was described by Kramer and Horger (2000). The plant is in the Partnership for Safe Water, and filtered water turbidity routinely is below 0.10 ntu. This plant produces an annual average of 175 mgd (660 ML/day), operating in two parallel treatment trains (North Side and South Side). The North Side treatment train was operated in a sweep flocculation mode, whereas the South Side started a plant-scale trial of enhanced coagulation in 1998. Ferric chloride was the coagulant used in both treatment trains. Thus the applicability of using streaming current instruments was evaluated in two different coagulation modes for treatment of water from the Delaware River.

Use of Streaming Current Instruments at Sweep Flocculation Facility

The North Side Treatment Train had only one pH adjustment point in pretreatment. To meet the finished water pH goal of 7.4, the pH of coagulation was maintained in a range of 8.0 to 9.2. Sweep flocculation occurred in this treatment train. Adjustment of pH was accomplished by adding slaked lime. Under these operating conditions, the streaming current instrument was insensitive to changes in ferric chloride dosage, responding if the ferric chloride dosage increased 150% or decreased 50%. This was not useful, as coagulant dosage changes typically were on the order of 5% to 7%. An additional problem was that addition of slaked lime ahead of the streaming current instrument resulted in fouling of the streaming current instrument's sensor. Under conditions of high pH (8.0 or above) and the addition of slaked lime, the streaming current instrument did not provide useful information on coagulation.

Use of Streaming Current Instruments at Enhanced Coagulation Facility

The South Side Treatment Train employed enhanced coagulation, with downward pH adjustment to a coagulation pH of 6.5. Hydrated lime usually was added in pretreatment to keep pH from dropping below 6.5 and to maintain alkalinity at 12 mg/L (as $CaCO_3$) or higher. Sampling for the streaming current instrument was done about five to ten minutes after addition of ferric chloride, and about two minutes after addition of the hydrated lime. Hydrated lime also was added after sedimentation to adjust pH upward. When coagulation was carried out at a pH of 6.5, the streaming current instrument was able to detect a change of coagulant dosage in the range of 1.2 to 2.4 mg/L. This was sufficiently sensitive to

provide useful information to plant operators. Kramer and Horger (2000) noted that plant staff cleaned the streaming current sensor on a weekly basis, and after cleaning, filled the streaming current sample cell with a neutral pH 7 stock solution and set the unit to zero. After the instrument was zeroed, the sample cell was flushed with deionized water before the instrument was returned to service.

In this treatment train, the streaming current instrument has been used to optimize coagulation, to provide information on chemical dosage during a major storm event caused by Hurricane Floyd in 1999, and to alert operators to a coagulant or lime feed failure. Coagulant optimization involves using the minimum coagulant dosage needed to maintain satisfactory combined filter effluent turbidity and satisfactory performance of flocculation and sedimentation facilities. Streaming current readings were useful when operators slightly decrease coagulant dosage. Operators used streaming current readings and raw water turbidity data to make decisions on increasing chemical dosage when source water turbidity increased. After Hurricane Floyd brought extremely heavy rains to southeastern Pennsylvania, operators were able to quickly assess the effects of a turbidity increase caused by heavy flooding. During this event, combined filtered water turbidity, based on bench-top turbidimeters, always was in the range of 0.05 to 0.06 ntu, which is the normal range for the plant. A lime feed failure in March 2000 was immediately evident from the streaming current readings. If operators had relied on plant chemistry grab sampling and analysis procedures, the failure might not have been detected for a couple of hours.

Lessons Learned

An important lesson learned at the Baxter Water Treatment Plant relates to the amount of experience needed for operators to be confident with the use of streaming current instruments. Guest (2000) recommends that data collection be undertaken for a year to determine plant-specific streaming current target ranges, and the seasonal effects on those ranges. At Philadelphia, data were collected on coagulant dosages, pH, raw water flow, alkalinity, and turbidity. These data and streaming current data were examined over an 18-month period of time to determine the appropriate streaming current ranges. Guest (2000) also noted that water that has been dosed according to jar test results can be used to determine streaming current readings and the target ranges. These observations indicate that users should not expect to install a streaming current instrument and immediately operate their treatment plant based on streaming current readings. Rather, operation should continue as usual while operators develop a sense of the significance of streaming current readings and how those data can be used as an aid to operation.

Kramer and Horger (2000) presented the following among their conclusions on the use of streaming current instruments at Philadelphia:

- Streaming current instruments can be sluggish if sweep flocculation at high pH is used.
- Poor slaked lime mixing caused the instrument's sensor to become fouled quickly.
- For coagulation at pH below 7.0, streaming current instruments can respond rapidly to minor changes in coagulant dosage. The instrument was quite effective for coagulation operated in the charge neutralization mode.
- Streaming current readings were helpful for alerting plant staff to chemical feed equipment failures.
- Successful use of the streaming current instrument depended upon:
  - Locating the instrument properly so it received coagulated, thoroughly mixed water
  - Carrying out a routine maintenance program to clean and calibrate the sensor
  - Properly delivering the sample to the cell
  - Establishing a baseline value for optimized coagulation
  - Providing an on-line display of streaming current information for operators to enable them to see data trends.

REHABILITATION OF FILTERS AT BRICK UTILITIES

Introduction

In 1996 the staff at the Brick Township Municipal Utilities Authority (Brick Utilities) undertook the task of rehabilitating the filters at the William Miller Central Water Treatment Plant. This case study describes that project, based on a published account (Kirman and Rissel 1998) and on information provided in thisproject. The filtration plant was built in 1975 with four filters measuring 17 feet x 17 feet (5.2 m x 5.2 m). Capacity was 8 mgd (30 ML/d). Filters were built with monolithic Wheeler bottoms. All filters were equipped with surface wash for auxiliary scour. In 1986 the plant capacity was doubled by addition of four more filters, identical to the first four. This plant uses a river for about 80% of the source water and uses ground water for the balance. In 1998 the river water turbidity averaged 6 ntu, ranging from 3 to 23 ntu. True color of the river water averaged 89color units, ranging from 39 to 251 color units.

Rehabilitation of Filters

Brick Utilities officials reviewed the circumstances related to rebuilding filters, investigating a number of options for completing the project. They decided to use in-house personnel to rebuild the filters for reasons of cost and because they could maintain better control of the timing of the work by scheduling Brick Utilities employees to perform the rehabilitation. The rehabilitation effort included replacement of 400 cubic yards (300 cubic meters) of support gravel, sand, and anthracite. Also more than 20,000 porcelain spheres were obtained to replace the existing spheres in the Wheeler bottoms. After the materials were obtained, the rehabilitation was completed by 15 Brick Utilities employees in three weeks. The filters were rebuilt in succession to minimize disrupting treatment operations at the plant. The first step involved removal of old filter media by use of a vacuum truck of the type used by public works departments to collect debris from curbs, catch basins, and right of way areas. A new hose was purchased so the equipment used would not contribute contamination to the filters. The vacuum truck was used because 50 cubic yards (37 cubic meters) of media had to be removed from each filter. With the media and porcelain spheres removed, filter underdrains could be pressure washed and inspected.

When the inspection was completed, 2600 spheres were replaced in the Wheeler bottom for each filter, and the support gravel and filter media were placed in the filter. AWWA Standard B100 was followed strictly in the rebuilding. Brick Utilities had quality assurance testing performed by a third party laboratory, as a check on the materials provides by vendors. Some gravel was found to be outside of specifications, and this material was replaced by the vendor. Work was carefully done to be sure that filter material depths were proper and that the material was level. After the materials were placed, each filter was disinfected for 12 hours and then backwashed thoroughly. After backwashing the rehabilitated filter was tested for total coliform bacteria. None of the filters were positive for coliform bacteria.

Labor costs for the project totaled less than $20,000. Kirman and Rissel (1998) wrote that the use of in-house crews ensured that the work was completed on time and to the standards of the utility, and that the cost of the work was ".... substantially less cost than if an outside contractor had been enlisted."

Results

Kirman and Rissel reported that after the rehabilitation was completed, the filter performance improved, with run times being 50% to 70% longer than the runs before rehabilitation. As reported for this project, maximum daily filtered water turbidity in the clearwell ranged from 0.03 to 0.29 ntu and averaged 0.07 ntu in 1998. The utility is very satisfied with the outcome of this rehabilitation effort.

CASE STUDY OF MODIFICATIONS TO AIR SCOUR SYSTEM

Introduction

This case study describes how the conceptual and process design of a water treatment plant, which offered capital cost savings in the short term, led to a plant which was inherently unstable to operate. The design of the plant made reliable treatment unsustainable and so extensive capital upgrade was required several years after commissioning. The study describes how the filter and air scour design influenced treatment performance and water quality and the process solution proposed to rectify the problems encountered with operating the plant.

Original Design and Associated Problems

The treatment plant, which was constructed in 1993, has been the subject of a number of modifications since commissioning. While many of these achieved their desired outcomes, they did not resolve the fundamental design weakness of the plant and in fact, often created other problems.

- The plant originally consisted of five in-filter dissolved air flotation-filtration (DAFF) units designed with a very high filtration rate (approximately 5.9 gpm/sf or 14.5 m/h) rising to 7.4 gpm/sf (18.0 m/h) when one filter was washing). It was found impossible to operate productively at these high loading rates and an additional in-filter unit was added in 1998 to reduce filtration velocity to 4.9 gpm/sf (12 m/h) and 5.9 gpm/sf (14.5 m/h) respectively.
- The raw water treated at this plant is characterized as being highly colored, moderate in DOC and low in turbidity and alkalinity (87 color units, DOC 10.4 mg/L, 3.7 ntu and alkalinity 58 mg/L respectively). Coagulation using alum is capable of removing 50 % or more of the DOC. Potassium permanganate is dosed in to the raw water to control manganese.

- The original design utilized a hydraulic rapid mixer for coagulant addition, which gave poor floc formation. Polymer was required to be dosed at the inlet of the individual DAFF units. However, inlet water flow distribution between the filters was uneven, resulting in variable polymer dose rates.
- Coagulated water was distributed to individual DAFF units over a weir with a free fall of about 1 foot (0.3 m). This together with the high shear imparted as water flowed through inlet valves to the filter resulted in the destruction of pre-formed floc.
- The original filter media installed comprised three layers using anthracite, sand and fine garnet, providing a total depth of 38 inches (97 cm), however this resulted in short filter runs. A coarse monomedium (es 1.25 - 1.35 mm uc = 1.3) was selected for direct replacement following pilot trials.
- The coarseness of the filter media and its relatively shallow depth necessitated the application of high polymer doses (0.15 - 0.17 mg/L polyacrylamide) to meet filtered water turbidity requirements.
- The proximity of the wash out trough (2.3 ft or 0.70 m) to the top of the filter media and the use of combined air scour filter backwashing resulted in excessive filter media loss.
- The application of such high polymer doses made the filter media sticky and difficult to clean leading to the replacement of media on an annual basis.
- Mudball formation was common and required frequent manual removal.

Fundamental Problem

The plant design and associated operational problems described previously were compounded by the fundamental design weakness of the treatment plant -- the design of the filter floor. The ability to effectively backwash media is an essential prerequisite for the operation of rapid gravity filters. The original design was based upon a lateral system, constructed from rectangular pipe (3.1 by 3.9 inches or 80 mm by 100 mm) which was used for distributing backwash air and water and for collecting filtrate.

A sub-fluidizing combined air scour wash phase is included as part of the filter backwash process at this plant. During this phase, air and water are introduced into the lateral simultaneously in the correct ratios. However, the lateral system installed does not permit the two fluids to be distributed evenly into the bed in the correct ratios. Even distribution of air through the individual nozzles in a lateral floor depends upon achieving a flat and stable water level in the lateral during air scour.

An evaluation of the plant indicated that air scour, when operated alone, does attain uniform action. Figure 13.12 shows how good distribution of air is achieved during the separate air scour stage of the backwash process. Before the air scour starts the filtered water duct and laterals are all full of water. When the blowers start, air is distributed through the headers into the two top entry points of each lateral. Water is displaced from the overt of the lateral through the nozzles into the filter until the air control orifices in the nozzles are exposed. Air is then metered through each nozzle into the filter media and the air scour begins. The water level in the lateral will equilibrate in a position where the head loss through the control orifice is equivalent to the distance between the orifice and water level. This condition is stable and the interface between air and water is level in all laterals. A good, even air scour is assured. This is confirmed in Figure 13.13, which demonstrates good distribution of air in a filter undergoing the air scour phase of a backwash.

Combined air scour is carried out by first starting the separate air scour as shown in Figure 13.12. Then after the backwash pumps are started, water flows vertically from the filtered water duct through control orifices in the bottom of each lateral then splits two ways, turns through 90 degrees and flows horizontally along the laterals. The vertical velocity is about 1.3 ft/s (0.4 m/s) so the air-water interface above the duct is destroyed and air is virtually excluded from adjacent nozzles. The filter media above the duct will have only water, at well below fluidization velocity, passing through it.

Between the air injection points and the duct the two fluids travel in opposite directions, which is not conducive to a stable interface. Much waving and splashing can be expected in these zones. The relatively high velocity of water in this area (> 3 ft/s or 1.0 m/s) will have significant kinetic energy thereby reducing water level, probably to below the bottom of the nozzle stems, allowing an easy route for air to escape. It is likely that mostly air passes into the media in these zones.

Towards the dead end of the lateral pressure energy will be recovered as the water velocity reduces. This will result in a rise in water level with some bubbles and slugs of air dragged with the water flow. The ratio of air to water in these zones will be variable.

The filter floor design used at this water treatment plant was not applicable for combined air water filter backwashing and was a design only suitable for separate air and water distribution only.

Figure 13.14 illustrates how the simultaneous introduction of backwash water with air scour destroys the level air/water interface in the laterals and hence the air distribution breaks down. This creates a wave action in the lateral, which results in unequal distribution of air and water into the filter media. When viewed from above the filter, a poor air scour pattern is seen with localized violent eruptions breaking at the filter surface (Figure 13.15). The effect of this is that different zones of the

bed will receive high air and low water and visa versa, neither of which will support effective combined air water filter backwashing.

To confirm this hypothesis, filter media was sampled from all six filters at different depths and locations after filter backwashing and tested for silt content. Results obtained from this exercise demonstrated high residual silt concentrations, typically greater than 0.81 pound per cubic foot (13 kg per cubic meter) of filter media and confirmed ineffective filter backwashing was taking place. It was believed that by improving the filter floor layout to permit combined air water backwashing in the collapse-pulse mode, clean filter media could be established. Pilot trials were undertaken to demonstrate the potential of using collapse-pulse for filter backwashing.

Correctly applied combined air scour back washing in the collapse-pulse mode was found to be highly effective in cleaning filter media cleaning the dirty to media to a silt content of less than 0.12 pound per cubic foot (2 kg/m^3). In fact it was observed during the pilot studies, that mudballs, typically of diameter 1/6 inch (4 mm), migrated to the surface of the filter.

The Proposed Solution

A wide range of capital upgrades are in progress to improve the overall performance of the treatment plant including:

- Installing a mechanical in-line flash mixer to improve coagulant addition.
- Improving the hydraulic distribution of inlet water to individual DAFF units by installing an inlet manifold with orifice plate and lowering the free fall across the weir.
- Relocating the polymer dosing to individual DAFF units using orifice plates for mixing.
- Raising the backwash launder to allow the media depth to be increased and to minimize media losses during filter backwashing.
- Utilizing the existing lateral system for water only distribution and retrofit a separate air scour lateral to distribute air to enable combined air scour filter back washing in the collapse-pulse mode.
- Undertaking pilot tests to determine best media selection in order to achieve satisfactory filter run times while maintaining low filtered water quality with reduced polymer dose.

IMPROVING FILTERED WATER TURBIDITY BY CONTINUOUS DOSING OF SUPPLEMENTARY COAGULANT AT THAMES WATER UTILITIES

Introduction

The Shalford Water Treatment Works is a conventional water treatment works taking lowland river water directly from the rivers Wey and Tillingbourne, located approximately 40 miles (65 km) south west of London. The water passes through coarse screens and is prechlorinated at 2 mg/L. Prior to clarification the water is dosed with NaOH to compensate for the pH change caused by the $FeCl_3$ coagulant. The coagulated water passes to the Densadeg® clarifier. This clarification process comprises a flocculation chamber where polyelectrolyte (Magnafloc LT25) is dosed, a lamella settlement tank with picket fence thickeners, and a sludge recirculation process, which recycles a proportion of the settled sludge to the flocculation vessel where it is blended with the coagulated raw water. Excess sludge is pumped away.

The clarified water passes to 6 dual media filters having 20 cm (8 inches) depth of 1.2-2.5 mm anthracite over 50 cm (20 inches) depth of 0.5-1.0 mm sand). The filters operated at a nominal rate of 5 m/h (2 gpm/sf). Backwashing consists of 30 seconds of air scour, 5 minutes of combined air scour and water washing under collapse pulsing conditions, and 5 minutes of water wash to drive dirt out of the bed and reclassify the media. The filter is run to waste for 22 minutes at approximately 2 m/h (0.8 gpm/sf). Backwashing is automatically initiated by one of the following triggers: 0.5 ntu filtrate, high head loss, or 36 hours elapsed filter run time.

Older flat bottomed clarifiers were replaced in a works refurbishment program which also included rebuilding the filters with new floors, pipe work, backwash troughs and wash program and new media. The work was completed in early 1999.

Experimental investigation

In the autumn of 1999 concerns were expressed that despite achieving excellent clarified water turbidity of around 0.3 to 0.5 ntu, the filtered water turbidity was not as low as was desired. Filtered water turbidity values were in the region of 0.3 ntu and varied. The goal was a consistent flat line around 0.1 ntu.

Filter head loss development was extremely slow, and ripening appeared to last the entire duration of the filter run. Initial attempts to raise and lower the coagulant dose to the clarifier had the effect of causing poorer filtered water quality.

The investigators identified a number of clues that suggested what the problem might be and helped determine a means of improving filtered water turbidity. The clarified water was very low in turbidity and no carry over of floc took place. The low rate of head loss development and the continuous improvement in turbidity throughout the filter run suggested that a very low solids (particulate matter) loading was coming onto the filter. The variation in filtered water turbidity was similar to observations made on a contact filtration pilot plant (Chipps 1998). From this observation it was inferred that the particles carried over from the filter did not have their surface charge properly destabilized. This was confirmed by the fact that the filters seemed to be able to remove only about 50% of the applied turbidity at best. This helped explain why ripening and head loss development were slow.

The fundamental cause of this potential problem was unknown, but the hypothesis was made that small, stabilized particles were passing through the clarifier, because they were very difficult to filter. A lack of familiarity and experience with the clarifier meant that testing the hypothesis and producing a temporary fix for the problem would be more successful if the investigation concentrated on optimizing the filter performance.

An experiment was set up to add a supplementary dose of $FeCl_3$ coagulant at the weir where the clarifier discharged into the flume feeding the filters. A spare dosing pump and line left over from the operation of the flat-bottomed clarifier were called back into service. A new sparge pipe was installed above the weir to introduce the coagulant. Sufficient hydraulic fall occurred at the weir to ensure rapid mixing of the coagulant. The water passed down the channel and into the filters through three 90-degree bends and an inlet penstock. The degree to which these may have contributed to particle flocculation is not known. As a result it is not possible to say precisely whether this supplemental dose should be considered to be contact filtration or direct filtration. Since there was no deliberate flocculation vessel it is preferable to think of it as contact filtration.

Results

An initial dose of 0.5 mg/L as Fe was tried, and successful operating ranges of 0.3 to 0.6 mg/L were found. Upon commencing supplemental dosing an almost immediate response was recorded by the filters. Turbidity fell to less than 0.1 ntu in less than 1 hour, and remained steady throughout the

filter run. With the exception of peaks due to backwashing filtered water turbidity has remained at this value (less than 0.1 ntu) throughout the nine months that this temporary fix has been in place. The logged filter turbidity data showed classic ripening curves. The rate of head loss development has not been greatly changed by the extra coagulant load, and backwashing remains typically at 36-hour intervals.

Figure 13.16 shows the turbidity from the six filters operated over 48 hours in the summer of 2000. Data from Hach 1720C turbidimeters were logged by SCADA at one-minute intervals. At approximately 01:00 the supplementary coagulant supply failed. The filtered water turbidities immediately started to deteriorate, and within 4 hours had risen from less than 0.1 ntu to between 0.1 and 0.2 ntu (filters 1, 3, 5 and 6). During this time filters 3 and 4 were backwashed. After the wash these filters were producing turbidity between 0.2 and 0.25 ntu. The faulty dosing pump was replaced at 09:00 and within an hour all the turbidities had returned to less than 0.1 ntu. It is not clear why filter 2 did not respond to the loss of supplementary coagulant in the same way as the other filters.

Discussion

As a scientific investigation this work has left several questions unanswered. What are the particles leaving the clarifier? Are they particles originating in the river that have avoided the coagulation and flocculation? Are they particles that have been released in the sludge recirculation process? What are the charges on the particles? Is the hypothesis that has formed the basis of the contact filtration work correct? Is there another explanation? How should these be tested and proved? Can the operation of clarifier itself be changed in a way that can eliminate the need for the supplementary coagulant dose? Is the water coming out of the clarifier too clean for effective filtration? How does the contact filtration work? Presumably the filter performance is improved due to the extra load resulting from the increased capture efficiency of the destabilized particles and the production of ferric hydroxide floc.

The works managers were very pleased with this solution to their problem. In fact they were so pleased they have not allowed the investigators to carry out trials which involve turning the supplementary coagulant dose off. This resulted in the rather limited data presented in Figure 13.16.

Summary

Filtered water turbidity was improved from a variable value around 0.3 ntu to a consistent value less than 0.1 ntu by adding a small supplementary dose of coagulant to the outlet of the clarifier. The filtration process became a hybrid of conventional treatment and contact filtration. The cause of the underlying problem with operating the works in conventional mode has not yet been identified. The temporary fix has proved popular with the plant operators and is being converted into the full-scale answer pending further investigation of conventional filtration solutions.

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SHORTENING FILTER RIPENING TIME BY SHORT TERM ADDITIONAL COAGULANT DOSING

Introduction

The Shalford Water Treatment Works is a conventional water treatment works taking lowland river water directly from the rivers Wey and Tillingbourne, located to the south west of London. The treatment process has been described in the case study on improving filtered water turbidity by continuous dosing of supplementary coagulant. The work reported in this case study used an extra short term addition of $FeCl_3$ coagulant as well as the continuous supplementary dose described in the other Shalford case study.

A distinct ripening period follows filter backwashing at Shalford, in common with the majority of water filtration plants. Researchers have described adding coagulants or polymers to filter backwash water to reduce the ripening period (Harris, 1970, Cranston and Amirtharajah 1987). In Europe Francois and Van Haute (1985) and Janssens et al. (1982) have described pilot plant studies where an excess of coagulant was introduced into the water for between 10 and 40 minutes at the start of the filter run. Both sets of results indicated that this extra chemical dosage could reduce the ripening peak and duration, but that too high a dosage or too long a duration could result in the initial improvement being followed by a deterioration in quality resulting in higher turbidity values than the turbidity attained by

use of a constant coagulant dosage. Some water utilities participating in this project reported using supplemental coagulant or polymer dosages to reduce the magnitude of the initial turbidity spike, as indicated in Chapter 7 of this manual. A study of supplemental alum addition done by the Greenville Water System was described earlier in this chapter on case studies.

The problem with adding coagulant or polymer to the backwash water is that the chemical is dosed on the filtrate side of the filter and could potentially cause problems with final water quality, due to residual metal ion concentration or polymer, without a filter-to-waste period. This would be counter-productive. It is also difficult to set up as a temporary trial, or retrofit at a full-scale water treatment plant.

Adding an excess of coagulant as the filter refills could help to condition the media and destabilize any charges on the particles left in the filter or the supernatant after the backwash. As compared to adding coagulant chemical to backwash water, adding it when the filter box refills is less likely to cause coagulant to pass into the filtered water as long as turbidity remains low, and is easy to test. Retrofitting dosing lines to the inlet of several filters, however, is potentially more complex than retrofitting facilities to add chemical to the backwash water tank or pipe work.

Experimental investigation

A short-term trial was undertaken in July 2000. An appropriate volume of $FeCl_3$ coagulant was carefully poured into the influent water as it entered the side channel of the filter. This channel is separated from the main body of the filter by a weir. Dirty backwash water is discharged out of the filter across this weir. Influent water gently refills the filter by passing into the filter across the weir. When the inlet penstock is initially opened the water enters the side channel with considerable force. This energy was used to mix the coagulant. It took approximately four minutes for the side channel to reach the weir height. The researcher emptied the coagulant at an even rate over this time. This represented an additional contact filtration stage.

As every filter run is unique and this was taking place on a full-scale plant with "real" water, it was not possible to carry out precisely controlled experiments. For this reason an experimental run was compared with the previous and following runs on the same filter and with runs on adjacent filters that were backwashed within a few minutes of the experimental filter.

The additional coagulant dose was calculated as a nominal dose based on the mass of Fe added into the volume of water in the side channel and above the filter media when the filter had reached its maximum water level. This occurs before the filter-to-waste process starts.

Results

Four different nominal additional coagulant doses were tested over three days. Doses of approximately 1.2, 2.4, 2.9 and 4.8 mg/L as Fe were added on top of the normal coagulant dose (Table 13.5).

Table 13.6 compares the turbidity of each Rapid Gravity Filter at the restart on supply. The data show how the extra coagulant dose enabled the filtrate quality goal of 0.1 ntu to be achieved before the end of the period of running the filter-to-waste with the highest dose, 4.8 mg/L.

Table 13.5

Details of additional dosing experiments

RGF number	Date	Nominal dose applied as Fe, mg/L
RGF 2	July 25, 2000	2.5
RGF 2	July 26, 2000	1.2
RGF 3	July 26, 2000	4.8
RGF 6	July 26, 2000	2.9

Table 13.6

Filter ripening summary statistics

Filter	Extra dose applied (nominal mg Fe/L)	Time from peak to restart (mins)	Turbidity when RGF restarted into supply (ntu)	Turbidity 1 hour after restart into supply (ntu)
RGF1	0	10	0.20	0.09
RGF2	1.2	12	0.12	0.07
RGF3	4.8	12	0.08	0.07
RGF4	0	9	0.22	0.09
RGF5	0	9	0.19	0.08
RGF6	2.9	9	0.12	0.06

The results are presented on the following graphs showing the initial peak turbidity value and calling this Time t = 0 and monitoring the ripening period after this peak. Data were logged every minute from Hach 1720C turbidimeters.

Figure 13.17 compares the Rapid Gravity Filter 2 turbidity after the backwash turbidity peak from the 21st, 22nd, 24th, 25th, 26th of July. Filtered water turbidity improved to 0.10 ntu most quickly for the filters receiving the supplemental iron coagulant.

Figure 13.18 compares the Rapid Gravity Filter 3 turbidity after the backwash turbidity peak from the 21st, 23rd, 24th, 25th, 26th of July. Filter 3 also demonstrated the most rapid improvement to 0.10 ntu when an extra iron coagulant dosage of 4.79 mg/L was used, but the run on July 25 was similar although no extra coagulant was added on that date.

Figure 13.19 compares the Rapid Gravity Filter 6 turbidity after the backwash turbidity peak from the 23rd, 24th, 25th, 26th of July. Again the run with the shortest ripening time to 0.10 ntu was the one in which extra iron coagulant was added.

Figure 13.20 compares the turbidities after the backwash turbidity peak on the 26th of July, for three filters with extra coagulant and three filters without extra coagulant. Every one of the filters receiving extra iron reached 0.10 ntu more quickly than the three that were not dosed with extra coagulant.

The data from 24 July were affected by the loss of the supplementary continuous coagulant dose described in the other case study from Shalford. This is seen in Figures 13.17 and 13.18, in which Filters 2 and 3 ripened more slowly on 24 July than on days before and after that date.

Discussion

Filter ripening time was reduced by adding a small supplementary dose of coagulant to the water refilling the filter inlet channel after the inlet penstock opened. Reduction of filter ripening time offers the possibility of reducing the amount of time a filter is run to waste after backwashing and therefore presents the possibility of cost savings related to starting filters after washing. Further work is required with measuring the residual metal ion concentration and pH. A particle counting study would complement the turbidity data. On some waters this technique might have a deleterious affect on pH, so extra lime or caustic soda might be required.

Acknowledgement

The author is grateful to his colleagues in Thames Water and at the University of Surrey for their help in carrying out the investigations that are reported here. Special thanks go to Shelley May, John Grant, Benoit Danne and Robin Bayley.

CORING OF DUAL MEDIA LEADS TO IDENTIFICATION OF CAUSE OF MEDIA LOSS

Introduction

The benefits of filter coring were demonstrated at one utility where a new dual media filtration plant was found to be steadily losing filter media over a period of 3 months. The design media specification was for a deep bed of 3.9 ft (1.2 m) of 1.2 mm to 2.5 mm anthracite media over 1.6 ft (0.5 m) of 0.5 mm to 1 mm silica sand. Three layers of gravel of 5 mm, 10 mm and 20 mm size protected the under-drain, filter floor, plenum chamber from ingress of sand media through 3-mm slot nozzles. The plant was designed to treat 1.3 mgd (5.0 ML/d) through 3 filter cells of 10-ft by 10-ft (3-m by 3-m) plan area. The answer to the problem was revealed by a program of filter coring.

Action Taken

It was visually noticed after about 1 month of operation that filter media level appeared to be slowly dropping in an even manner across each of the 3 filter beds at the plant. Accurate level measurements were made on each filter bed after a full backwash cycle and found to confirm loss of media since installation.

At first it was suspected that anthracite media was being washed out of the filter box during backwash as a relative new (at the time) backwash procedure had been installed at the plant. This consisted of air scour, combined (rising) air and water wash, followed by a high rate, fluidizing (30% bed expansion) water wash. Little evidence of anthracite media was found, however, in backwash troughs or in the backwash water, settling tank where lost media might settle out. Over a period of three months media level dropped 1 foot (0.3 m) so a full filter media inspection was planned.

Each filter was backwashed and drained to enable an operator to stand on the media and attempt to excavate down to the filter floor. This was found to be difficult to achieve in a deep filter (5.9 ft or 1.8 m of media and gravel) of small plan area (10 ft by 10 ft or 3 m by 3 m).

A filter media coring tool was improvised from thin-wall PVC plastic drainpipe purchased from a local hardware store. The pipe was cut in half along its length and then re-assembled as a pipe, held together by strips of duct tape. It was found relatively easy to drive the improvised pipe-coring device up to 5 ft (1.5 m) into the filter bed. A few rotary twists were found to isolate the core contents from the supporting filter media base and insertion of a rubber bung in the top of the pipe enabled extraction of intact media cores.

When the duct tape was cut and the pipe halves opened and contents split with a knife the media was found to contain well-stratified anthracite close to the specified depth but very little evidence of a defined sand layer. Some grains of sand were intermixed with the bottom 0.3 ft (0.1 m) of anthracite. None of the gravel material could be retrieved by this coring technique but measuring core length against filter design indicated that there was at least 0.6 ft (0.2 m) of gravel although the design specification was for 0.82 ft (0.25 m) in 3 size layers. Several more cores in each filter gave similar results.

The cores were taken as evidence of a major filter floor problem and excavation of all media from one filter cell was carried out in layers. This confirmed the presence of the design depth of anthracite but that most of the 0.5 mm to 1 mm sand layer was missing. Continuing excavation through the gravels showed that the top layer of 3-5 mm gravel was also missing. The 10 mm and 20 mm gravel layers were present and were not disrupted in a manner that suggested that failure of individual nozzles had occurred or that the plenum filter floor had been broken. This was confirmed by removing the gravel.

Resolution of Problem

The hunt for the missing sand media was soon solved when the plenum chambers under the filter floor were pumped out and inspection hatches opened. The sand was in the filter under-drains and had to be hand dug out. No evidence of the missing layer of 3-5 mm gravel was found, until a tour of the site's remaining construction area found bags of unopened and never-placed 3-5 mm gravel!

Rebuilding the filter bed with the specified 3 gravel layers and recovered sand and anthracite media resulted in a fully functioning filter that did not lose media at anything other than typical 1 cm to 2 cm per annum of the finer anthracite, washed over filter troughs by attachment to air bubbles during the fluidizing water wash.

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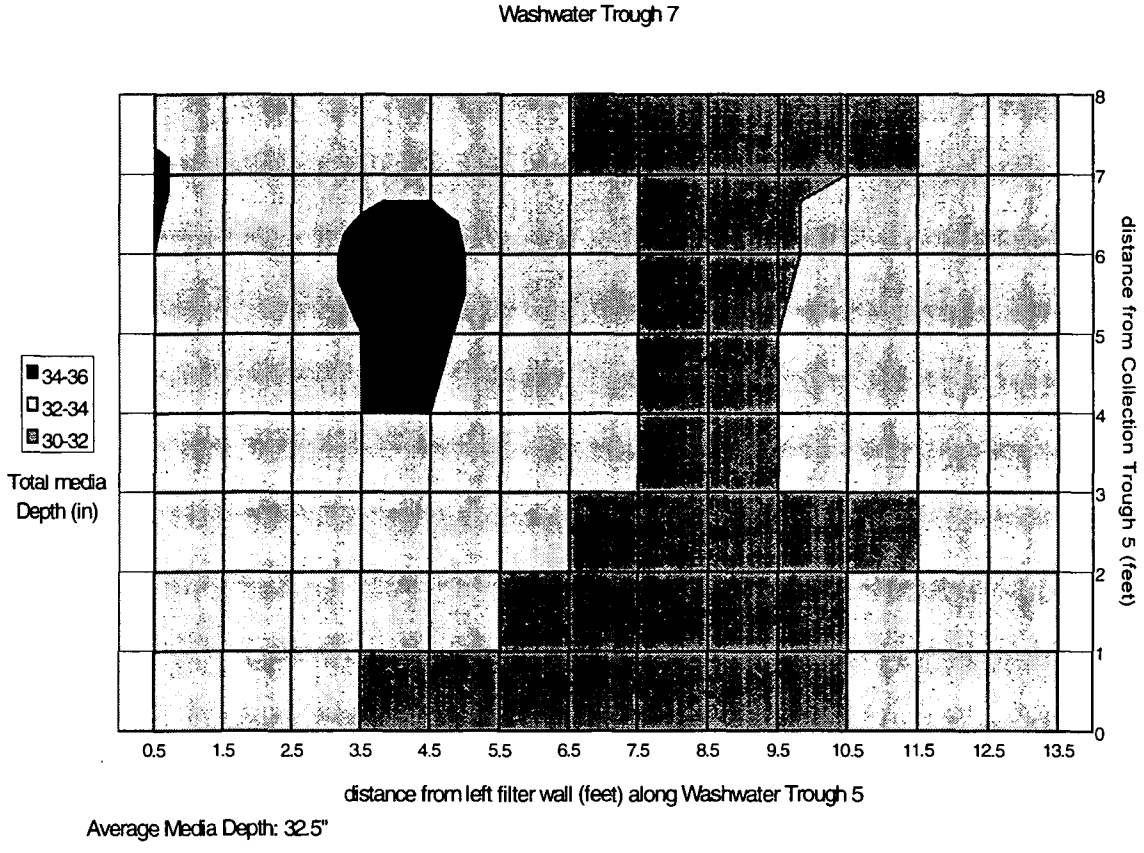


Figure 13.1 Topography of filter media surface (*Source*: City of Austin WTP 2000)

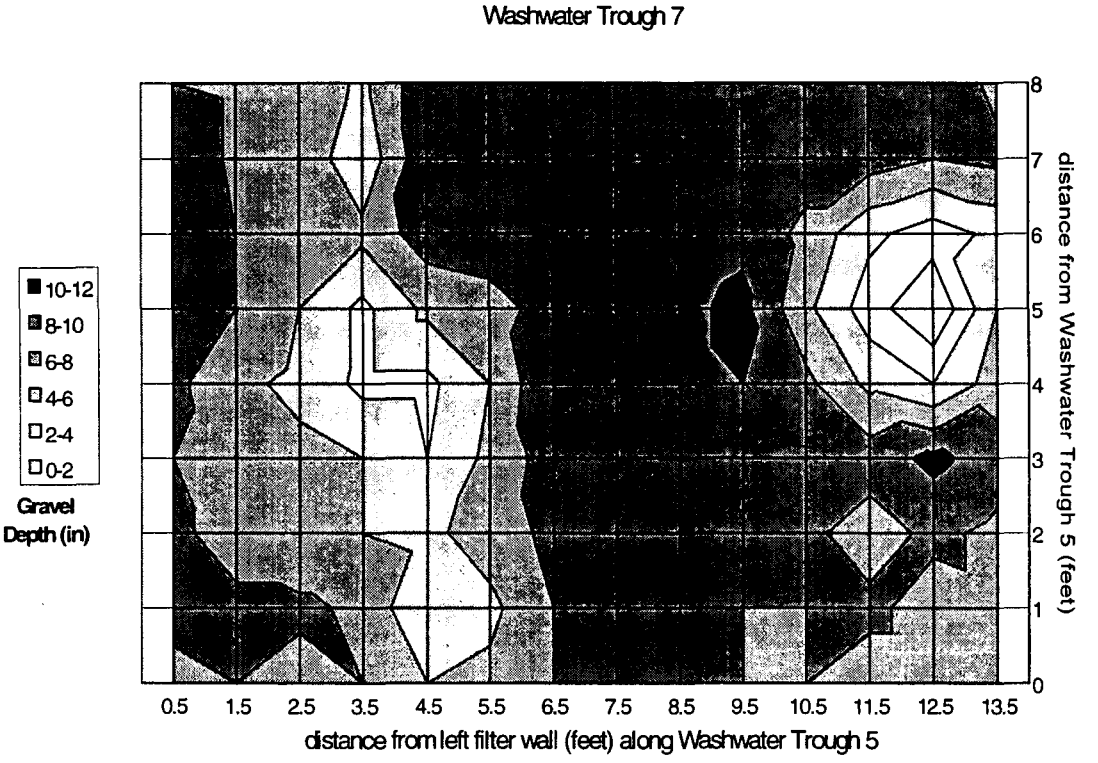


Figure 13.2 Support gravel topography (*Source*: City of Austin WTP 2000)

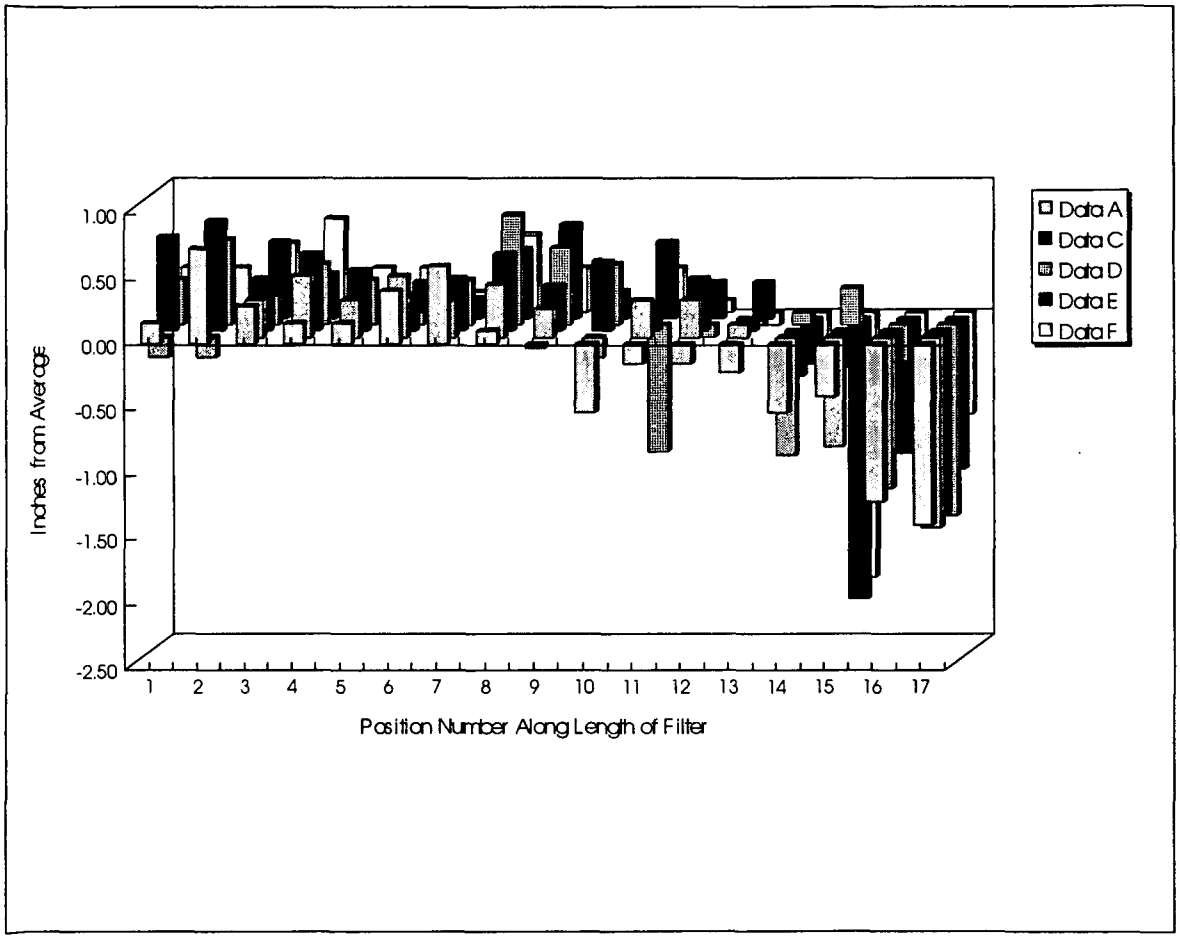


Figure 13.3 Under-gravel footprint for filter four (*Source*: MID 2000)

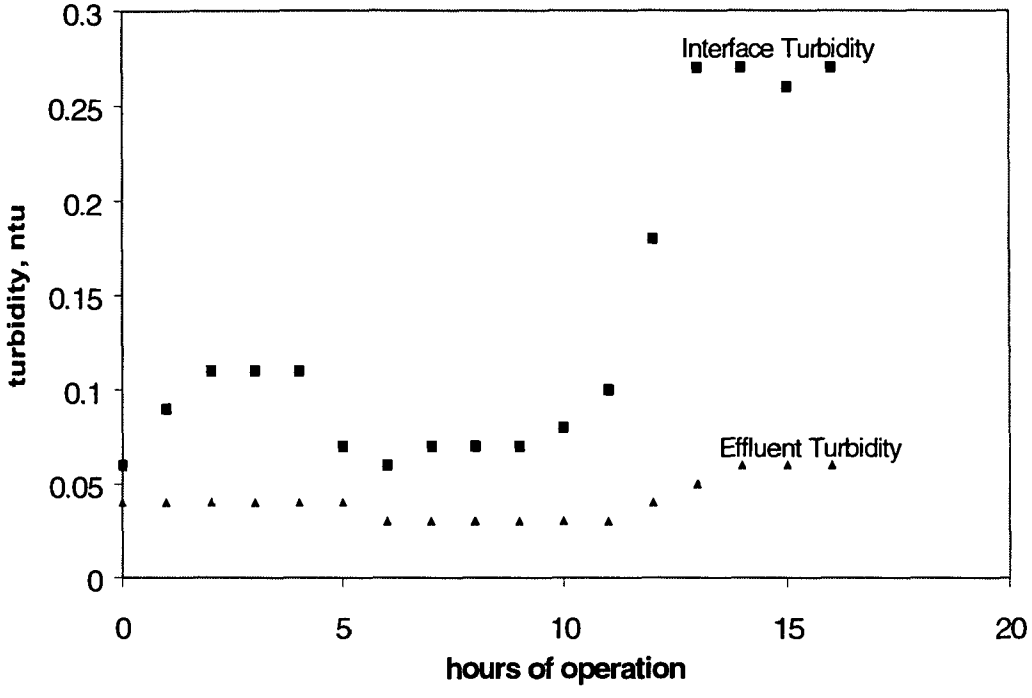


Figure 13.4 Swift Creek WTP interface and effluent turbidity during run when influent turbidity was 0.52 ntu to 0.82 ntu. Run ended at 25+ hours with interface turbidity at 0.34 ntu and effluent turbidity at 0.10 ntu. (*Source*: Swift Creek WTP 2000)

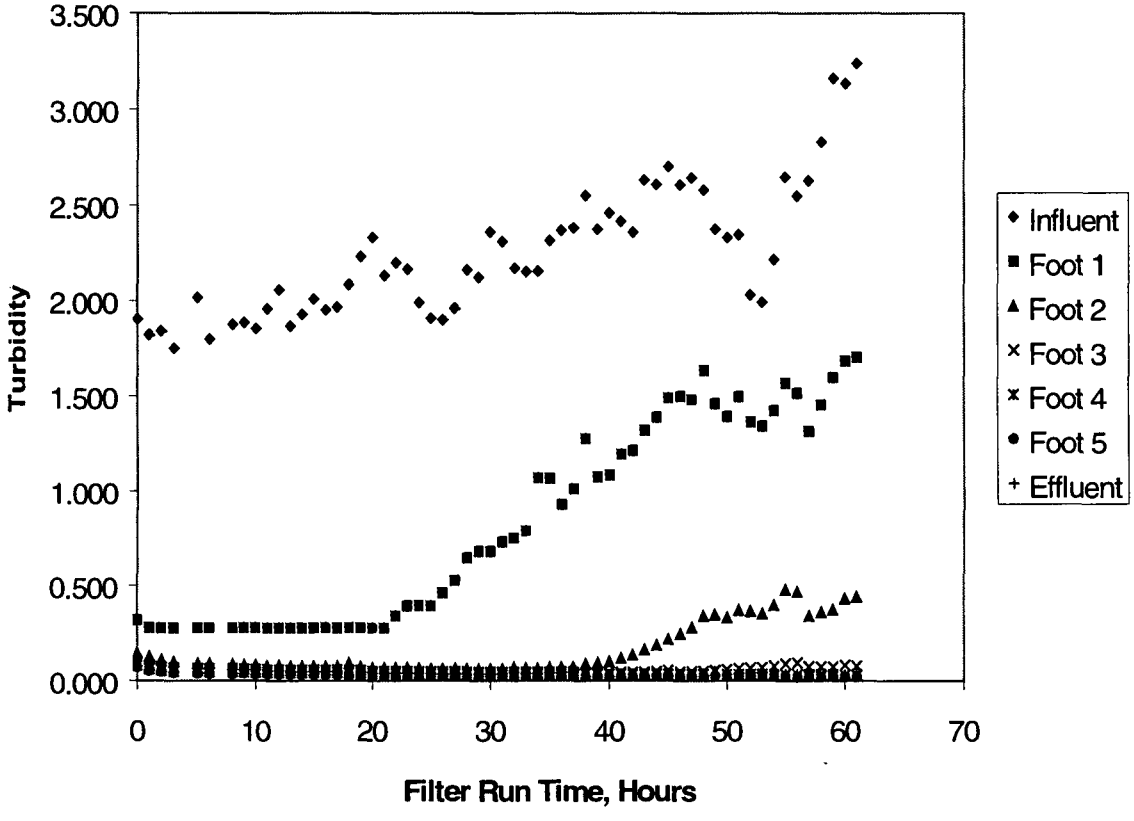


Figure 13.5 Filter turbidity profile in 6-ft monomedium anthracite bed (*Source*: MID 2000)

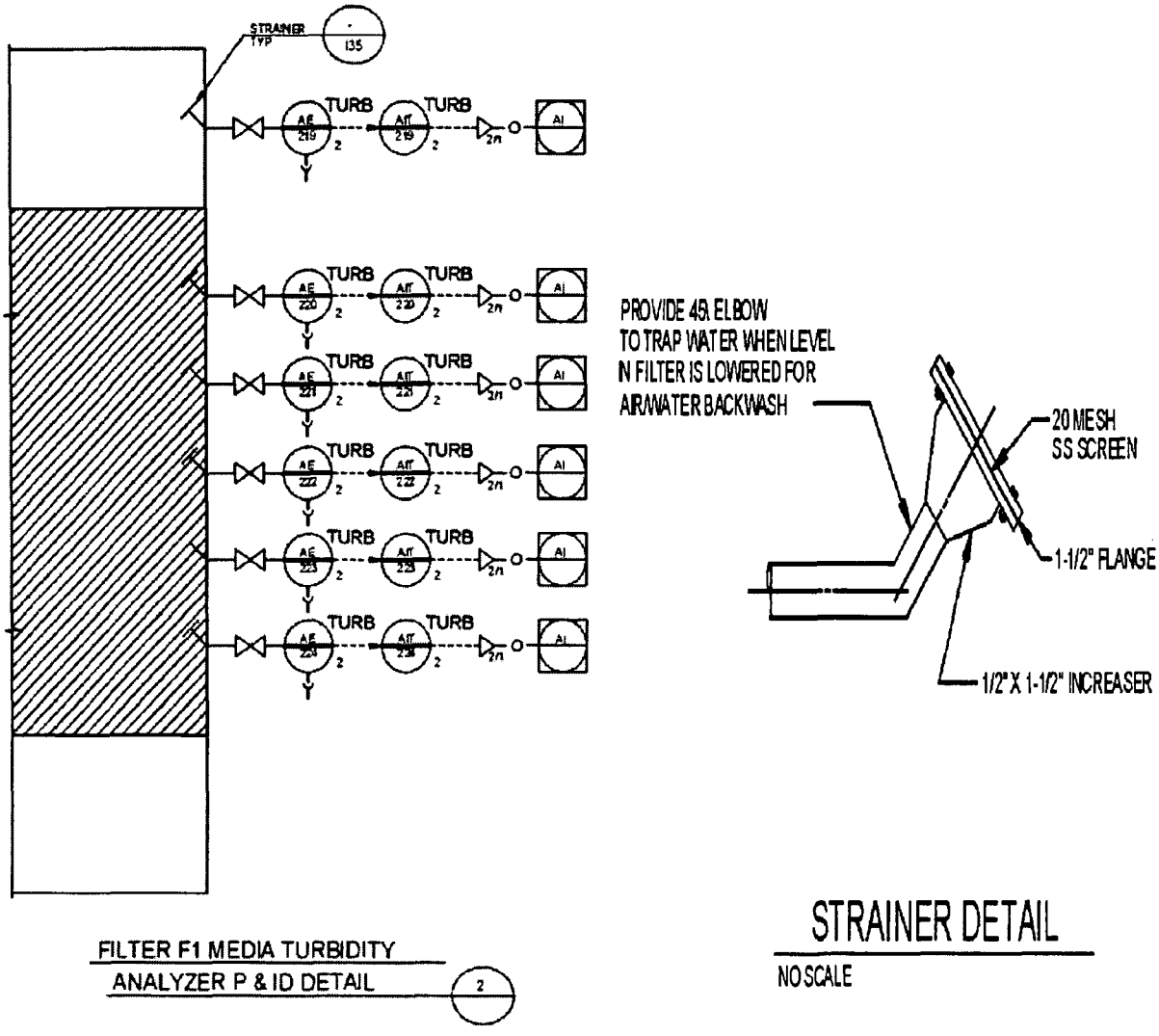


Figure 13.6 Filter FI media turbidity/Strainer Detail (*Source*: Black & Veatch 2000)

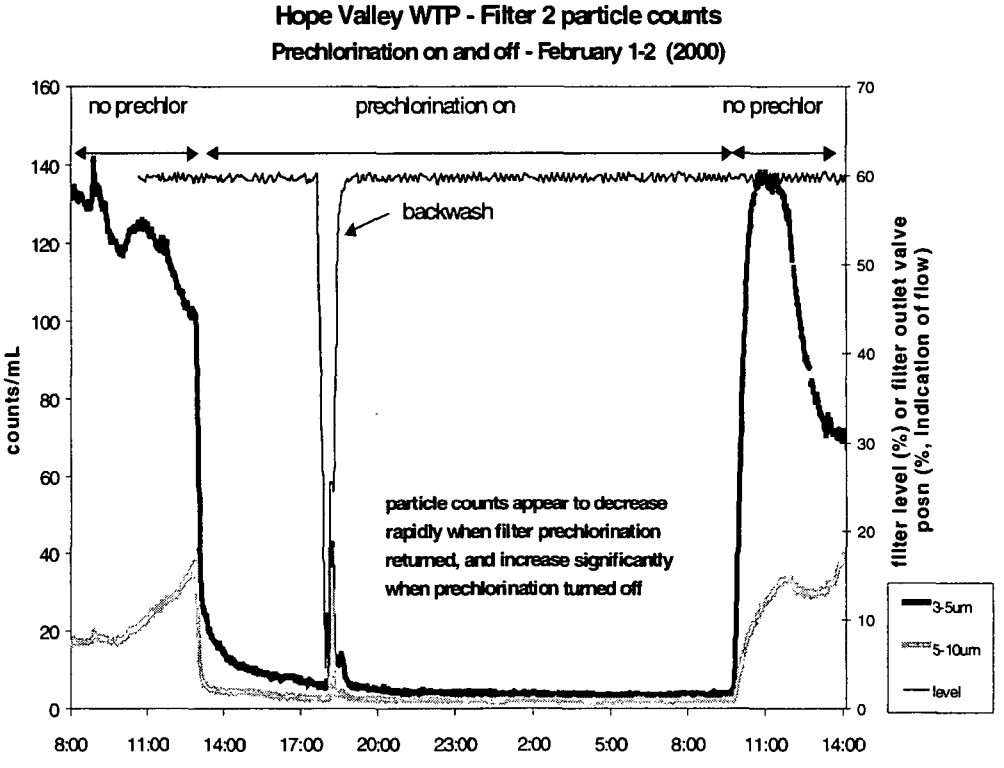
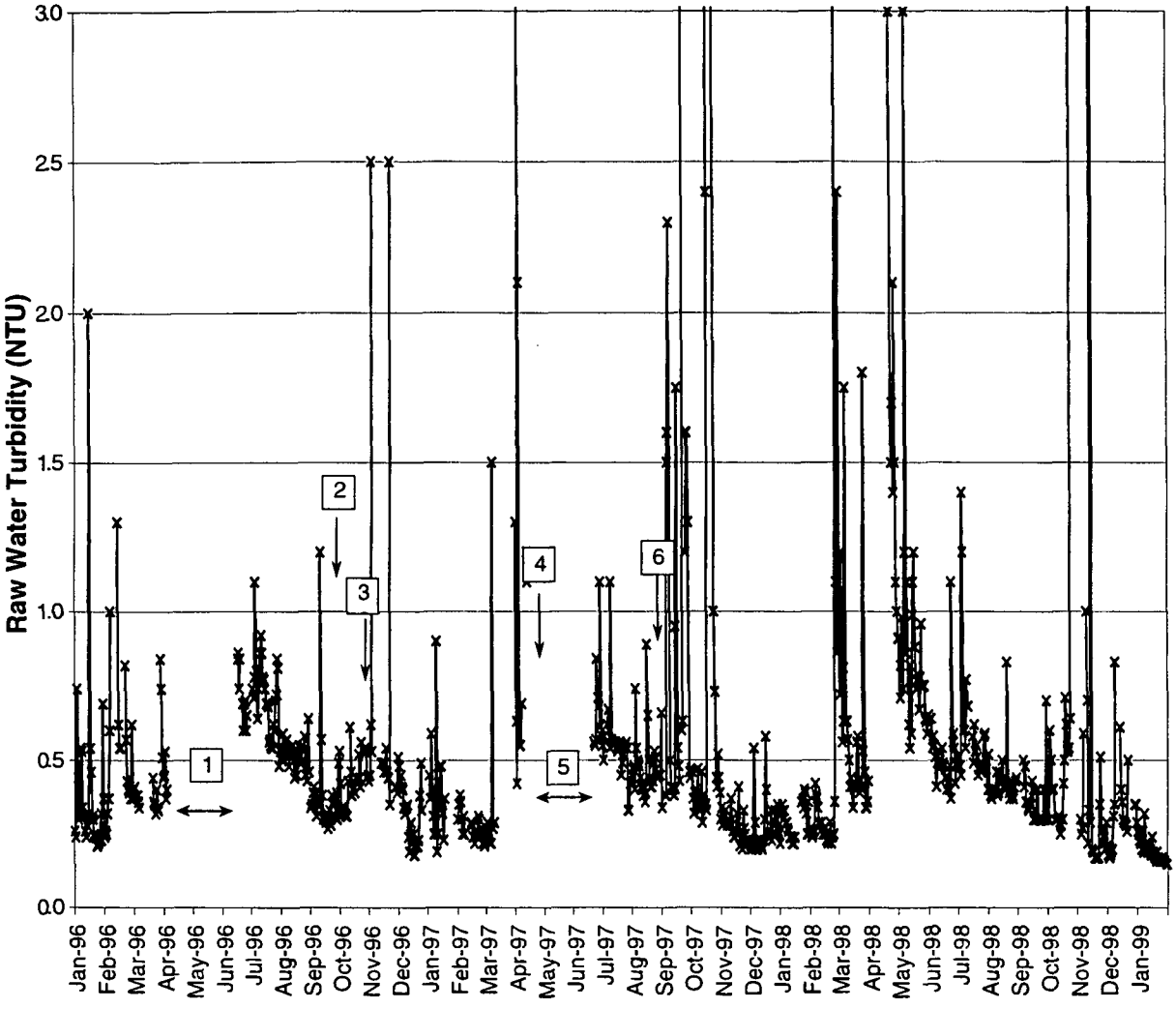


Figure 13.7. Hope Valley WTP filter 2 particle counts - prechlorination on and off



1 – Surface water plant was off-line.

2 – Plant staff initiated use of coagulant and filter aids to improve plant performance (October 1997).

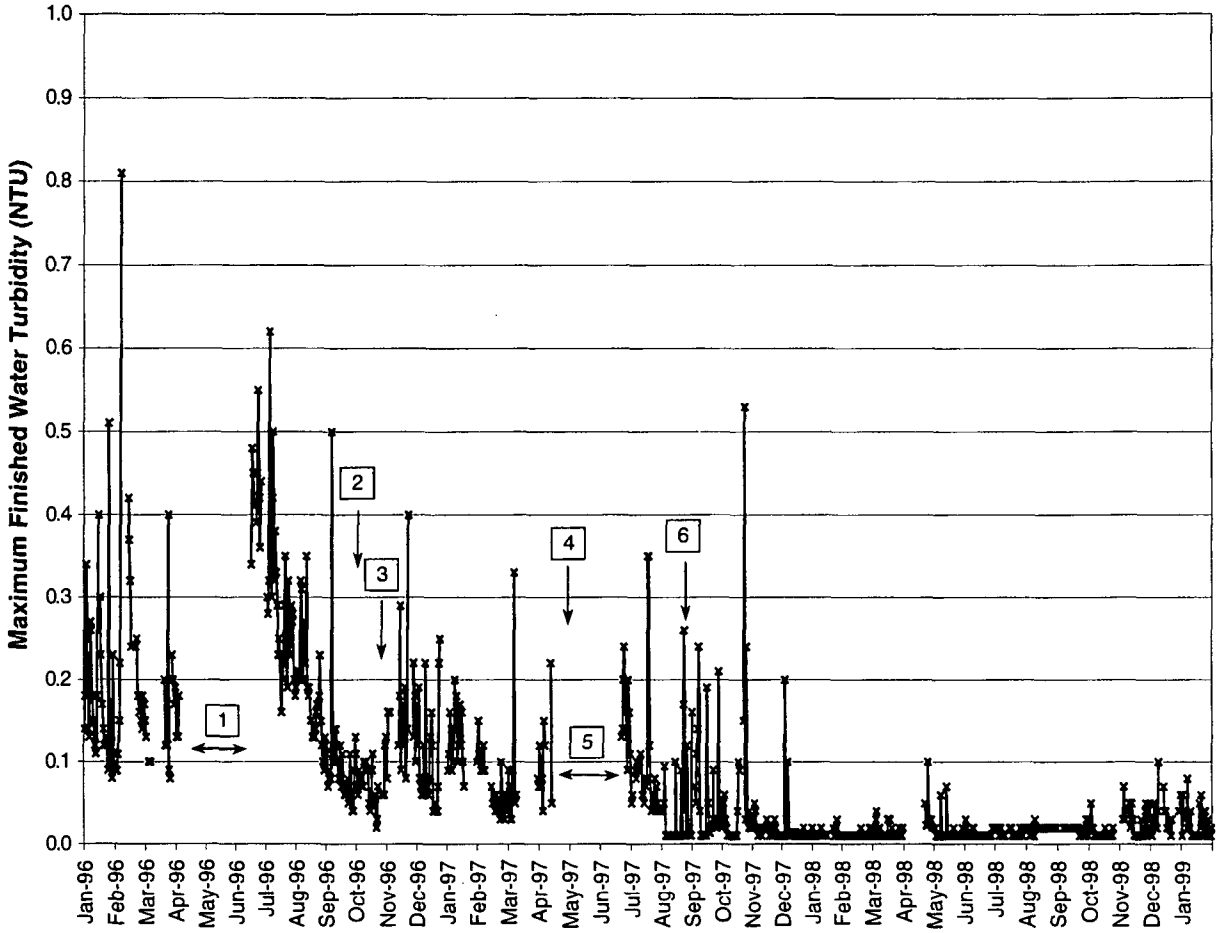
3 – CPE conducted.

4 – CTA initiated.

5 - Surface water plant was off-line.

6 – Changed primary coagulant (August 1997).

Figures 13.8 Raw Water Turbidity For 1/96 through 2/99 (*Source:* Hegg et al. 2000)



1 – Surface water plant was off-line.

2 – Plant staff initiated use of coagulant and filter aids to improve plant performance (October 1997).

3 – CPE conducted.

4 – CTA initiated.

5 - Surface water plant was off-line.

6 – Changed primary coagulant (August 1997).

Figures 13.9 Maximum Water Turbidity For 1/96 through 2/99 (*Source*: Hegg et al. 2000)

Figure 13.10 Anthracite filter media before and after chemical cleaning (*Source*: Adkinson and Schnieders 2000)

Figure 13.11 Sand filter media before and after chemical cleaning (*Source*: Adkinson and Schnieders 2000)

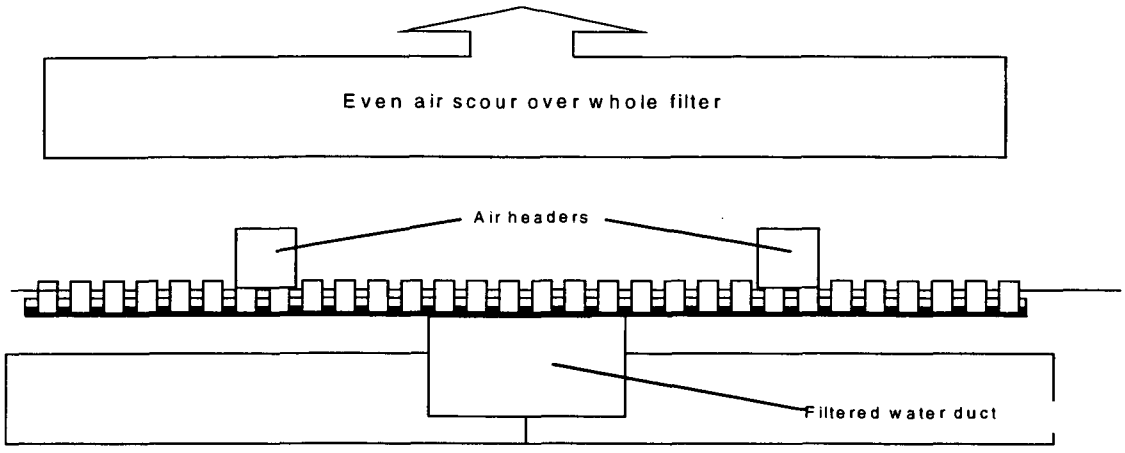


Figure 13.12 Single lateral during separate air scour (*Source*: Thames Water Utilities, 2000)

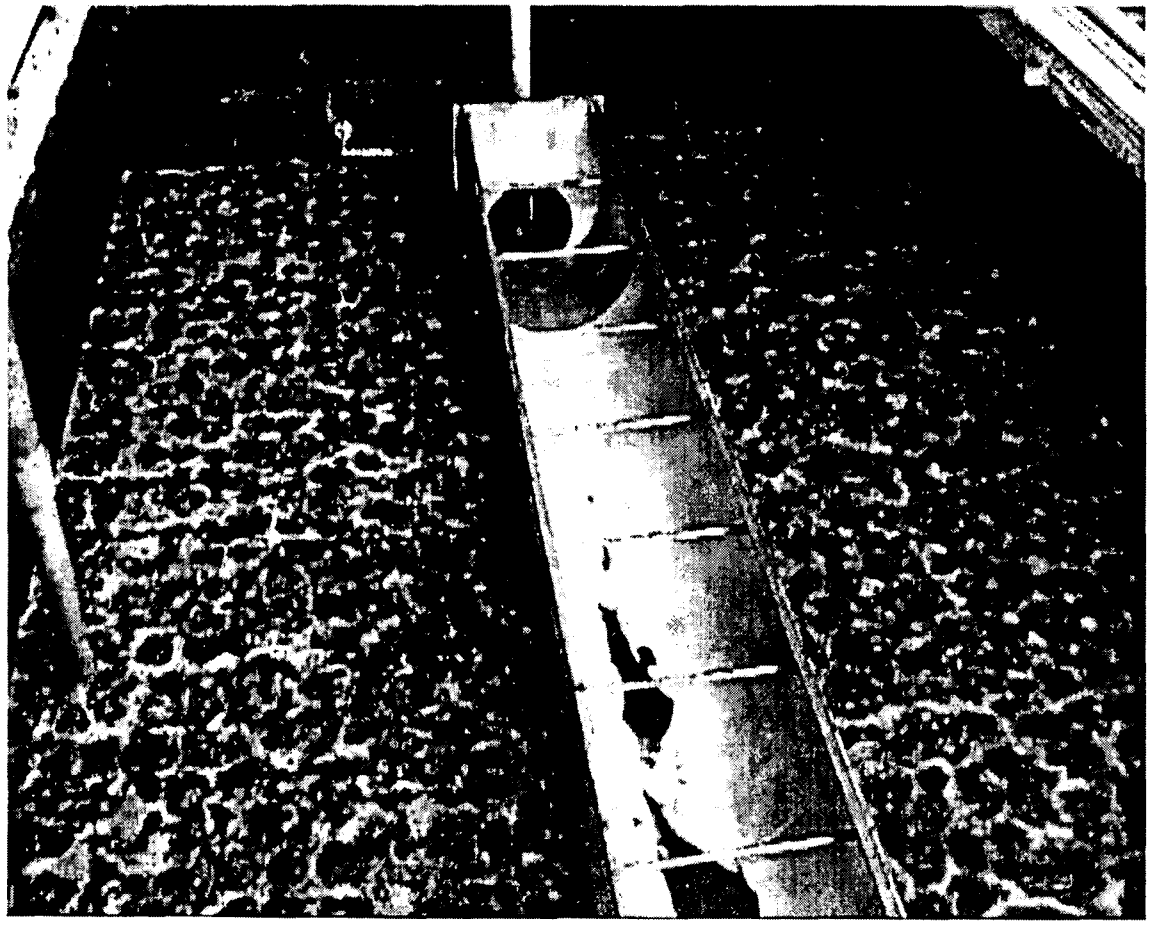


Figure 13.13 Filter with air scour but not backwash flow, achieving even scouring action (*Source*: Thames Water Utilities 2000)

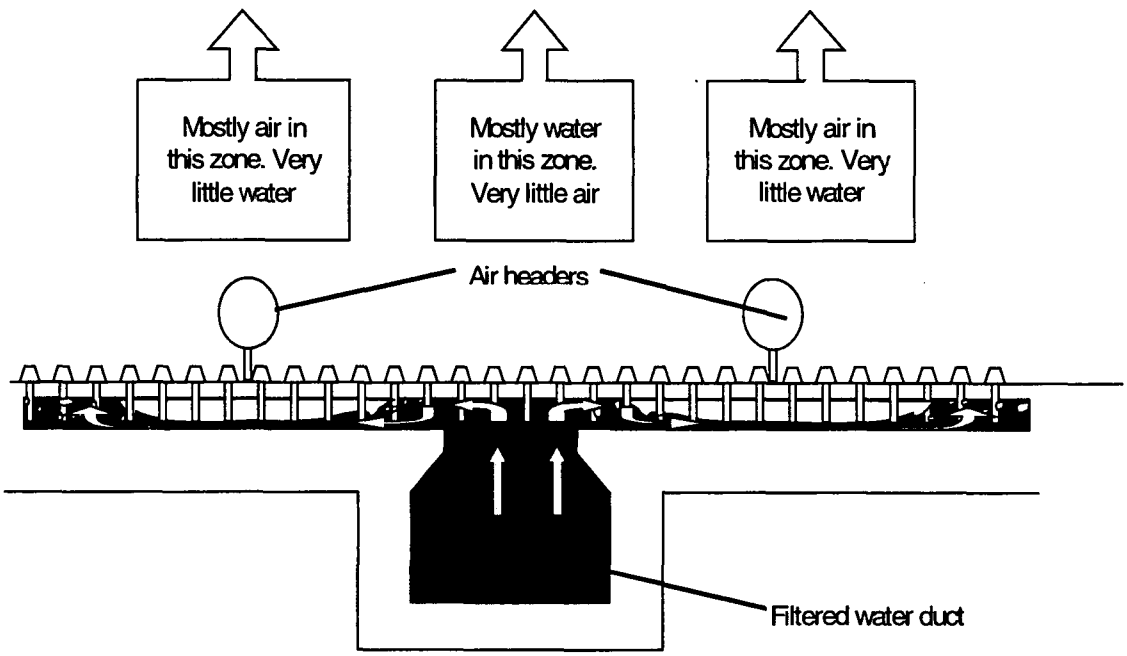


Figure 13.14 Single lateral during combined air scour and backwash water washing (Source: Thames Water Utilities 2000)

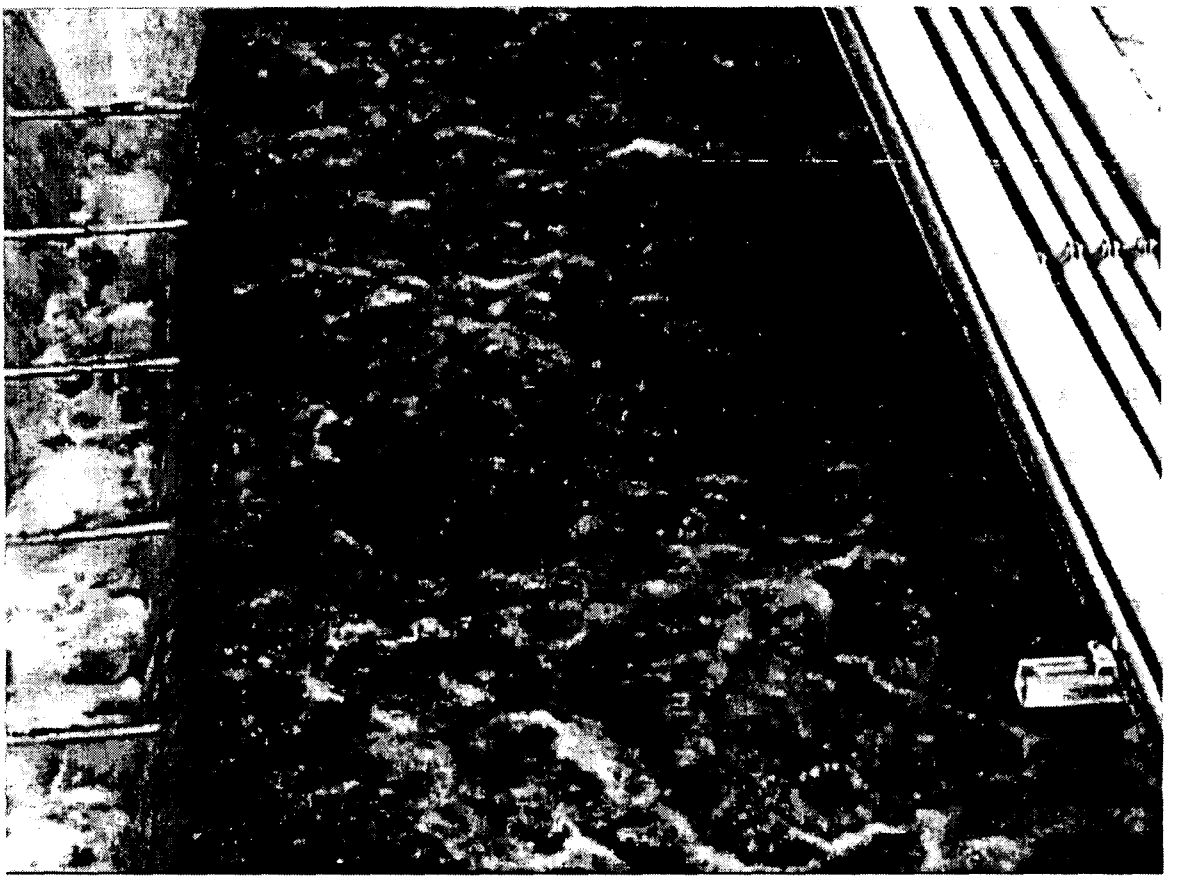


Figure 13.15 Combined air scour and water wash with localized violent agitation (*Source*: Thames Water Utilities 2000)

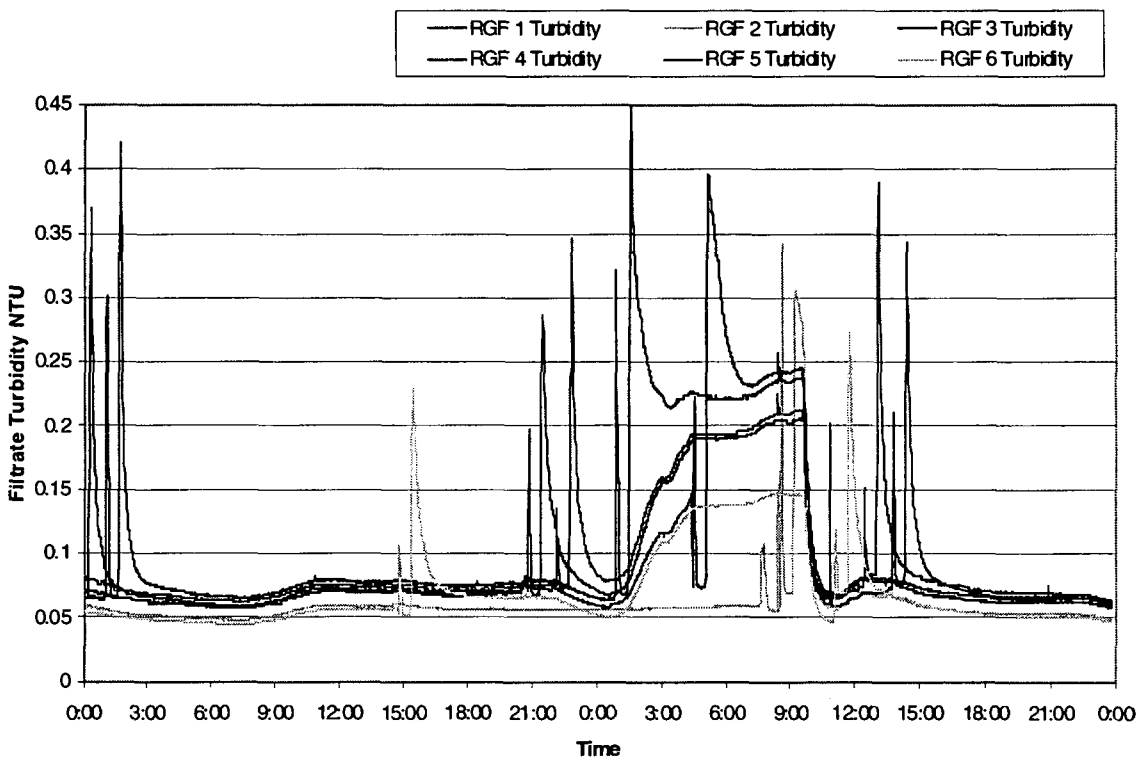


Figure 13.16 Filtered water turbidity data showing the impact of the loss of the supplementary coagulant dose at 01:00 and resumption of feed at 09:00. [Although this figure is printed in black and white, note that filtered turbidity for all filters except one rose dramatically after the supplemental coagulant feed was lost, and all returned to normal turbidity below 0.1 ntu after resumption of supplemental coagulant feed.]

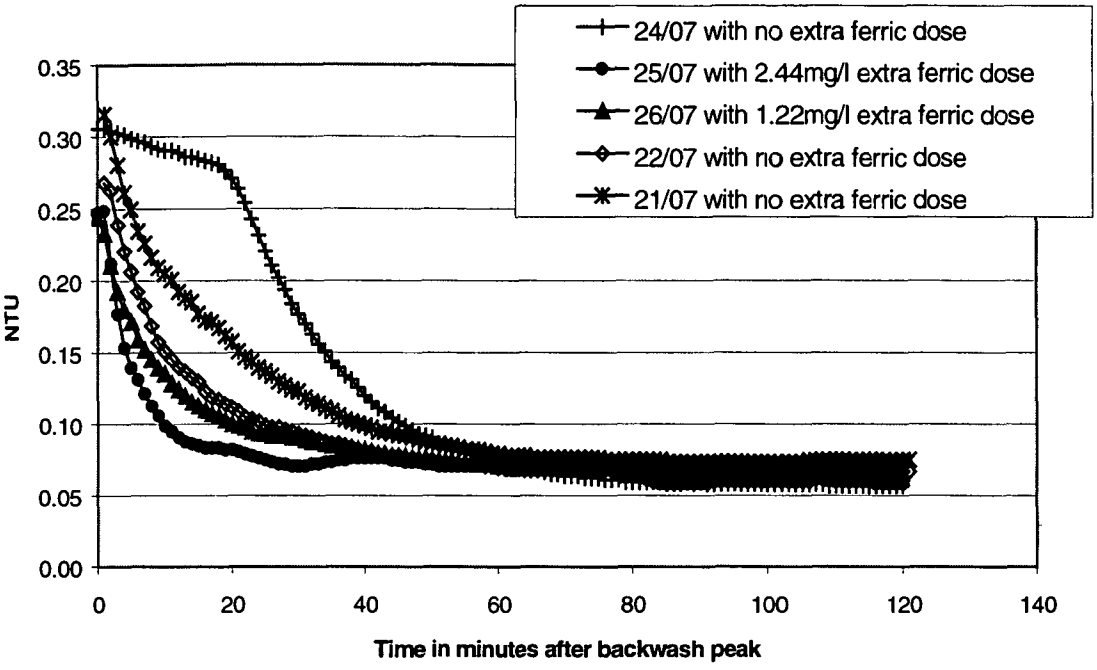


Figure 13.17. Filter 2 ripening curves with and without additional ferric dose. (Note on 24/07 the supplementary coagulant had failed and the effect of its restart appeared about 20 minutes after the backwash peak.)

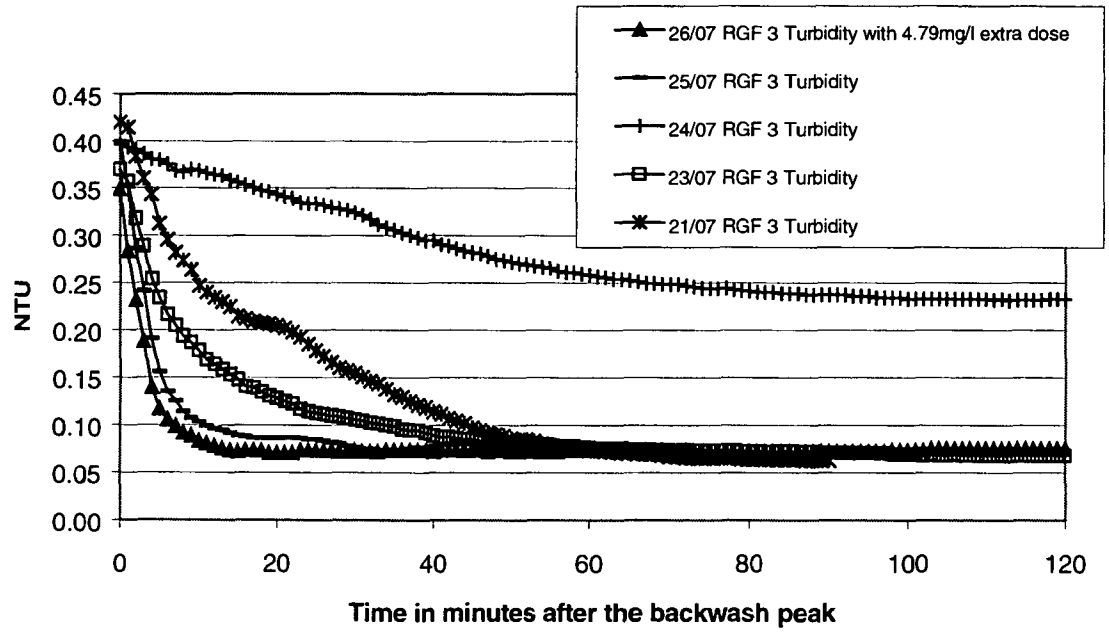


Figure 13.18. Filter 3 ripening curves with and without additional ferric dose. (Note: on 24/07 the supplementary coagulant had failed.)

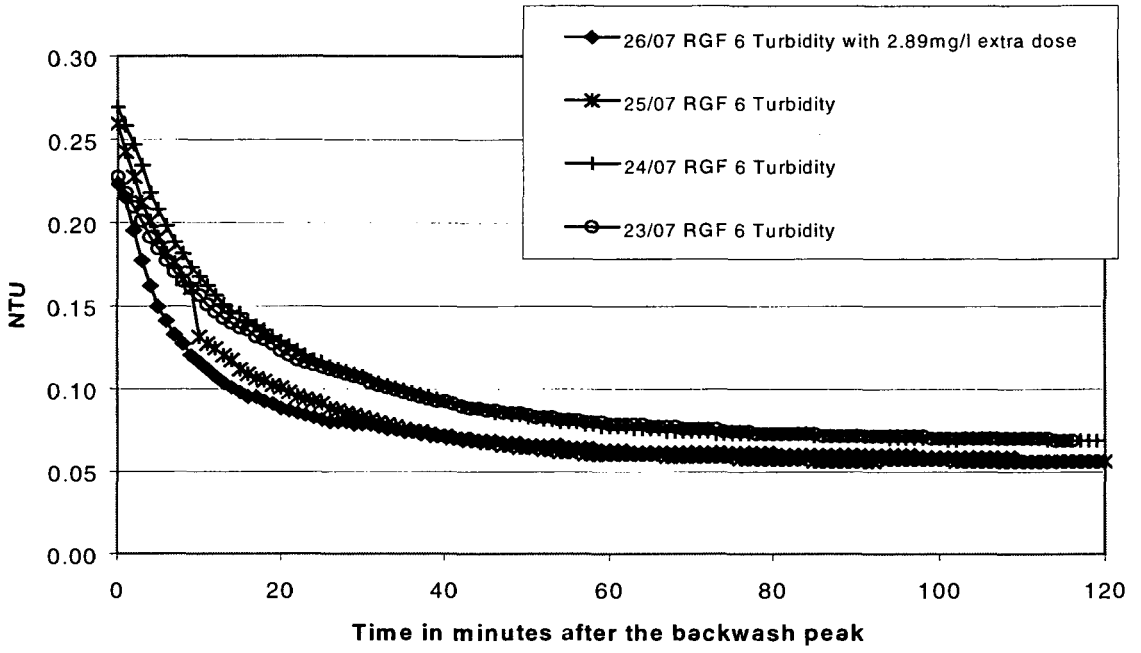


Figure 13.19 Filter 6 ripening curves with and without additional ferric dose.

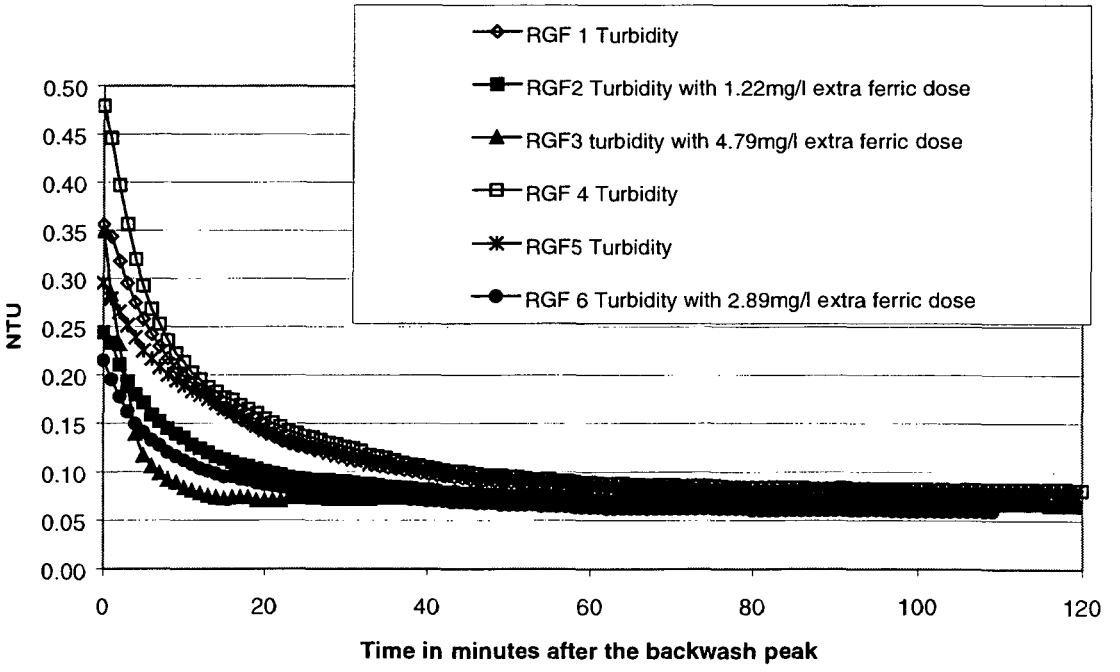


Figure 13.20. Filter ripening curves with and without additional ferric dose. All filters backwashed over 8 hours on 26th July.

CHAPTER 14

EQUATIONS, EXAMPLE PROBLEMS, AND JAR TEST PROCEDURES

Equations are used in research on water treatment and in design of filtration plants. This chapter contains some equations that may be useful to persons who operate or evaluate granular media filtration and pretreatment processes. Examples of the use of equations to solve problems are presented in both traditional (English) units and metric units. Each example problem begins at the top of a new page, to avoid confusion among the problems in this chapter. Some of the equations referenced in this chapter may be found in *Water Quality & Treatment, 5th Ed.*, Chapter 8.

This chapter presents equations for filtration plant operations calculations such as

- surface overflow rate for clarifiers,
- filter loading rate,
- unit filter run volume,
- backwash vertical rise rate,
- backwash rate,
- uniformity coefficient (uc) and size of media, and
- temperature conversion from Fahrenheit to Celsius and from Celsius to Fahrenheit.

Example calculations in traditional (English) units and metric units are presented for:

- porosity of filter medium,
- sieve analysis calculations
- minimum fluidization velocity for a filter bed,
- head loss through a fixed bed of filter medium,
- mixing power and velocity gradient,
- baffled flocculation tank velocity gradient,
- settling velocity of very small particles in the laminar flow region by Stokes' equation, and
- calculation of normalized (standardized) clean bed head loss.

Example calculations are presented for sieve analysis in metric units only, as sizes of filtering materials such as sand, anthracite, garnet, ilmenite, and GAC are expressed in millimeters, not inches.

A detailed discussion of jar test procedures is presented at the end of this chapter.

FILTER OPERATIONS CALCULATIONS

Surface Overflow Rate

SOR (gpm/ft^2) = flow rate (gpm) / settling basin surface area (ft^2)

SOR (m/hr) = flow rate (m^3/hr / settling basin surface area (m^2)

Filter Loading Rate

FLR (gpm/ft^2) = filter flow rate (gpm) / surface area of filter (ft^2)

FLR (m/hr) = filter flow rate (m^3/hr) / surface area of filter (m^2)

Unit Filter Run Volume

UFRV ($gallons/ft^2$) = volume filtered per run (gallons) / filter surface area (ft^2)

UFRV (m^3/m^2) = volume filtered per run (m^3) / filter surface area (m^2)

Backwash Vertical Rise Rate

$$\text{Vertical Rise Rate (in/min)} = \frac{\text{backwash flow}\,(\text{gal/min})(1\,\text{ft}^3/7.48\,\text{gal})(12\,\text{in/1 ft})}{\text{filter surface area}\,(\text{ft}^2)}$$

$$\text{Measured Vertical Rise (in/min.)} = \frac{[\text{rise volume}\,(\text{ft}^3)]\times 12\ \text{in}}{[\text{filter surface area}\,(\text{ft}^2)]\times \text{ft}\times \text{time of rise(sec)}}$$

$$\text{Backwash Rate}\,(\text{gpm/ft}^2) = \frac{\text{backwash rate (gpm)}}{\text{filter surface area}\,(\text{ft}^2)}$$

$$\text{Backwash Rate (m/hr)} = \frac{\text{backwash flow rate } (m^3/hr)}{\text{surface area of filter } (m^2)}$$

$$= \frac{\text{backwash flow rate (L/min)} \times (1\,m^3/1000\,L) \times (60\,min/1\,hr)}{\text{surface area of filter } (m^2)}$$

Uniformity Coefficient, uc and d_{90} size = d_{60}/d_{10}

d_{60} = the media diameter at which 60% of the media, by weight, is smaller

d_{10} = the media diameter at which 10% of the media, by weight, is smaller

$d_{90} = d_{10}\,(10^{\,1.67 \log uc})$

Temperature Conversions:

Degrees F = (Degrees C) x (9/5) + 32

Degrees C = (Degrees F) – 32 x (5/9)

POROSITY OF FILTER MEDIUM

Statement of Problem

Determine the porosity ratio of filter sand in a pilot filter column using the following given conditions, solving in metric units:

1. Filter column diameter = 15.24 cm
2. Filter sand added to the column = 21.732 kg
3. Depth of the sand in the column after soaking in water spacing, backwashing and being allowed to settle freely in the water = 76.2 cm
4. Density of the filter sand grains determined by separate lab experiment = 2,650 kg/cubic meter. The porosity ratio is defined as the ratio of the void volume of a granular mayerial divided by the gross volume of the bed. The ratio can also be expressed as a percentage by multiplying by 100.

Solution to the Problem

Calculate the gross volume of the sand in the column:

V = Filter area x depth of sand in the column

$$V = \frac{\pi \times (15.24\,\text{cm})^2}{4} \times \text{sand depth}\,(76.2\,\text{cm}) = 13{,}900\,\text{cubic cm}$$

Calculate the grain volume of the sand in the column:

V (grains) = mass of grains/ density of the grains

= 21.732 Kg/2650 Kg/m^3

= 0.008201 m^3

= 8201 cm^3

Calculate the porosity ratio = 1 - grain volume/gross volume in the column

= 1 - 8201/13900 = 0.41 or 41 % voids in the column

Determine the porosity ratio of filter sand in a pilot filter column using the following given conditions, solving in traditional (English) units:

1. Filter column diameter = 6.00 in
2. Filter sand added to the column = 47.92 lb
3. Depth of the sand in the column after soaking in water , backwashing and being allowed to settle freely in the water = 30.0 in
4. Density of the filter sand grains determined by separate lab experiment = 165.4 lb/cubic foot.

The porosity ratio is defined as the ratio of the void volume of a granular material divided by the gross volume of the bed. The ratio can also be expressed as a percentage by multiplying by 100.

Solution to the Problem

Calculate the gross volume of the sand in the column:

V = Filter area × depth of sand in the column

$$V = \frac{\pi \times (3.00\ \text{in})^2}{4} \times \text{sand depth}\ (30.0\ \text{in}) = 848\ \text{in}^3$$

Calculate the grain volume of the sand in the column:

V (grains) = mass of grains/ density of the grains

= 47.92 lb/165.4 lb/ft^3

= 0.290 ft^3

= 501 in^3

Calculate the porosity ratio = 1 - grain volume/gross volume in the column

= 1 - 501/848 = 0.41 or 41 % voids in the column

SIEVE ANALYSIS PROBLEM

Statement of Problem

The following sieve analysis has been presented by a supplier of anthracite filter medium. Calculate the percent passing by weight for each of the sieves that retained some of the medium. Plot cumulative % passing on the X-axis and sieve opening on the Y-axis of the graph. You can use ordinary arithmetic graph paper if you wish, or log-probability paper if you have it available. On the latter paper, the sieve opening should be on the log scale and the cumulative % passing on the probability scale. From your plotted graph, read the effective size (d_{10}) and the d_{60} and d_{90} size. Calculate the uniformity coefficient (d_{60}/d_{10}).

US Sieve Size (No.)	Sieve Opening (mm)	Weight Retained(g)	Cumulative Wt. Retained (g)
#10	2.000	0.000	0.000
#12	1.700	0.620	0.620
#14	1.400	25.480	26.100
#16	1.180	48.240	74.340
#18	1.000	34.260	108.600
#20	0.850	10.040	118.640
#25	0.710	2.980	121.620

No anthracite medium passed the #25 sieve

Sieve Analysis Problem Solution

Calculate the % passing each sieve using the fact that :

$$\% \text{ passing} = \frac{(1 - \text{gram retained on a particular sieve}) - 100}{\text{cumulative total sample retained}}$$

For the data given for example, the percent passing the #12 sieve is:

$$\% \text{ passing} = (1 - 0.62/121.62)\,(100) = 99.5\%$$

Using this procedure for each sieve retaining filter medium, we get the following:

Sieve No	% Passing
#12	99.5
#14	78.5
#16	38.9
#18	10.7
#20	2.5
#25	0.0

Now plot the data as instructed. Two graphs are presented to show the difference in type of graph paper and the graph that results. When plotted on log-probability paper, the graph tends to plot

close to a straight line making it possible to read the desired diameters more closely.

The sizes read from the two graphs are:

Effective size	d_{10}	d_{60}	d_{90}	uniformity coefficient d_{60}/d_{10}
Arithmetic plot	1.00 mm	1.28 mm	1.52 mm	UC = 1.28
Log-probability	1.00 mm	1.28 mm	1.50 mm	UC = 1.28

Such plots are often made on two cycle, semi-log paper by commercial laboratories with the sieve opening on the log scale and percent passing on the arithmetic scale. This method was developed for widely graded aggregates and road materials. But it is the worst way to plot data for filter media because the sizes of the media span only a narrow range. Therefore, when the sieve opening is plotted on the log scale in this manner, the graph is very compressed making it very difficult to read the desired diameters. Utilities and consultants should insist that the plots be presented on log-probability paper (Figures 14.1 and 14.2).

MINIMUM FLUIDIZATION VELOCITY OF A FILTER BED, EXAMPLE PROBLEM

Statement of Problem

Calculate the minimum fluidization velocity for an anthracite filter bed at a water temperature of 20° C using an anthracite density of 1.6 g/cm^3 (1600 Kg/m^3). Base the solution on the d_{90} size taken from a sieve analysis of the filter medium, which has been determined to be 2.9 mm or 0.29 cm (2.9 x 10^{-3} m).

Solution to Problem

Use the Wen & Yu Equation as follows:

$$V_{mf} = \frac{\mu}{\rho d_{eq}}\left(33.7^2 + 0.0408\text{Ga}\right)^{0.5} - \frac{33.7\mu}{\rho d_{eq}}$$

where Ga = the dimensionless Galileo number as follows:

$$Ga = \frac{d_{eq}^{\ 3}\rho(\rho_S - \rho)g}{\mu^2}$$

where V_{mf}= minimum upward flow rate to fluidize the filter grains

μ = absolute viscosity of the fluid

ρ = mass density of the fluid

ρ_s = mass density of the filter grains

d_{eq} = grain diameter of a sphere of equal volume. Usually the sieve mid-diameter is used as an acceptable alternative diameter.

g = acceleration due to gravity

Solving in SI units, in which 1 Newton (N) = 1 kgm/s^2:

where μ = 1.002×10^{-3} Ns/m^2

ρ = 998.207 Kg/m^3

μ/ρ= ν = 1.004×10^{-6} m^2/s = kinematic viscosity of the fluid

g = 9.81 m/s^2

d_{eq}(use d_{90} as an approximation) = 2.9×10^{-3} m

$$Ga = \frac{\left(2.9\times10^{-3}\right)^3 \times 998(1600-998)9.81}{(1.002\times10^{-3})^2} = 143170$$

A check of the units used above would result in dimensionless Ga

$$V_{mf} = \frac{1.002\times10^{-3}\left(33.7^2 + 0.0408\times143170\right)^{0.5}}{(998)\left(2.9\times10^{-3}\right)} - \frac{(33.7)\left(1.002\times10^{-3}\right)}{(998)\left(2.9\times10^{-3}\right)} = 0.01725 \text{ m/s}$$

A check of the units used above would result in fluidization velocity in m/s.

The recommended backwash rate would be up to 30 percent higher, so:

Backwash rate = 1.3 V_{mf} = (1.3) (0.01725) = 0.0223 m/s or 80 m/h

$$\frac{0.0223\,m^3}{m^2 s}\times\frac{1000L}{m^3}\times\frac{gal}{3.785L}\times\frac{0.0929\,m^2}{ft^2}\times\frac{60s}{min} = 32.8\,gpm/ft^2$$

This is a higher than normal backwash rate because of the very coarse anthracite grain size, the rather warm water, and the choice of 30 percent factor above V_{mf}. Without that factor applied, the rate would be 25.2 gpm/ft^2.

Solving the same problem in traditional (English) units using properties from *Wastewater Engineering: Treatment/Disposal/Reuse, 2nd Ed.* (Metcalf & Eddy, Inc. 1979):

$$\rho_s = 1600\,kg/m^3 \times \frac{1.940\,slugs/ft^3}{1000\,kg/m^3} = 3.104\,slugs/ft^3$$

From Newton's Law, F = ma (force = mass x acceleration)

1 lb_f accelerates 1 slug mass at 1 ft/s^2 so the slug unit is equal to $lb_f s^2/ft$

Also slugs/ft^3 = $lb_f s^2/ft^4$

μ = 2.09218 x 10^{-5} lb_f s/ft^2

ρ = 1.937 slugs/ft^3 at 20° C (68° F)

$\mu/\rho = \nu$ = 1.0807 x 10^{-5} ft^2/s = kinematic viscosity of the fluid at 20 C (68° F)

g = 32.17 ft/s^2

d_{eq} (use d_{90}) = 0.29 cm x 0.03281 ft/cm = 0.00951 ft

$$Ga = \frac{d_{eq}^{\ 3}\rho(\rho_S - \rho)g}{\mu^2}$$

$$Ga = \frac{0.00951\,ft^3 \times 1.937\,slugs/ft^3\,(3.104\,slugs/ft^3 - 1.937\,slugs/ft^3) \times 32.17\,ft/s^2}{(2.09218\times10^{-5}\,lbs/ft^2)^2}$$

Ga = 143,010 dimensionless

A check of the units used above results in dimensionless Ga

$$Ga = \frac{(ft^3)(slugs/ft^3)(slugs/ft^3)(ft/s^2)}{(lb_f\,s/ft^2)^2}$$

$$= \frac{(ft^3)(lb_f s^2/ft^4)(lb_f s^2/ft^4)(ft/s^2)}{(lb_f\,s/ft^2)^2} = \text{dimensionless}$$

$$V_{mf} = \frac{\mu(33.7^2+0.0408\,Ga)^{0.5}}{\rho d_{eq}} - \frac{33.7\mu}{\rho d_{eq}}$$

$$V_{mf} = \frac{2.09218\times10^{-5}(33.7^2 + 0.0408\times143010)^{0.5}}{(1.937)(0.00951)} - \frac{(33.7)(2.09218\times10^{-5})}{(1.937)(0.00951)}$$

V_{mf} = 0.05655 ft/s

HEAD LOSS THROUGH A FIXED BED OF FILTER MEDIUM, EXAMPLE PROBLEM

Statement of Problem

Calculate the head loss for a 3 ft (0.91m) deep bed of filter sand at a filtration rate of 6 gpm/ft^2 (14.6 m/h) and a water temperature of 20° C, using a grain sphericity of 0.75 and a porosity of 0.42. Sphericity and porosity can be assumed constant for the full bed depth.

The sieve analysis of the filter medium has been used to select five mid-diameter sizes of the filter medium as follows: d_{10}= 0.54 mm, d_{30}= 0.66 mm, d_{50}= 0.73 mm, d_{70}= 0.80 mm, d_{90}= 0.87 mm, each diameter represents 20% of the bed by weight.

Solution to the Problem

Because the sand covers a range of size and will be stratified during backwashing, divide the bed into five equal segments and use the given middle sieve opening sizes for the diameter term in the solution.

Kozeny Equation: $$\frac{h}{L} = \frac{k\mu}{\rho g} \times \frac{(1-\varepsilon)^2}{\varepsilon^3} \times \frac{a^2}{v^2} \times V$$

where h = head loss in depth of bed, L (dimensionless)

g = acceleration due to gravity = 9.81 m/s^2

ε = porosity ratio of the medium (dimensionless)

a/v = grain surface area per unit grain volume = specific surface (Sv)= 6/d for spheres and 6/ψd for irregular grains

d_{eq} = grain diameter of a sphere of equal volume

V = superficial velocity approaching the bed = flow rate/bed area (i.e., the filtration rate)

μ = absolute viscosity of the fluid

ρ = mass density of the fluid

k = the dimensionless Kozeny constant commonly found close to 5.

ψ = sphericity

Solving in S.I. units:

$$\frac{a}{v} = \frac{6}{\psi d} = \frac{6}{0.75d}$$

$$\frac{\mu}{\rho} = v = 1.004 \times 10^{-6} \text{ m}^2/\text{s} \quad \text{at } 20^\circ\text{C}$$

V = 6 gpm/ft^2 = 4.08 x 10^{-3} m/s

$$\frac{h}{L}=5\times\frac{1.004x10^{-6}}{9.81}\times\frac{(1-0.42)^2}{0.42^3}\times\frac{6^2}{0.75^2d^2}\times4.08x10^{-3}=\frac{6.0671x10^{-7}}{d^2}$$

A check of the units used will indicate that *h/L* will be dimensionless if the diameters are in meters. Using the given mid-diameters, calculate *h/L* for each selected mid-diameter.

Size	Mid-diameter (m)	$\frac{h}{L}$	Layer depth, L (m)	head loss, h (m)	
d_{10}		0.00054	2.08	0.183	0.38
d_{20}		0.00066	1.39	0.183	0.25
d_{50}		0.00073	1.14	0.183	0.21
d_{70}		0.00080	0.95	0.183	0.17
d_{90}		0.00087	0.80	0.183	0.15
Average		1.27	Total	0.91	1.16

Alternatively, because each layer was the same depth, the average *h/L* can be used to calculate the head loss for a 0.91m bed of sand, $L = 0.91$ m, average $h/L = 1.27$, $h = 1.27 \times 0.91 = 1.16$m of water.

Solving in traditional (English) units:

Kozeny Eq. $$\frac{h}{L}=\frac{k\mu}{\rho g}\times\frac{(1-\varepsilon)^2}{\varepsilon^3}\times\frac{a^2}{v^2}\times V$$

$$\frac{a}{v}=\frac{6}{\psi d}=\frac{6}{0.75d}$$

$$\frac{\mu}{\rho}=v=\left(1.004\times10^{-6}\ m^2/s\right)(1ft/0.3048m)^2=1.0807\times10^{-5}\ ft^2/s \quad \text{at } 20^\circ C$$

where $g = 32.17$ ft/s^2

k = Kozeny's constant which is typically 5 (dimensionless) for common filter media

$$V = \frac{6\,\text{gal}}{\text{min} \times \text{ft}^2} \times \frac{\text{ft}^3}{7.48\,\text{gal}} \times \frac{1\,\text{min}}{60\text{sec}} = 0.01337\,\text{ft/sec}$$

$$\frac{h}{L} = 5 \times \frac{1.008x10^{-5}}{32.17} \times \frac{(1-0.42)^2}{0.42^3} \times \frac{6^2}{0.75^2 d^2} \times 0.01337 = \frac{6.52595x10^{-6}\,\text{ft}^2}{d^2} \text{ with } d \text{ in ft}$$

Unit check: $\frac{h}{L} = \frac{\text{ft}^2/\text{s}}{\text{ft/s}^2} \times \text{dimensionless} \times (1/\text{ft})^2 \times \text{ft/}s$

Therefore *h/L* is dimensionless when *d* is used in feet

Using the given mid-diameters and the equation for *h/L*, calculate *h/L* for each selected mid-diameter.

Size	Mid-diameter (ft)	$\frac{h}{L}$	Layer depth (ft)	headloss, *h* (ft)
d_{10}	0.00177	2.08	0.6	1.25
d_{20}	0.00217	1.39	0.6	0.83
d_{50}	0.00240	1.13	0.6	0.68
d_{70}	0.00262	0.95	0.6	0.57
d_{90}	0.00285	0.80	0.6	0.48
	Average *h/L* =	1.27	Total = 3.0	= 3.81

EXAMPLE PROBLEMS INVOLVING CALCULATION OF VELOCITY GRADIENT, *G*, AND THE *GT* PRODUCT

Background Information on *G* Value

About six decades ago the concept of the *G* value, or root mean square velocity gradient was introduced (Camp and Stein 1943) as a means of describing the intensity of turbulent mixing. For many years engineers have used *G* and *GT*, the dimensionless product of mixing intensity and time (*T*), when designing flocculation and rapid mixing processes. Nevertheless, the usefulness of *G* and *GT* has been questioned by some authors (O'Melia 1972, Ives 1968) as far as flocculation is concerned. *GT* is said to incompletely describe flocculation. A preferred approach using *GTC* (dimensionless) where *C* equals the dimensionless volume fraction of particles in suspension is recommended by Ives (Ives 2001). A concept similar to *GTC* was recognized as early as 1965 (Hudson 1965), who used the term *V* for the volume of floc per unit volume of water (also a dimensionless number). Hudson evaluated jar test data and concluded that floc volume was proportional to the dosage of coagulant used, for *G* values up to about 30 sec^{-1} but that at higher *G* values, floc could be compacted, creating denser flocs that had improved settling characteristics. Hudson also noted that the very high concentration of flocculated particles (*V*) in solids contact reactors would explain the good performance of the reactors in spite of short flocculation times and considerable short-circuiting. Use of only *GT* would not take into account the high concentration of flocs in the reactor. Cleasby (1984) questioned whether *G* was a valid parameter for turbulent flocculation.

In spite of these reservations, *G* is still widely used and is recommended in the absence of a readily applied alternative. According to Cleasby (2001), predicting the value of *C* to be used in a *GTC* design calculation for conventional flocculation tanks is beyond our ability at the present time. Letterman, Amirtharajah, and O'Melia (1999) discussed *G* and stated, "Our understanding of turbulent flow in mechanically agitated vessels is incomplete but growing rapidly. Unfortunately, sensitive methods for measuring flocculator performance, especially the performance of full-scale units, are not available. Until this capability improves, it seems reasonable to use the Camp and Stein *G* value for flocculator design and scale-up."

Based on the variety of opinions about whether *G* and/or *GT* is appropriate for use in design of mixing and flocculation processes, engineers are cautioned to carefully consider the above information

when deciding whether or not to use G and/or GT for design purposes. The following example calculations involving G are provided for persons who may wish to determine whether G values being used for mixing and flocculation at their treatment plants are consistent with the G values that were intended by the design engineers. A comparison of the applied G value to the design value for G, together with plant performance information, may indicate whether changes in mixing or flocculation might improve treatment plant performance.

A brief list of references is provided for those wanting more information on G.

REFERENCES RELATED TO G AND GT

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STATEMENT OF PROBLEM FOR DETERMINATION OF MIXING POWER AND VELOCITY GRADIENT

A large water treatment plant is treating 400 MGD of high quality reservoir water by direct filtration including rapid mixing, flocculation, filtration and disinfection. It is equipped with four parallel flash mixing tanks, each followed by two stage rapid mixing. Each parallel train is treating 100 MGD. Each flash mixing tank is 8 feet square with 22 ft water depth and is equipped with one radial flow, vertical shaft, turbine mixer with 6 flat blades with an outside diameter of 4 ft. Each mixer is driven by a 15 hp, 460 volt, three-phase motor at 1750 rpm with a rated full load amperage of 19.3 amps. The mixer speed is 56 rpm achieved by a gear reducer between the motor and the mixer. Field measurements during operation were made of the current drawn by each wire as follows: 18.3 amps, 18.6 amps, and 18.8 amps while the voltage was 471 volts. The water temperature at the time was 50° F.

Calculate for one flash mixing tank the root mean square (r.m.s.) velocity gradient (G), the dimensionless G x t product, and the horsepower delivered per MGD of flow through the tank.

Solution to Problem

Solve in Traditional (English) Units

The root mean square velocity gradient, G, can be calculated by the well-known equation presented by Camp and Stein:

$$G = (P/\mu V)^{0.5}$$ Eq. 6.24, *Water Quality & Treatment, 5th Ed.*

where P = Power input into the water

V = Volume of water in which the power is dissipated – usually the volume in the tank

μ = Absolute viscosity of the water

In this example, the power input can be calculated from the current and voltage, and reduced by power factor and efficiency of the motor and the gear reducer efficiency.

Motor output power for three-phase motors is:

$$P = \text{volts x amps x } \sqrt{3} \text{ x Power Factor x Motor Efficiency}$$

where P = Power in watts (output of motor)

Amps = Average amperage of the 3 wires

Power Factor = 0.89 From Smeaton R.W. (Ed.) *Motor Operations & Maintenance Handbook.* McGraw Hill, N.Y. 1987

Motor Efficiency = 0.87 From motor efficiency curves, same source.

$$P = 471\frac{(18.3+18.6+18.8)}{3}\times\sqrt{3}\times 0.89\times 0.87 = 11728 \text{ watts motor output}$$

$$11728 \text{ watts motor output} \Big/ 746 \text{ watts per hp} = 15.72 \text{ hp}$$

Power delivered to water:

Estimated efficiency of gear reducer 90%

Power delivered $= 15.72 \text{ hp}\times 0.90 = 14.15 \text{ hp}\times 550 \text{ ft lb}_f/\text{s/hp} = 7782 \text{ ft lb}_f/\text{s}$

Volume of water in tank $= 8\text{ft}\times 8\text{ft}\times 22\text{ft} = 1408 \text{ ft}^3$

$$G = \left(\frac{P}{\mu V}\right)^{0.5} = \left(7782 \text{ ft lbs}_f/\text{s} \Big/ \left[(2.735x10^{-5} \text{ lb}_f \text{ s/ft}^2)(1408\text{ft}^3)\right]\right)^{0.5}$$

μ = 2.735 x 10^{-5} lb_f s/ft^2

Or μ = 1.307 x 10^{-3} Ns/m^2

G = 450 s^{-1}

Solve for G in SI units recognizing that 1 watt = 1 Nm/s

Power to water = 11728 x 0.90 = 10555 watts

Volume of tank = 39.875 m^3

μ = 1.307 x 10^{-3} Ns/m^2

$G = (P/\mu V)^{0.5}$

$$= \left(\frac{10555 \frac{\text{Nm}}{\text{s}}}{1.307 \times 10^{-3} * \frac{\text{Ns}}{\text{m}^2} * 39.875 \text{m}^3} \right)$$

$G = 450\ \text{s}^{-1}$

Solve for dimensionless G x t product

t = theoretical detention time in the tank

$$t = V/Q = \frac{1408 \text{ft}^3}{100 \text{MGD} \times 1{,}547 \text{cfs/MGD}} = 9.1 \text{s}$$

$Gt = 450\ (s^{-1})$ x 9.1 (s) = 4095 dimensionless

Solve for the power delivered to the water per MGD

$$\text{hp/MGD} = \frac{14.15 \text{ hp}}{100 \text{ MGD}} = 0.14 \text{ hp/MGD}$$

The two-stage rapid mixing that follows the flash mixing provides an additional 15 seconds of mixing detention time at an rms: G of 290 s^{-1}. The combination of the flash mixing plus the rapid mixing provides a total G x t of 8445 (dimensionless) and a total power input of 0.28 hp/MGD. Both of these criteria satisfy common modern design criteria for rapid mixing tanks.

STATEMENT OF PROBLEM FOR CALCULATING VELOCITY GRADIENT IN BAFFLED FLOCCULATION TANK

An 8 MGD water treatment plant is treating a river water using conventional treatment (rapid mixing, flocculation, sedimentation, filtration and disinfection). Flocculation is provided by two parallel baffled flocculation tanks using around-the-end baffles. Details about each flocculation tank are as follows:

Length = 120 ft

Width = 15 ft

Bottom slopes 1.0 ft along the full length to facilitate periodic cleaning, and is lower at the exit end.

Water depth at exit end = 9.0 ft

Total baffles = 94, each is 3 inches thick

Baffle spacing is 6 inches at entrance end, and increases gradually to 21 inches at exit end. Maximum baffle length is 14.5 ft; minimum baffle length is 13.25 ft; average baffle length is approximately 13.875 ft.

The end opening for each baffle is the same as the spacing between baffles at that baffle location.

During operation at the design flow of 4 MGD/tank, the total head loss is observed to be 1.9 ft at a water temperature of 50° F.

1. Calculate the root mean square (r.m.s.) velocity gradient (G) based on the total head loss observed, and calculate the dimensionless G x t product and the power dissipation in the water in hp/MGD.

2. Also calculate the *r.m.s.* velocity gradient for the first baffle using the empirical relation that the head loss around the end of the baffle = 3 $V^2/2g$, and assuming that the energy of that head loss is dissipated in the next flow space before flowing around the end of the next baffle.

3. Do the same for the last baffle at the exit end of the tank.

Figure 14.3 is a representation of the plan view of the tank.

Solution in English Units

Analysis of one tank at 4 MGD = 6.188 cfs

Tank water area = (120)(15) – (94)(0.25)(13.875) = 1474 ft^2

Water depth at exit = 9 ft

Water depth at entrance = 9 ft – 1 ft slope + 1.9 ft head loss = 9.9 ft

Average Depth = 9.45 ft

Water volume at design flow = 1474 ft^2 x 9.45 ft = 13,929 ft^3

Use volume = 13,930 ft^3

$$\text{Theoretical Detention} = \frac{13930 ft^3 \times (1 min/60s)}{4 mgd \times (1.547 ft^3/s)(1/mgd)} = 37.5 \text{ min}$$

Calculate r.m.s. *G*

$$\text{Energy Dissipated} = Q \gamma \Delta H$$

where Q = Flow rate ft^3/s

γ = specific weight of water = ρ x g

ρ = mass density of water

g = acceleration due to gravity

ΔH = head loss

$$\text{Energy dissipated} = \left(6.188 \frac{ft^3}{s}\right) \times \left(1.94 \frac{slugs}{ft^3}\right) \times \left(32.17 \frac{ft}{s^2}\right) \times 1.9 ft$$

$$= 733.8 \frac{ft\ lb_f}{s}$$

Unit check recognizing that 1 slug = 1 $lb_f s^2/ft$

$$\left(ft^3/s\right) \times \left(lb_f s^2/ft\right) \times \left(1/ft^3\right) \times \left(ft/s^2\right) \times ft = ft\ lb_f/s$$

$$hp = \frac{733.8 ft\ lb_f/s}{550 ft\ lb_f/s/hp} = 1.33 hp$$

$$G = (P/\mu V)^{0.5}$$

where μ at 50° F = 2.735 x 10^{-5} lb_f s/ft^2

V = 13930 ft^3 prior calc.

P = 733.8 ft lb_f / s prior calc.

$$G = \left(\frac{733.8 ft\ lb_f/s}{2.735 \times 10^{-5}\ lb_f s/ft^2 \times 13930 ft^3}\right)^{0.5}$$

G = $44 s^{-1}$ (This is the average r.m.s G for the whole tank)

Find G x t product

$$G \times t = \frac{44}{s} \times 37.5\,\text{min} \times \frac{60\,\text{s}}{\text{min}} = 99{,}000 \text{ dimensionless}$$

Find power dissipated/MGD

$$\text{hp/MGD} = 1.33/4 = 0.33\text{hp/MGD}$$

All of the above satisfy common design guidelines for conventional flocculation tanks.

Find G for the first baffle space

Width of the opening = 0.5 ft

Water depth = 9.9 ft

Flow area between baffles and at first end around space = 9.9 x 0.5 ft = 4.95 ft^2

$V = Q/A$ = (6.188 ft^3/s) / 4.95 ft^2 = 1.25 ft/s

$V^2/2g$ = 0.024 ft

ΔH = $3V^2/2g$ = 0.072 ft

Energy dissipated = $Q\,\gamma\Delta H$ same as before

= 6.188 x 1.94 x 32.17 x 0.072

= 27.80 ft lb_f /s

This energy is dissipated in the next flow channel before the next turn around the next baffle.

Volume = 15 ft x 0.5 ft wide x 9.9 ft deep

= 74.25 ft^3

$G = (P/\mu V)^{0.5}$ as before

$$= \left(\frac{27.80}{2.735x10^{-5} \times 74.25} \right)^{0.5} = 117 s^{-1}$$

Find G at the exit end of the tank.

Width of opening = 1.75 ft given

Water depth = 9 ft given

Flow area $= 9\,\text{ft} \times 1.75\,\text{ft} = 15.75\,\text{ft}^2$

$$V = \frac{Q}{A} = \frac{6.188\ \text{ft}^3/\text{s}}{15.75\ \text{ft}^2} = 0.39\ \text{ft/s}$$

$V^2/2g = 0.00239$ ft

$\Delta H = 3V^2/2g = 0.0072$ ft

Energy dissipated = $Q\,\gamma\Delta H$ as before

= 6.188 x 1.94 x 32.17 x 0.0072

= 2.78 ft lb_f/s

Volume in which dissipated

= 15 ft x 1.75 ft x 9 ft = 236 ft^3

$G = (P/\mu V)^{0.5}$ as before

$$= \left(\frac{2.78}{2.735\times10^{-5}\times236}\right)^{0.5} = 20.8\text{s}^{-1}$$

Solution in SI units, solved only the overall tank G & Gt to illustrate the SI solution.

Q = 4 MGD = 6.188 ft^3/s x 0.02832 m^3/ft^3 = 0.1753 m^3/s

Tank volume at design flow.

= 13930 ft^3 x 0.02832 m^3/ft^3 = 394.5 m^3

Head loss = 1.9 ft x 0.3048 m/ft = 0.579 m

$$\gamma = \rho g = 999.7\,\text{kg/m}^3 \times 9.81\,\text{m/s}^2 = 9807\,\text{N/m}^3$$

recognizing that $\frac{1\text{kg}}{\text{s}^2}\text{m} = 1\text{N}$

$\mu = 1.307 \times 10^{-3}\,\text{Ns/m}^2$ at 10°C

Energy dissipated = $Q\,\gamma\Delta H$

$$\frac{0.1753\,\text{m}^3}{\text{s}} \times \frac{9807\,\text{N}}{\text{m}^3} \times 0.579\,\text{m}$$

= 995.4 Nm/s = 995.4 watts

$$G = \left(\frac{P}{\mu V}\right)^{0.5}$$ as before

$$= \left(\frac{995.4\,\text{Nm/s}}{1.307 \times 10^{-3}\,\text{Ns/m}^2 \times 394\,\text{m}^3}\right)^{0.5}$$

= 44 s^{-1} dimensionless

$$\text{Detention time} = \frac{394.5\text{m}^3}{0.1753\,\text{m}^3/\text{s}} = 2250\text{s}$$

$$G \times t = 44/s \times 2250\,s = 99{,}000\,\text{dimensionless}$$

As expected, the *G* & *Gt* are the same as calculated previously in English units.

SETTLING VELOCITY OF VERY SMALL PARTICLES IN THE LAMINAR REGION BY STOKES' EQUATION

Example Problem

Find the terminal settling velocity of a small, spherical, particle with a diameter of 0.1 mm and a specific gravity of 1.1, in water at a temperature of 10° C (50° F). Assume Stokes' equation applies but check the particle Reynolds number based on calculated settling velocity to confirm that the Re is < 0.2 and is appropriate for Stokes' equation. See *Water Quality & Treatment, 5th Edition*, pages 7.6-7.8 for complete theory of the settling of discrete particles.

Solution in SI Units:

Stokes' Equation:

$$v_t = g(\rho_s - \rho)\, d^2 / 18\mu$$

where v_t = terminal settling velocity of a discrete particle

g = acceleration due to gravity

ρ_s = mass density of the solid particle

ρ = mass density of the fluid

d = spherical particle diameter

μ = absolute viscosity of the fluid

Example problem in SI units

Where g = 9.81 m/s^2

ρ_s = 1.1 x 999.7 = 1099.67 kg/m^3 so 1100 is close enough

ρ = 999.7 kg/m^3

d = 1.0 x 10^{-4} m

μ = 1.307 x 10^{-3} Ns/m^2

$$v_t = \frac{(9.81\text{m/s}^2)(1100-999.7)(\text{kg/m}^3)(1\text{x}10^{-4})^2\,\text{m}^2}{(18)(1.307\text{x}10^{-3}\ \text{Ns/m}^2)}$$

From Newton's Law, F = Ma and 1 Newton accelerates 1 kg mass at 1 m/s^2 so

1 N = 1 kg m/s^2

v_t = 0.000418 m/s = 0.418 mm/s

Unit check, substituting kg m/s^2 for N

$$v_t = \frac{(\text{m/s}^2)(\text{kg/m}^3)(\text{m}^2)}{(\text{kg})(\text{m/s}^2)(\text{s/m}^2)} = \text{m/s}$$

Check the particle Reynolds number based on the calculated settling velocity:

$$Re = \frac{dv_t\rho}{\mu}$$

$$\text{Re} = \frac{((1.0\text{x}10^{-4})(4.18\text{x}10^{-4})(999.7))}{1.307\text{x}10^{-3}}$$

Re = 0.032 [dimensionless] which satisfies Re < 0.2 so Stokes' equation is applicable.

Check units on Re

$$Re = dv_t\,\rho/\mu = \frac{(\text{m})(\text{m/s})(\text{kg/m}^3)}{\text{Ns/m}^2}$$

Substituting kgm/s^2 for N

$$Re = \frac{(\text{m})(\text{m/s})(\text{kg/m}^3)}{(\text{kg}\cdot\text{m/s}^2)(\text{s/m}^2)} = \text{dimensionless, OK}$$

Solving in English (traditional) units:

Where g = 32.17 ft/s^2

ρ_s = 1.1 x 1.940 = 2.134 slugs/ft^3

ρ = 1.940 slugs/ft^3

d = (0.1 mm) (3.281 ft/m) (1 m/1000 mm) = 3.281 x 10^{-4} ft

μ = 2.735 x 10^{-5} $lb_f s/ft^2$

$$v_t = \frac{(32.17 ft/s^2)(2.134 - 1.940)(slugs/ft^3)(3.28x10^{-4})^2 ft^2}{(18)(2.735x10^{-5} lb_f s/ft^2)}$$

v_t = 0.001369 ft/s = 0.000417 m/s as before

Unit check recognizing from Newton's Law 1 lb_f accelerates 1 slug at 1 ft/s^2
so 1 slug = 1 lb_f s^2/ft

and 1 slug/ft^3 = 1 lb_f s^2/ft^4

$$v_t = \frac{(ft/s^2)(slugs/ft^3)(ft^2)}{lb_f s/ft^2} = \frac{(ft/s^2)(lb_f s^2/ft^4)(ft^2)}{lb_f s/ft^2} = ft/s$$

Check the particle Reynolds number as before:

$$Re = d\, v_t\, \rho/\mu = \frac{(3.281x10^{-4})(1.369x10^{-3} ft/s)(1.940 slugs/ft^3)}{2.735x10^{-5} lb_f s/ft^2}$$

Re = 0.032 [dimensionless] which satisfies Re < 0.2 so Stokes' equation is applicable.
Unit check recognizing 1 slug = 1 lb_f s^2/ft and 1 slug/ft^3 = 1 lb_f s^2/ft^4

$$Re = \frac{(ft)(ft/s)(lb_f s^2/ft^4)}{(lb_f s/ft^2)} = \text{dimensionless, OK}$$

SETTLING VELOCITY OF LARGER, HEAVIER, SPHERICAL SAND GRAIN IN TRANSITIONAL REYNOLDS NUMBER REGION

Find the settling velocity of a spherical sand grain with a specific gravity of 2.65 and a diameter of 0.5 mm in water at 10° C (50° F).

Solution: In the transitional regime, must use the basic equation for settling of spherical particles as follows:

$$v_t = \left(\frac{4g(\rho_s - \rho)d}{3C_D\rho} \right)^{0.5}$$

Eq. 7.5 *Water Quality & Treatment, 5th Ed.*

And an empirical relation for C_D versus particle Reynolds number based on settling velocity as follows:

$$C_D = 24/Re + 3/Re^{0.5} + 0.34$$

Eq. 7.9 *Water Quality & Treatment, 5th Ed.*

Where $Re = dv_t \rho / \mu$

Since v_t equation requires C_D and C_D equation requires Re, which contains v_t, this is a trial and error solution. Alternatively, to avoid the trial and error solution, one can use a curve of $C_D Re^2$ versus Re and make a direct solution. See Figure 14.4.

In this example problem in SI units

Determine $C_D Re^2$

From equation 7.5 above

$$C_D = (4g/3)\frac{(\rho_s - \rho)}{\rho}\left(d/v_t^2\right)$$

$$Re^2 = d^2 v_t^2 \rho^2 / \mu^2$$

$$C_D Re^2 = (4g/3)\frac{(\rho_s - \rho)}{\mu^2}\left(\rho d^3\right)$$

Note that v_t is eliminated on the right hand side.

For this solution in SI units

ρ = 999.7 kg/m^3

ρ_s = 2.65 x 999.7 = 2649.2 kg/m^3

d = 0.5 x 10^{-3} m

μ = 1.307 x 10^{-3} Ns/m^2

g = 9.81 m/s^2

$$C_D Re^2 = \frac{(4/3)(9.81\,\text{m/s}^2)(2649.2 - 999.7)(\text{kg/m}^3)(999.7\,\text{kg/m}^3)(0.5\text{x}10^{-3}\,\text{m})^3}{(1.307\text{x}10^{-3})^2(\text{Ns/m}^2)^2}$$

$C_D Re^2$ = 1578.3

From the $C_D Re^2$ versus Re graph, for this $C_D Re^2$ we read Re = 28

Unit check on $C_D Re^2$

$$C_D Re^2 = \frac{(\text{m/s}^2)(\text{kg/m}^3)(\text{kg/m}^3)(\text{m}^3)}{N^2\text{s}^2/\text{m}^4} = \frac{(\text{kg}^2)/(\text{s}^2)(\text{m}^2)}{(N^2)(\text{s}^2)/(\text{m}^4)}$$

Substituting 1 N = 1 kg m/s^2 gives

$$\frac{(kg^2)/(s^2)(\text{m}^2)}{(\text{kg}^2\text{m}^2/\text{s}^4)(\text{s}^2/\text{m}^4)} = \frac{(\text{kg}^2)/(\text{s}^2)(\text{m}^2)}{(\text{kg}^2)/(\text{s}^2)(\text{m}^2)}$$

The result is dimensionless

Solve for v_t from this Re value:

Re = d vt ρ/ μ dimensionless Re

$$28 = \frac{0.5\text{x}10^{-3}(\text{m})\text{v}_t(\text{m/s})999.7(\text{kg/m}^3)}{1.307\text{x}10^{-3}\,\text{Ns/m}^2}$$

Solve for v_t

v_t = 0.073 m/s or 73 mm/s

Unit check on v_t:

$$v_t = \frac{\text{N s/m}^2}{\text{m kg/m}^3} = \frac{(\text{kg m/s}^2)(\text{s/m}^2)}{\text{m kg/m}^3} = \text{m/s}$$

Now that we have a direct solution for v_t, we can go back to the basic equation (Eq. 7.5 *Water Quality & Treatment, 5th Ed.*) for a check.

$C_D = 24/Re + 3/Re^{0.5} + 0.34$ Eq. 7.9 *Water Quality & Treatment, 5th Ed*

$$= (24/28) + (3/28^{0.5}) + 0.34 = 1.764$$

$$v_t = \left[\frac{4g(\rho_s - \rho)d}{3C_D\rho}\right]^{0.5}$$ Eq. 7.5 *Water Quality & Treatment, 5th Ed.*

$$v_t = \left[\frac{(4)(9.81\,\text{m/s}^2)(2649.2 - 999.7)(\text{kg/m}^3)(0.5\text{x}10^{-3}\,\text{m})}{(3)(1.764)(999.7\,\text{kg/m}^3)}\right]$$

v_t = 0.078 m/s which is reasonably close to the prior direct solution. The difference is created by the approximate fit of Equation 7.9. Because of that fact, the prior result is probably the best result (i.e., v_t = 0.073 m/s).

Solve the same problem in English (customary) units:

ρ = 1.940 slugs/ft^3

ρ_s = 2.65 x 1.940 = 5.141 slugs/ft^3

d = (0.5 x 10^{-3} m) (3.281 ft/m) = 1.64 x 10^{-3} ft

μ = 2.735 x 10^{-5} lb$_f$s/ft^2

$g = 32.17\ \text{ft/s}^2$

$C_D Re^2$ should be the same since it is dimensionless

$$C_D Re^2 = \frac{(4g/3)(\rho_s - \rho)(\rho d^3)}{\mu^2}$$

$$= \frac{(4/3)(32.17\text{ft/s}^2)(5.141 - 1.940)(\text{slugs/ft}^3)(1.94\,\text{slugs/ft}^3)(1.64\text{x}10^{-3}\,\text{ft})^3}{(2.735\text{x}10^{-5})^2(\text{lb}_f\,\text{s/ft}^2)^2}$$

$C_D Re^2 = 1571$ close to the SI solution, dimensionless

From the $C_D Re^2$ versus Re graph, for this $C_D Re^2$ we read $Re = 28$

Unit check on $C_D Re^2$

$$C_D Re^2 = \frac{(\text{ft/s}^2)(\text{slugs/ft}^3)(\text{slugs/ft}^3)(\text{ft}^3)}{(\text{lb}_f\,\text{s/ft}^2)^2}$$

Substituting for slugs, 1 slug = 1 $\text{lb}_f\text{s}^2/\text{ft}$ and 1 slug/ft^3 = 1 $\text{lb}_f\,\text{s}^2/\text{ft}^4$

$$C_D Re^2 = \frac{(\text{ft/s}^2)(\text{lb}_f\text{s/ft}^4)(\text{lb}_f\text{s/ft}^4)(\text{ft}^3)}{(\text{lb}_f{}^2\text{s}^2)/\text{ft}^4} = \text{dimensionless, OK}$$

Solve for v_t from this Re value:

$Re = d \times vt \times \rho/\mu$

$$28 = \frac{1.64\times10^{-3}(\text{ft})\ v_t(\text{ft/s})1.94(\text{slugs/ft}^3)}{2.735\times10^{-5}\ \text{lb}_f\,\text{s/ft}^2}$$

Solve for v_t

v_t = 0.24 ft/s or 0.073 m/s as before

CALCULATION OF NORMALIZED (STANDARDIZED) CLEAN BED HEAD LOSS

As an alternative to sampling and analyzing filter media for accumulated suspended solids, it is possible to monitor the effectiveness of backwashing by recording the rate of filtration, water temperature, clean bed head loss (starting head loss at the beginning of the run, after backwashing) of each filter run from the day media was first installed. Assuming constant water temperature and filtration rates, if the clean bed head loss remains constant over time (and no loss of media is taking place) it can be assumed that the media is being maintained in its original clean condition. It is important to ensure that variations in clean bed head loss are not due to different flow rates or changes in water viscosity. From Kozeny's equation (equation 1), head loss in a filter is proportional to flow rate and proportional to water viscosity (*Water Quality & Treatment, 5th Ed.*).

$$\frac{h}{L} = \frac{k\mu}{\rho g}\frac{(1-\varepsilon)^2}{\varepsilon^3}(a/v)^2 V \qquad \text{Equation 1}$$

Where: h = head loss in depth of bed L
g = acceleration due to gravity
ε = porosity
a/v = grain surface area per unit grain volume
V = flow rate / bed area
μ = absolute viscosity of water
ρ = water density
k = Kozeny constant

Calculating the filtration-rate-and-temperature-normalized (standardized) clean bed head loss (NHL_0) and looking for changes in this value over time can therefore check filter media condition. At plants employing a slow filter starts and gradual increases to full rate, operators should collect filtration rate, temperature, and head loss data only after the full filtration rate has been attained. At plants where

the filter is started at the full operating rate rather than being ramped up, the first four head loss measurements taken at 15-minute intervals during the first hour of operation are averaged for the normalization (standardization) calculations. The filtration rate and temperature selected as standard conditions must be used for all normalization calculations

$$H_f = H_{QT} (Q_n / Q) \qquad \text{Equation 2}$$

Where: H_f = flow normalized head loss

H_{QT}= measured head loss at flow rate Q and temperature T°

Q_n = flow rate used as standard for normalization

Q = measured flow rate (m/h)

Head loss can also be normalized for temperature based on equation 3.

$$H_n = H_f (\mu_T / \mu) \qquad \text{Equation 3}$$

Where: H_n = flow and temperature normalized head loss

H_f = flow normalized head loss from equation 2

μ_T = absolute viscosity of water at the normalized (standardized) temperature

μ = absolute viscosity of water at the mean weekly water temperature, °C (kg/m/s)

Calculate standardized head loss using traditional (English) units

Given a clean bed head loss of 1.2 feet at a filtration rate of 2 gpm/sf and 39° F, calculate the normalized (standardized) head loss for conditions of 3 gpm/sf and 60° F.

The viscosity of water at 39° F is approximately 0.00003274 slugs/ft-sec

The viscosity of water at 60° F is approximately 0.00002359 slugs/ft-sec

Making the adjustment for filtration rate

$$H_f = H_{QT} (Q_n / Q) = 1.2 \left(\frac{3}{2}\right) = 1.8 \text{ ft}$$

Making the adjustment for viscosity difference, based on temperature

$$H_n = H_f(\mu_T/\mu)$$

$$H_f = 1.8(0.00002359/0.00003274)$$

$$H_f = 1.3\,\text{ft}$$

JAR TEST INFORMATION AND PROCEDURES

Jar tests have been used for decades by water treatment plant operators to develop information on the chemical dosages that should be used to achieve effective coagulation and sedimentation. Many of the water utilities using jar tests have developed modifications or variations to adapt this procedure to the specific conditions encountered at their plants. This is appropriate, but certain common aspects of the jar test procedure should be considered and incorporated by most water utilities. A more detailed and very useful discussion of jar tests and procedures for jar testing is found in "Chapter 1, Jar Testing," in AWWA Manual M37, *Operational Control of Coagulation and Filtration Processes.*

Equipment

The fundamental piece of equipment needed for jar tests is the multi-place stirrer. These have been produced by one or more manufacturers over the years and are available commercially. Generally jar test stirrers have a built-in tachometer to indicate the rotational speed of the stirrer. Checking the rpm is good QA practice. To do this, tape a small paper "flag" to the top of the jar test shaft (for stirrers which drive the mixer paddle from the top down) and use a stopwatch to determine the rpm of stirring. Stirrer types include a rectangular paddle mounted on a long shaft and driven from above the jar by a gear mechanism, and a rectangular paddle mounted on stand in the test jar and rotated by a magnet located in the drive mechanism on which the jar is placed. AWWA Manual M37 has charts showing the relationship between paddle rpm and the velocity gradient developed in a square cross-sectioned jar. Consult that information source for more details, particularly when attempting to match the flocculation intensity in the jar (as indicated by G value) with the flocculation intensity in the plant.

Along with the stirrer, jars are needed. Round glass beakers were commonly used in the past and may continue to be used by some water utilities because of the modest cost. Round jars or beakers are not shaped properly for good mixing. When a jar tester is set at high rpm to perform rapid mixing, the entire body of water in the round beaker can rotate, and when this happens the mixing energy imparted to the water is reduced. In contrast to round beakers, jars with a square cross section will have eddies at the corners, and greater mixing energy can be attained during rapid mixing. Jars having a square cross section are available commercially and are the best choice for jar testing, because they are designed for withdrawing samples from a specified depth within the jar. A photo of a jar test apparatus is shown in Figure 8.1 at the end of this chapter.

Treatment chemicals

Before jar tests are started, stock solutions of treatment chemicals should be prepared for the chemical(s) to be tested, and for chlorine and caustic or acid (if desired). Excessive dilution of coagulation chemicals or polymers must be avoided, as this will render the coagulant less effective or ineffective for its intended purpose. Manual M37 recommends that dilution of inorganic coagulants should not result in solutions having a strength of less than 0.1 percent, or 1000 mg/L (1 mg/mL). Liquid alum at its usual commercial strength of 5.3 pounds of dry alum (filter alum in granular or powdered form, $Al_2(SO_4)_3 \cdot 14\ H_2O$) per gallon (0.63 Kg per liter) can be prepared as a 10 mg/mL stock solution by adding 15.6 mL of the full-strength liquid alum to a 1.00 L volumetric flask and making up the volume to 1.00 L by adding distilled water. To make a solution having a strength of 20 mg/mL, use 31.2 mL of liquid alum. Filter alum in granular or powdered form [$Al_2(SO_4)_3 \cdot 14\ H_2O$] can be used to make up a stock solution containing 10 mg/mL by adding 10.0 grams of dry alum to a 1.00 L volumetric flask about one third filled with distilled water, and diluting the contents to 1.00 L by adding more distilled water. A stock having a strength of 20 mg/mL would be made by adding 20.0 grams of dry alum. Manual M37 also gives directions for making stock solution of ferric coagulants. Directions vary, depending on whether the ferric chemical is liquid or dry, and whether ferric sulfate or ferric chloride is the coagulant. Consult M37 for details on preparing ferric coagulants.

Treatment chemical strength must be known so calculations for dosing can be made, and so dilutions, if needed to obtain stock solutions for dosing, can be performed. When the strength of liquid commercial chemicals is expressed as lb/gal, this can be converted to g/mL by multiplying by 0.1198. The resulting concentration in g/mL can be used to calculate the number of mL of stock to add to a liter to make a solution having the desired concentration for dosing in jar tests.

Careful preparation of polymers for jar tests is necessary if meaningful results are to be obtained. The accuracy and precision of test results can be no better than the accuracy and precision of the dilution or weighing procedures used to prepare stock solutions used in the jar test.

For dry polymer preparation, if possible weigh to +/- 1%. If 1.00 gram is to be weighed, the balance should be accurate to 10 mg or 0.01 gram. It is better to prepare an excess of polymer solution and throw some away than to weigh small quantities with poor precision.

Dilution of liquid polymers is challenging. Generally these are viscous, and they often are measured by volume. A syringe may be useful for measuring and transferring liquid polymers and emulsion polymers. If large-mouth pipettes are used, rinsing out the residual polymer that adheres to the

inside of the pipette is a challenge. When a pipette is used to measure and deliver a volume of liquid polymer, the pipette should be repeatedly rinsed with distilled water to wash out residual polymer that did not drain out initially because of the high viscosity. In like fashion, if liquid polymer is weighed, the weighing pan must be rinsed repeatedly to avoid leaving part of the polymer on the pan instead of transferring it into the volumetric flask. Failure to rinse out the residue will result in overestimation of the amount of polymer transferred, causing inaccurate results. For example, if 10% of the polymer adhered to the pipette, then an apparent polymer dosage of 0.10 mg/L in a jar test would really be 0.09 mg/L. Especially when comparing competing brands of polymers, attaining the highest practical degree of accuracy and precision is important.

Techniques for preparation of stock solutions of polymers are given in M37, which recommends measuring both liquid and dry polymers by weighing. A stock solution of polymer at a strength of 0.2 mg/mL can be made by weighing out 0.2 grams of polymer and adding it to a 1.00 L volumetric flask about one third filled with distilled water, and making up the volume to 1.00 L by adding distilled water. Whereas with a liquid polymer only one minute of shaking is recommended, for dry polymers, at least 2 hours of mixing are called for. If liquid polymers are measured by volume rather than by weight, the volume to add can be calculated by adjusting for the specific gravity [grams of polymer added = (milliliters polymer added) x (specific gravity)].

Shelf life of coagulants and polymers has to be considered when doing jar tests. As coagulant chemical stock solutions and polymer stock solutions age, the chemicals deteriorate and are less effective than fresh solutions. Using an aged and deteriorated chemical in jar tests might cause overdosing at the plant, or jar tests might falsely indicate that the chemical did not work at all. Manual M37 recommends that stock solutions of inorganic coagulant at a strength of 10 mg/mL be prepared each day. This can be done rather easily when liquid coagulants are used but requires more time if dry chemicals must be weighed. The manual also recommends that stock solutions of polymer having a strength of 0.2 mg/mL should be prepared each day.

All chemicals to be added during a testing sequence should be pre-measured to the prescribed dose for addition during the test. A convenient method for adding chemicals is through the use of plastic syringes that can be obtained in varying sizes. This allows the chemical to be pre-measured prior to the start of the test sequence so that all of the additions can take place at nearly the same time once the test procedure has begun. Some laboratories in the United Kingdom use a tilting rack, to which test tubes are secured with spring clips. The rack is on a longitudinal pivot such that by turning it by hand the contents of all the test tubes (acid, alkali, coagulant) are tipped into the jars simultaneously.

The square jar test jars are made to hold 2 liters of raw water. If this volume of water is used in the test, chemical dilutions and dosing volumes should be based on adding sufficient chemical to treat a 2-liter volume of water. For example, a stock solution of coagulant at a concentration of 20 mg/mL yields a dosage of 10 mg/L for each milliliter of stock added to a jar test jar holding 2 liters of water. If 2-liter jars are used, calculations for dosing the jars are done more easily when stock solution strengths are 20, 2.0, or 0.2 mg/mL, as adding 1.0 mL would result in chemical concentrations of 10, 1.0, or 0.1 mg/L, respectively. Relatively small syringes, holding in the range of 1 to 5 milliliters, would be appropriate for most jar testing. All syringes needed for chemical dosing should be filled with the appropriate volumes of chemical before the jar test starts, and placed at the jar test apparatus in a manner that will eliminate confusion about which syringe or syringes are to be used for a given jar.

To avoid effects of different rapid mixing times, chemical addition should occur in the shortest time interval possible. When chemicals are added at the beginning of a jar test, the action can be fast and hectic. As one way to minimize errors in chemical addition, labels could be placed appropriately to indicate the dosage for each jar. Furthermore, each syringe should be labeled carefully or placed on a surface where labels are affixed, so no confusion can arise about the dosages used to treat the water in each jar A senior shift operator at the Modesto Irrigation District's filtration plant has built a device that can be used to inject chemical dosages simultaneously by means of syringes. Instructions and a diagram have been presented in *Opflow* (Mical 1997; and Mical 1998). If beakers are used to hold chemicals for dosing, 50-mL plastic beakers are recommended. These are slightly tapered, which permits them to be placed into holes cut into a small 1 inch x 3 inch or 1 inch x 4 inch (nominal size) board that is as long as the jar test apparatus. Holes are spaced so each beaker is over the center of a jar during dosing. When the beakers are snugly inserted into the board, the board is lifted up and located over the jar test jars, and then rotated to dump in the chemicals at the beginning of the test. This approach is easier to use with jar test devices that employ a magnetic drive underneath the jars, rather than ones with a drive mechanism located above the jars.

Test water

The water being tested must be representative of the water that is being or will be treated. Obtain a sample of raw water at a continuously flowing plant tap immediately prior to performing a jar test. This should minimize possible quality changes before treatment. For very cold waters, it may be necessary to use a water bath to keep the test water cold during the rapid mixing and flocculation stages

of jar testing. As an alternative, jar testing could be performed in a cold room where the difference between water temperature and air temperature is only a few degrees C. When raw water temperature is in the vicinity of 41° F (5° C) or lower this is especially important. Very cold water would exert the greatest influence on coagulation, with smaller effects on flocculation and sedimentation. Maintaining low temperature is most important early in the jar test, and if water does not warm up more than 2° F (1° C) during coagulation and more than 4° or 5° F (2° or 3° C) during flocculation, using a cold water bath may not be necessary. This needs to be evaluated on-site when raw water temperature is low and warming of the test water in the water works laboratory could lead to misleading jar test results.

As a shortcut for jar testing, some treatment plant operators take a sample of water entering the flocculator and place it in jar test jars, stirring at the appropriate rotational speed. They view the floc for size and may evaluate its settling characteristics. This method could provide a quick insight into an existing treatment practice and has merit for this. It would not give information on the effect of other dosages. A floc size chart is shown in Chapter 9.

Jar test procedure

The jar test is intended to imitate, in a 2-liter jar, the processes of coagulation, flocculation, and sedimentation in a full-scale plant. Jar tests can closely mimic a full-scale plant with regard to order of addition of treatment chemicals to the water, but differences in residence times in pretreatment may be difficult to overcome.

The effect of the order of adding treatment chemicals is one of the useful aspects for study in jar tests. Water chemistry is not affected by scale or size. Jar tests can be used to decide if caustic or alum should be added first, when water low in alkalinity is treated and both chemicals are needed for effective treatment. Additionally, optimum delay times between adding sequential chemicals may be determined. The sequence of chemical addition might be as follows:

- pH adjusting chemical
- coagulant chemical
- polymer (most cationic polymers are added during the rapid mix, but for nonionic and anionic polymers it is often better to add the polymer immediately following the rapid mix step in the test.

An alternative chemical addition sequence might be:

- coagulant chemical
- pH adjusting chemical
- polymer

In some cases the addition of coagulant chemical ahead of the addition of pH adjustment chemical may prove to be more effective.

Jar tests and treatment plants have some major differences. As compared to the treatment plant, jar tests are very different in terms of size or scale, and jar tests are done on a batch basis, whereas the treatment plant utilizes continuous flow processes in pretreatment. Varying degrees of short-circuiting of water flow occur in a full-scale plant in rapid mixing, flocculation, and sedimentation. In contrast, in the jar test the times for rapid mixing, flocculation, and sedimentation are well defined and exact because the jar test is done on a batch basis. The appropriate times for mixing, flocculation, and sedimentation are not likely to be identical to the theoretical detention times in the full-scale plant.

The rapid mixing technique used in a jar test may differ considerably from the rapid mixing technique used in the plant. When in-line mixers or pumped jet mixers are used full-scale, the jar test may be able to approximate the Gt product (the mixing intensity, G per second, multiplied by the mixing time in seconds) although the exact nature of the mixing could not be reproduced.

Various types of flocculators are used in treatment plants, and again an approximation may be the limit of similarity that can be attained in the jar test. For plants using tapered flocculation, with a greater energy input during the first stage of flocculation and lower energy inputs in later stages, the flocculation process can be performed in stages in the jar test.

Sedimentation often is evaluated in jar tests by determining the overflow rate for the settling basin and evaluating sedimentation at that rate. When the rate of flow and the surface area are known for a settling basin, the overflow rate can be calculated by dividing the flow by the surface area. Typically this calculation will yield an overflow rate expressed as gpm/ft^2. For jar test work, a 1 gpm/ft^2 overflow rate = a settling velocity of 4 cm/min. When the overflow rate for a settling basin is known, that rate can be used to calculate the time interval for which settling should take place in the jar test jars before samples are withdrawn for turbidity measurement. Table 8.1 in Chapter 8 is a compilation of some typical sedimentation basin overflow rates and corresponding times for withdrawing samples from a 10 cm depth in a jar test jar.

Jar test procedures may need to be adjusted to account for changes in plant flow. When a plant is operating at its rated capacity, detention times will be half as long as when the plant is operating at 50 percent of its capacity, if all process basins are in use in both circumstances. The jar test procedure adopted for a specific plant will be subject to change. If an extensive jar test program was carried out when the plant was operating at half its capacity, later on when flows are close to design capacity, adjustments in detention times for rapid mixing and flocculation, and adjustments in holding times before sampling in the sedimentation process would be appropriate.

As discussed in Manual M37, the holding times that are appropriate for evaluating the settling properties of floc in jar tests are very short, because those times are related to the overflow velocity of the full-scale basin and are based on a settling distance of 10 cm in the jar test jars. This typically results in sample collection after just a few minutes of settling in a jar test jar. For example, if the overflow rate to be simulated is 1 gpm/sf (about 4 cm/min) the sampling time at the 10 cm depth would be 10 cm / 4 cm/min = 2.5 minutes. Whereas a short detention time is appropriate for evaluating the settling of floc particles, a short holding time can not provide valid data when time-dependent chemical reactions such as formation of DBPs in pretreatment are being studied. If jar tests were being done to evaluate a change of coagulants at a plant practicing prechlorination, to develop data on DBP formation during pretreatment, the holding time in the jar tests would need to approximate closely the holding time in the full-scale plant. The jar test procedure must be evaluated in the context of the type of data being sought, and the procedure used must fit the circumstances that are appropriate to the purposes of the testing. In the case of DBP formation, sampling for turbidity and information on floc settling could be done after a few minutes, as described above, but sampling of water for measurement of DBPs would need to be done after the actual detention time in the full-scale settling basin had been attained in the jar. In jar tests, the water treatment chemistry scales up well, but physical (engineering) parameters are much more difficult to scale up.

When jar testing is conducted to evaluate treatment of low-turbidity waters, the typical procedure of rapid mix-flocculate-settle may not provide adequate information. If raw water turbidity is near 1 ntu, measuring settled water turbidity may not reveal much about effective coagulant dosages. In such a situation, after the flocculation step, flocculated water should be filtered through Whatman #40 filter paper, as recommended by Wagner and Hudson (1982). This simulates treatment by direct filtration, for estimating chemical dosages needed for coagulation. Note that filter paper filtration can NOT provide any data on time variations of filtrate quality or on head loss development in direct filtration, so using jar tests for estimating chemical dosages to be used in direct filtration is merely a first step in determining

the appropriate chemical treatment. Head loss development data can be obtained only by operating either a pilot filter or a full-scale granular media filter.

Recording jar test data

The following data should be recorded for each jar test performed:

- raw water temperature just before treatment chemicals are added
- raw water turbidity
- raw water pH
- raw water alkalinity
- temperature at the beginning of the flocculation step and at the end of the flocculation step (for cold water treatment)
- settled water temperature at end of settling period
- settled water turbidity, each jar (with depth of sampling and time of sampling identified)
- settled water pH, each jar
- dosage of coagulant chemical, each jar
- dosage of caustic or acid, each jar

Additional analyses can be performed if thought appropriate for the particular coagulant chemical being tested. When jar tests are performed for purposes of removing constituents from water other than turbidity, other analyses may be necessary. For example, jar testing for enhanced coagulation would involve TOC analysis, and testing for control of DBPs could involve chlorination of settled water samples and subsequent testing for DBPs in incubated water samples after a specified period of time.

Issues of quality control and good practice

Plant operators who perform jar tests should put a strong emphasis on quality control aspects of jar testing and should be aware of what to do to get good jar test data and what to avoid.

Examples of practices to avoid include:

- Failure to use a cold water bath in winter, collecting jar test data at room temperature when water in the plant is near freezing
- Improper dilution of treatment chemicals and polymers or holding diluted chemicals beyond their shelf life, resulting in ineffective treatment chemicals
- Improper collection or storage of raw water, giving non-representative raw water for jar test studies
- Mixing at energy inputs that have no relationship to the actual plant, and settling for unrealistic times to obtain data
- Attempting to use sedimentation results from jar test when raw water turbidity is very low and direct filtration is being used in the plant

Examples of good practices include:

- Careful documentation of preparation of treatment chemicals, including date of dilution and recommended expiration date beyond which chemical should not be used.
- Checking the accuracy of the tachometer for measuring rpm of stirrers
- Performing a jar test with 2 or 3 jars having identical chemical dosing, mixing, and flocculation times, as a check on reproducibility of the procedure in the hands of treatment plant operators.
- Performing jar tests in which conditions are similar to plant conditions, to verify that jar tests are a good predictor of plant performance.
- Maintaining jar test results and records for at least several years, for purposes of historical review and for future reference when raw water quality may be similar to that encountered in the past.

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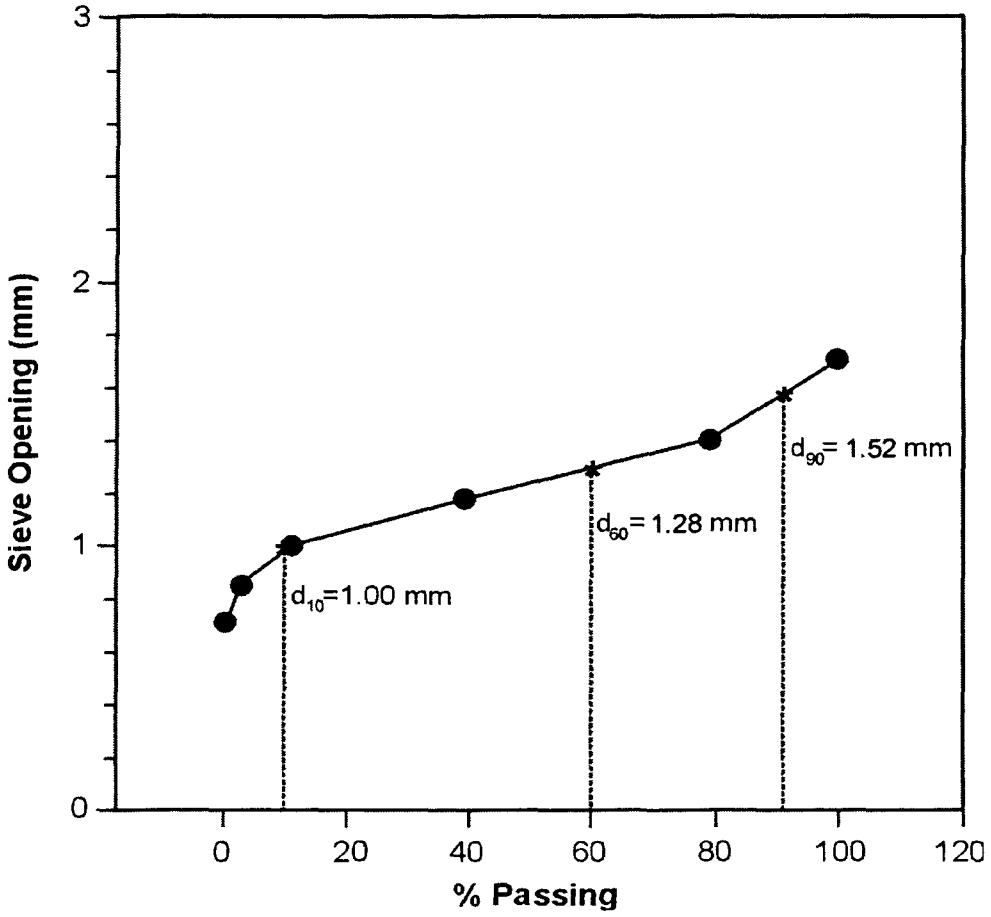

Figure 14.1 Sieve analysis Plot -Arithmetic (*Source*: Adapted from Cleasby 2001)

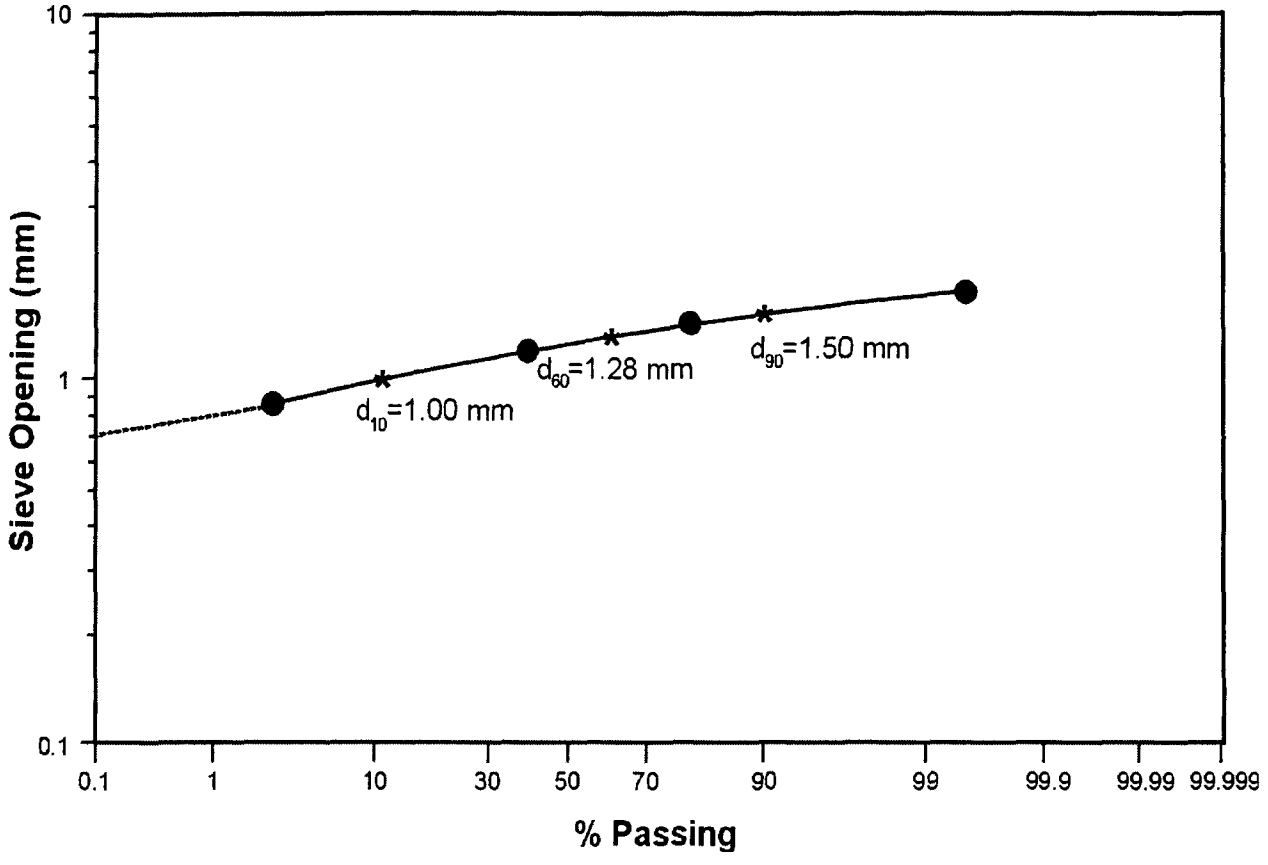

Figure 14.2 Sieve analysis- Log Probability (Source: Adapted from Cleasby 2001)

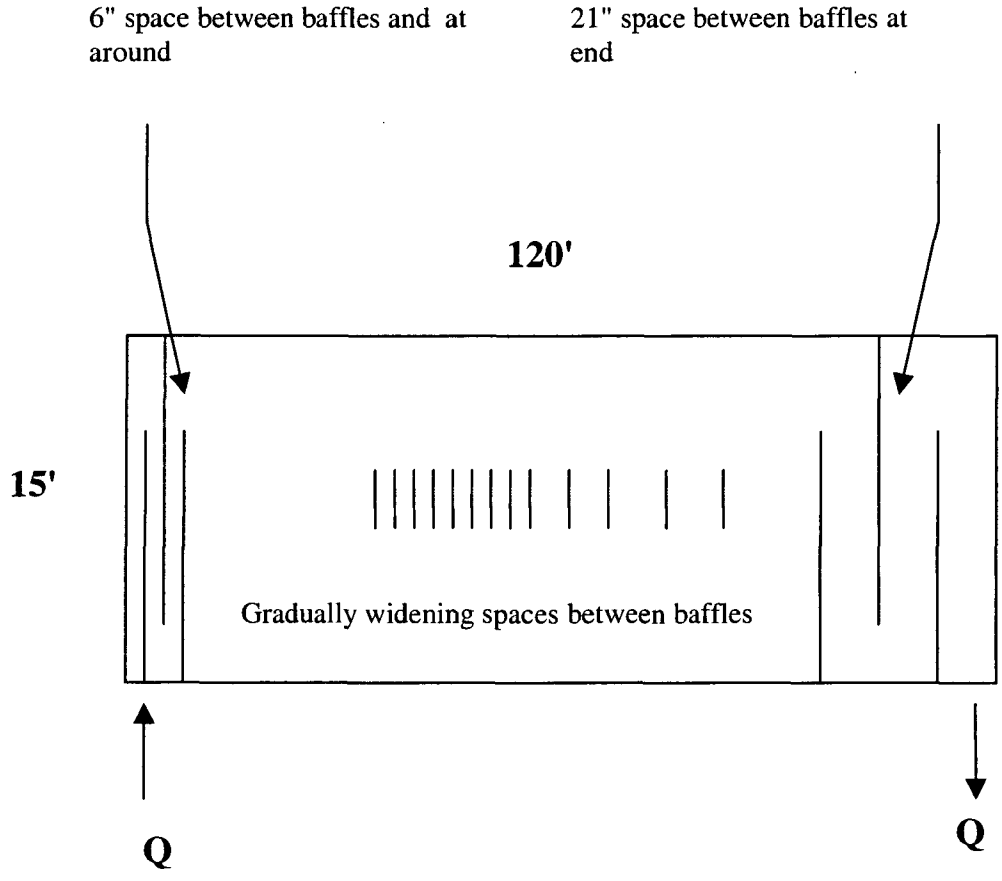

Figure 14.3 Plan view of baffled flocculation tank for calculating velocity gradient (Adapted from Cleasby 2001)

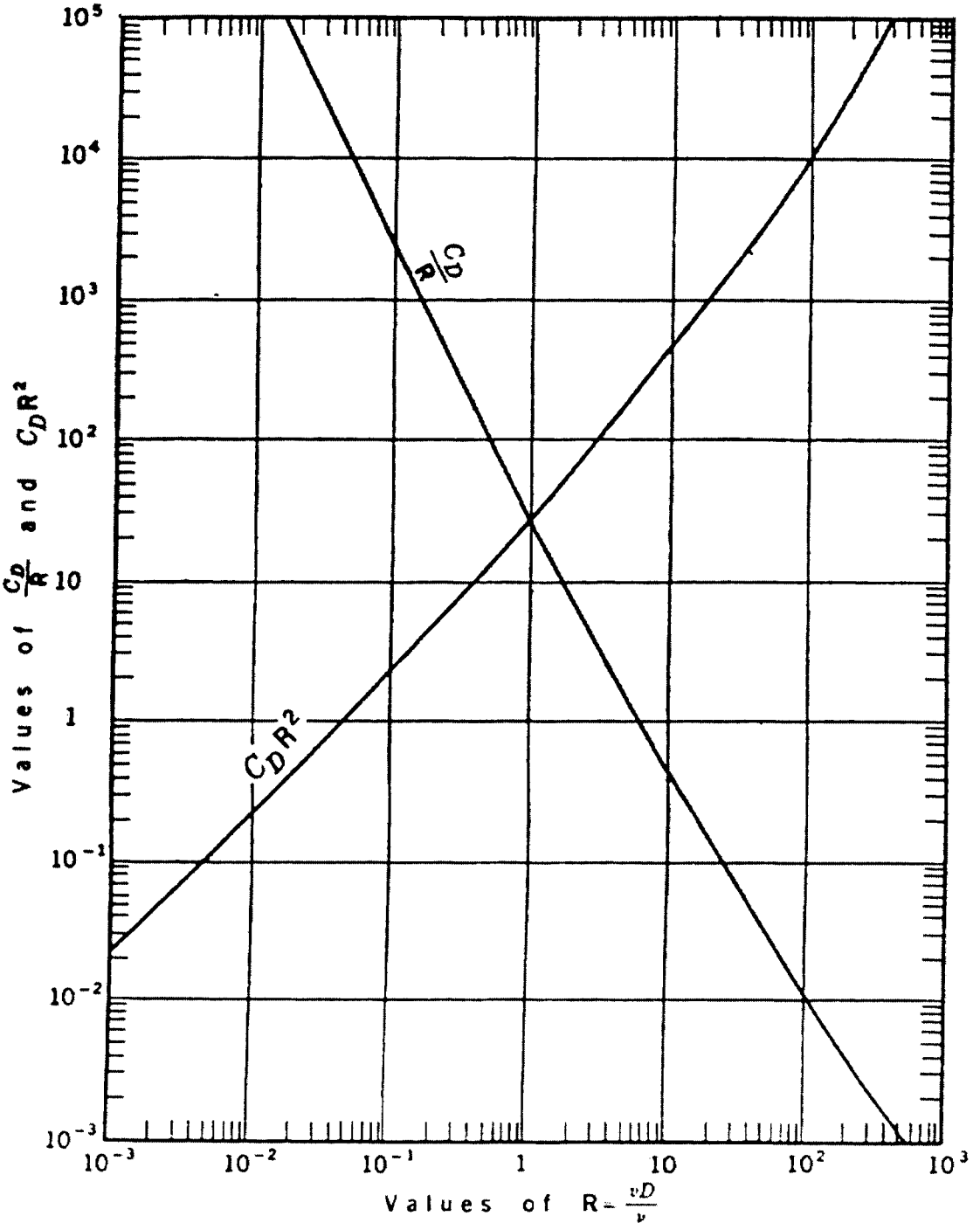

Figure 14.4 Values of settling velocities and varying Reynold's numbers for spherical particles (Source: Camp T. R. 1946. *Sedimentation and the Design of Settling Tanks.* A.S.C.E. Transactions, Vol.111: 895-936)

CHAPTER 15

RESEARCH NEEDS IDENTIFIED IN THIS PROJECT

During the study of filter operation and maintenance a number of questions arose (from members of the Participating Utilities via the survey form), and from these questions some research needs can be suggested. In addition, based on the experience of the authors, additional research needs have been identified. Some of the questions for which answers are needed on the topic of filter operation and maintenance are listed in this chapter. Brief discussions of the issues relevant to the questions are also presented.

FILTER RIPENING

To what extent do backwash remnants cause the ripening spike and does the extra solids load they impose on the filter actually help ripen a filter? Can a filter be washed so long or so vigorously that it is "too clean" when returned to service?

From time to time the idea has been expressed that a small amount of "dirt" remaining in the filter after backwash can help a filter ripen when it is started again. Some operators are concerned that if a filter is backwashed until it is "too clean" the ripening period may be longer.

What tests (short of full-scale) could be performed to determine the dosage of coagulant chemical or polymer to add to backwash water to condition the filter bed for the next run and shorten the ripening period? What tests (short of full-scale) can be used to identify the dosage of coagulant chemical or polymer to add to filter influent as the filter box is refilled after backwash?

In the present state of our knowledge of this matter, trial-and-error solutions using pilot plant filters or full-scale filters appear to be the only workable approach to determining the answers needed to these questions.

WHEN TO FINISH A BACKWASH

How clean should a filter be when backwashing is ended? Does a single number exist for spent washwater turbidity that could signal adequacy of backwash? Where do you sample this spent backwash water?

Work done many years ago by practitioners such as John Baylis established that an upflow backwash assisted by auxiliary scour surface wash was more effective than upflow backwash only in controlling mudballs. Inadequate filter washing practiced over the long term can lead to problems with filter media. Recommendations on a numerical value for the turbidity of spent washwater when the filter is sufficiently clean vary from 10 to 15 ntu, but information collected in the study performed to develop this manual indicated a wider variation in actual practice. One Utility said they stopped a backwash at 60 ntu.

MEDIA CONDITION ASSESSMENT

How can filter media be tested to ascertain if it has been worn excessively and thus should be replaced? Would different tests be needed for different minerals, such as sand, garnet, ilmenite, and anthracite coal? How could the durability of these filter materials be evaluated before they are used in filters? How could the durability of granular activated carbon be evaluated in a way that would indicate its resistance to abrasion during backwashing?

Criteria are needed for deciding when media replacement is appropriate for a filter that has "old" media. At present a recommendation would be to assess filtered water quality and other measures of filter performance such as head loss development and unit filter run volumes when considering media replacement.

Is air scour sufficiently more vigorous in its scrubbing action than surface wash so that air scour could abrade and wear filtering materials more quickly than surface wash?

Readers of the AWWA Standard for Filtering Material, B100-96, will find text in the Foreword that indicates that the AWWA Standards Committee on Filtering Material that developed the standard struggled to resolve this question. The same issues were part of the deliberations of this committee during the middle and latter 1980s when G. S. Logsdon was the committee chair. This research need has been recognized for 15 years or more, without being resolved.

NOVEL ALTERNATIVES / SUPPLEMENTS TO FILTER BACKWASHING

What novel techniques might be adapted for cleaning filter media or the filter floor using less water and possibly using no added chemicals? For example, could ultrasonic probes aid in cleaning media or filter nozzles? What is the possibility for using high-pressure washers, and would use of high

pressure washers of the kind commonly used for cleaning surfaces of buildings and other objects be likely to break up filter media, especially anthracite or granular activated carbon?

Some presently-used chemical cleaning methods leave a residual waste that may cause disposal problems. If non-chemical alternatives could be developed perhaps the disposal problems and the safety problems related to use of chemical cleaners might be avoided.

FILTER MEDIA INSPECTION *IN SITU*

Could new physical techniques be developed to replace filter coring, sieve analysis, and dirt retention based on geophysical techniques used to probe underground? Could Seeing Into The Earth (SITE) technology be used to locate and size mudballs?

An investigation is needed related to the potential for application of technologies used to locate underground objects, to determine if filters could be examined by some of the new technologies that have been developed.

GAINING CONFIDENCE IN INSTRUMENTATION

Given the increasing dependence on water quality and filter performance data derived from on-line instrumentation, can QA procedures be developed that are less time-consuming so plant staff would be able to perform them at more frequent intervals? How can operators know when on-line data have become invalid?

It is imperative that on-line data have appropriate accuracy and precision such that treatment plant operating decisions made on the basis of those data are correct. Operators can not and must not make decisions on invalid and incorrect data, as this has serious public health implications or economic implications or both for water utilities. On the other hand, a balance must be struck between adequate QA to ensure valid data and the real-world constraint of operational costs in water treatment. The majority of data obtained at the water treatment plant must be actual operating data, not QA verification and testing data, which give operators no direction or guidance on actual water quality.

FILTER PERFORMANCE INDEX / ONLINE FILTER SELF-ASSESSMENT

Can a comprehensive filter performance index be developed to encompass both public health concerns and the need for water treatment to be operated in a cost-effective manner? What are the tradeoffs, and what weighting factors would be used for a performance index that includes both public health and economic factors?

The concept of a filter performance index has been elusive. A number of persons or water utilities have tried to develop and use such an index. One of the conundrums in this matter is how to weight public health concerns versus water production (economic) concerns. A major obstacle at present is the lack of any on-line test or tests that could within a few minutes signal that the microbiological quality of drinking water is unsafe and it must not be supplied to consumers. One would wonder about the overall value of a filter performance index if public health issues were not somehow integrated. Without considering public health, a main purpose of water filtration, a filtration index would be mainly an economics-driven index.

What techniques can be used to determine effective pretreatment chemistry for source waters with high counts of algal cells?

Chemical pretreatment and filtration for algae removal have been acknowledged to be especially difficult for a long time. Nevertheless research to date has not been sufficient to present the water industry with a variety of treatment options. Clearly dissolved air flotation (DAF) is highly superior for removal of algae and this can be considered in the design of new facilities. Meanwhile, many older conventional water treatment plants with sedimentation basins are not well-equipped at present to cope with algae blooms if they occur.

Can treatment plant staff predict the appropriate time interval for major filter bed inspections, and if so, how?

The survey of water filtration plant O&M practices that was conducted as a task for development of this manual revealed a wide variation in practice for filter bed inspections. At some plants, major filter bed inspections are done annually, while others inspect at intervals of several years. Clearly conditions are different in different plants. What is needed is a way to estimate the appropriate time interval for major inspections at a specific plant. Perhaps some of the techniques described in this manual, such as the acid solubility test (at lime softening plants), Kawamura's floc retention test, or Chipps' normalized clean bed head loss assessments might be suitable predictors for learning when media condition dictated a major inspection. Other measures of filter performance also would need to

be considered, as a major inspection may involve checking on condition of support gravel or underdrains as well as the media.

TEST TO EVALUATE FLOC STRENGTH AT WATER TREATMENT PLANTS

Can a practical technique be developed so the strength of floc leaving a flocculator could be evaluated at a water treatment plant?

There is the need for some sort of test for "floc strength" which could be used to predict the performance of floc in filters. For example, with a weak floc formed with high levels of NOM in soft water, breakthrough can often occur at low head loss. Some sort of floc strength measure could be used to predict this and the optimum amount of filter aid polymer needed to overcome the problem. Optimum adjustment of floc strength could result in filter runs that are not terminated prematurely due to head loss accumulation (floc too strong) or due to turbidity breakthrough (floc too weak). For treatment plant operators to benefit from using such a test, it needs to be a procedure that can be carried out in a reasonable amount of time from the operator's perspective, and without need for highly expensive equipment.

ABBREVIATIONS

ABW	automatic backwash
amp	ampere
AMSWTF	Alfred Merritt Smith Water Treatment Facility
Anon.	Anonymous
ANSI	American National Standards Institute
APHA	American Public Health Association
ASTM	American Society for Testing and Materials
ASU	areal standard unit
Auth.	Authority
avg.	average
ARMCANZ	Agricultural and Resource Management Council of Australia and New Zealand
AWTW	Advanced Water Treatment Works
AWWA	American Water Works Association
AwwaRF	Awwa Research Foundation
Bd.	Board
BSS	British Sieve Size
BW	backwash
C	residual disinfectant concentration
°C	degrees Celsius
CFR	Code of Federal Regulations
cfs	cubic feet per second
cfu	colony-forming units
COCO-DAFF™	counter-current dissolved air flotation-filtration
Comm.	Commission
conv.	conventional
cm	centimeter
cm^3	cubic centimeter
cm/min	centimeters per minute

Cnty.	County
CRWD	Clackamas River Water District
CT	disinfectant residual concentration × time
CWA	Chester Water Authority
DAF	dissolved air flotation
DAFF	dissolved air flotation-filtration
d_b	diameter of bubble
DBP	disinfection byproduct
D/d	ratio of filter column diameter to filter media diameter
D/DBP Rule	Disinfectants and Disinfection Byproducts Rule
DEP	Department of Environmental Protection
Dept.	Department
Dir.	Direct
Dist.	District
DOC	dissolved organic carbon
DOHS	Department of Health Services
DWI	Drinking Water Inspectorate
EBMUD	East Bay Municipal Utility District
ed.	edition
EEC	European Economic Community
e.g.	for example
el.	elevation
EPA	Environmental Protection Agency
ES	effective size
et al.	and others
etc.	and so forth
EU	European Union
^{o}F	degrees Fahrenheit
FBR	Filter Backwash Rule
FCWTF	Fort Collins Water Treatment Facility

FLR	filter loading rate
ft	foot
ft^2	square foot
ft/s	feet per second
FTU	formazin turbidity unit
FTW	filter-to-waste
g	gram
G	velocity gradient
GAC	granular activated carbon
g/cm^3	grams per cubic centimeter
g/m^2	grams per square meter
gpm/sf	gallons per minute per square foot
Gt or GT	product of velocity gradient and mixing time
GTC	product of velocity gradient, mixing time, and floc concentration
h	hour
HGI	Hardgrove's Grindability Index
HMSO	Her Majesty's Stationery Office
hp	horsepower
HPC	heterotrophic plate count
hr	hour
hr/d	hours per day
IAWQ	International Association for Water Quality
ID	inside diameter
i.e.	that is
IESWTR	Interim Enhanced Surface Water Treatment Rule
IMS®	Integral Media Support
in	inch
in/min	inches per minute
ISO	International Organization for Standardization

IWSA	International Water Supply Association
Jour.	Journal
kg	kilogram
kg/m^2	kilograms per square meter
kg/m^3	kilograms per cubic meter
kPa	kilopascals
L	liter
lb	pound
lb_f	pound force
$lb_f s^2/ft$	pound force-second squared per foot
L/d	ratio of filter bed depth L to filter material diameter d (both in mm)
L/min	liters per minute
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
Ltd.	Limited
m	meter
m^2	square meter
m^3	cubic meter
MAV	maximum acceptable value
max.	maximum
MCL	maximum contaminant level
MFL	million fibers per liter
mg/cm^3	milligrams per cubic centimeter
mgd	million gallons per day
mg/L	milligrams per liter
m/hr	meters per hour
m^3/hr	cubic meters per hour
MID	Modesto Irrigation District

min	minute
mL	milliliter
ML/d	million liters per day
mm	millimeter
mM	millimolar
MPA	microscopic particulate analysis
MRDL	maximum residual disinfectant level
m/s	meters per second
N	normal or normality
n.b.	note well
NHMRC	National Health and Medical Research Council
nm	nanometer
No.	number
NOM	natural organic matter
ntu	nephelometric turbidity unit
O&M	operation and maintenance
ORP	oxidation-reduction potential
OSHA	Occupational Safety and Health Administration
p.	page
PAC	powdered activated carbon
PACl	polyaluminum chloride
PCV	Prescribed Concentration or Value
Ph.D.	Doctor of Philosophy
PLC	programmable logic controller
POC	particulate organic carbon
pp.	pages
ppb	parts per billion
prechlor	prechlorination
psi	pounds per square inch

PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
RGF	rapid gravity filter
r.m.s.	root mean square
rpm	revolutions per minute
San.	Sanitary
SCADA	supervisory control and data acquisition
scfm/sf	standard cubic feet per minute per square foot
sec.	seconds
Sed.	Sedimentation
SI	International System of Units
SOR	surface overflow rate
SS	stainless steel
Suburb.	Suburban
SUVA	specific ultraviolet absorbance
Syst.	System
T	disinfectant contact time in minutes
TDS	total dissolved solids
TOC	total organic carbon
trav.	traveling
turb.	turbidity
TUD	Tuolumne Utilities District
TWU	Thames Water Utilities
Typ.	typical
uc	uniformity coefficient
UFRV	unit filter run volume

U.K.	United Kingdom
UKWIR	U.K. Water Industry Research, Limited
U.S.A.	United States of America
USEPA	United States Environmental Protection Agency
UV	ultraviolet
UV_{254}	ultraviolet light having a wave length of 254 nanometers
V_b	velocity of bubble
V_{mf}	velocity of minimum fluidization
w/	with
WAN	wide area network
WEF	Water Environment Federation
WHO	World Health Organization
W.S.	water surface
WSSC	Washington Suburban Sanitary Commission
wt.	weight
WTP	Water Treatment Plant
WTW	Water Treatment Works
w/w	weight per weight
ZP	zeta potential
µg/L	micrograms per liter

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. Definitions from *The Drinking Water Dictionary* were provided by the American Water Works Association.

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 ANSI-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) An increase in the pressure of air trapped in soil interstices, which decreases the rate of water infiltration into the soil.

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) (*see also* air backwash) The practice of admitting air through the underdrain system to ensure complete cleaning of media during filter 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 pre-set limit. Alarms may be used in conjunction with on-line 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 litre (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-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.

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.

AOC See Assimilable organic carbon

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 towards the top of the filter bed as it flows down in the filter box. 1 gpm/sf = 8.02 cubic feet per square foot per hour (8.02 ft/hr) or 2.44 m/hr.

assimilable organic carbon The fraction of organic carbon that can be used by specific microorganisms and converted to cell weight. AOC also represents a potential for biological

regrowth in distribution systems. Ozone (O_3) can convert organic matter in water to assimilable organic carbon, whereas biological filtration can reduce the AOC level.

automatic backwash filter (1) A filter that backwashes automatically upon reaching maximum head loss, using filtered water being produced by other filters as the source of backwash water. Often these are fabricated in clusters of four filters with three filters providing wash water for the one filter being washed. (2) A long, rectangular filter box subdivided into numerous filter cells that extend across the width of the box. When a traveling bridge is activated it washes each filter cell in turn, progressing from one end of the long rectangular filter box to the other.

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.

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 types of microporous membranes for cleaning purposes to remove particles.

backwash recycle The practice of reusing spent or dirty backwash water by returning this water to the treatment plant. Generally backwash recycle is returned to the influent raw water. Future US EPA rules are likely to require that backwash recycle be returned to a point in the treatment plant that is upstream of the point where the primary coagulant is added. *See* recycle.

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.

balancing tank (balancing reservoir) A holding basin in which variations in flow and composition of a liquid are averaged. Such a basin is used to provide a flow of reasonably uniform volume and composition to a treatment plant. It is also called an equalizing basin.

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 4 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.

BDOC See Biodegradable organic carbon

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.

biodegradable organic carbon That portion of the organic carbon in water that can be mineralized by heterotrophic microorganisms. Ozone (O_3) can convert organic matter in water to biodegradable organic carbon, whereas biological filtration can reduce the biodegradable organic carbon level.

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.

boil A rise in the water surface caused by the turbulent upward movement of water.

box-and-whisker plot A graphic presentation of the statistical analysis of a data set in which the bottom and top of the box equal the twenty-fifth and seventy-fifth percentile values, respectively; an additional line within the box corresponds to the median level; lines perpendicular to and above or below the box indicate the maximum or minimum values excluding statistical outliers; and

outliers are shown as separate points. Other variations are possible on this representation in which (1) a dotted line within the box corresponds to the mean level or (2) the sides of the box can be notched to indicate the 95 percent confidence interval for the median.

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.

bulk density The mass per standard volume (usually kilograms per cubic metre or pounds per cubic foot) of material as it would be shipped from the supplier to the treatment plant.

calcium carbonate precipitation potential The amount of solid calcium carbonate ($CaCO_3$) that will precipitate or dissolve as water equilibrates.

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 litre. *See also* calcium carbonate equivalent

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.

CCPP *See* Calcium carbonate precipitation potential.

chain-and-flight sludge collector A device for removing sludge from a rectangular basin by a scraping mechanism. Collected sludge is scraped into a hopper, from which it typically is discharged to solids processing by means of a screw conveyer. The scrapers, or flights, are attached to chains that are driven along the length of the basin by rotating cogs located at the ends of the basin. The chains move longitudinally along the basin bottom and across the top of the basin in a circular fashion.

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 plants clarification often is accomplished by using gravity sedimentation. Other clarification processes used include dissolved air flotation and roughing 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 on-site 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.

collapse pulsing backwash A method of cleaning a filter by introducing air and subcritical fluidization backwash water, causing the formation and collapse of air pockets within the bed, a

condition called collapse pulsing. This condition enhances the abrasion between the media grains for removing retained particles.

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 ($CoCl_2 \cdot 6\ H_20$). Adding the following amounts in 1,000 millilitres of distilled water produces a solution with a color of 500 color units: 1.246 grams potassium chloroplatinate, 1.00 grams cobaltous chloride, and 100 milliliters 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.

combined air and water wash A filter backwashing technique that employs a gentle, non-fluidizing 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 inches 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.

conchoidal fracture Refers to a mineral fracture that shows no cleavage. Cleavage is the tendency of a substance to break along defined planes. In a conchoidal fracture the mineral does not break along defined cleavage planes, rather it results in irregular breaking, producing concave shaped edges where fracture has occurred. Regular straight-edged geometric shapes are not produced.

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.

cusum chart A statistical process control technique used to produce a chart that allows systematic trends to be determined from data where simple presentation of raw data may hide an underlying pattern. In the case of filtration the daily mean filtered water turbidity is calculated for each filter. The difference between this value and a target value is plotted against date. The target value may be a fixed turbidity target (e.g. 0.1 ntu) or the mean of all the daily values, or the mean turbidity achieved in the previous month. The cusum chart should show if the filters behave in a similar way of if one or more consistently produces higher or lower turbidity water. A change in gradient of the cusum line may indicate a significant operating change. Cusums may be reset monthly with the mean turbidity from the previous month from either the individual filter or the bulk filtrate set as the new target value.

DAF *see* Dissolved air flotation

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 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.

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*, # 9216. It is a technique that can be used to evaluate the passage of bacteria through filters. The technique detects both viable and non-viable 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-litre or nanogram-per-litre 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. Upon release, the lower pressure in the unit results in the formation of bubbles that collect particles as they rise to the sur-

face. The floated particles are then skimmed for subsequent processing. This process is effective in removing low-density solids and algae.

dissolved oxygen The concentration of oxygen in aqueous solution, which is often expressed in units of milligrams per litre. It is usually determined by one of two methods: a dissolved oxygen probe or Winkler titration.

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 millimetres.

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 asμm/s per volt/cm. This term is often used in colloid analysis and coagulation. Electrophoretic mobility is related to the electrokinetic potential on a particle.

endoscope Originally an instrument used to conduct visual examinations of hollow organs inside the human body, endoscopes have been adapted for use to examine inside machinery, and have been used to observe the interior of granular media filter beds.

equalization basin (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

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 In this manual, the term 'filter aid' is used in reference to polymers that are added to pretreated water to improve its filtering properties. Such filter aids typically are high molecular weight polymers.

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 to 17% as Al_2O_3.

filter boil *See* boil.

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 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 filer media is fluidized by backwashing water through the filter. *See also* backwash.

formazin turbidity unit (ftu) A turbidity unit appropriate when a chemical suspension of formazin is used as a standard to calibrate a turbidimeter. If a nephelometric turbidimeters is used,

nephelometric turbidity units and formazin turbidity units are equivalent. *See also* nephelometric turbidity unit.

G *See* mean velocity gradient.

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.

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.

greensand (1) A naturally occurring mineral that consists largely of dark greenish grains of glauconite and possesses ion exchange properties. Greensand was the original product used in commercial and home cation exchange water-softening units and was the base product for manufacturing manganese greensand zeolite products. (2) A filter that adsorbs soluble iron and manganese through the use of a sand medium coated with manganese dioxide (MnO_2). When chlorine (Cl_2) or potassium permanganate ($KMnO_4$) is added to the influent, the adsorbed iron and manganese are oxidized, thus "regenerating" the greensand filter.

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.

GtC A dimensionless group where C is the volumetric concentration (volume of the particles per unit volume of the suspension being flocculated). This is a more complete criterion of the flocculation process as it allows for the enhancement of flocculation by the presence of particles colliding with other particles.

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.

head loss probe A portable electronic instrument that can be used to measure the head loss within a filter bed during filtration or during backwashing.

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.

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.

hydraulic size The hypothetical diameter of uniform spherical grains of filter media that would result in the same loss of head as the variable size mixture of media at the same flow rate usually employed in rapid rate filtration (assuming the material has the same voidage or porosity). The hydraulic size is calculated from a sieve analysis and provides the media size parameter used in the Kozeny-Carman equation to calculate head loss for a given depth of this media at the flow rates and water viscosities to be encountered.

hydrolysis A chemical reaction in which water molecules react with a substance to form two or more substances.

hydropneumatic wand A device developed by staff at the Fort Collins Water Treatment Facility to break up mudballs in a filter bed. This device was a long pipe, with a Tee-shaped end having

nozzles that delivered air and water into the filter bed. It could be placed and used at specific locations within the bed where backwashing and auxiliary scour were considered to be weak or not sufficiently effective.

ilmenite A high-density filtering material having a specific gravity of 4.68-4.76, 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 inches (5 centimetres) 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*). Cocurrent 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 inches (5 centimetres) 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.

in-filter DAF Proprietary dissolved air flotation processes in which the DAF clarifier is integrated into the filter bed, with clarification occurring as the floc is floated to the top of the clarifier, and the water is filtered through the medium in the bottom of the clarifier. This approach is sometimes used where saving space is important.

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.

interstitial velocity The mean velocity of water within the pore, or interstices, of a granular media filter bed.

Jackson candle turbidimeter A device formerly used to determine turbidity in water. This type of turbidimeter consisted of a standard candle, a calibrated glass tube, and a supporting frame. It was used for many years, but it was not capable of reporting a turbidity less than 25 Jackson turbidity units. The device was included in the 16th edition of *Standard Methods for the Examination of Water and Wastewater* but was eliminated from the 17th edition in 1989. Jackson candle methods were replaced with nephlometric methods of measuring turbidity. *See also* nephelometric turbidimeter.

Jackson turbidity unit (JTU) An obsolete term for expressing turbidity. *See also* nephelometric turbidity unit.

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.

Langelier Saturation Index The most famous of the calcium carbonate ($CaCO_3$) saturation indexes, the formula for the Langelier saturation index is based on a comparison of the measured pH of a water (pH_a) with the pH the water would have (pH_s) if at saturation with $CaCO_3$ (calcite form) given the same calcium hardness and alkalinity for both pH cases. Many of the other indexes found in the water treatment and corrosion literature are merely approximations. Several versions of the LSI exist in the literature. The version presented here is the one developed by J.R. Rossum and D.T. Merrill for the quadratic equation form of the pH_s equation solution; This material has been updated using newer equilibrium constant and activity coefficient data. (Note that a simplified approximation equation originally formulated by T.E. Larson and A.M. Buswell was presented in the National Interim Primary Drinking Water Regulations amendments.) The basic formula for the Langelier saturation index is:

$$LSI = pH_a - pH_s$$

It is interpreted in the following way: If LSI > 0, water is potentially scale forming (supersaturated with respect to CaCO3). If LSI = 0, water is in equilibrium with $CaCO_3$, not tending to dissolve or

precipitate it. If LSI < 0, water will potentially dissolve existing $CaCO_3$ deposits (undersaturated with respect to $CaCO_3$). For information on how to calculate the LSI, refer to *Water Quality & Treatment, 5th Ed.*

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 washwater 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.

launder wings Structures added to the sides of the backwash trough to divert air bubbles away from the edge of the backwash trough. This provides an air-free region for any sand that is disturbed by the air bubbles left in the bed after air scour to settle back into the filter during backwashing. Wings are also used to allow simultaneous combined air scour and water washing to take place with water passing over the washout trough, but avoiding sand being carried over.

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 to 8.5% as Al_2O_3, or about half the strength of dry alum. *See* 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.

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.

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 micrometre. 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.

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 feet (1.8 metres), and use large-diameter media (from 1.2 to more than 1.8 millimetres 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.

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 inches (2.5 to 5 centimetres) 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.

mudleg A deliberately-constructed low spot in instrument piping for collection of debris and sediment.

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 gallons per minute per square foot (5 metres per hour).

natural organic matter 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 1:4000 dilution of a stock solution of 5.0 millilitres of a 1.000-gram hydrazine sulfate ($(NH_2)_2 \cdot H_2SO_4$) in 100 millilitres of distilled water solution plus 5.0 millilitres of a 10.00-gram hexamethylenetetramine ($(CH_2)_6N_4$) in 100 millilitres of distilled water solution that has stood for 24 hours at 25 $\pm$ 3° Celsius.

nonionic polymer A polymer that has no net electrical charge.

normalized headloss 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.

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.

oxidation-reduction potential The potential required to transfer electrons from the oxidant to the reductant, used as a qualitative measure of the state of oxidation in treatment systems. It is a dimensionless value. The more positive the value, the more oxidizing the solution; more negative values represent more reducing conditions. Aerobic waters in equilibrium with the atmosphere have a pE value of approximately +13. Anaerobic waters may have a pE of –4. Because electron activity varies with the pH of water, referring to graphs of pE as a function of pH is often useful. In this manner, the range of thermodynamically stable species can be illustrated.

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.

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 American Water Works Association 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.

patch test A quick test in which a 1-liter sample of filtered water from the treatment plant is filtered through a membrane filter having 0.45 μm pores, and allowed to air dry after which the color is observed. Dried membranes are saved to document past performance. This is used by the Chester Water Authority as a means of comparing filter performance from day to day.

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 on-line filtered water turbidity results or on-line 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.

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 litre). For example, if the

concentration of hydrogen ions is 10^{-7} moles per litre, 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.

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 Manual 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.

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.

presedimentation A preliminary treatment process used to remove gravel, sand, and other gritty material from the source water before the water enters the main treatment plant. This treatment is usually performed without the use of coagulating chemicals.

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.

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 metres 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.

proprietary floor A filter floor of proprietary or patented design

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. *See* backwash recycle.

restratification The act of returning a multi-media 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 metres 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 inches (15 centimetres) 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 upon entry to the DAF clarifier, a fine cloud of air bubbles forms.

SCADA *See* Supervisory control and data acquisition.

Secchi disk A circular metal plate, 8--12 inches (20 – 30 centimeters) in diameter, that is painted 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.

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 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).

solids contact basin 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 feet (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 nanometres (measured in units of per metre) divided by the dissolved organic carbon concentration (in milligrams per litre). Typically, a specific ultraviolet absorbance less than 3 litres per metre-milligram corresponds to largely nonhumic material, whereas a specific ultraviolet absorbance in the range of 4–5 litres per metre-milligram 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 washwater 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.

Stokes' Law A formula for calculating the rate of fall of particles through a liquid medium. In the laminar flow region, the rate at which a spherical particle will fall when suspended in a liquid medium varies directly with the square of the particle's diameter, the density of the particle, and inversely with the viscosity of the fluid. In equation form,

$$V_s = g(\rho_s - \rho)\, d^2 / 18\mu$$

Where (in any consistent set of units):

V_s = the settling velocity

g = the gravity constant

ρ_s = the density of the particle

ρ = the density of the fluid (water)

d = the diameter of the particle

μ = the absolute viscosity

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 on-line 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.

sub-fluidizing velocity A backwash rise rate insufficient to fluidize granular filter media.

supervisory control and data acquisition A computer-monitored alarm, response, control, and data acquisition system used by drinking water facilities to monitor their operations.

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.

total alkalinity *see* alkalinity.

trigger values Water quality parameter values set in conjunction with alarms, so that plant operators are automatically alerted if a value is reached. Commonly used with on-line turbidimeters and automated data collection systems. *See* alarms.

triple-media filter A filter containing three media—typically anthracite coal, supported by sand, supported by garnet—that stratify after backwashing according to their respective specific gravities. Triple-media filtration *may* have improved filtration properties over dual-media filters in some applications. A triple-media filter is sometimes called a mixed-media filter.

tube settler A unit constructed of parallel tubes that are typically arranged in a honeycomb fashion and are approximately 2 inches (5 centimetres) in width oriented at a 45° to 60° angle from horizontal. Tube settlers are used to improve settling in a sedimentation basin. The units are placed at the end of the 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, resulting in a low overflow rate, and they are often used to maintain particle removal at higher flow rates, thereby reducing the need to construct additional basins.

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* Jackson turbidity unit, formazin turbidity unit, and nephelometric turbidity unit.

uc *see* uniformity coefficient

UFRV *see* Unit filter run volume.

ultraviolet (UV) absorbance at 254 nanometers (UV-254 or UV_{254}) A measure of water's ultraviolet absorption at a wavelength of 254 nanometres. 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 A measure of how well a sediment is graded. The coefficient may be calculated as follows:

$$uc = d_{60}/d_{10}$$

Where:

d_{60} = the grain size, in millimetres, 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 millimetres, 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 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.

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 metre squared or pascal seconds)

τ = shear stress, in pound force per foot squared (newtons per metre 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 ft/second or square cm/second

ρ = density in slugs/ft^3 or kg/m^3

Water at 68° Fahrenheit (20° Celsius) 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.

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 90^{th} percentile values, typically the value exceeded by 10% of the data, that is, the value for which 90% of the data are equal to or less than.