

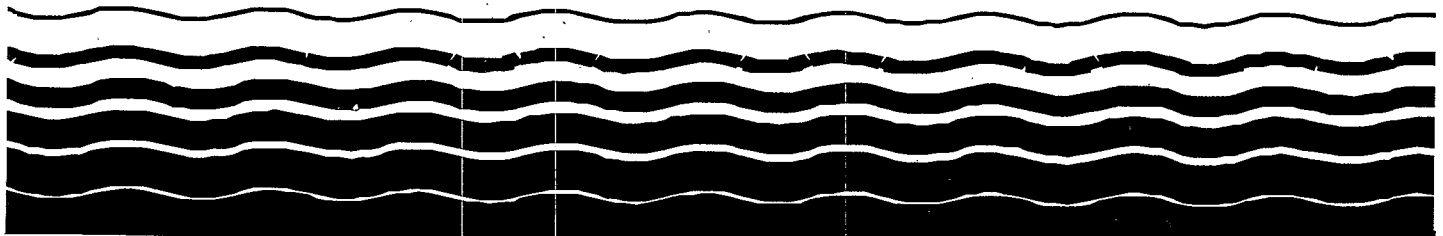
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Guidance Manual for Compliance with the Interim Enhanced Surface Water Treatment Rule: Turbidity Provisions



DISCLAIMER

This manual provides public water systems and drinking water primacy agencies with guidance for complying with the turbidity provisions found within the Interim Enhanced Surface Water Treatment Rule (IESWTR).

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ACRONYMS

| | |
|--------|--|
| AIDs | Acquired Immune Deficiency Syndrome |
| ASCE | American Society of Civil Engineers |
| AWWA | American Water Works Association |
| AWWARF | American Water Works Association Research Foundation |
| CB | Calibration Blank |
| CCP | Composite Correction Program |
| CDC | Centers for Disease Control |
| CDHS | California Department of Health Services |
| CFR | Code of Federal Regulations |
| CPE | Comprehensive Performance Evaluation |
| CSO | Combined Sewer Overflow |
| CTA | Comprehensive Technical Assistance |
| CWSS | Community Water System Survey |
| DCS | Distributed Control Systems |
| DBP | Disinfection Byproduct |
| DE | Diatomaceous Earth |
| EPA | Environmental Protection Agency |
| FR | Federal Register |
| FTU | Formazin Turbidity Units |
| GLI | Great Lakes Instrument |
| GWUDI | Ground Water Under the Direct Influence |
| HIV | Human Immunodeficiency Virus |
| IESWTR | Interim Enhanced Surface Water Treatment Rule |
| IPC | Instrument Performance Check Solution |
| ISO | International Organization for Standardization |
| JTU | Jackson Turbidity Units |
| LAN | Local Area Network |
| LCR | Linear Calibration Range |
| LRB | Laboratory Reagent Blank |
| LED | Light Emitting Diode |
| MCL | Maximum Contaminant Level |
| MSDS | Material Safety Data Sheet |
| NAS | National Academy of Sciences |
| NCEPI | National Center for Environmental Publications and Information |
| NOM | Natural Organic Matter |
| NPDES | National Pollution Discharge Elimination System |
| NPDWR | National Primary Drinking Water Regulation |
| NSF | National Science Foundation |
| NTU | Nephelometric Turbidity Units |
| PAC | Powdered Activated Carbon |
| PC | Personal Computer |
| PCAL | Primary Calibration Standard |
| PCBs | Polychlorinated Biphenyls |
| PWS | Public Water System |
| QA | Quality Assurance |
| QC | Quality Control |
| QCS | Quality Control Sample |
| RIA | Regulatory Impact Analysis |
| SCADA | Supervisory Control and Data Acquisition |
| SCAL | Secondary Calibration Standards |
| SDWA | Safe Drinking Water Act |
| SOP | Standard Operating Procedure |
| SS | Secondary Calibration Standard |
| SSS | Stock Standard Suspension |

CONTENTS

| | |
|------|------------------------------|
| SWTR | Surface Water Treatment Rule |
| TOC | Total Organic Carbon |
| THM | Trihalomethane |

1. INTRODUCTION

1.1 Purpose of Document

The Interim Enhanced Surface Water Treatment Rule (IESWTR) establishes a number of provisions related to the performance of filters in drinking water treatment. These provisions include treatment technique requirements restricting turbidity levels in the combined filter effluent, as well as monitoring requirements for individual filters at conventional and direct filtration plants. These requirements are designed to decrease the risk from waterborne microbial pathogens by limiting levels of particulate material in finished water.

The objective of the guidance manual is to provide public water systems (PWSs) with guidance for complying with the turbidity provisions found within the IESWTR. The primary audience of the guidance manual is utility personnel at public water systems which utilize filtration and the staff of state drinking water programs that work with PWSs to protect water quality.

The document is divided into two sections. The first section contains technical information regarding specific requirements of the IESWTR relating to turbidity and is intended for experienced operators and others in the regulated community. The second section of the document provides background on concepts surrounding turbidity and serves as a primer for less experienced operators and individuals.

1.2 Summary of Chapters

As noted, the document is broken up into two sections. The first section of the manual outlines the specific requirements of the rule and includes detailed information specific to the rule. Section 1 consists of Chapters 2 through 6:

Chapter 2 - Turbidity Requirements: IESWTR

Chapter 2 outlines the regulatory requirements, reporting and recordkeeping requirements, and additional compliance aspects of the IESWTR related to turbidity. Flow charts are provided which graphically demonstrate the requirements.

Chapter 3 - Turbidity Methods & Measurement

Chapter 3 provides information regarding approved turbidity methods, analytical issues associated with turbidimeters and turbidity measurement, quality assurance and quality control issues, and data collection and management issues.

Chapter 4 – Approach for Compliance

Chapter 4 provides information on EPA's suggested approach for compliance with turbidity requirements of the IESWTR. Plant optimization is the focus of this chapter, and areas are highlighted which, in the experience of the Agency and other water professionals, most often can be improved to optimize water treatment at systems. Two programs, the Composite Correction Program and the Partnership for Safe Drinking Water, are briefly discussed as systems are encouraged to utilize these programs to optimize plant performance.

Chapter 5 – Individual Filter Self Assessment

Chapter 5 provides detailed guidance on conducting a filter self assessment. Necessary components are discussed including conducting filter profiles, assessing hydraulic loading conditions, and assessing support media and underdrains. Systems may be required to conduct an individual filter self assessment based on individual filter monitoring results.

Chapter 6 – Comprehensive Performance Evaluation

Chapter 6 provides a general overview of the Composite Correction Program (CCP) and specifically the first component of the CCP, the Comprehensive Performance Evaluation (CPE). Fundamental concepts are discussed including major CPE components, standard CPE activities and CPE quality control measures. Systems may be required to arrange for a CPE based on individual filter monitoring results.

The second section of the manual provides background in order to provide readers with an understanding of basic concepts that underlie turbidity and the provisions found in the IESWTR.

Chapter 7 – Importance of Turbidity

Chapter 7 provides an introduction into the importance of turbidity and includes background on turbidity as a water quality parameter. It discusses the significance of turbidity to human health, provides a brief discussion of waterborne disease outbreaks, and the relationship between turbidity removal and pathogen removal.

Chapter 8 – Particles Contributing to Turbidity

Chapter 8 provides an overview of the characteristics of particles which contribute to turbidity. The section provides brief discussions of organic, inorganic, and biotic particles, particles created during the treatment process, and a brief introduction into the electrokinetic properties of particles.

Chapter 9 – Turbidity in Source Water

Chapter 9 describes the various factors that effect turbidity in rivers, lakes and reservoirs, and groundwater under the direct influence (GWUDI). The chapter also includes information on other watershed considerations that effect turbidity.

Chapter 10 – Turbidity Through the Treatment Process

Chapter 10 provides a general description of the typical treatment processes intended to remove suspended solids and reduce turbidity as well as information on the level of turbidity reduction that is commonly achieved through each.

Chapter 11 – Basic Turbidimeter Design and Concepts

Chapter 11 provides readers with basic information on turbidimeter designs, measuring principals, design configurations, and various types of turbidimeters.

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2. TURBIDITY REQUIREMENTS: IESWTR

2.1 Introduction

Under the 1996 Safe Drinking Water Act (SDWA) Amendments, EPA must supplement the existing 1989 Surface Water Treatment Rule (SWTR) with the Interim Enhanced Surface Water Treatment Rule (IESWTR) to improve protection against waterborne pathogens. Key provisions established in the IESWTR include (USEPA, 1998):

- A maximum contaminant level goal (MCLG) of zero for *Cryptosporidium*; 2-log (99 percent) *Cryptosporidium* removal requirements for systems that filter;
- Strengthened combined filter effluent turbidity performance standards;
- Individual filter turbidity monitoring provisions;
- Disinfection benchmark provisions to assure continued levels of microbial protection while facilities take the necessary steps to comply with new disinfection byproduct standards;
- Inclusion of *Cryptosporidium* in the definition of ground water under the direct influence of surface water (GWUDI) and in the watershed control requirements for unfiltered public water systems;
- Requirements for covers on new finished water reservoirs; and
- Sanitary surveys for all surface water systems regardless of size.

Figure 2-1 presents the general IESWTR requirements.

The following chapter outlines the regulatory requirements, reporting and recordkeeping requirements, and additional compliance aspects of the IESWTR related to turbidity.

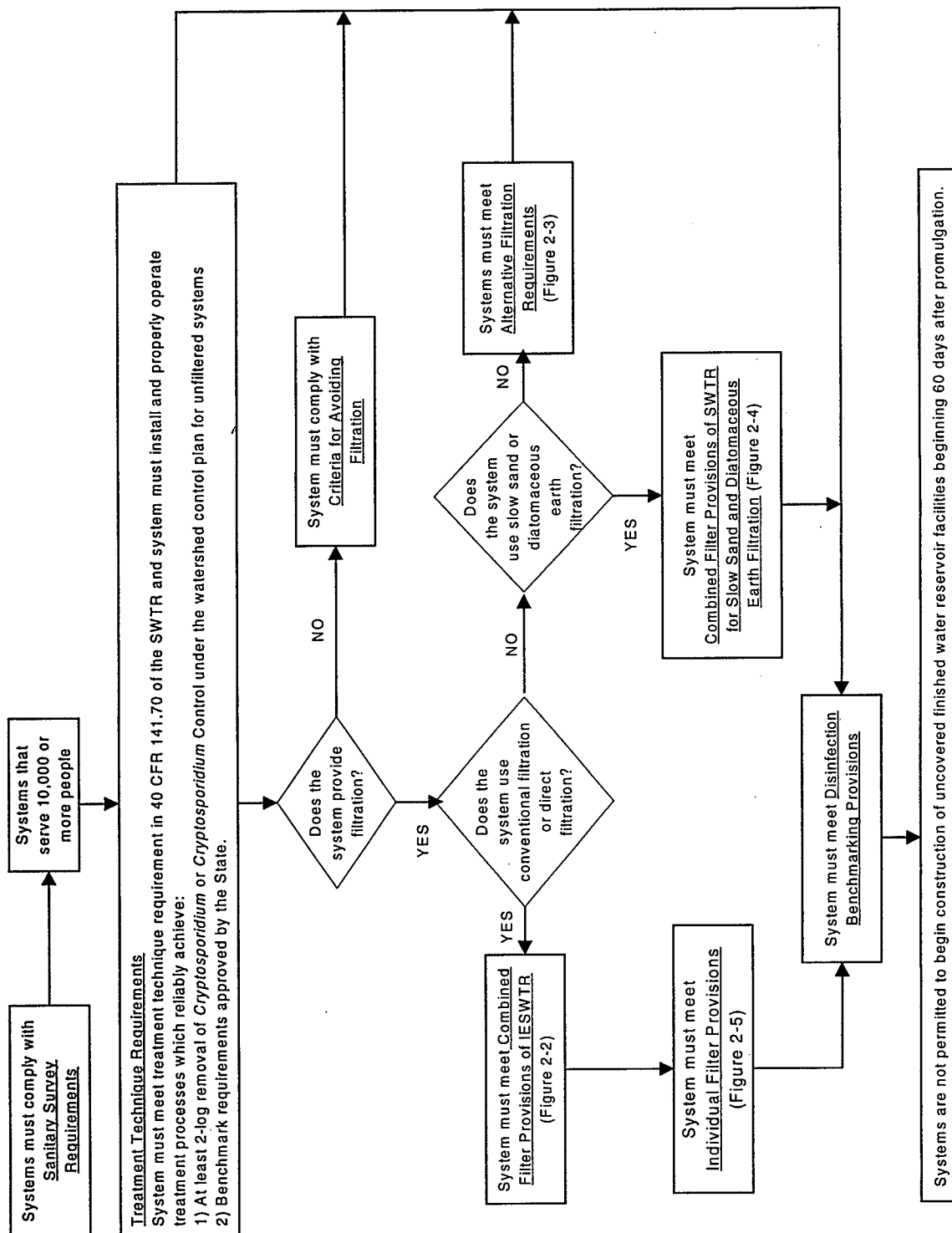


Figure 2-1. Flowchart of IESWTR General Requirements

2.2 Regulatory Requirements

As described above, the Interim Enhanced Surface Water Treatment Rule contains several key provisions including strengthened combined filter effluent turbidity performance standards and individual filter turbidity monitoring.

2.2.1 Applicability

Entities potentially regulated by the IESWTR are public water systems that use surface water or ground water under the direct influence of surface water and serve at least 10,000 people (including Industries, State, Local, Tribal, or Federal governments). To determine whether your facility may be regulated by this action, you should carefully examine the applicability criteria in subpart H (systems subject to the Surface Water Treatment Rule) and, subpart P (subpart H systems that serve 10,000 or more people) of the final rule.

Systems subject to the turbidity provisions of the IESWTR are a subset of systems subject to the IESWTR, which utilize rapid granular filtration (i.e., conventional filtration treatment and direct filtration) or other filtration processes (excluding slow sand and diatomaceous earth filtration).

2.2.2 Combined Filter Effluent Monitoring

Under the SWTR, a subpart H system which provides filtration treatment must monitor turbidity in the combined filter effluent. Turbidity measurements must be performed on representative samples of the system's filtered water every four hours (or more frequently) that the system serves water to the public. A public water system may substitute continuous turbidity monitoring for grab sample monitoring if it validates the continuous measurement for accuracy on a regular basis using a protocol approved by the State.

The turbidity performance requirements of the IESWTR require that all surface water systems which use conventional treatment or direct filtration and serve a population $\geq 10,000$ people must meet two distinct combined filter effluent limits: a maximum limit and a 95% limit. These limits, set forth in the IESWTR, are outlined below for the different types of treatment employed by systems.

Conventional Treatment or Direct Filtration

For conventional and direct filtration systems (including those systems utilizing in-line filtration), the turbidity level of representative samples of a system's filtered water (measured every four hours) must be less than or equal to **0.3 NTU** in at least 95 percent of the measurements taken each month. The turbidity level of representative samples of a system's filtered water must not exceed **1 NTU** at any time.

Conventional filtration is defined as a series of processes including coagulation, flocculation, sedimentation, and filtration resulting in substantial particulate removal.

Direct filtration is defined as a series of processes including coagulation and filtration but excluding sedimentation resulting in substantial particle removal. Figure 2-2 presents a flowchart of the combined filter provisions for conventional and direct filtration systems.

Other Treatment Technologies (Alternative Filtration)

For other filtration technologies (those technologies other than conventional, direct, slow sand or diatomaceous earth filtration), a system may demonstrate to the State, using pilot plant studies or other means, that the alternative filtration technology, in combination with disinfection treatment, consistently achieves 99.9 percent removal and/or inactivation of *Giardia lamblia* cysts and 99.99 percent removal and/or inactivation of viruses, and 99 percent removal of *Cryptosporidium* oocysts. For a system that makes this demonstration, then representative samples of a system's filtered water must be less than or equal to *a value determined by the State which the State determines is indicative of 2-log Cryptosporidium removal, 3-log Giardia removal, and 4-log virus removal* in at least 95 percent of the measurements taken each month and the turbidity level of representative samples of a system's filtered water must at no time exceed *a maximum turbidity value determined by the State*. Figure 2-3 presents a flow chart of combined filter provisions for alternative filtration technologies. Examples of such technologies include bag or cartridge filtration, microfiltration, and reverse osmosis. EPA recommends a protocol similar to the "Protocol For Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants," prepared by NSF International with support from EPA. Information regarding this protocol may be found at NSF's website at: <http://www.nsf.org/verification/verification.html>.

Slow Sand & Diatomaceous Earth Filtration

The IESWTR does not contain new turbidity provisions for slow sand or diatomaceous earth (DE) filtration systems. Utilities utilizing either of these filtration processes must continue to meet the requirements for their respective treatment as set forth in the SWTR (1 NTU 95%, 5 NTU max). Figure 2-4 presents a flowchart of combined filter provisions for slow sand and diatomaceous earth filtration.

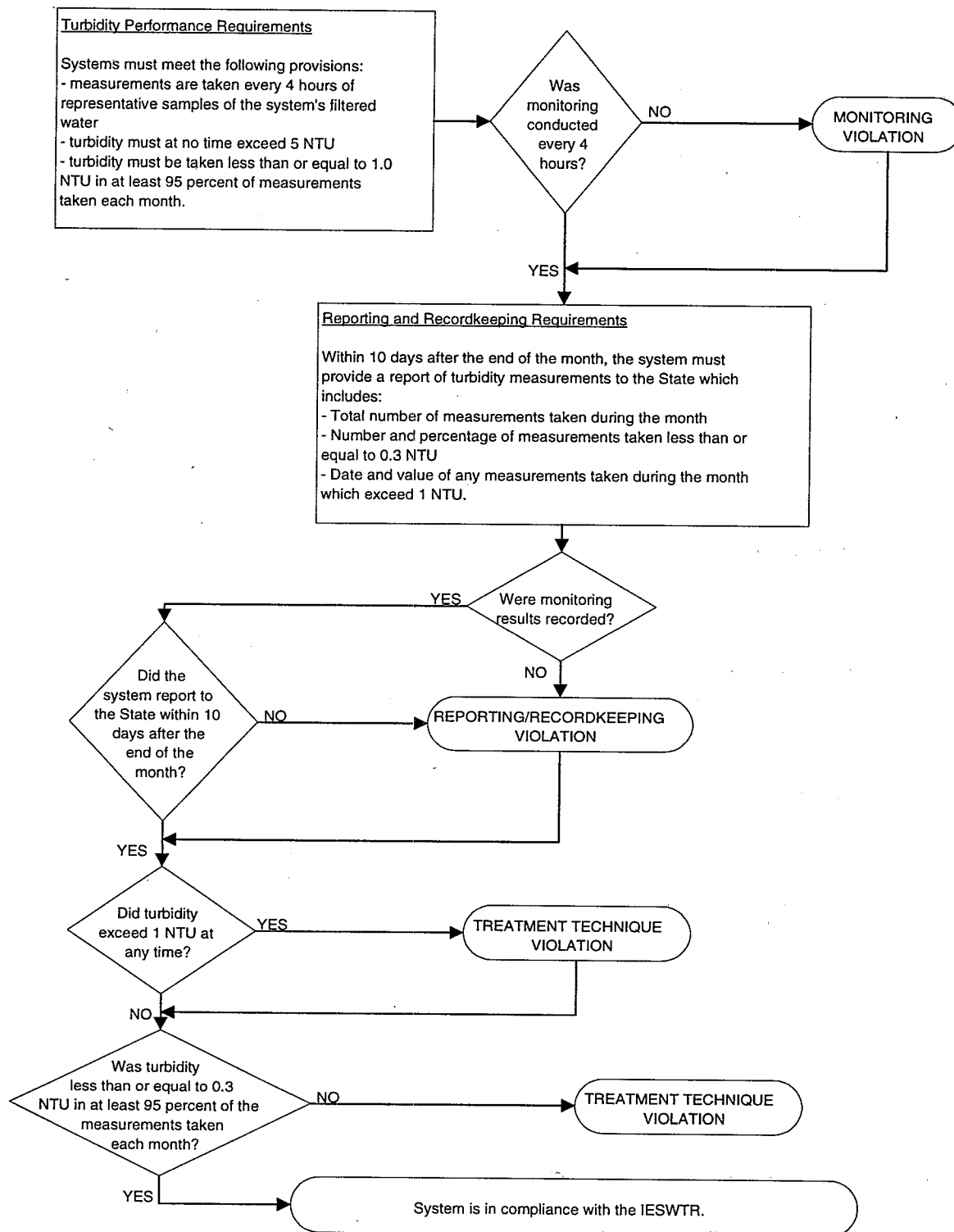


Figure 2-2. Flowchart of IESWTR Combined Filter Provisions for Conventional and Direct Filtration Systems

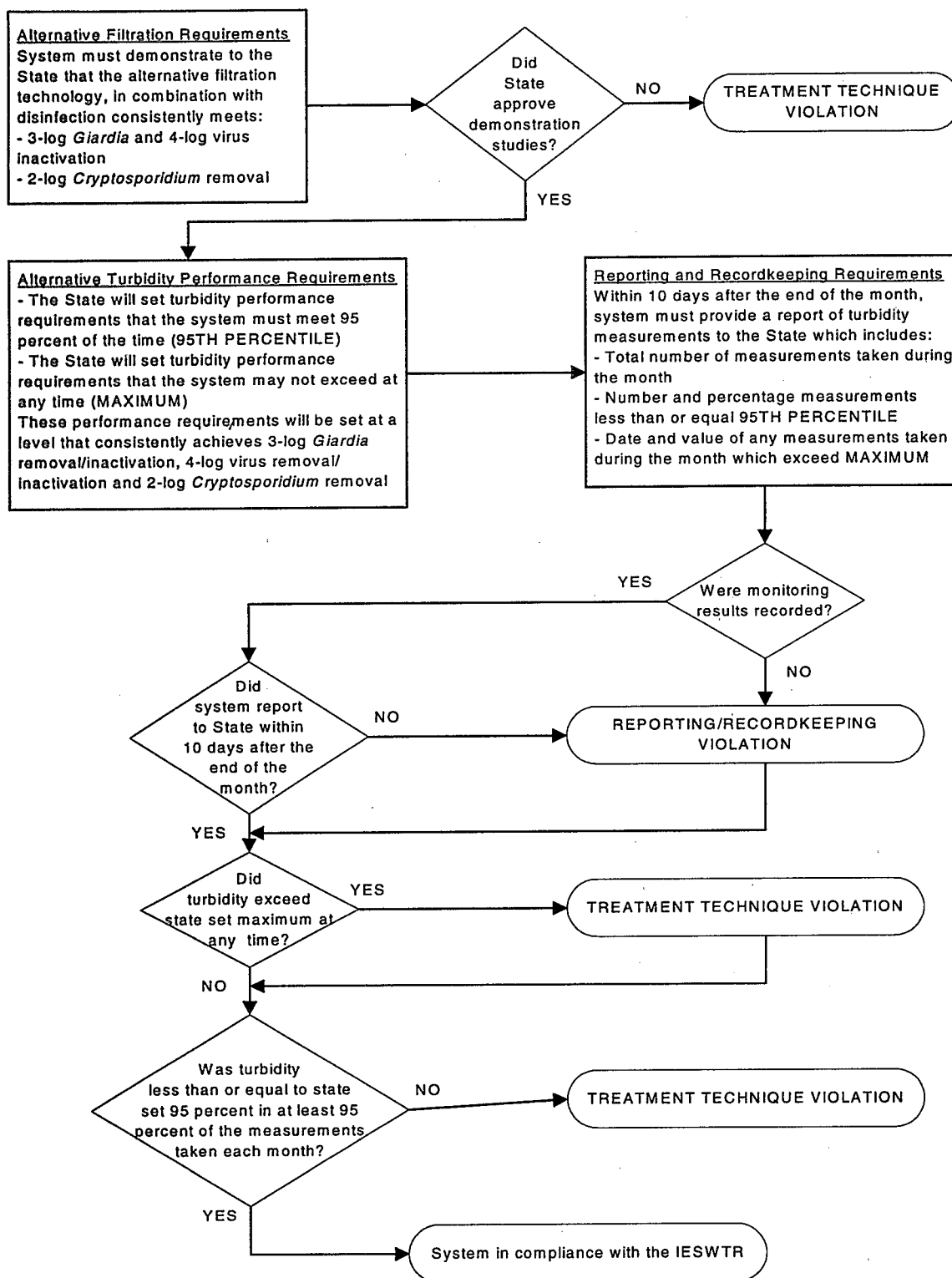


Figure 2-3. Flowchart of IESWTR Combined Filter Provisions for Alternative Filtration Technologies

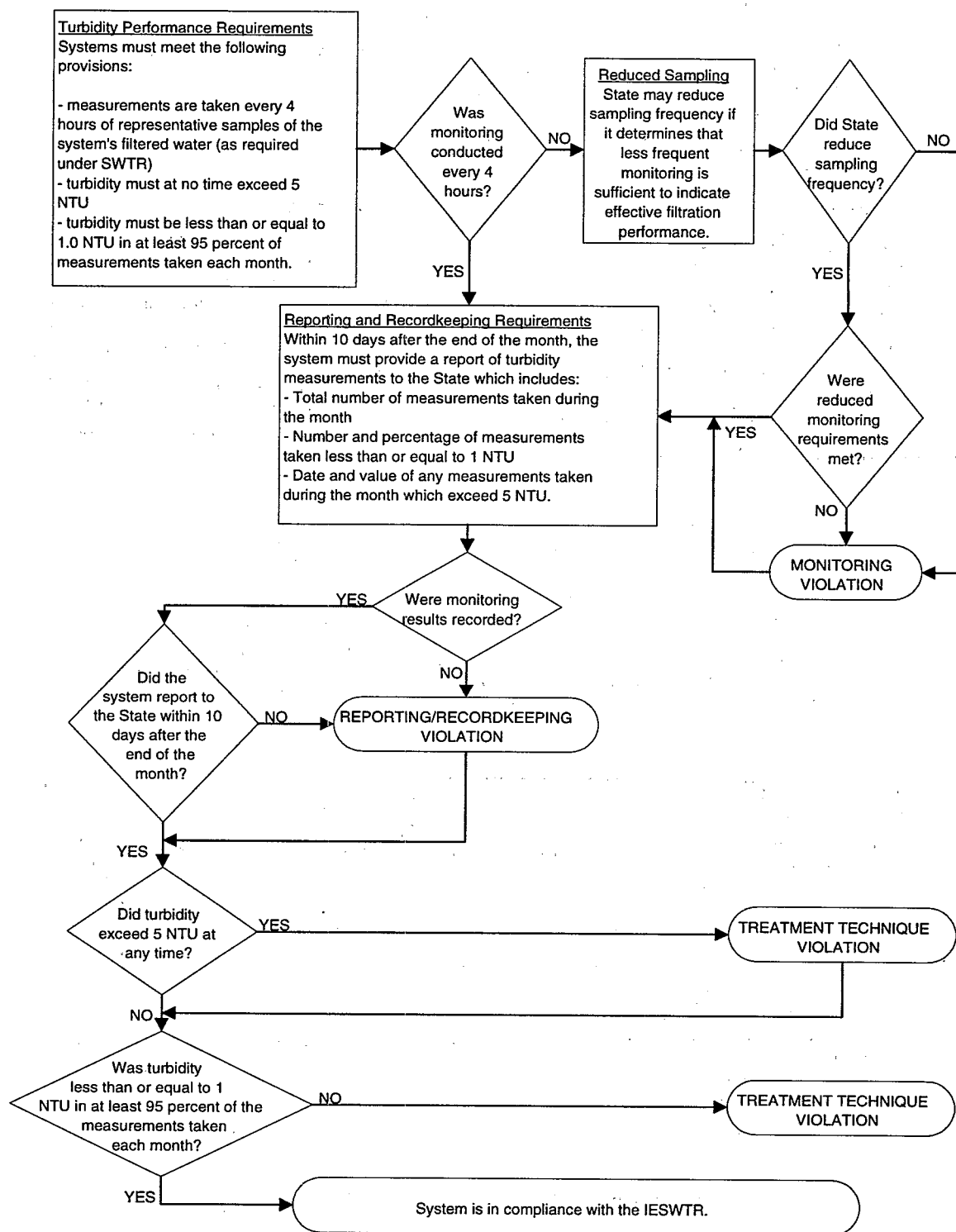


Figure 2-4. Flowchart of SWTR Combined Filter Provisions for Slow Sand and Diatomaceous Earth Filtration

Systems which Utilize Lime Softening

Systems which practice lime softening may experience difficulty in meeting the turbidity performance requirements due to residual lime floc carryover inherent in the process. EPA is allowing such systems to acidify turbidity samples prior to measurement using a protocol approved by States. The chemistry supporting this decision is well documented in environmental chemistry texts.

EPA recommends that acidification protocols lower the pH of samples to <8.3 to ensure an adequate reduction in carbonate ions and corresponding increase in bicarbonate ions. Acid should consist of either hydrochloric acid or sulfuric acid of Standard Lab Grade. Care should be taken when adding acid to samples. Operators should always follow the sampling guidelines outlined in Section 3.4.4 of this document.

If systems choose to use acidification, EPA recommends systems maintain documentation regarding the turbidity with and without acidification as well as pH values and quantity of acid added to the sample.

2.2.3 Individual Filter Monitoring

In addition to the combined filter effluent monitoring discussed above, those systems that use *conventional treatment or direct filtration* (including in-line 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. Systems must record the results of individual filter monitoring every 15 minutes. If the individual filter is not providing water which contributes to the combined filter effluent, (i.e., it is not operating, is filtering to waste, or recycled) the system does not need to record or monitor the turbidity for that specific filter.

Systems which utilize filtration other than conventional or direct filtration are not required to conduct individual filter monitoring although EPA recommends such systems consider individual filter monitoring.

If there is a failure in continuous turbidity monitoring equipment, the system must conduct grab sampling every four hours in lieu of continuous monitoring, but must return to 15 minute monitoring no more than five working days following the failure of the equipment.

2.3 Reporting and Recordkeeping

There are distinct reporting and recordkeeping requirements for the turbidity provisions of the IESWTR for both systems and States.

2.3.1 System Reporting Requirements

Under the IESWTR, systems are tasked with specific reporting requirements associated with combined filter effluent monitoring and individual filter effluent monitoring.

Combined Filter Effluent Reporting

Turbidity measurements as required by §141.173 must be reported within 10 days after the end of each month the system serves water to the public. Information that must be reported includes:

1. The total number of filtered water turbidity measurements taken during the month.
2. The number and percentage of filtered water turbidity measurements taken during the month which are less than or equal to the turbidity limits specified in §141.173. (0.3 NTU for conventional and direct and the turbidity limit established by the State for other filtration technologies)
3. The date and value of any turbidity measurements taken during the month which exceed 1 NTU for systems using conventional filtration treatment or direct filtration and the maximum limit established by the State for other filtration technologies.

This reporting requirement is similar to the reporting requirement currently found under the SWTR.

Individual Filter Requirements

Systems utilizing conventional and direct filtration must report that they have conducted individual filter monitoring in accordance with the requirements of the IESWTR within 10 days after the end of each month the system serves water to the public. Figure 2-5 presents a flowchart of individual filter requirements.

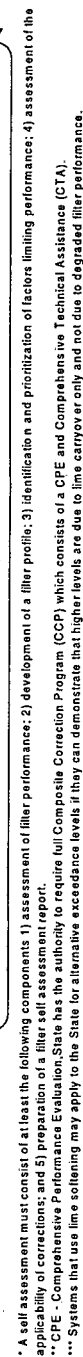


Figure 2-5. Flowchart of IESWTR Individual Filter Provisions

Additionally, systems must report individual filter turbidity measurements within 10 days after the end of each month the system serves water to the public *only if* measurements demonstrate one of the following:

- Any individual filter has a measured turbidity level greater than 1.0 NTU in two consecutive measurements taken 15 minutes apart. The system must report the filter number, the turbidity measurement, and the date(s) on which the exceedance occurred. In addition, the system must either produce a filter profile for the filter within 7 days of the exceedance (if the system is not able to identify an obvious reason for the abnormal filter performance) and report that the profile has been produced or report the obvious reason for the exceedance.
- Any individual filter has a measured turbidity level of greater than 0.5 NTU in two consecutive measurements taken 15 minutes apart at the end of the first four hours of continuous filter operation after the filter has been backwashed or otherwise taken offline. The system must report the filter number, the turbidity, and the date(s) on which the exceedance occurred. In addition, the system must either produce a filter profile for the filter within 7 days of the exceedance (if the system is not able to identify an obvious reason for the abnormal filter performance) and report that the profile has been produced or report the obvious reason for the exceedance.
- Any individual filter has a measured turbidity level of greater than 1.0 NTU in two consecutive measurements taken 15 minutes apart at any time in each of three consecutive months. The system must report the filter number, the turbidity measurement, and the date(s) on which the exceedance occurred. In addition, the system shall conduct a self-assessment of the filter.
- Any individual filter has a measured turbidity level of greater than 2.0 NTU in two consecutive measurements taken 15 minutes apart at any time in each of two consecutive months. The system must report the filter number, the turbidity measurement, and the date(s) on which the exceedance occurred. In addition, the system shall contact the State or a third party approved by the State to conduct a comprehensive performance evaluation.

2.3.2 State Reporting Requirements

Under §142.15, each State which has primary enforcement responsibility is required to submit quarterly reports to the Administrator of the EPA on a schedule and in a format prescribed by the Administrator, which includes:

1. New violations by public water systems in the State during the previous quarter with respect to State regulations adopted to incorporate the requirements of national primary drinking water regulations.

2. New enforcement actions taken by the State during the previous quarter against public water systems with respect to State regulations adopted to incorporate the requirements of national primary drinking water standards.

Any violations or enforcement actions with respect to turbidity, would be included in the quarterly report noted above. EPA has developed a State Implementation guidance manual which includes additional information on State reporting requirements.

2.3.3 System Recordkeeping Requirements

Systems must maintain the results of individual filter monitoring taken under §141.174 for at least three years. These records must be readily available for State representatives to review during Sanitary Surveys or other visits.

2.3.4 State Recordkeeping Requirements

Records of turbidity measurements must be kept for not less than one-year. The information retained must be set forth in a form which makes possible comparison with limits specified in §§141.71, 141.73, 141.173, and 141.175.

Records of decisions made on a system-by-system and case-by-case basis under provisions of part 141, subpart H or subpart P, must be made in writing and kept by the State (this includes records regarding alternative filtration determinations). EPA has developed a State Implementation guidance manual which includes additional information on State recordkeeping requirements.

2.4 Additional Compliance Issues

The following section outlines additional compliance issues associated with the IESWTR. These include Schedule, Individual Filter Follow-up Action, Notification, and Variances and Exemptions.

2.4.1 Schedule

The IESWTR was published on December 16, 1998, and became effective on February 16, 1999.

The SDWA requires, within 24 months following the promulgation of a rule, that the Primacy Agencies adopt any State regulations necessary to implement the rule. Under Sec. 1413, these rules must be at least as stringent as those required by EPA. Thus, primacy agencies must promulgate regulations which are at least as stringent as the IESWTR by December 17, 2000.

Beginning December 17, 2001, systems serving at least 10,000 people must meet the turbidity requirements in §141.173.

2.4.2 Individual Filter Follow-up Action

Based on the monitoring results obtained through continuous filter monitoring discussed in Section 2.3 of this chapter, a system may have to conduct one of the following follow-up actions due to persistently high turbidity levels at an individual filter:

- Filter profile
- Individual filter self assessment
- Comprehensive Performance Evaluation.

These specific requirements are found in §141.175(b) (1)-(4).

Abnormal Filter Operations- Filter Profile

A filter profile must be produced if no obvious reason for abnormal filter performance can be identified. A filter profile is a graphical representation of individual filter performance based on continuous turbidity measurements or total particle counts versus time for an entire filter run, from startup to backwash inclusively that includes assessment of filter performance while another filter is being backwashed. The run length during this assessment should be representative of typical plant filter runs. The profile should include an explanation of the cause of any filter performance spikes during the run. An example filter profile is included in Figure 2-6.

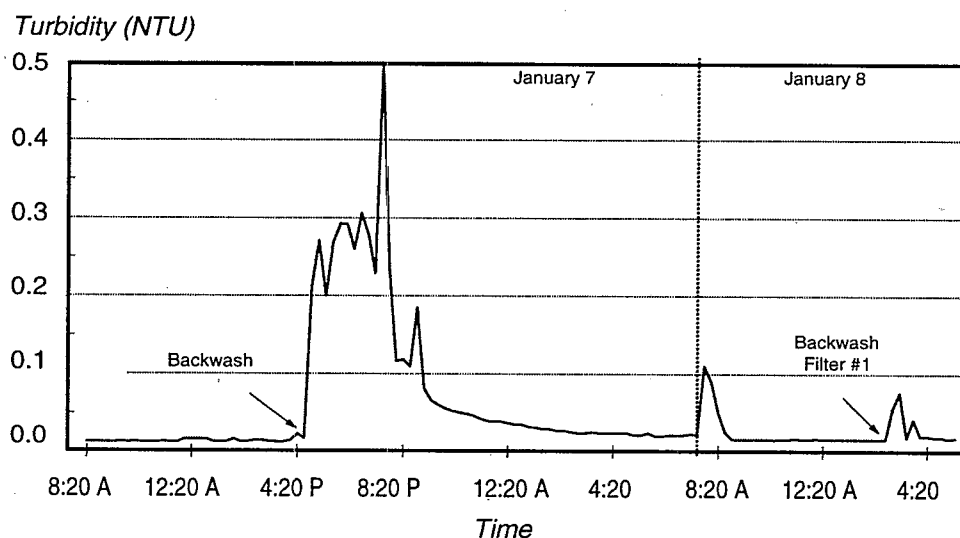


Figure 2-6. Example Filter Profile

Additional information regarding filter profiles is found in Chapter 5, Individual Filter Self Assessment. Examples of possible abnormal filter operations which may be obvious to operators include the following:

- Outages or maintenance activities at processes within the treatment train
- Coagulant feed pump or equipment failure
- Filters being run at significantly higher loading rates than approved

It is important to note that while the reasons for abnormal filter operation may appear obvious they could be masking other reasons which are more difficult to identify. These may include situations such as:

- Disruption in filter media
- Excessive or insufficient coagulant dosage
- Hydraulic surges due to pump changes or other filters being brought on/offline.

Systems need to use best professional judgement and discretion when determining when to develop a filter profile. Attention at this stage will help systems avoid the other forms of follow-up action described below.

Individual Filter Self-Assessment

A system must conduct an individual filter self-assessment for any individual filter that has a measured turbidity level of greater than 1.0 NTU in two consecutive measurements taken 15 minutes apart in each of three consecutive months. The system must report the filter number, the turbidity measurement, and the dates on which the exceedances occurred. Chapter 5 discusses how to conduct an individual filter assessment or self-assessment.

Comprehensive Performance Evaluation

A system must conduct a comprehensive performance evaluation (CPE) if any individual filter has a measured turbidity level of greater than 2.0 NTU in two consecutive measurements taken 15 minutes apart in two consecutive months. The system must report the filter number, the turbidity measurement, and the date(s) on which the exceedance occurred. The system shall contact the State or a third party approved by the State to conduct a comprehensive performance evaluation.

Chapter 6 briefly discusses how to conduct a Comprehensive Performance Evaluation. Additionally, EPA has developed a guidance document called, *Handbook: Optimizing*

Water Treatment Plant Performance Using the Composite Correction Program
(EPA/625/6-91/027, Revised August 1998).

2.4.3 Notification

The IESWTR contains two distinct types of notification: State and public. It is important to understand the differences between each and the requirements of each.

State Notification

Systems are required to notify States under §141.31. Systems must report to the State within 48 hours, the failure to comply with any national primary drinking water regulation. The system within 10 days of completion of each public notification required pursuant to §141.32, must submit to the State a representative copy of each type of notice distributed, published, posted, and/or made available to persons served by the system and/or the media.

The water supply system must also submit to the State (within the time stated in the request made by the State) copies of any records required to be maintained under §141.33 or copies of any documents then in existence which the State or the Administrator is entitled to inspect pursuant to the authority of section 1445 of the Safe Drinking Water Act or the equivalent provisions of the State Law.

Public Notification

The IESWTR specifies that the public notification requirements of the Safe Drinking Water Act (SDWA) and the implementation regulations of 40 CFR §141.32 must be followed. These regulations divide public notification requirements into two tiers. These tiers are defined as follows:

- **TIER 1**
 - Failure to comply with MCL
 - Failure to comply with prescribed treatment technique
 - Failure to comply with a variance or exemption schedule
- **TIER 2**
 - Failure to comply with monitoring requirements
 - Failure to comply with a testing procedure prescribed by a NPDWR
 - Operating under a variance/exemption. This is not considered a violation but public notification is required.

The IESWTR classifies violations of §§141.70, 141.71(c), 141.72 and 141.73, and 141.173 (i.e., treatment technique requirements as specified in §141.76) as Tier 1

violations and violations of §§141.74, and 141.174 as Tier 2 violations. Violations of §§141.75 and 141.175 (reporting requirements) do not require public notification.

There are certain general requirements which all public notices must meet. All notices must provide a clear and readily understandable explanation of the violation, any potential adverse health effects, the population at risk, the steps the system is taking to correct the violation, the necessity of seeking alternate water supplies (if any) and any preventative measures the consumer should take. The notice must be conspicuous, and not contain any unduly technical language, unduly small print, or similar problems. The notice must include the telephone number of the owner or operator or designee of the public water system as a source of additional information concerning the violation where appropriate. The notice must be bi- or multilingual if appropriate.

Tier 1 Violations

In addition, the public notification rule requires that when providing notification on potential adverse health effects in Tier 1 public notices and in notices on the granting and continued existence of a variance or exemption, the owner or operator of a public water system must include certain mandatory health effects language. For violations of treatment technique requirements for filtration and disinfection, the mandatory health effects language is:

The United States Environmental Protection Agency (EPA) sets drinking water standards and has determined that the presence of microbiological contaminants are a health concern at certain levels of exposure. If water is inadequately treated, microbiological contaminants in that water may cause disease. Disease symptoms may include diarrhea, cramps, nausea, and possibly jaundice, and any associated headaches and fatigue. These symptoms, however, are not just associated with disease-causing organisms in drinking water, but also may be caused by a number of factors other than your drinking water. EPA has set enforceable requirements for treating drinking water to reduce the risk of these adverse health effects. Treatment such as filtering and disinfecting the water removes or destroys microbiological contaminants. Drinking water which is treated to meet EPA requirements is associated with little to none of this risk and should be considered safe.

Further the owner or operator of a community water system must give a copy of the most recent notice for any Tier 1 violations to all new billing units or hookups prior to or at the time service begins.

The medium for performing public notification and the time period in which notification must be sent varies with the type of violation and is specified in §141.32. For Tier 1 violations, the owner or operator of a public water system must give notice:

1. By publication in a local daily newspaper as soon as possible but in no case later than 14 days after the violation or failure. If the area does not have a daily newspaper, then notice shall be given by publication in a weekly newspaper of general circulation in the area, and
2. By either direct mail delivery or hand delivery of the notice, either by itself or with the water bill no later than 45 days after the violation or failure. The Primacy Agency may waive the requirement if it determines that the owner or operator has corrected the violation within 45 days.

Although the IESWTR does not specify any acute violations, the Primacy Agency may specify some Tier 1 violations as posing an acute risk to human health; examples might include:

- A waterborne outbreak in an unfiltered supply
- Turbidity of a filtered water exceeds 1.0 NTU at any time
- Failure to maintain a disinfectant residual of at least 0.2 mg/L in the water being delivered to the distribution system.

For these violations or any others defined by the Primacy Agency as 'acute' violations, the system must furnish a copy of the notice to the radio and television stations serving the area as soon as possible but in no case later than 72 hours after the violation. Depending on the circumstances particular to the system, as determined by the Primacy Agency, the notice may instruct that all water be boiled prior to consumption.

Following the initial notice, the owner or operator must give notice at least once every three months by mail delivery (either by itself or with the water bill), or by hand delivery, for as long as the violation or failures exist.

There are two variations on these requirements. First, the owner or operator of a community water system in an area not served by a daily or weekly newspaper must give notice within 14 days after the violation by hand delivery or continuous posting of a notice of the violation. The notice must continue for as long as the violation exists. Notice by hand delivery must be repeated at least every three months for the duration of the violation.

Secondly, the owner or operator of a noncommunity water system (i.e., one serving a transitory population) may give notice by hand delivery or continuous posting of the notice in conspicuous places in the area served by the system. Notice must be given within 14 days after the violation. If notice is given by posting, then it must continue as long as the violation exists. Notice given by hand delivery must be repeated at least every three months for as long as the violation exists.

Tier 2 Violations

For Tier 2 violations (i.e., violations of 40 CFR §§141.74 and 141.174) notice must be given within three months after the violation by publication in a daily newspaper of general circulation, or if there is no daily newspaper, then in a weekly newspaper. In addition, the owner or operator shall give notice by mail (either by itself or with the water bill) or by hand delivery at least once every three months for as long as the violation exists. Notice of a variance or exemption must be given every three months from the date it is granted for as long as it remains in effect.

If the area is not served by a daily or weekly newspaper, the owner or operator of a community water system must give notice by continuous posting in conspicuous places in the area served by the system. This must continue as long as the violation exists or the variance or exemption remains in effect. Notice by hand delivery must be repeated at least every three months for the duration of the violation or the variance or exemption.

For noncommunity water systems, the owner or operator may give notice by hand delivery or continuous posting in conspicuous places; beginning within three months of the violation or the variance or exemption. Posting must continue for the duration of the violation or variance or exemption, and notice by hand delivery must be repeated at least every three months during this period.

The Primacy Agency may allow for owner or operator to provide less frequent notice for minor monitoring violations (as defined, by the Primacy Agency if EPA has approved the Primacy Agency's substitute requirements contained in a program revision application).

2.4.4 Variances and Exemptions

As with the SWTR, no variances from the requirements in §141 are permitted for subpart H systems.

Under Section 1416(a), EPA or a State may exempt a public water system from any requirements related to an MCL or treatment technique of an NPDWR if it finds that (1) due to compelling factors (which may include economic factors such as qualification of the PWS as serving a disadvantaged community), the PWS is unable to comply with the requirement or implement measures to develop an alternative source of water supply; (2) the exemption will not result in an unreasonable risk to health; and (3) the PWS was in operation on the effective date of the NPDWR, or for a system that was not in operation by that date, only if no reasonable alternative source of drinking water is available to the new systems; and (4) management or restructuring changes (or both) cannot reasonably result in compliance with the Act or improve the quality of drinking water.

2.5 References

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3. TURBIDITY METHODS & MEASUREMENT

3.1 Introduction

The IESWTR requires systems to measure the turbidity of combined filter effluent and individual filter effluent. Because these measurements are used for reporting and compliance purposes (as described in Chapter 2), accurate measurement and strict adherence to approved methods is of paramount importance. The following chapter describes approved methods, analytical issues associated with turbidimeters, quality assurance and quality control issues, and data collection and management.

3.2 Approved Turbidity Methods

Currently, the Agency has approved three methods for the measurement of turbidity as described in §141.74. Systems must utilize turbidimeters which conform to one of the following methods for compliance purposes. If the instrument does not conform, then it may not be used for monitoring under the requirements of the IESWTR. A brief description of each of the methods is found below.

3.2.1 EPA Method 180.1

EPA method 180.1, "Determination of Turbidity by Nephelometry", is found in the Agency's publication, *Methods for Chemical Analysis of Water and Wastes*. The method is based upon a comparison of the intensity of light scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension. The higher the intensity of scattered light, the higher the turbidity. Readings, in NTUs, are made in a nephelometer designed according to specifications laid out in the method. A primary standard suspension is used to calibrate the instrument. A secondary standard suspension is used as a daily calibration check and is monitored periodically for deterioration using one of the primary standards. See Appendix B for EPA Method 180.1.

3.2.2 Standard Method 2130B

Standard Method 2130B, found in *Standard Methods* (1995), is similar to EPA Method 180.1. The method is also based on a comparison of the intensity of light scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension under the same conditions. The higher the intensity of scattered light, the higher the turbidity. Formazin polymer is used as the primary standard reference suspension. See Appendix C for Standard Method 2130B.

3.2.3 Great Lakes Instrument Method 2 (GLI 2)

Great Lakes Instruments Method 2 is an instrument specific, modulated four beam method using a ratiometric algorithm to calculate the turbidity value from the four readings that are produced. The comparison is also based on a comparison of light scattered by the sample under defined conditions with the intensity of the light scattered by the reference suspension. The higher the intensity of the scattered light, the higher the turbidity. Readings in NTUs, are made in a nephelometer designed according to specifications in the method. See Appendix D for Great Lakes Instrument Method 2.

3.3 Turbidimeters

As noted, turbidimeters must conform to one of the three approved methods for measuring turbidity. For regulatory reporting purposes, either an on-line or a benchtop turbidimeter may be used. A system may find it appropriate to utilize on-line turbidimeters to monitor individual filter effluent, while utilizing either a benchtop or on-line turbidimeter for combined filter effluent. If a system chooses to utilize on-line units for monitoring combined filter effluent, they must validate the continuous measurements for accuracy on a regular basis using a protocol approved by the State.

3.3.1 Bench Top Turbidimeters

Bench top units are used exclusively for grab samples and include glass cuvettes for holding the sample. Measurement with bench top units requires strict adherence to the manufacturer's sampling procedure to reduce errors from dirty glassware, air bubbles in the sample, and particle settling. Plant operators should read and be fully familiar with the operation manuals for all bench-top turbidimeters used in the plant. Many maintenance and operational issues are specific to turbidimeter make and model, and instruments are usually supplied with a thorough user's manual.

Bench-top Basics

Although durable, turbidimeters need to be stored and operated in a safe and protected environment. Moisture and dust need to be prevented from entering and accumulating inside turbidimeters. Humidity also needs to be controlled to prevent condensation inside the instrument. Turbidimeters should be located where they will not be exposed to corrosive chemicals or fumes. Chemicals such as chlorine and acids can ruin instrumentation. Finally, turbidimeters should be located in an environment that is temperature controlled, at a consistent temperature between 0° and 50°C.

Generally the instrument should be left on at all times (unless otherwise specified in the user's manual). If any instrument is not left on at all times, it may require a warm-up period before sample analysis.

The length of the sample piping or tubing from the sampling location to the point where the sample is drawn off should be minimized. Long sample lines can lead to problems with biological fouling and scaling which can impact turbidity values. It is best to limit

sample lines to ten feet or less. Long sample lines can also cause confusion due to the lag time as the sample travels through the piping. The longer the lag time, the more difficult it is to correlate turbidity fluctuations to actual process changes that might be occurring.

Sample taps in piping should be located on the sides of pipes. Samples taken from the top or bottom will not accurately represent the turbidity of the water. Samples taken from the bottom will often times contain sediment while samples from the top may contain a greater number of air bubbles. Ideally, sample taps should be angled into the water flow at an angle of 0-45 degrees and extend into the center of the flow channel. Sample taps should be located away from items which disturb flow such as fittings, bends, meters, or pump discharges.

Operation and Maintenance

Preventative and routine maintenance should be carried out according to manufacturers' instructions. Do not make repairs to the instrument unless specified in the instruction manual. Even if a repair can be made, consider sending the unit back to the manufacturer. Keep track of maintenance and repair on a log sheet located next to the unit.

Maintain benchtop instruments in accordance with manufacturer recommendations. Inspect the cleanliness of bulb and lenses daily. Clean lenses, light sources, and other glassware with appropriate materials to avoid scratches and dust accumulation. Avoid the use of chemicals or other materials when cleaning unless instructed by the manufacturer. Do not touch the optical components with bare hands (soft cotton gloves are recommended). Recalibrate the instrument after any significant maintenance or cleaning procedure.

Bench-top turbidimeters, just like most instruments, have an effective service life. Various elements within the instrument can deteriorate over time and with repeated use. Daily usage can result in wear on electronics due to movement and temperature. Microprocessor based electronics are also prone to memory loss during power supply fluctuations. Service personnel can often provide insight on instrument life and can make recommendations for specific maintenance items. Since turbidimeters have become integral parts of a water treatment plant operation and reporting, it is imperative to maintain instruments and budget for replacements.

Replace incandescent turbidimeter lamps annually, or more frequently if recommended by the manufacturer. Recalibrate the instrument whenever optical components (e.g., lamp, lens, photodetector, etc.) of the turbidimeter are replaced or cleaned.

Calibration

Calibration is an essential part of accurate turbidity measurement, and as such, instrument calibration should be verified on a daily basis. Calibration verification can be completed using primary or secondary standards. If verification indicates significant deviation from

the standard (true) value (greater than $\pm 10\%$), thoroughly clean and recalibrate the instrument using a primary standard. If problems persist the manufacturer should be contacted. At a minimum regardless of calibration results, turbidimeters should be thoroughly cleaned and calibrated with primary standards *at least quarterly*.

After calibration, performance of the turbidimeter should be verified with a secondary standard. If the instrument has internal electronic diagnostics designed to assist in determining proper calibration, the operator should use these tools to verify proper calibration and operation. Calibration is discussed in significant detail in Section 3.4.5.

3.3.2 On-Line Turbidimeters

On-line turbidimeters are process instruments which sample a side stream split-off from the treatment process. The sample flows through the on-line instrument for measurement and then wasted to a drain or recycled through the treatment process.

Selection of the flow rate through on-line turbidimeters should be in accordance with manufacturer specifications. The sample flow should be constant without variations due to pressure changes or surges. Installation of a flow control device such as a rotameter on the sample line can eliminate fluctuations in flow rate.

To the extent possible, turbidimeter samples should be obtained directly from the process flow and not pumped to a remote instrument location. Pumped samples can be non-representative of the process flow due to changes in the character of particles caused by the pump or the addition of bubbles due to rapid pressure changes. If pumping is required, the use of peristaltic pumps are desirable, as they have the least amount of impact on particles in the sample.

Several of the on-line turbidimeters available today have various sample chamber sizes. It is important to note that the size of the sampling chamber will affect the instrument response. The path length of the light passing through the sample is inversely proportional to resolution of the instrument. Therefore, the larger the sample size, the more likely that the turbidity reading will be dampened.

Installation

On-line turbidimeters should be installed in accordance with manufacturer instructions. The goal of proper installation is to ensure proper operation, easy access for maintenance and calibration procedures that should be performed, and obtain an accurate, representative and timely sample.

Carefully consider the location of the sample tap. The tap should provide a representative sample of the water being monitored. If an individual filter is being monitored, locate the sample tap as close to the filter as possible. The tap should provide a sample from the centerline of the pipe, as opposed to the bottom or top of the pipe where sediment or air bubbles may interfere with sample integrity. Ideally, the sample will flow by gravity from

the sample tap to the turbidimeter without a sample pump. Sample pumps may have an effect on turbidimeter measurements.

The length of conduit between the sample tap and the instrument should be minimized, to the extent possible. Lengthy sample runs can delay instrument response time and may cause changes in sample quality (i.e., settling of particulate matter, increased opportunity for biological growth). In selecting sample tubing or pipe, the required sample flow rate and pressure should be considered. Sample lines of insufficient diameter may not provide adequate flow to the instrument and may be prone to clogging. Excessively large diameter sample lines will delay the instrument response and may permit settling of particulate matter. Line flushing valves and ports may be necessary depending on the water being sampled. Carefully consider these items when installing an on-line turbidimeter.

A good sample tap location and plumbing arrangement will minimize the potential for bubble formation. Most on-line turbidimeters have the capability to eliminate minor bubble interference through baffles and/or degassing chambers, but if the problem is severe, the turbidity measurements may be affected.

The turbidimeter should be installed in a location that provides easy access for routine maintenance and calibration procedures. It should be protected from direct sunlight, extreme temperatures ($<32^{\circ}\text{F}/0^{\circ}\text{C}$ and $>104^{\circ}\text{F}/40^{\circ}\text{C}$), and rapid temperature fluctuations. It should also be firmly mounted so as to avoid vibrations, which may interfere with the accuracy of turbidity measurements.

The turbidimeter drain should provide easy access for flow verification and collection of calibration verification samples. Flow rate and calibration verification samples are important in establishing data validity. Therefore, hard piping the turbidimeter drain without an airgap is not recommended.

Operation and Maintenance

Preventative and routine maintenance should be carried out according to manufacturer's instructions. A regular cleaning schedule is necessary to ensure proper operation of on-line turbidimeters. A weekly inspection is recommended, but this frequency may vary depending on the instrument location and raw water quality. Warm or turbid samples may dictate more frequent cleaning. An instrument mounted in a dusty environment may also require more frequent cleaning. Items to inspect and clean include, but are not limited to, lenses, light sources, sample reservoirs, air bubble traps, and sample lines. Clean lenses, light sources, and other glassware with appropriate materials to avoid scratches and dust accumulation. During maintenance, care needs to be taken not to touch the surface of any bulbs or detectors without proper covering on the fingers. Soft cotton gloves should be worn when changing bulbs or detectors. Recalibrate the instrument after any significant maintenance or cleaning procedure.

On-line turbidimeters, just like most instruments, have an effective service life. Various elements within the instrument can deteriorate over time and with repeated use. Daily usage can result in wear on electronics due to movement and temperature. Microprocessor based electronics are also prone to memory loss during power supply fluctuations. Many on-line units with unsealed sensor electronics are vulnerable to damage by outside contamination and splashing. Service personnel can often provide insight on instrument life and can make recommendations for specific maintenance items. Since turbidimeters have become integral parts of a water treatment plant operation and reporting, it is imperative to maintain instruments and budget for replacements.

Incandescent turbidimeter lamps should be replaced annually or more frequently if recommended by the manufacturer. The instrument should be recalibrated whenever optical components (e.g., lamp, lens, photodetectors, etc.) of the turbidimeter are replaced.

Systems should consider verifying sample flow rates on a weekly basis. Flow rates should be within a range specified by the manufacturer.

Calibration

EPA recommends that on-line turbidimeters have calibration verified on a weekly basis, if being utilized for combined filter effluent monitoring. Less frequent verification may be more appropriate for turbidimeters monitoring individual filter turbidity, but EPA recommends verification be conducted with a frequency of **at least** once per month.

Calibration verification can be completed using primary standards, secondary standards, or by comparison to a properly calibrated turbidimeter. If verification indicates significant deviation from the standard (true) value (greater than $\pm 10\%$), the instrument should be thoroughly cleaned and recalibrated using a primary standard. If problems persist, the manufacturer should be contacted. Regardless of calibration results, turbidimeters should be thoroughly cleaned and calibrated with primary standards **at least quarterly**.

EPA does not recommend calibrating on-line instruments by comparison with a bench-top turbidimeter. It has been determined that this procedure is likely to introduce unacceptable levels of error into the calibration.

After calibration, verify instrument performance with a secondary standard or by comparison with another properly calibrated instrument. If the instrument has internal electronic diagnostics designed to assist in determining proper calibration, the operator should use these tools to verify proper calibration and operation. For additional information on calibration see Section 3.4.5.

3.4 Quality Assurance/Quality Control

Although using proper techniques and equipment is an important part of conducting proper turbidity measurements, it is imperative that operators are aware of factors in the

processes which may lead to poor quality data. Such factors include poor lab techniques, calculation mistakes, malfunctioning or poorly functioning instrumentation, and out-of-date and deteriorated chemicals. Development of a Quality Assurance and Quality Control (QA/QC) Program ensures that lapses do not occur which allow inaccurate measurements or erroneous reporting. Systems may want to establish plans to provide assurance that measurements are being made accurately and consistently.

3.4.1 Quality Assurance Organization and Responsibilities

A good QA/QC plan provides clear organization and defines who is responsible for each of the aspects laid out in the plan and what their responsibilities are. This section should include a list of the positions (by title) that have responsibilities and what those responsibilities are. The appropriate training or skills necessary for each of the positions listed should also be included.

3.4.2 Quality Assurance Objectives

The objectives of the Quality Assurance Program need to be laid out and understood by the staff members. Objectives should be succinct, and clear. SOPs should be developed with input from staff, enabling them to effectively conduct work activities in compliance with applicable requirements. Systems may wish to include one primary objective, followed by a number of goals which all relate to the objective. An example might look like the following:

The primary objective of the Quality Assurance Program is to ensure that turbidity measurements are accurate and consistent. Based on this, the goals of the Quality Assurance Program at a generic water treatment plant are the following:

- To adhere to proper sampling techniques as set forth in the Standard Operating Procedures.
- To maintain and operate all turbidimeters at the plant properly in accordance with manufacturer instructions and Standard Operating Procedures.
- To perform calibration of instruments on a routine and as-necessary basis.
- To communicate and report all, malfunctions, abnormalities, or problems which may compromise the ability to accurately and consistently measure turbidity.

3.4.3 Standard Operating Procedures

Standard Operating Procedures (SOPs) are a way to ensure that activities are accomplished in a consistent manner, and that each activity is understood by all involved. SOPs should be kept as simple as possible in order to ensure that each operator is consistent in undertaking the task at hand. The title of the procedure should be clear, concise, and descriptive of the equipment, process, or activity. Systems should consider adopting SOPs for any of the following activities:

- Cleaning turbidimeters
- Creating Formazin Standards
- Calibrating Turbidimeters
- Referencing Index Samples

Instructional steps should be concise and precise, using the following guidelines:

- Steps should contain only one action.
- Commands should be written with an action verb at the beginning.
- Limits/and or tolerances for operating parameters should be specific values and consistent with the accuracy of the instrumentation. Procedures should not include mental arithmetic.
- **“Cautions”** should be used to attract attention to information that is essential to safe performance.
- **“Notes”** should be used to call attention to supplemental information. Notes present information that assists the user in making decisions or improving task performance.
- Documentation methods should be incorporated as part of the procedure including what data needs to be recorded, if the individual needs to sign or date data, etc.

After developing an SOP, the author(s) should consider the following questions:

- Can the procedure be performed in the sequence it is written?
- Can the user locate and identify all equipment referred to in the procedure?
- Can the user perform the procedure without needing to obtain direct assistance or additional information from persons not specified by the procedure?
- Are words, phrases, abbreviations, or acronyms that have special or unique meaning to the procedure adequately defined?
- Is there a need for special controls on data collection and recordkeeping?

After completing the SOP it should be tested to the extent possible. It is also a good idea to ask a technical reviewer to verify the accuracy of the procedure. SOPs should be reviewed at least once every 2 years to determine if the procedure and requirements are still accurate.

The following is a simplified example of an SOP written for the development of Formazin.

Creating a 4000 NTU Formazin Stock Suspension

1. Dissolve 1.000 g of ACD grade hydrazine sulfate, $\text{N}_2\text{H}_4 \cdot \text{H}_2\text{SO}_4$ in ultra filtered deionized water and dilute to 100 mL in a Class A, 100 mL volumetric flask.
2. Dissolve 10.00 g of analytical grade hexamethylenetetramine, $(\text{CH}_2)_6\text{N}_4$, in ultra filtered deionized water and dilute to 100 mL in a Class A, 100 mL volumetric flask.
3. Combine the equal volumes of the hydrazine sulfate solution and the hexamethylenetetramine solution into a clean, dry flask and mix.
4. Let the mixture stand for 48 hours at 24-26 °C.
5. Store the suspension in a bottle that filters ultraviolet light.

3.4.4 Sampling Strategy and Procedures

The procedure for conducting sampling should be laid out clearly and concisely, preferably in SOPs (discussed in Section 3.4.3). It should include information such as sampling location and frequency, collection methods, sample handling, and any logistical considerations or safety precautions which are necessary. Adherence to proper techniques is an important step in minimizing the effects of instrument variables and other interferences (Sadar, 1996). Measurements will be more accurate, precise, and repeatable if operators follow and incorporate the techniques listed in this section.

All turbidimeter manufacturers emphasize proper techniques and include detailed instructions in their literature. Water treatment plant operators responsible for conducting turbidity measurements are urged to review these instructions and incorporate them into their SOPs. Specific instruction for securing samples and measuring turbidity will differ for the various instrument manufacturers and models, but there are certain universally accepted techniques that should be utilized when conducting measurements. The following paragraphs highlight some of these techniques.

Handling of Cuvettes/Sample Tubes

Sample cells must be handled with absolute care to avoid contamination or damage, such as marks and scratches, which might change the optical characteristics of the glass. Scratches, fingerprints, and water droplets on the sample cell or inside the light chamber can cause stray light interference leading to inaccurate results. Cells can be acid washed periodically and coated with a special silicone oil to fill small scratches and mask the imperfections in the glass. Since the silicone oil required for this application should have the same refractive characteristics as glass, it is recommended that the oil be obtained from the instrument manufacturer. Care should be taken to not apply excessive oil that could attract dirt or contaminate the sample chamber in the instrument. Once the oil has

been applied to the cell, the excess oil should be removed with a lint-free cloth. The result should be a sample cell surface with a dry appearance, but with all imperfections filled with oil. Sample cells should always be handled at the top of the cell or by the cap to avoid fingerprints or smudges. After a cell has been filled with a sample and capped, the outside surface should be wiped with a clean, lint-free absorbent cloth until it is dry. Store cells in an inverted position on clean surfaces to reduce contamination by dirt or dust or store capped and filled with low turbidity water.

Orientation and Matching of Sample Cells

Since imperfections in the sample cell glass can influence light scattering, the cell should be inserted in the turbidimeter with the same orientation each time it is used. At the Philadelphia Water Department, new cells are indexed and are not allowed to vary by more than 0.01 NTUs. Philadelphia reports that as many as one quarter of the cells are never used due to imperfections in sample cells (Burlingame, 1998).

Matched sample cells are required to minimize the effects of optical variation among cells. If possible, it is better to use a single sample cell for all measurements to minimize the variability due to cell-to-cell imperfections. Once the orientation of a cell has been established, the operator should always use the same orientation when placing the sample cell into the instrument. Techniques for matching and indexing are provided below.

Indexing Cells (Steps 1-2) Matching Cells (Steps 1-3)

- Step 1. Pour ultra-pure dilution water into a sample cell (several cells if performing matching) that has been cleaned according to the techniques described previously in this section.
- Step 2. Select sample cell, and place it into the turbidimeter. Rotate the cell within the instrument until the display reads the lowest value. Record the reading. Using a marker or pen, place a mark on the top of the sample cells neck. **Do not put the mark on the cap.** Use this mark to align sample cells each time a measurement is made.
- Step 3. Select another sample cell, place it into the turbidimeter and rotate the cell slightly until the reading matches that of the first sample cell (within 0.01 NTUs). Using a marker or pen, place a mark on the top of the sample cells neck. If unable to match the readings select a different sample cell. Repeat the process until the appropriate number of cells have been matched.

Degassing of the Sample

Water samples almost always contain substantial amounts of entrained gases that can be released during turbidity measurement. Bubbles are either generated during the filling of a sample container, occur due to temperature fluctuations resulting in a reduced solubility

of the gas in a liquid, or are due to chemical and/or biological processes. Bubbles within a sample act much like particles and can scatter light resulting in an incorrect measurement. Many on-line turbidimeters contain apparatuses inside the instrument that serve to trap, collect, and vent air bubbles. Usually these consist of baffled entries or membranous chambers. Some vendors also manufacture add-on units which can be placed in the sample line before the on-line turbidimeter. There are several other options for removing bubbles from water (degassing) to reduce the effect they have on measurements. The most commonly used methods include, addition of a surfactant, application of a partial vacuum, and use of an ultrasonic bath.

Addition of a surfactant compound to a water sample lowers the surface tension of the water and allows entrained gases to readily escape. There are a variety of surfactants used in turbidity measurements today. Because of the variety in chemical composition, it is difficult to provide guidance for their use. It is important to note that some surfactants may have constituents which serve as a coagulant and cause particles to aggregate and settle out. Other chemicals might contain constituents with an ionic charge that cause particles to rise to the surface. The use of surfactants is more appropriate for measurement of highly turbid waters such as raw water. The most appropriate instrument-specific advice regarding the use of surfactants can be obtained by contacting the instrument manufacturer.

Application of a partial vacuum to a sample lowers the partial pressure above the liquid surface and allows entrained gases to escape. Partial vacuums can be created by a simple syringe or by use of a vacuum pump. Some instrument manufacturers and suppliers provide pre-made vacuum kits that include syringes for degassing samples. The most common arrangement is the use of a syringe and a stopper sized for the opening of the sample cell or test tube.

The use of an ultrasonic bath creates vibrations in the sample to facilitate the escape of gases. Ultrasonics is a specialty field/science that utilizes an inaudible spectrum of sound frequencies ranging from about 20,000 cycles per second to 100,000 cycles per second. Ultrasonic baths are used for thoroughly cleaning supplies in the medical, electronic, and metals industries. When high frequency sound waves are passed through a cleaning fluid, such as water with suitable detergent additive, many millions of microscopic bubbles form and then rapidly collapse. The bubbles are the result of the stretch and compress phases of the sound waves within the fluid, a process known as cavitation. Ultrasonic devices may be most effective in severe turbidity conditions or with viscous samples, however if used for degassing samples, samples should be sonified **for no more than 1 to 2 seconds**. Sonification can change particle size ranges, affecting a turbidimeters response if improperly utilized (Burlingame, 1998).

Timeliness of Sample

Samples should be measured expeditiously after being secured to prevent changes in particle characteristics due to temperature and settling. Temperature can affect particles by changing their behavior or creating new particles if precipitates are created. Dilution

water may dissolve particles or change their characteristics (Sadar, 1996). Operators are encouraged to draw samples only when turbidimeters are ready to be operated. Do not draw a sample and allow it to sit while the instrument warms up or is being readied.

Other Important Sampling Techniques

- Samples should not be violently agitated as particles can be broken apart or air may be entrained into the fluid. Gentle agitation such as swirling the sample cell is advisable to reduce particle settling.
- Sample cells should be used only with the instruments for which they were intended. Do not mix and match.
- Perform a visual observation of the sample cell every time a measurement is made. Verify that there are no visible bubbles in the sample and the cell is clean and free of scratches.
- Samples entering the turbidimeters should be at the same temperature as the process flow samples. Changes in temperature can cause precipitation of soluble compounds and affect readings.
- Sample cells should be evaluated with a low turbidity water (after cleaning) to determine if cells remain matched. If the evaluation determines that a cell is corrupted, discard the cell. Systems should consider conducting this evaluation weekly.
- When in doubt, throw it out - If you have a question as to whether a sample cell is too scratched or stained get rid of it.

3.4.5 Calibration

Turbidimeters, like all instrumentation, need to be calibrated periodically to ensure that they are working properly and provide true and accurate readings.

Calibration should always be conducted according to manufacturer instructions.

Determine the appropriate technical requirements for calibration based on the following

- Manufacturer
- Model name and/or number
- Parameters to be calibrated
- Range to be calibrated
- Acceptance criteria
- Mandatory calibration procedures or standards
- Required calibration program

After calibration, performance of the turbidimeter should be verified with a secondary standard. If the instrument has internal electronic diagnostics designed to assist in determining proper calibration, the operator should use these tools to verify proper calibration and operation.

Calibration Standards

A calibration standard must be used to conduct a calibration. Standards are materials with a known value which, when placed in the instrument, should be used to adjust the instrument to read the known value.

There are a variety of standards on the market today which are used to calibrate turbidimeters. They are most often characterized as Primary, Secondary, or Alternative standards. Standard Methods describes Primary Standards as a standard which is prepared by the user from traceable raw materials, using precise methodologies and under controlled environmental conditions. (Standard Methods, 1995) Standard Methods defines Secondary Standards as those standards a manufacturer (or an independent testing organization) has certified to give instrument calibration results equivalent (within certain limits) to results obtained when an instrument is calibrated with a primary standard.

Standard Methods and EPA differ in their definitions of each of these standards. EPA recognizes the following three Standards for approved use in the calibration of turbidimeters.

- FORMAZIN (user prepared and commercially produced)
- AMCO-AEPA-1® MICROSPHERES
- STABLCAL® (STABILIZED FORMAZIN)

Users need to realize that some instruments have been designed and calibrated on specific primary standard(s) listed above. For optimal results, users should contact the manufacturer of the instrument to determine the recommended primary standard to be used for calibration.

Additionally, EPA recognizes Secondary Standards for use in monitoring the day-to-day accuracy of turbidimeters by checking the calibration. This check is used to determine if calibration with a Primary Standard is necessary. Secondary Standards are used to check whether an instrument produces measurements within acceptable limits around a nominal value (typically 10%). Examples of *SECONDARY STANDARDS* include:

- GELEX®
- GLASS/CERAMIC CUBES
- MANUFACTURER PROVIDED INSTRUMENT SPECIFIC SECONDARY STANDARDS

The need to reconcile the definitions and differences among Primary and Secondary Standards will be a continuing issue. It has been recognized that the standards need to be unbiased, easy to use, safe, available for a range of turbidities, and reproducible. Future efforts of the Agency, in concert with other organizations and manufacturers, will focus on ensuring the most appropriate, variation-free, and technologically feasible standards are available and used for calibration of turbidimeters.

Conducting the Calibration

All reputable turbidimeters have been factory-calibrated before leaving the manufacturer. As described previously, turbidimeters, like most instrumentation, tend to lose accuracy over time due to a variety of factors, making periodic calibration very important to maintain accurate measurements. The most important point to remember is:

Calibration should always be conducted according to manufacturer instructions.

Manufacturers differ in the steps to conduct a calibration, but the following points are applicable to all calibrations.

- Standards should be checked to ensure they have not expired. Never pour a standard back into its original container.
- Care should be taken when preparing Formazin. If a spill occurs, clean up immediately according to the Material Safety Data Sheets (MSDSs) provided with your chemicals. Make sure to inspect the tube/cuvette for scratches and chips prior to pouring the solution in.
- Check to make sure the tube/cuvette is lined up properly according to the indexing. Be sure not to scratch the tube when inserting, and ensure that the tube/cuvette is free of dust, smudges, and scratches.
- When obtaining the reading, write the value legibly onto a form similar to the one found in Figure 3-1. Make sure to record the date of the calibration, the individual conducting the calibration, the value, and any peculiar situations or deviations from normal calibration procedures (e.g., switch to a new lot of Formazin, switch in standards, use of a new tube/cuvette, etc.) These measurements will allow for an understanding of whether the performance of a turbidimeter is in question. For example, if for 6 months a turbidimeter reads approximately 20.152 when calibrated using polystyrene beads and one morning it reads 25.768, this could be an indication that the bulb in the turbidimeter has a problem. Conversely, if the standard in use was switched that morning, the resulting change might be due to change in standards.
- Conduct the calibration the same way each time. Variations in how the calibration is conducted could yield inaccurate measurements.
- It is extremely important that individuals who conduct the calibration have been trained to do so. Systems should consider creating Standard Operating Procedures to be read, learned, and followed by operators at the plant.

Frequency of Calibration

EPA recommends that the calibration of units be verified daily with secondary standard and recalibration occur at least quarterly with primary standards. Specific calibration procedures should be developed for each individual instrument location. Listed below are several guidelines for selecting calibration frequencies and procedures:

- Select a frequency for checking instrument calibration with secondary standards and for full re-calibration of instrument with primary standards .
- Establish the acceptable deviation from the primary standard during secondary verifications. Readings in excess of the deviation should trigger immediate re-calibration of the instrument. ($\pm 10\%$ is recommended by EPA)
- Choose a time of day when full attention can be devoted to the calibration. Calibration at the end of a shift or right before a break can often lead to mistakes and sources of error. A calibration time should be established when operators are fully alert and focused on completing the task.
- Identify and schedule in advance the dates for full turbidimeter calibration on the plant calendar or work scheduling chart.
- Make preparations and maintain adequate supplies to prevent delays in the calibration schedule. It is important to keep an appropriate stock of standards. Due to the limited shelf-life of various standards, the age of the stored standards should be monitored so they can be replaced or reformulated as needed.
- Assign calibration duties to a select group of individuals, and make it one of their standard activities. Train all appropriate individuals/operators in conducting a calibration in the event that one of the regular individuals is not available.
- Create a Standard Operating Procedure for conducting a calibration and post next to the turbidimeter.

3.4.6 Data Screening, Validation, and Reporting

The methods for data screening, validation, and reporting should be detailed to ensure that measurements are recorded calculated and reported correctly. These methods should be designed to meet the Quality Assurance Objectives. Again, the development and implementation of SOPs will facilitate those goals.

| CALIBRATION CHECKLIST | | | | |
|-----------------------|----------|-------|----------|----------|
| Month _____ | | | | |
| Year _____ | | | | |
| Date | Initials | Value | Standard | Comments |
| | | | | |
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Figure 3-1. Calibration Checklist

3.4.7 Performance and System Audits

Performance and system audits should be conducted periodically to determine the accuracy of the total measurement system(s) or component parts thereof. Performance audits may include review of documentation and log books for legibility and completeness. The systems audit consists of evaluation of all components of the sampling and measurement systems to determine their proper selection and use. This audit includes a careful evaluation of both field and laboratory quality control procedures and can include verification of written procedures and analyst(s) understanding, verification and documentation of procedures, as well as adherence to any SOPs.

3.4.8 Preventative Maintenance

Preventive maintenance should be conducted on all instrumentation. The maintenance program consists of scheduled (preventive) and non-scheduled maintenance procedures. All maintenance performed and the results of calibrations should be documented. Maintenance procedures and schedules for equipment used should be available to the appropriate staff. Adherence to maintenance schedules and procedures may be investigated during a systems audit. A preventive maintenance schedule recommended

by the respective manufacturers should be followed for each instrument. This preventive maintenance will include regular battery checks and maintenance of a sufficient stock spare parts and supplies. Manufacturers' procedures identify the schedule for servicing critical items to minimize downtime of the measurement system.

3.5 Data Collection and Management

The final steps in turbidity measurement deal with the collection of data and management of collected data. The advent of the personal computer revolution has provided much needed assistance to tasks that were once time consuming, although automation still requires operators who are skilled and trained in the use of sometimes sophisticated equipment. This section describes the several methods available to systems for the collection of data and provides a brief description of the management of that data.

Data obtained from Supervisory Control and Data Acquisitions (SCADAs), data recorders, or strip charts should be verified on a weekly basis by comparing the turbidimeter reading with the data recording device reading. If verification indicates greater than $\pm 10\%$ deviation, the electronic signal should be recalibrated according to manufacturer instructions.

3.5.1 Data Collection Methods

Acquisition of data from turbidimeters is an important step in the turbidity measurement process. With the individual filter turbidity requirements, systems will be required to continuously monitor each filter. Each of the methods discussed below are typically used for on-line turbidimeters. Readings using benchtop units are typically recorded by hand or entered into a PC without the use of the data collection equipment listed below. Systems may have experience using these methods in monitoring other water quality parameters.

Strip Recorders and Circular Chart Recorders

Strip Chart and Circular Chart Recorders are a relatively established technique for recording data. The units are set to obtain a reading at a timed interval. A pen records the reading on paper at the interval. As additional readings are taken, the pen moves back and forth (or up and down in the case of a circular recorder) recording the values that are being monitored.

Newer models include digital readouts as well as the capability to transfer data to data loggers or other data acquisition systems. The greatest disadvantages to using chart recorders is the difficulty in incorporating data into electronic format and archiving such data. Recorders also require the purchasing of replacement pens and charts.

Data Loggers

Data Loggers are "black boxes" which store data which is received from input channels. The box records the data in memory which can then be downloaded at a future time. Data loggers consist of two distinct components: hardware and software.

Hardware

The units themselves typically consist of a device containing solid state memory encased in a plastic weatherproof enclosure. Units have a varying number of inputs that can be either analog (records actual numbers) or digital (records a series of 0s and 1s), as well as an output to download data. Systems most often are battery powered, but some can be connected to existing power supplies. Nearly all systems contain lithium or other batteries to keep memory active in the event of a power failure.

Software

Two software components are important to data loggers/acquisition devices. First, specialized software is necessary to configure the logging unit. This configuration specifies the unit frequency at which to obtain turbidity readings. The second part of the software is used to retrieve the data from the logger and import it into a usable format on a PC. Most companies offer integrated packages that allow users to import the data and immediately plot and graph the data to depict trends or produce reports. Data should be downloaded at regular intervals, as data loggers cannot store data indefinitely.

Several methods exist to transfer data from the logger into the PC. Data acquisition systems are often equipped to be compatible with telemetry to upload data to PCs via telephone, cellular telephone, or radio. Alternatively, either a laptop or palmtop can be connected to the unit to download information, or the data logger can be brought into the office where the PC is located and plugged into one of the input/output ports on the PC. The better method could necessitate utilizing a second data logger to take the place of the first logger when it is being downloaded. Systems may wish to schedule downloads to occur at times when a filter may not be in operation (when off-line or being backwashed).

SCADA

SCADA systems are devices used for industrial measurement and control. They consist of a central host (base unit), one or more field gathering and control units (remotes), and a collection of standard and/or custom software used to monitor and control remotely located field data elements. The base unit and the remote units are linked via telemetry, and the base unit receives data and provides instructions as specified in the software. SCADA systems at treatment plants are also often times referred to as Distributed Control Systems (DCS). DCSs function the same as SCADA systems except that field gathering and control units are located in a more confined area and communications may be via a local area network (LAN) as opposed to remote telemetry.

SCADA systems can take inputs from a variety of sources and instruments. These systems collect and display the data produced by a variety of instruments so that the plant operator can monitor the entire treatment process from one location. SCADA systems are typically used for a variety of functions at a water treatment plant including flow control, pH and temperature monitoring, automated disinfection dosing, and a host of other functions. Control may be automatic or initiated by operator commands. The inclusion

of continuous turbidity monitoring could be incorporated into the regime of items being measured and controlled by a SCADA/DCS system at a treatment plant.

SCADA systems can also be used to log and store data for recording purposes. Signals sent from remote instruments located on the plant site are interpreted at the base unit. This unit provides the logic to interpret all of the different signals and display real-time measurements. The central unit can be programmed to automatically transfer historical data to other storage media such as a tape drive or Zip-drive.

3.5.2 Data Management

There are two distinct objectives to management of turbidity data: (1) Regulatory Compliance, and (2) Checking Process Control and Treatment Plant Optimization. The turbidity reporting and monitoring requirements set forth in Chapter 2 establish the types of data which must be collected and the analysis which must be done to meet the requirements of the rule. In order to meet these requirements, operators must understand three areas of data management:

- Data Format;
- Data Storage; and
- Data Analysis.

Format

Storage of the data in a usable format is the first step to effective data management. Operators should have the ability to download data from their acquisition equipment into a usable and manageable format. Data is typically placed in one of many different formats such as Excel, Access, dBASE, and Lotus 123. Data should be converted into a format that can be used by the facility. Many systems currently utilize software such as those listed above. The key to selecting a format is the ease at which the data can be viewed, manipulated, and or converted. Certain software packages allow users to create reports, tables, or graphs based on the data.

Storage

Storage of the data is the next step in effective data management. Maintaining these data points for future analysis may pose a problem due to the amount of disk space required. Systems should consider the use of Zip-Drives or tape-drives for storage of data. Hard drives can be used to store data while manipulating or evaluating. Tape and Zip-Drive backups are also recommended due to the possibility of a PC crashing.

Interpreting and Analyzing Data

Data Analysis is the last step in effective data management. Systems are encouraged to utilize the Data Collection Spreadsheets and Macros developed for the Partnership for Safe Water. A description of the Partnership for Safe Water is found in Chapter 4.

Spreadsheets were prepared for the Partnership for Safe Water to assist utility partners in collecting performance data. The spreadsheets were developed to capture turbidity data from raw water, sedimentation basin effluent and filter effluent, but can be used to measure repetitive data of any kind, from any point in the process for up to 365 days. Macros have been written to generate frequency distributions on a monthly and annual basis, to help evaluate trends and summarize large amounts of data. Graphics capabilities of the spreadsheets are also built in to automatically plot trend charts and frequency distributions. There are also capabilities for generating summaries of the data to report as background information. Other data summaries within the capabilities of each spreadsheet software version could be generated as well. A disk containing the software along with guidance for using the software is found in the Composite Correction Program Handbook published by EPA.

The software provided with many of the data acquisition systems, which can be custom designed for SCADA/DCS systems, also allow operators to trend and analyze data. Easy-to-use software provides clear graphics for operators to evaluate. Typically, data can be exported to various spreadsheets or database programs for later analysis. Software is typically interactive, with the ability to change colors, and graph sizes.

Systems should analyze turbidity data to check process control and treatment plant optimization. Systems may wish to evaluate backwash turbidity spikes for individual filters, how storm events affect the filtration capabilities, or the effect of various chemical dosages on filtered effluent. Analysis could be undertaken to compare different filters within a system or the effect of different flow rates. Chapter 5 provides information on conducting a Filter Self Assessment and analysis which systems may wish to implement.

3.6 References

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4. APPROACH FOR COMPLIANCE

4.1 Compliance Approach for Turbidity Requirements

While many systems already meet or will meet turbidity requirements prior to compliance deadlines, some systems will need to evaluate their treatment plants to determine what changes, if any, are needed to comply with the requirements. Utilities which determine they may have difficulty complying with the turbidity requirements of the IESWTR should first evaluate the system and begin to optimize plant performance. Section 4.2 outlines the Agency's suggested approach for utilities to evaluate their systems, and identifies key areas which systems should evaluate.

Although it is anticipated that compliance with the IESWTR will generally be possible through adjustments to existing treatment processes, additional treatment processes or other treatment technologies or enhancements may be required in some cases. It is not anticipated that systems will need to make major capital improvements, but those systems considering capital improvements in order to meet requirements of the IESWTR should conduct an optimization activity similar to the Composite Correction Program to assess the real need of construction. Section 4.3 briefly outlines many of the process enhancements that, in the opinion of the Agency and other water professionals, are the most likely to be employed by systems, if optimization alone does not permit a system to comply with turbidity requirements.

4.2 System Evaluation & Plant Optimization

A thorough treatment plant evaluation and improvement program is the best way to ensure pathogen-free drinking water. With an emphasis on improved performance at minimal cost, optimization is an economical alternative for compliance with the turbidity requirements. Currently, two programs serve as excellent resources for systems wishing to follow a systematic and proven approach to optimizing water treatment plant performance. These are:

- **Composite Correction Program**

The Composite Correction Program (CCP) is a systematic action oriented approach that federal or state regulators, consultants, or utility personnel can implement to improve performance of existing water treatment plants. The Comprehensive Performance Evaluation phase of the CCP is described in greater detail in Chapter 6. The Agency has developed a guidance manual that may be obtained by calling the EPA Safe Drinking Water Hotline at 1-800-426-4791.

- **Partnership for Safe Water**

The Partnership is a voluntary cooperative effort between the EPA, AWWA and other drinking water organizations, and over 186 surface water utilities representing 245 water treatment plants throughout the United States. The goal of this common sense cooperation is to provide a new measure of safety to millions of Americans by implementing prevention programs where legislation or regulation does not exist. The preventative measures are based around optimizing treatment plant performance and thus increasing protection against microbial contamination in America's drinking water supply. Information regarding the Partnership is found at AWWA's website <http://www.awwa.org/partner1.htm> or may be obtained by calling (303) 347-6169.



Systems are strongly encouraged to utilize one of the above noted programs if intending to optimize plant performance.

While systems should consider the above noted programs, this section provides information utilities may find useful in evaluating their system and optimizing their plant's performance. It is important to remember that the items listed in this chapter may or may not apply to all systems. Optimizing water treatment plants is a site-specific endeavor. As such, this section does not seek to serve as a recipe for how to optimize water treatment for lowered turbidity. It does however highlight the areas which, in the experience of the Agency and other water professionals, most often can be improved to optimize water treatment at PWSs. The items discussed in this section are addressed in greater detail in the Composite Correction Program and the Partnership for Safe Water.

4.2.1 Coagulation/Rapid Mixing

Coagulation is the process by which small particles are combined to form larger aggregates and is an essential component in water treatment operations. Evaluation and optimization of the Coagulation/Rapid Mixing step of the water treatment process includes a variety of aspects. Optimal coagulant dosages are critical to filter performance. Maintaining the proper control of these chemicals can mean the difference between an optimized surface plant and a poorly run surface plant. Inadequate mixing of chemicals or their addition at inappropriate points within the treatment plant can limit performance. The following issues may be evaluated as they may improve the performance of this step in the treatment process.

Chemicals

An evaluation of the chemicals used in the treatment process can identify the appropriateness of the coagulation chemicals being used. A thorough understanding of coagulation chemistry is necessary, and changes to coagulation chemicals should not be made without careful consideration. The following aspects relating to coagulation chemicals may be considered by systems:

- Operating procedures should not call for the shutting off of coagulant chemical addition when raw water is less than 1 NTU.
- Are chemicals being dosed properly, paying special attention to pH? Is dose selection based on frequent jar testing or other testing methods such as streaming current monitoring, zeta potential, or pilot filters? Relying exclusively on past practice is not good practice.
- Do Standard Operating Procedures exist for coagulation controls? Systems should develop SOPs, and establish a testing method that is suited to the plant and personnel.
- Are the correct chemicals being utilized? Is the best coagulant being used for the situation? Changing coagulant chemicals or adding coagulant aids may improve the settleability of the flocculated water and in turn optimize performance. Coagulants may also be changed seasonally.
- Do operators have the ability to respond to varying water quality by adjusting coagulation controls to ensure optimum performance? Systems should provide operators with such learning opportunities so that they can react to various conditions with understanding and confidence.
- Are solutions used promptly? Most solutions should be utilized within 48 hours of their formulation. Are chemicals utilized before manufacturer recommended expiration or use-by dates?
- Is pH a consideration? Measurement of pH is a key aspect in coagulation chemistry. Do not dilute coagulant solutions to pH levels higher than 3.3 for alum and 2.2 for iron salts. Manufacturers instructions should be followed when diluting polymers.
- Are chemicals being added in the correct order? The order of chemicals is very important, as certain chemicals interfere with others. Jar tests should be utilized to develop optimal sequences.
- Is the chemical feed system operating properly? Operators should consider checking the accuracy of systems at least once daily or once per shift.

Feed Systems

Feed systems are another important aspect of the coagulation step in typical treatment processes. These systems are responsible for delivering coagulants into the system at

rates necessary for optimal performance. The following aspects should be evaluated regarding feed systems.

- Is redundancy a consideration? Redundancy may be built into the feed systems so that proper feeding of chemicals can be maintained in the event of failure or malfunction of primary systems.
- Is the feed system large enough? Feed systems should be sized so that chemical dosages can be changed to meet varying conditions.
- Are chemical pumping equipment and piping checked on a regular basis? Maintenance of these systems should be a priority and incorporated into routine maintenance performed at the system.
- Is a diaphragm pump utilized? A continuous pump allows coagulants to be added in such a way as to avoid pulsed flow patterns.

Satisfactory Dispersal/Application Points

Finally, proper coagulation and mixing also depends on satisfactory dispersal of coagulation chemicals and appropriate application points. Coagulants should be adequately dispersed so that optimal coagulation may occur. A sufficient number of feed points should exist such that chemicals have the opportunity to mix completely. Utilities should evaluate the following items:

- Is adequate dispersion taking place? If chemicals are added at a hydraulic pump, ensure that the chemicals are distributed across the width of the flow stream and at the location where turbulence is greatest. The rapidity of coagulation necessitates even dispersal as soon as possible.
- Are coagulants being added at the proper points? Metal salts should be introduced at the point of maximum energy input. Low molecular weight cationic polymers can be fed with metal salts at the rapid mix or to second stage mixing following the metal salt. High molecular weight nonionic/anionic floc/filter aids should be introduced to the process stream at a point of gentle mixing.
- Is rapid mixing equipment checked frequently? Systems should check the condition of equipment, and ensure that baffling provides for adequate, even-flow.

4.2.2 Flocculation

Flocculation is the next step in most treatment plants (in-line filtration plants being the exception). It is a time-dependent process that directly affects clarification efficiency by providing multiple opportunities for particles suspended in water to collide through gentle and prolonged agitation. The process takes place in a basin equipped with a mixer that provides agitation. This agitation should be thorough enough to encourage interparticle contact but gentle enough to prevent disintegration of existing flocculated particles. Effective flocculation is important for the successful operation of the sedimentation

process. Several issues regarding flocculation should be evaluated by utilities to ensure optimal operation of flocculation basins.

Flocculation Mixing and Time

Proper flocculation requires long, gentle mixing. Mixing energy should be high enough to bring coagulated particles constantly into contact with each other, but not so high as to break up those particles already flocculated. Utilities should consider evaluating:

- How many stages are present in the flocculation system? Three to four are appropriate to create plug flow conditions and allow desired floc formation.
- Is the mixing adequate to form desired floc particles? Tapered mixing is most appropriate. "G" values should be variable through the various stages from 70 sec^{-1} to 15 sec^{-1} .
- Are mechanical mixers functioning properly? Are flocculator paddles rotating at the correct rates?
- If flow is split between two flocculators, are they mixing at the same speed and "G" value? If the flocculators have different characteristics, dosages may be proper for one, but not both.

Flocculator Inlets and Outlets

If water passes through the flocculation basin in much less time than the volumetric residence time, the influent stream has short circuited. Inlet and outlet turbulence is oftentimes the major source of destructive energy in flocculation basins that contributes to short circuiting. Utilities should evaluate the following:

- Do basin outlet conditions prevent the breakup of formed floc particles? Basin outlets should avoid floc breakup. Port velocities should be <0.5 fps. The velocity gradient at any point from the flocculation basin to the sedimentation basin should be less than the velocity gradient in the last flocculation stage.
- Do inlet conditions prevent the breakup of formed floc particles? Inlet diffusers improve the uniformity of the distribution of incoming water. Secondary entry baffles across inlets to basins impart headloss for uniform water entry.
- What size are the conduits between the rapid mix basin and the flocculation basin? Larger connecting conduits help reduce turbulence which can upset floc.

Flocculator Basin Circulation

Baffles are used in flocculator basins to direct the movement of water through the basin. Baffling near the basin inlet and outlets improves basin circulation and achieves more

uniform circulation. A system may think about the following items when evaluating flocculation.

- Is current baffling adequate? Can baffling be added to improve performance or does existing baffling require repair? Serpentine baffling is better than over/under. Baffling should allow headloss through opening to prevent short-circuiting and to allow plug flow conditions.
- Induced velocity in floc chambers should vary from 2 fps in first stage to 0.25 fps in the last stage. Velocity through openings in the baffle should be slightly less than the induced velocities.

4.2.3 Sedimentation

Sedimentation is the next step in conventional filtration plants (direct filtration plants omit this step). The purpose of sedimentation is to enhance the filtration process by removing particulates. Sedimentation requires that water flow through the basin at a slow enough velocity to permit particles to settle to the bottom before the water exits the basin. Utilities should consider the following items when evaluating sedimentation basins.

- Is sludge collection and removal adequate? Inadequate sludge collection and removal can cause particles to become re-suspended in water or upset circulation. Systems should disrupt the sludge blanket as little as possible. Sludge draw-off rates can effect the sludge blanket. Sludge draw off procedures should be checked periodically, making sure sludge levels are low; and sludge should be wasted if necessary. Sludge pumping lines should be inspected routinely to ensure that they are not becoming plugged. These lines should also be flushed occasionally to prevent the buildup of solids.
- Do basin outlet conditions prevent the breakup of formed floc particles? Settling basin inlets are often responsible for creating turbulence that can break up floc. Improperly designed outlets are also often responsible for the break-up of floc. Finger launders (small troughs with V-notch weir openings that collect water uniformly over a large area of the basin) can be used to decrease the chance of short-circuiting.
- Is the floc the correct size and density? Poorly formed floc is characterized by small or loosely held particles that do not settle properly and are carried out of the settling basin. This is the result of inadequate rapid mixing, improper coagulant dosages, or improper flocculation. Systems should look to previous steps in the treatment train to solve this problem.
- Is the basin subject to short circuiting? If the basin is not properly designed, water bypasses the normal flow path through the basin and reaches the outlet in less time than the normal detention time. The major cause of short-circuiting is poor influent baffling. If the influent enters the basin and hits a solid baffle, strong currents will result. A perforated baffle can successfully distribute inlet water without causing strong currents. Tube or plate settlers

also improve efficiency, especially if flows have increased beyond original design conditions. Tube settlers can result in twice the basin's original settling capacity.

- Are basins located outside and subject to windy conditions? Wind can create currents in open basins that can cause short-circuiting or disturbances to the floc. If wind poses a problem, barriers lessen the effect and keep debris out of the unit.
- Are basins subject to algal growth? A problem that occurs in open, outdoor basins is the growth of algae and slime on the basin walls.
- In solids contact clarifiers, is the sludge blanket maintained properly? Operators should be able to measure the sludge depth and percent solids to ensure the sludge blanket is within the manufacturer's recommendations.

4.2.4 Filtration

Filtration is the last step in the particle removal process. Improperly designed, operated, or maintained filters can contribute to poor water quality and sub-optimal performance. There are a host of items which systems will need to evaluate regarding filters that may be contributing to poor performance. Many of the items listed below are detailed in Chapter 5, Individual Filter Self-Assessment.

Design of Filter Beds

It is important to verify that the filters are constructed and maintained according to design specifications. Utilities should consider the following items when evaluating the design of filter beds.

- Media – Is the correct media being used? Issues such as size, uniformity coefficient, and depth need to be evaluated.
- Underdrains – Are underdrains adequate or have they been damaged or disturbed?

Filter Rate and Rate Control

The rate of filtration and rate control is another important aspect of filters that should be evaluated. Without proper control, surges may occur which would force suspended particles through the filter media.

- Are surges in flow an issue of concern? Systems should avoid sudden changes to filter rate. Systems should minimize plant flow rate changes, throttle filter control valves slowly, and bring a filter on-line when one is being backwashed).
- Is the plant operating at the appropriate flow rate? At some plants (typically smaller systems), the flow is operated at a level that hydraulically overloads

unit processes. Operating at lower flow rates over longer periods of time prevents overloading and increases plant performance.

- At what flows are the filters rated? Make sure not to exceed flow rates on remaining in-service filters when taking filters off-line or out of service for backwash.

Filter Backwashing

Filter backwashing has been identified as a critical step in the filtration process. Many of the operating problems associated with filters are a result of inadequate backwashing. Utilities should consider the following items when evaluating filter backwash practices.

- Is the rate of filter backwash appropriate for the filter? Filters can be either underwashed or overwashed. Utilities need to determine the appropriate flow that will clean the filter and prevent mudballs, but will not upset the filter media to the extent that the underdrain is damaged or filter media is lost. (20-50 percent bed expansion is typical)
- Are criteria set for initiating backwash? Systems should establish criteria such as time, headloss, turbidity, or particle counts for initiating backwash procedures.
- How are filters brought back on-line? Media should be allowed to settle after backwashing before bringing filters back on-line. Filters should be brought back on line slowly. Several filters should not be brought on line at the same time. Filters should not be brought back on-line without backwashing first.
- When a filter is backwashed, is more water diverted to the remaining filters, causing them to be overloaded during backwash? During the backwash, flow going to the remaining filters may need to be cut back to ensure the filters are not overloaded or "bumped" with a hydraulic surge causing particle pass through.

4.3 Process Enhancements/Technologies

As noted at the beginning of this chapter, some systems may need to provide additional treatment processes or make enhancements to existing processes to meet the requirements of the IESWTR. **The Agency stresses that utilities need to first fully evaluate their systems, specifically utilizing either the CCP or Partnership for Safe Water programs, prior to installing new treatment or equipment. EPA believes that most systems will be able to meet requirements through process optimization.**

EPA expects that systems might use a combination of equipment modifications and process enhancements or treatment processes to meet requirements if process optimization alone does not bring the system into compliance. The Agency developed a *Cost and Technology Document for the Interim Enhanced Surface Water Treatment Rule*,

which discusses these treatment processes/enhancements. Treatment process enhancements fall into the following categories:

- Chemical Modifications
- Coagulant Improvements
- Rapid Mixing Improvements
- Flocculation Improvements
- Settling Improvements
- Filtration Improvements
- Hydraulic Improvements
- Laboratory Modifications
- Process Control Modifications

By no means is this list exhaustive or do the process enhancements which fall under each category represent the only modifications available to systems. They represent enhancements that, in the opinion of the Agency and other water professionals, are the most likely to be employed by systems. For further information regarding these enhancements, the reader is directed to the *Cost and Technology Document for the Interim Enhanced Surface Water Treatment Rule*, dated July 28, 1998, which was developed in support of the Regulatory Impact Analysis (RIA) for the IESWTR.

Certain technologies, especially those involving large financial expenditures, should only be implemented with appropriate engineering guidance, and should consider factors such as the quality and type of source water, turbidity of source water, economies of scale and potential economic impact on the community being served, and treatment and waste disposal requirements. An engineering study should be conducted, if needed, to select a technically feasible and cost-effective method to meet the unique needs of each system for improved filter effluent quality to comply with the IESWTR. Some situations may require more extensive water quality analyses or bench and/or pilot scale testing. The engineering study may include preliminary designs and estimated capital, operating and maintenance costs for full-scale treatment.

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5. INDIVIDUAL FILTER SELF ASSESSMENT

5.1 Introduction

Based on individual filter monitoring requirements in the IESWTR, some systems may be required to conduct an individual filter self assessment. Specifically, a system must conduct an individual filter self-assessment for any individual filter that has a measured turbidity level greater than 1.0 NTU in two consecutive measurements taken 15 minutes apart in each of three consecutive months. The system must report the filter number, the turbidity measurement, and the dates on which the exceedances occurred.

Filters represent the key unit process for the removal of particles in surface water treatment. Although filters represent only one of the "barriers" in a treatment process their role is the most critical as the final physical "barrier" to prevent passage of chlorine resistant pathogenic microorganisms into distribution systems. Properly designed filters used in conjunction with coagulation, flocculation and sedimentation processes (if in use), when in proper physical and operational condition, are capable of treating raw water sources.

For any situation regarding a single poor performing filter, or a bank of poor performing filters:

- Performance limitations observed at the start of a filter run are most often attributed to improper chemical conditioning of the filter;
- Limitations observed during the filter run are most often attributed to changes in hydraulic loading conditions; and
- Limitations observed at the end of the filter run are most often related to excessive filter runs.

Filter performance issues may only be apparent during excessive hydraulic loading and care should be taken to not attribute all turbidity spikes to hydraulic bumping or overloading. In some circumstances performance "symptoms" for other causes may only be evident during these hydraulic episodes. Oftentimes disrupted filter media may cause filter performance problems. The following chapter describes the process of an individual filter self assessment and is intended to provide clarity regarding which of these areas are limiting the performance of a filter.

The following chapter will include each of the following components of an individual filter assessment:

- **A general description of the filter** including size, configuration, placement of washwater troughs and surface wash type (if applicable) and filter media design

(e.g., type, depth and placement) and if filter-to-waste is present and/or used and if any special conditions exist regarding placing a filter back into service (i.e., is the filter rested, polymer or coagulant added prior to placement into service, etc.).

Table 5-1 provides a worksheet to assist the evaluator in collecting this information.

- **The development of a filter run profile** of continuous turbidity measurements or total particle counts versus time for an entire filter run from start up to backwash, including assessment of filter performance while another filter is being washed. The run length during this assessment should be representative of typical plant filter runs. The profile should include explanations of the cause of performance spikes during the run.
- **An assessment of the hydraulic loading conditions of the filter** which includes: the determination of the peak instantaneous operating flow for the individual filter, an assessment of the filter hydraulic loading rate at this peak instantaneous operating flow, and an assessment whether plant flow is distributed evenly among all the filters.
- **An assessment of the actual condition and placement of the media** with a comparison to the original design specifications. The filter bed should be investigated for surface cracking, proper media depth, mudballs and segregation of media in dual media filters. The media should be examined (using coring and/or gross excavation techniques as appropriate) at several locations to determine the depth of the different media layers in dual and multi-media filters.
- **A description of backwash practices** including length, duration, presence of and type of surface wash or air scour, and method for introducing wash water (i.e., via pump, head tank, distribution system pressure, etc.) and criteria for initiating the wash (i.e., degraded turbidity or particle counts, head loss, run time, etc.), the backwash rate, and bed expansion during the wash.
- **An assessment of the condition of the support media/underdrains** including a filter grid detailing placement of support media, as well as a summary of inspection of the clearwell for the presence of filter media and any observances of boils or vortexing during backwash.
- **An assessment of the filter rate-of-flow controllers and filter valving infrastructure adequacy.** The rate-of-flow controllers and ancillary valving related to the filter can also have an impact on filter performance and should be visually inspected to assure proper operation.

Table 5-1. Individual Filter Self Assessment Worksheet

| Topic | Description | Information |
|-------------------------------------|---|-------------|
| General Filter Information | Type (mono, dual, mixed) | |
| | Number of filters | |
| | Filter control (constant, declining) | |
| | Surface wash type (rotary, fixed, none)/Air Wash | |
| | Configuration (rectangular, circular, square) | |
| | Dimensions (length, width, diameter) | |
| | Filter-to-waste (capability/specify if used) | |
| | Surface area per filter (ft ²) | |
| Hydraulic Loading Conditions | Average operating flow (mgd) | |
| | Peak instantaneous operating flow (mgd) | |
| | Average hydraulic surface loading rate (gpm/ft ²) | |
| | Peak hydraulic surface loading rate (gpm/ft ²) | |
| Media Design Conditions | Depth, type | |
| | Media 1 – Sand | |
| | Media 2 (if applicable) – Anthracite | |
| | Media 3 (if applicable) – Garnet | |
| Actual Media Conditions | Depth | |
| | Media 1 – Sand | |
| | Media 2 (if applicable) – Anthracite | |
| | Media 3 (if applicable) – Garnet | |
| | Presence of mudballs, debris, excess chemical, cracking, worn media | |
| Support Media/Underdrain Conditions | Is the support media evenly placed (deviation <2 inches) in the filter bed? | |
| | Evidence of media in the clearwell or plenum | |
| | Evidence of boils/vortexing during backwash | |

Table 5-1. Individual Filter Self Assessment Worksheet (continued)

| Topic | Description | Information |
|----------------------|--|-------------|
| Backwash Conditions | Backwash initiation (headloss, turbidity/particle counts, time) | |
| | Sequence (surface wash, air scour, flow ramping, filter-to-waste) | |
| | Duration (minutes) | |
| | Introduction of wash water (via pump, head tank, distribution system pressure) | |
| | Backwash rate (gpm/ft ²) | |
| | Bed expansion (percent) | |
| | Coagulant or polymer added to wash water | |
| | Filter rested prior to return to service | |
| Other Considerations | | |
| | | |
| | | |
| | | |

5.2 Developing A Filter Run Profile

The profile for the filter being evaluated shall include a graphical summary of filter performance for an entire filter run from start-up to backwash inclusively. Performance is typically represented by turbidity although total particle counts may be used in addition to, or in lieu of, turbidity measurements. Use of particle counting in conjunction with turbidity monitoring of filter effluents may offer additional insights to filter performance, however, care should be taken in the interpretation of particle count results. The interpretation should focus on the change in count levels as opposed to the discreet particle count numbers. Plotting the performance data versus time on a continuous basis is the desirable approach for development of the filter profile. However, time increments less than a continuous basis may be used with the understanding that the intent is to identify and minimize "real" deviations in performance. The filter run should be representative of a typical run and should encompass the time period when another filter is being washed. The profile shall include an explanation of the cause of performance spikes during the run.

Example

A utility has plotted total turbidity data versus time for a filter that cannot meet requirements for individual filters. The filter run is typically 24 to 28 hours with a resting period after backwash that varies from 8 to 10 hours. The generated filter profile is shown below in Figure 5-1. The review of turbidity data showed an inordinate number of spikes occurring during the filter run. This data corroborated with turbidity data that triggered the filter assessment. These spikes corresponded to changes in hydraulic loading rates made by the staff and may be indicative of greater problems within the filter itself. The significant increases in turbidity passing the filters occurred when the plant staff initiated recycle of treated backwash water to the head of the plant and when plant loading rates were modified during the evening to take advantage of off-peak electrical costs (represented by item B&D). Table 5-2 provides explanations for turbidity spikes.

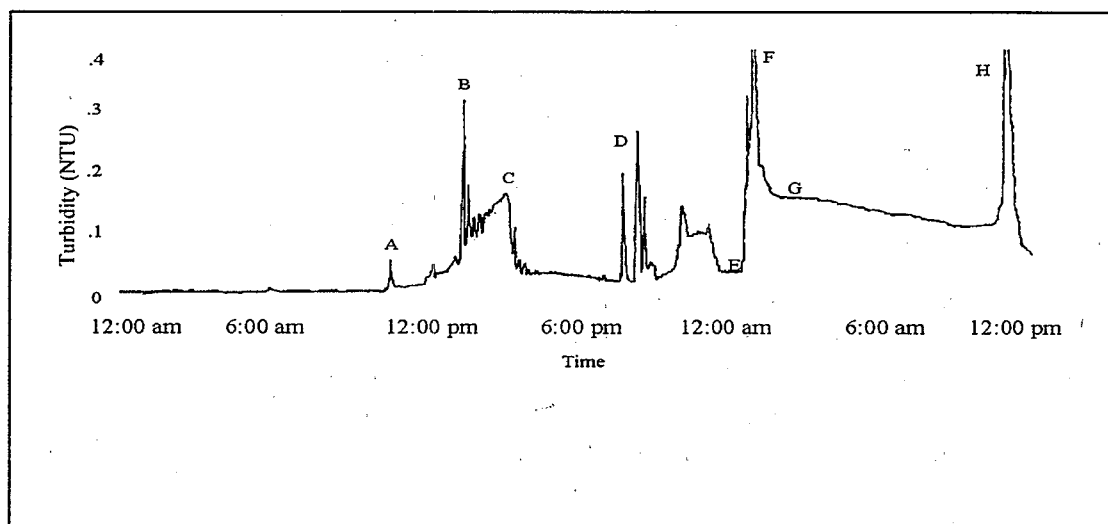


Figure 5-1. Filter Run Profile – Turbidity (NTU) vs. Time

Table 5-2. WTP Performance Deviation Trigger Events

| Event | Performance Deviation Trigger Explanation |
|-------|---|
| A | Pump change |
| B | Backwash water decant recycle to head of plant initiated |
| C | Backwash water decant recycle completed |
| D | Pumping rate increased to take advantage of off-peak electrical costs |
| E | Immediately following backwash of adjoining filter |
| F | Filter backwash |
| G | Filter taken out of service |
| H | Filter placed back in service |

5.3 Assessing Hydraulic Loading Conditions Of Filter

Filters with properly chemically pretreated influents are most vulnerable to pass particles (including pathogenic microorganisms) at peak loading rates in excess of filter design or during sudden changes in hydraulic loading rates. Table 5-3 presents a summary of acceptable filter loading rates for various filters. **However, filters may exhibit capable performance at loading rates in excess of those presented in Table 5-3; these values are rule-of-thumb and provide a basis for evaluating excessive filter hydraulic loading.** State requirements may differ from acceptable industry loading rates and should be considered during the assessment.

Since the filters are most vulnerable during excessive loading rates, it is critical to determine the peak flow on an instantaneous basis that filters are performing under and to minimize incidences when filters are expected to perform at these higher loading rates. Peak instantaneous operating flow rate is identified through review of operating records and observations of operational practices and flow control capability.

A review of plant flow records can be misleading in determining the peak instantaneous operating flow. For example, peak daily water production can only be used when those values are generated during a 24-hour operational day during specific conditions. If values are used that were generated for a day when the plant only was in operation for 12 hours, the peak instantaneous operating flow would be $\frac{1}{2}$ of the true value. Additionally, if pumps are used in multiple combinations throughout the operational day, care should be taken to determine the actual peak loading on the filters during the day. The peak instantaneous operating flow should be determined based on the flow distributed to the filters on a maximum daily minute. The peak instantaneous operating flow that each filter sees is dependent on the minimum number of filters used per day at the plant's peak instantaneous operating flow.

Table 5-3. General Guide to Acceptable Filter Hydraulic Loading Rates

| Filtration Type | Air Binding | Loading Rate |
|-----------------------------------|-------------|--------------------------------|
| Sand Media | None | ~2.0 gpm/ft ² |
| | Exists | ~1.0 - 1.5 gpm/ft ² |
| Dual/Mixed Media | None | ~4.0 gpm/ft ² |
| | Exists | ~2.0 - 3.0 gpm/ft ² |
| Deep bed (anthracite > 60 in.) | None | ~6.0 gpm/ft ² |
| | Exists | ~3.0 - 4.5 gpm/ft ² |

Example 1

A plant which operates 24 hours per day uses three 5-mgd pumps in various combinations throughout the year to meet system demand. The pumps are capable of being throttled to reduce individual flow to 80 percent of capacity. The average daily

production is 8 mgd while the peak production day over a previous 2-year period has been 12 mgd. The plant in the previous two years has never run all three pumps simultaneously for an entire day. However, for a 2-hour period each evening, all three pumps are used to fill on-site storage. Two pumps are used for the first hour with the third pump only used with the other two pumps for the last 30 minutes of the 2-hour period. During that 30 minute period plant flow increases to 14 mgd. The peak instantaneous operating flow that go onto the filters is 14 mgd. The plant's six dual media filters (each 425 ft²) would have a loading rate of 3.8 gpm/ft² at this 14 mgd peak flow.

Example 2

A plant with 8 dual media filters and a constant high service pumping rate of 8 mgd operates 24 hours per day and is unable to consistently meet the filter requirements. Each filter has 175 ft² of surface area and typically has a flow rate of 1 mgd. However, two filters are backwashed per day at the same time with no reduction in plant flow. During backwash the two filters are out of service for 40 minutes. During that 40 minute period the entire plant flow of 8 mgd is handled by just six filters. The peak instantaneous operating flow for each filter becomes 1.33 mgd. The hydraulic loading rate in gpm/ft² for each 175 ft² filter at this peak flow becomes 5.3 gpm/ft² (1.33 mgd converted to gpm divided by the filter surface area) which is at the upper end of the acceptable loading rates for a dual media filter and may be contributing to the unacceptable performance.

5.4 Assessing Condition & Placement Of Filter Media

Assessment of the condition and placement of the filter media is an integral step in identification of factors limiting performance of the filtration process. The presence of mudballs, surface cracking, or displaced media may often be attributed to excessive use of coagulant chemicals, inadequate backwashing or a more serious problem related to the underdrain system. The assessment of the condition and placement of the filter media should include a physical inspection of the filter bed and a comparison of the actual media findings to the original specifications. The filter bed should be investigated for surface cracking, proper media depth, presence of mudballs and segregation of media.



Figure 5-2. Box Used for Excavation

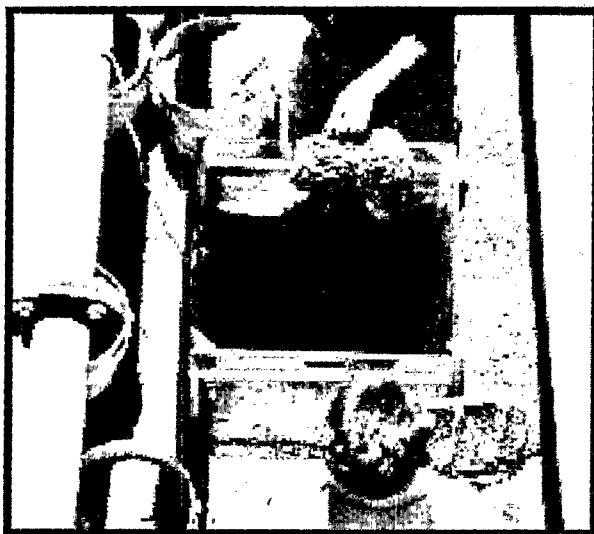


Figure 5-3. Box Excavation Demonstration

The filter inspection should begin by draining the filter. The filter should be drained enough to allow for excavation of the media to assess the depths of each media type, as well as, each media interface (e.g., just below the anthracite/sand interface in a dual media filter). Deeper excavation of the filter may be necessary if evidence suggests disrupted support gravels or an inadequate underdrain system (see Section 5.6). Care should be taken not to disrupt the support gravel/media.

Filter media assessments may be conducted using a gross excavation of media technique or application of a variety of coring devices (typically a 1½ to 2 inch pipe). Coring methods offer

the advantage of being able to apply the Floc Retention Analysis procedure, if conditions warrant (see to Section 5.5). Evaluators should place small pieces of plywood on the media prior to getting on the filters to avoid sinking into the media. The excavation technique may be conducted using a gross excavation of the media or a plexiglass box shown in Figures 5-2 and 5-3. The box excavation consists of sinking a plexiglass box into the media and excavating inside the box down to the support media. The box excavation technique allows for visual observation of the media depths and interfaces after the excavation is completed.

Whatever media excavation technique is used, the evaluators should note the depth of each media type, (comparing this to the original specifications), the general condition of the media interface, the presence of any mudballs or excess chemical. After the excavation is completed, the excavation team should make certain that the media is placed back in the excavations in the same sequence that it was removed. The filter should be backwashed after completion of the excavation prior to return to service.

5.5 Assessing Backwash Practices

Proper maintenance of filters is essential to preserve the integrity of the filter as constructed. Limitations of poor performing filters relating to filter media degradation or disruption of support gravel placement can often be attributed to inadequate backwashing or excessive backwashing rates. The duration of the backwash, if excessive, may also be detrimental. Different facilities have had different experiences in how clean the filters should be after backwashing. Consideration should be given to site-specific circumstances in the application of any recommendations regarding filter backwash procedures with the focus always being on filter effluent water quality. Table 5-4 summarizes guidelines for acceptable backwashing practices.

Table 5-4. Guidelines Regarding Acceptable Backwashing Practices

| Area of Emphasis | Guideline |
|-------------------------------|--|
| Basis for initiating backwash | focus on filter performance (turbidity, particle counts) degradation versus headloss or time |
| Backwash flow | slowly ramped to peak rate |
| Backwash flow rate | 15 - 20 gpm/ft ² |
| Bed expansion during backwash | 20 - 25 percent |

The assessment of the filter backwash procedure should include the following:

- A collection of general information related to the backwash;
- Verification of the adequacy of the backwash SOP;
- A visual inspection of a backwash; and
- Determination of the backwash rate and expansion of the filter media during the wash.

The individual filter assessment worksheet (Table 5-1) can be used to collect general information regarding the backwash.

An adequate backwash SOP should describe specific steps regarding when to initiate backwash, how flows are ramped during the wash, when to start and stop surface wash or air scour, and duration of the wash.

Backwash rates are designed to provide adequate cleaning of the filter media without washing media into the collection troughs or causing disruption of the support gravels. Table 5-4 identifies generally acceptable backwash rates. These values are to be used as a guide when assessing adequacy of the backwash procedures. Backwash rates in gpm/ft² may be determined by simple calculation if backwash pump rates or backwash flows are available and known to be accurate. If these values are unavailable or suspect, backwash rates can be determined by performing a rise rate test of the filter. Periodic rise rate tests can also be used to verify the backwash flow measurement instruments. The rise rate test entails determining the amount of time it takes backwash water to rise a known distance in the filter bed. Typically, a metal rod marked at 1-inch intervals is fixed in the filter to enable measurement of the distance that water rises during the wash. The rise rate test should be conducted such that measurements are taken without the interferences of the wash water troughs in the rise volume calculation. Extreme care and great attention to safety should be followed while conducting the rise rate test. Rise rate is used to calculate backwash rate by dividing the rise volume for a known time period by the filter area as follows:

$$\begin{aligned} \text{rise} \cdot \text{volume}(\text{gal}) &= \text{filter} \cdot \text{surface} \cdot \text{area}(\text{ft}^2) \times \text{rise} \cdot \text{distance}(\text{ft}) \times 7.48(\text{gal} / \text{ft}^3) \\ \text{backwash} \cdot \text{rate}(\text{gpm} / \text{ft}^2) &= \frac{\text{rise} \cdot \text{volume}(\text{gal}) / \text{rise} \cdot \text{time}(\text{min})}{\text{filter} \cdot \text{surface} \cdot \text{area}(\text{ft}^2)} \end{aligned}$$

Example backwash rate calculation: A filter having a 150 ft² surface area has wash water rise 10.7 inches in 20 seconds during the rise rate test. The backwash rate would be 20 gpm/ft².

$$\begin{aligned} \text{rise} \cdot \text{volume} &= 150 \text{ ft}^2 \times 10.7 \text{ in} \times \text{ft} / 12 \text{ in} \times 7.48 \text{ gal} / \text{ft}^3 = 1000 \text{ gal} \\ \text{backwash} \cdot \text{rate}(\text{gpm} / \text{ft}^2) &= \frac{1000 \text{ gal} / (20 \text{ sec} \times (\text{min} / 60 \text{ sec}))}{150 \text{ ft}^2} \\ \text{backwash} \cdot \text{rate} &= 20 \text{ gpm} / \text{ft}^2 \end{aligned}$$

In addition to backwash rate, it is also extremely important to expand the filter media during the wash to maximize the removal of particles held in the filter or by the media. Bed expansion is determined by measuring the distance from the top of the unexpanded media to a reference point (e.g., top of the filter wall) and from the top of the expanded media to the same reference point. The difference between these two measurements is bed expansion. A proper backwash rate should expand the filter 20 to 25 percent (AWWA and ASCE, 1990). Attention should be given to the influence of seasonal temperature changes on bed expansion during application of this procedure. Percent bed expansion is given by dividing the bed expansion by the total depth of expandable media (i.e., media depth less support gravels) and multiplied by 100 as follows:

$$\begin{aligned} \text{expanded} \cdot \text{measurement} &= \text{depth} \cdot \text{to} \cdot \text{top} \cdot \text{of} \cdot \text{media} \cdot \text{during} \cdot \text{backwash}(\text{inches}) \\ \text{unexpanded} \cdot \text{measurement} &= \text{depth} \cdot \text{to} \cdot \text{top} \cdot \text{of} \cdot \text{media} \cdot \text{before} \cdot \text{backwash}(\text{inches}) \\ \text{bed} \cdot \text{expansion} &= \text{unexpanded} \cdot \text{measurement}(\text{inches}) - \text{expanded} \cdot \text{measurement}(\text{inches}) \\ \text{bed} \cdot \text{expansion}(\text{percent}) &= \frac{\text{bed} \cdot \text{expansion} \cdot \text{measurement}(\text{inches})}{\text{total} \cdot \text{depth} \cdot \text{of} \cdot \text{expandable} \cdot \text{media}(\text{inches})} \times 100 \end{aligned}$$

A variety of apparatus can be used to measure bed expansion. The apparatus can vary from a metal shaft with a white disk attached on one end and a steel measuring tape fitted along the shaft to a metal pole with an attached collection of pipe segments of varying lengths each plugged at the bottom. The pipes are arranged like a set of church organ pipes with each pipe 1-inch longer than the next (see Figure 5-4). The unit is solidly affixed, resting on the top of the media.

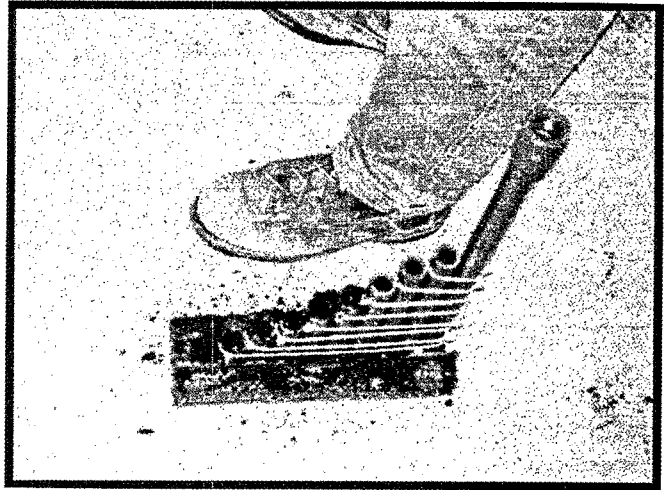


Figure 5-4. Pipe Bed Expansion

During backwashing, the expanded media fills each successive piece of pipe until the rise stops. Care should be taken to affix the pipe organ apparatus such that it can easily be determined where bed expansion ended because during certain situations, all of the pipe segments will be filled with expanded media making it impossible to accurately determine media expansion. During this situation, the apparatus should be emptied, affixed higher in the filter above the media and the bed expansion test repeated. The disk unit is used by placing the disk on the unexpanded media prior to backwash and recording the length of the metal rod to the reference point. The disk unit is then removed and backwashing is initiated. After the backwash is allowed to reach its peak rate the disk is lowered slowly into the backwashing filter until media is observed on the disk. The measurement of the expanded media is then recorded and percent bed expansion may then be determined. Figure 5-5 depicts the disk bed expansion apparatus. The key attribute of any method is that determination of the top of the expanded media be accurately characterized.



Figure 5-5. Bed Expansion Device

Example bed expansion calculation:

The backwashing practices for a filter with 30 inches of anthracite and sand is being evaluated. While at rest, the distance from the top of the media to the concrete floor surrounding the top of the filter is measured to be 41 inches. After the backwash has been started and the maximum backwash rate is achieved, a probe containing a white disk is slowly lowered into the filter bed until anthracite is observed on the disk. The distance from the expanded media to the concrete floor is measured to be 34½ inches. The resultant percent bed expansion would be 22 percent.

unexpanded measurement = 41 inches

expanded measurement = 34.5 inches

bed expansion = 6.5 inches

*bed expansion (percent) = (6.5 inches / 30 inches) * 100 = 22 percent*

Use of the Floc Retention Analysis procedure may be warranted if the filter is meeting backwash expansion and backwash rate guidelines while still not achieving turbidity performance criteria. (Kawamura, 1991, Wolfe & Pizzi, 1998.) The Floc Retention Analysis procedure allows for an extremely in-depth analysis of backwash practices.

5.6 Assessing Condition Of Support Media/Underdrains

Maintaining the integrity of the support gravels and underdrains is extremely important to the performance of a rapid granular filter. Disrupted or unevenly placed support media can lead to rapid deterioration of the filtered water quality noticeable by quick turbidity breakthroughs and excessively short filter runs (Peck, Smith). Should disruption of the support media be significant, the impacted area of the filter may act as a "short-circuit" allowing particulates and any microbial pathogens which are present to pass directly into the clearwell. Filter support gravels can become disrupted by various means including sudden violent backwash, excessive backwashing flow rates, or uneven flow distribution during backwash.

The condition of the support gravel is assessed in three steps. The first step consists of visually inspecting the filter during a backwash for the presence of excessive air boiling or noticeable vortexing as the filter is drained. The second step entails determining whether filter media has ever been found in the clearwell. This should be determined visually or by reviewing recent clearwell maintenance records. Clearwell inspections should be only be conducted following appropriate safety procedures while minimizing negative impacts on necessary plant operations. Clearwells containing a significant amount of filter media may indicate a greater problem than just disrupted support gravels. The problem may be attributed to a severe issue with the filter underdrain system. An in-depth assessment of the underdrains typically involves excavation of the entire filter bed. Systems should use best professional judgement and seek additional guidance if undertaking an underdrain assessment, as it is outside the scope of "typical" filter self

assessment. The third step is the most common method of assessing the placement of filter support media. This method involves "mapping" of the filter using a steel or solid probe. The mapping procedure involves a systematic probing through the filter media down to the support gravels of a drained filter at various locations in a grid-like manner. At each probe location, the depth of penetration into the filter is measured against a fixed reference point such as the wash water troughs. The distance from the fixed reference point to the top of the support gravels should deviate less than 2 inches. **Care should be taken during the filter probing not to disrupt the support gravel.**

Example

Operators, while draining a poor performing filter, observed vortexing occurring at the far end of the filter. The operators constructed a support gravel placement grid by probing through the media down to the support gravel every 2 feet throughout the filter using a 6 feet long aluminum rod that had been marked at 1-inch intervals. The operator using the probe measured the depth of probe penetration against the wash water trough.

Examination of the grid (shown in Table 5-5) indicated that the support gravels were extremely disrupted at the far end of the filter.

Table 5-5. Example Filter Support Gravel Placement Grid

Depth of Filter Support Gravels (in inches)
Measured from the Wash Water Trough

| | | | Filter Control Panel | | |
|-------|-------|-------|----------------------------|-------|-------|
| | 2 ft | 4 ft | 6 ft | 8 ft | 10 ft |
| 2 ft | 41 | 40.75 | 41 | 41 | 41 |
| 4 ft | 40.75 | 40.5 | 41 | 41 | 40.75 |
| 6 ft | 41 | 41.25 | 40.75 | 41 | 41 |
| 8 ft | 40.75 | 41 | 41 | 40.75 | 40.75 |
| 10 ft | 41 | 41 | 40.5 | 40.5 | 40.75 |
| 12 ft | 41 | 46 | 46.5 | 41 | 41 |
| 14 ft | 40.75 | 46 | 46.25 | 39 | 40.75 |
| 16 ft | 41 | 39 | 38.75 | 37 | 40.75 |
| 18 ft | 40.75 | 41.25 | 40.75 | 41 | 41 |

5.7 Assessing Rate-Of-Flow Controllers & Filter Valve Infrastructure

The rate-of-flow controllers and ancillary valving related to the filter can also have an impact on filter performance. Hydraulic changes (such as those caused by filter bumping) cause filters to shed particles. Maintaining the rate-of-flow controllers is important in minimizing hydraulic changes in the filter. Figure 5-6 shows on-line turbidity measurements for two filters in a treatment plant. Each of the two filters had rate-of-flow controller problems that became more evident as headloss built up in the filters. Just prior to initiating backwash in filter 4 the rate-of-flow controllers were opening and closing constantly "seeking" the correct position. This was first apparent to the filter evaluation team who observed constant turbidity fluctuations of the filter effluent during a filter performance review. Improperly seated valves can also have similar impacts on filter performance. Backwash valves may leak and allow wash water to compromise filter effluent coming from the filters remaining in operation. All filter assessments should include an evaluation of all the rate-of-flow controllers and filter valving.

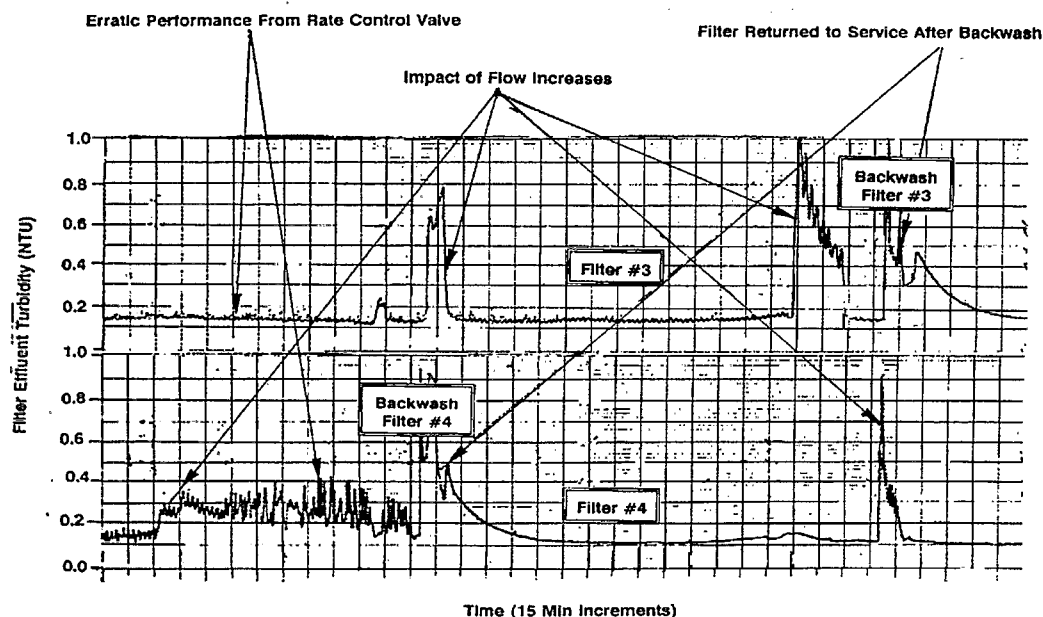


Figure 5-6. On-Line Turbidimeters Showing Performance Problems Due to Inoperable Rate-of-Flow Controllers

5.8 References

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6. COMPREHENSIVE PERFORMANCE EVALUATION

6.1 Introduction

Based on individual filter monitoring requirements in the IESWTR, some systems may be required to arrange for a Comprehensive Performance Evaluation (CPE). Specifically, systems must conduct a CPE if any individual filter has a measured turbidity level of greater than 2.0 NTU in two consecutive measurements taken 15 minutes apart in two consecutive months. The system must report the filter number, the turbidity measurement, and the date(s) on which the exceedance occurred. The system shall contact the State or a third party approved by the State to conduct a CPE.

A CPE is the evaluation phase of the Composite Correction Program (CCP). The CCP, including detailed CPE procedures and qualifications for CPE providers, is described in a separate handbook (USEPA, 1998). This chapter's goal is to present a fundamental discussion of CPE concepts and provide a general understanding of what a plant should expect when a CPE is completed. Detailed CPE procedures are not included in this guidance manual. Detailed CPE procedures should be obtained from the CCP Handbook (available by calling the EPA Safe Drinking Water Hotline at 1-800-426-4791).

6.2 Background On The CPE

The CCP is a systematic, comprehensive procedure that identifies and corrects the unique combination of factors, in the areas of design, operation, maintenance and administration, that limit the performance of a filtration plant. It was developed to improve performance at filtration plants using existing facilities thereby minimizing construction alternatives. The capable plant model, presented in Figure 6-1, shows conceptually how the CCP considers the various aspects of the operation, design, maintenance, and administration of a filtration plant. A plant is considered capable when it has treatment processes of sufficient size with adequate mechanical equipment to meet current water demand, adequate administrative support including funding and policies, and a maintenance program that keeps key equipment operational. Once these components are in place, proper operations capabilities are required for the plant to achieve its performance goals, whether for regulatory compliance or treatment optimization.

At the core of the CCP is the assumption that if a filtration plant cannot achieve specific performance, there is a unique combination of interrelated factors with respect to the design, maintenance, administration and/or operations of the filtration plant that are limiting its performance. The purpose of the CPE is to identify these factors and prioritize them with respect to their relative importance in preventing compliance and/or optimized performance. Once the factors are identified and prioritized they can be corrected so that performance can improve and compliance can be achieved. During a CPE, the historic performance of the plant is assessed with respect to pathogen removal

and inactivation. The design, administration, and maintenance of the plant are completely reviewed to determine if they properly support a capable plant. If they are not supporting a capable plant, the root causes are identified as to how they are contributing to the performance problem. Operational practices are also reviewed to assess if operators have the necessary skills to achieve required performance and compliance when provided with a capable plant.

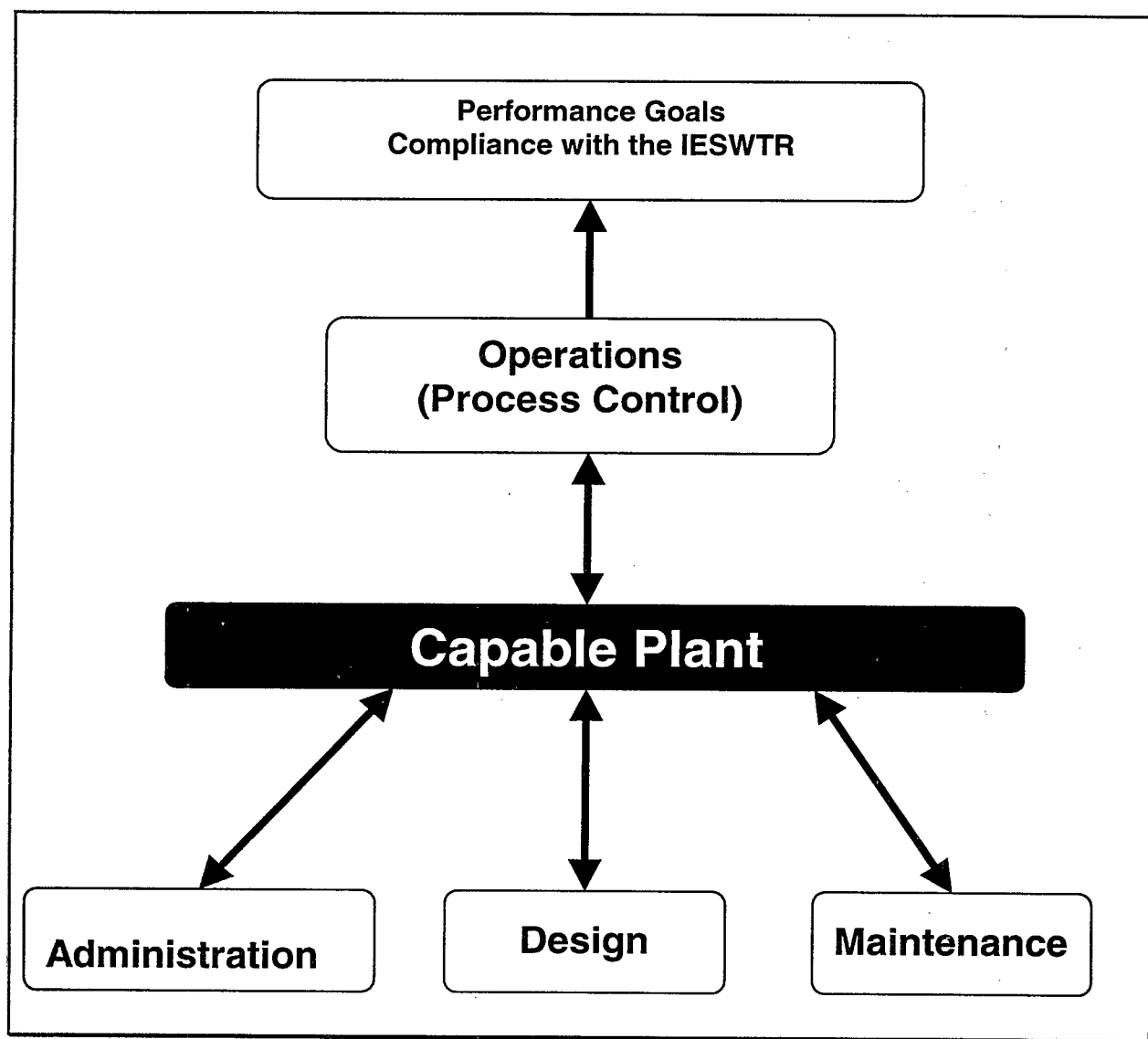


Figure 6-1. Capable Plant Model

In using the CPE/CCP it is important to understand that the approach has applications in addition to achieving regulatory compliance and should be applied as appropriate for meeting desired performance needs. All of the CPE procedures are designed to focus a plant toward meeting the compliance requirements and performance goals described in Table 6-1.

Table 6-1. CPE Treatment Performance Goals

| | IESWTR Compliance Requirements | CCP Optimized Performance Goals |
|--|---|---|
| <i>Minimum Data Monitoring and/or Reporting Requirements</i> | Continuous individual filter turbidity monitoring with values recorded at 15 minute intervals (conventional and direct filtration systems). Representative filtered/finished water effluent turbidity every 4 hours. | Daily raw water turbidity. 4-hour settled water turbidity from each sedimentation basin. On-line continuous turbidity from each filter. |
| <i>Individual Sedimentation Basin Performance Criteria</i> | Not applicable. | Settled water turbidity less than 1 NTU 95 percent of the time when raw water turbidity is less than or equal to 10 NTU. Settled water turbidity less 2 NTU 95 percent of the time when raw water turbidity is less than or equal to 20 NTU. |
| <i>Individual Filter Performance Criteria</i> | Maximum filtered water turbidity of 1 NTU in two consecutive measurements taken 15 minutes apart (conventional and direct filtration systems). Maximum filtered water turbidity 4 hours following backwash of less than 0.5 NTU in two consecutive measurements taken 15 minutes apart (conventional and direct filtration systems). | Filtered water is less than 0.1 NTU 95 percent of the time (excluding 15 minute period following backwashes) based on maximum values recorded during 4-hour increments. Maximum filtered turbidity measurement of 0.5 NTU. Maximum filtered water turbidity following backwash of less than 0.3 NTU. Maximum backwash recovery period of 15 minutes (e.g., return to less than 0.1 NTU). Maximum filtered water measurement of less than 10 total particles per milliliter (>30m) of particle counts are available. |
| <i>Combined Filtered Water Performance Criteria</i> | Representative filtered/finished water turbidity less than 0.3 NTU 95 percent of the time based on 4-hour measurements (conventional and direct filtration systems). Maximum filtered/finished water turbidity of 1 NTU based on 4-hour measurements (conventional and direct filtration systems). | |
| <i>Disinfection Performance Criteria</i> | CT values to achieve required log inactivation of <i>Giardia</i> and viruses. | CT values to achieve required log inactivation of <i>Giardia</i> and viruses. |

6.3 Components of a CPE

A CPE consists of the following three components:

- Performance assessment (evaluates historical plant performance);
- Major unit process evaluation (for assessing the physical plant capabilities); and
- Factors limiting performance.

The following subsections discuss each of these components; detailed procedures are provided in the CCP Handbook.

6.3.1 Performance Assessment

The performance assessment component of the CPE determines the status of a facility relative to achieving compliance requirements and performance goals and verifies the extent of any performance problems at the plant. This information also provides the CPE evaluators with some initial insights on possible causes of performance problems. These insights are then used to focus other activities during the CPE to assess the design, operation, maintenance and administration of the plant. Historical turbidity data from plant records is used, supplemented by data collected during the CPE.

To achieve desired performance levels (compliance or optimized), a water treatment plant should demonstrate that it can take a raw water source of variable quality and produce a consistent, high quality finished-water. Further, the performance of each unit process should demonstrate its capability to act as a barrier to the passage of particles at all times. The performance assessment determines if major unit treatment processes consistently perform at optimum levels to provide maximum multiple barrier protection. If performance is not optimized, the assessment also provides valuable insights into possible causes of the performance problems and serves as the basis for other CPE findings.

During the performance assessment, historical turbidity data for the raw, settled, and finished water is collected from the plant records and trends are charted as shown in Figure 6-2. From this example data the CPE evaluator can see that the plant treats a raw water that varies moderately throughout the year. The settled and finished water performance indicates that this plant has a performance problem since turbidity levels produced for treatment processes are significantly above compliance requirements and performance goals described in Table 6-1.

Figure 6-2 also shows how the CPE evaluator can use the performance assessment to gain some insights into the causes of the poor performance. In reviewing this data it is apparent that a spike in raw water turbidity on March 9th carried through the plant resulting in finished water turbidities close to 1 NTU. These pass through variations and spikes provide some insight into the root cause of these performance problems that the CPE evaluators will use to direct the subsequent portions of the CPE. Typically, these types of performance problems are related to the process control skills of the plant staff, but other design and/or administrative issues or raw water events may also make a

significant contribution to the problem. During their review of the design, operation and administration of the plant, the CPE evaluators will use these insights to focus the discussions they have with the plant staff. Information on the possible causes of this spike will be investigated until the evaluators are sure they understand the root cause.

Additional data is collected during the CPE to confirm the historical performance data, further assess the performance of individual treatment processes, and confirm insights on possible causes of poor performance. Typically additional data is collected through special studies including the following:

- Verification of filtered turbidity results by independently comparing a system's measurements with measurements from a continuous turbidimeter brought by the CPE evaluators. If the plant is not already individually measuring turbidity from each filter, the CPE team can select the filter which the operators believe has the most problems and collect individual filter data on that filter.
- Filter inspections for media depth and media condition.
- Filter media expansion during backwash.
- Verification of chemical dosages to be sure plant staff are actually adding the amount of chemicals they are intending to add.
- Verification of the benchtop turbidimeter in the plant laboratory with a unit brought by the CPE evaluators.

Additional data on the performance of individual sedimentation basins may also be collected depending on the needs of the CPE evaluators. Continuous monitoring of individual filters during the CPE allows for an in-depth assessment of the filter performance during critical periods of startup, backwash, and/or changes in plant flow rates. Figure 6-3 shows the performance of a filter during a CPE immediately after start-up following a backwash. Backwash spikes of this magnitude also indicate a possible problem with the plant's process control procedures.

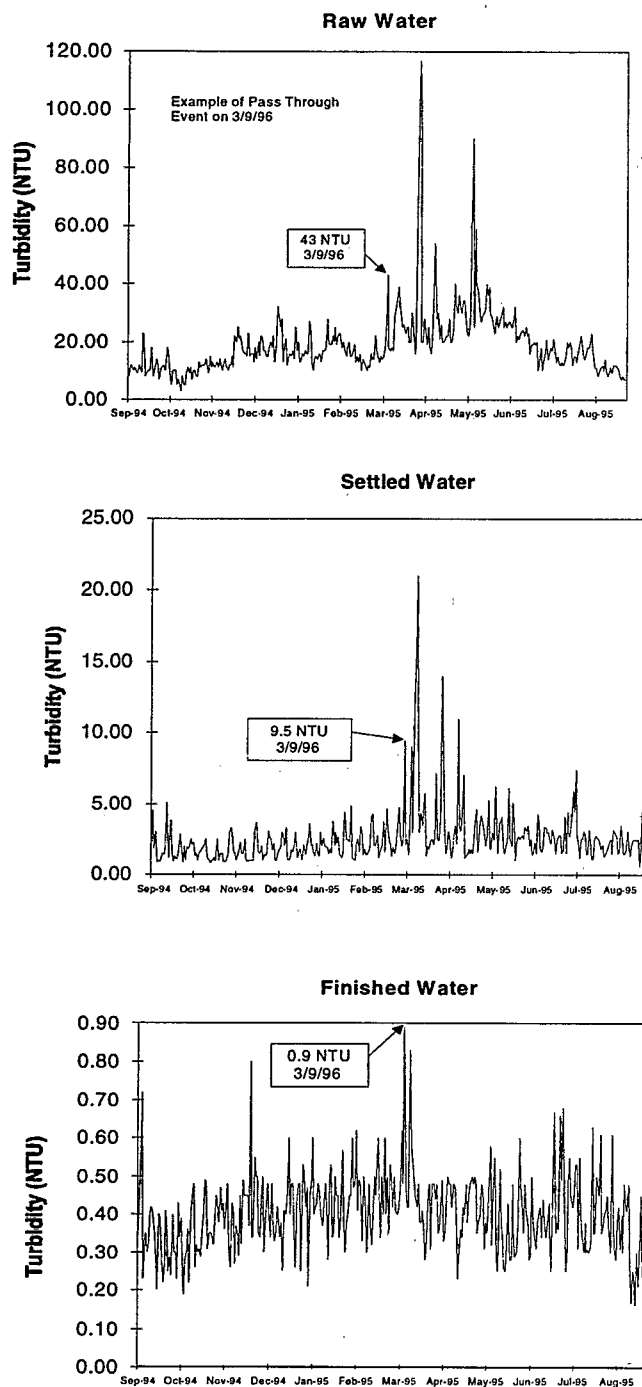


Figure 6-2. An Example of Performance Assessment Using Historical Data

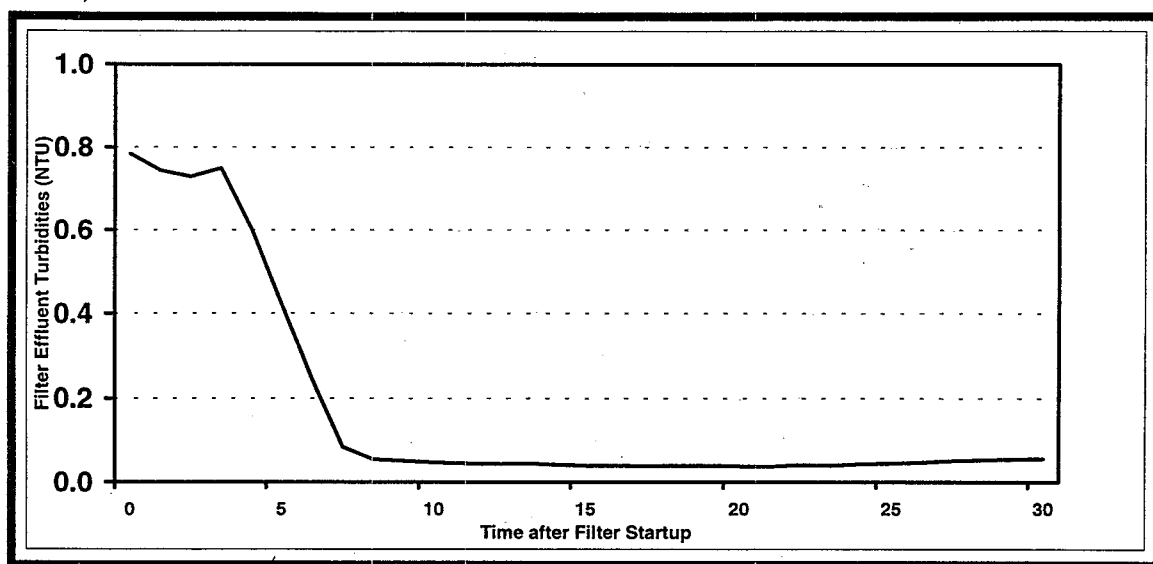
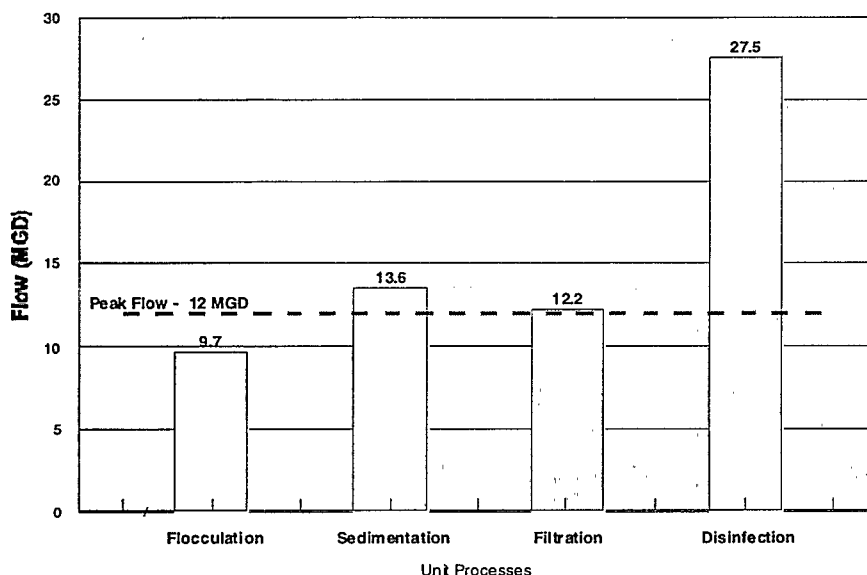


Figure 6-3. An Example of Individual Filter Data Collected During CPE

6.3.2 Major Unit Process Evaluation

After the performance assessment, the CPE begins to focus on the causes of the identified performance problems. The major unit process evaluation determines if the various key existing treatment processes in the plant, if properly operated, are of sufficient size to meet the performance goals at the plant's current peak instantaneous operating flows. If the evaluation indicates that the major unit processes are of adequate size, then the opportunity for the existing facility to achieve compliance by addressing operational, maintenance or administrative limitations is available. If, on the other hand, the evaluation shows that major unit processes are too small, then construction of new or additional processes may be required to obtain compliance or optimize performance.

The major unit process evaluation only considers if the existing treatment processes are of adequate size to treat current peak instantaneous operating flows and to meet the desired performance levels. The intent is to assess whether existing facilities, in terms of concrete and steel, are adequate. This evaluation does not review the adequacy or condition of existing mechanical equipment. The evaluation assumes that if the concrete and steel are not of adequate size then major construction may be warranted, and the pursuit of purely operational approaches to achieve performance may not be prudent. The condition of the mechanical equipment around the treatment processes is an important issue, but in this part of the CPE it is assumed that the potential exists to repair and/or replace this equipment without the disruption of the plant inherent to a major construction project. These types of issues are addressed in the factors limiting performance component of the CPE. It is also presumed in the major unit process evaluation that the necessary process control procedures are in place and practiced to meet performance goals. By assuming that the equipment limitations can be addressed and that operational practices are optimum, the evaluator can project the performance potential or capability of a unit process to achieve performance goals.



Flocculation criteria: Hydraulic detention time = 30 minutes; total volume = 202,500 gal; single stage, tapered flocculation
 Sedimentation criteria: Surface loading rate = 0.7 gpm/ft²; total surface area = 13,440 ft²; swd=15 ft
 Filtration criteria: Surface loading rate = 4 gpm/ft²; 6 filters in service; 30 inches mixed media
 Disinfection criteria: Total Giardia inactivation = 3 log, 0.5 log required by disinfection; available volume = 900,000 gallons @ depth = 10 ft; pH = 7.5; temp = 0.5 C; chlorine residual = 1.5 mg/L; T10/T = 0.7

Figure 6-4. Example Performance Potential Graph

During the CPE, a performance potential graph similar to that shown in Figure 6-4 is developed. The four treatment processes included in this major unit process evaluation are flocculation, sedimentation, filtration and disinfection. The CPE evaluators determine the peak instantaneous operating flow that the plant has seen over the last year and collect data on the sizes of the various basins. To prepare the performance potential graph, the CPE evaluators should select loadings for each process that they consider adequate for the plant to achieve the performance goals. The assumptions and loadings used in this example are shown at the bottom of the graph. Based on these loadings a projected capacity is calculated and shown as a bar on the performance potential graph. Bars above the dashed line in Figure 6-4 represent unit processes that have the capacity to treat the peak instantaneous flow. Bars below the dashed line indicate processes where major or minor changes may be necessary.

6.3.3 Factors Limiting Performance

The last and most significant component of a CPE is the identification of factors that limit the filtration plant's performance. All information collected during the CPE is reviewed and the root causes of any performance problems are identified and prioritized. This step is critical in defining the future activities that the plant will need to focus on to achieve the compliance or optimized performance goals. To assist in factor identification, a list of 50 different factors and definitions that could potentially limit water treatment plant performance is provided in the CCP Handbook. These factors are divided into the four broad categories of administration, design, operation, and maintenance. This list and

definitions are based on the results of more than 70 water treatment plant CPEs. Definitions are provided for the convenience of the user as a reference to promote consistency in the use of factors from plant to plant and to assist others in interpreting the CPE results.

While the definitions for the administrative, operation and maintenance factors adequately explain when these factors are identified, the plant staff may find several of the design factors confusing when reviewing the CPE findings. Design factors are included for each of the treatment processes in the major unit process evaluation. If any of the treatment processes in the major unit process evaluation were classified as marginal or inadequate, they would be identified in the CPE findings as a factor limiting the plant's performance. Treatment processes that were identified as adequate in the major unit process evaluation can also be identified as a factor when there are equipment related problems that are limiting performance. This would occur when key equipment (e.g., filter rate-of-flow control valves) needs to be repaired and/or replaced before desired performance can be achieved.

A CPE is intended to be a performance-based evaluation and therefore factors should be identified only if they impact performance. A proper CPE does not contain factors that are primarily observations that a utility does not meet a particular "industry standard" (e.g., utility does not have a documented preventive maintenance program or does not practice good housekeeping) unless a clear link is made between the practice and the identified performance problem.

The major challenge in identifying a plant's unique list of factors is making sure that the root causes are identified. This is difficult because the actual problems in a plant are often masked. This concept is illustrated in the following example:

Example

A review of plant records revealed that a conventional water treatment plant was periodically producing finished water with a turbidity greater than 0.5 NTU. The utility, assuming that the plant was operating beyond its capability, was beginning to make plans to expand both the sedimentation and filtration unit processes. Field evaluations conducted as part of a CPE revealed that settled water and finished water turbidities averaged about 5 NTU and 0.6 NTU, respectively. Filtered water turbidities peaked at 1.2 NTU for short periods following a filter backwash.

Conceivably, the plant's sedimentation and filtration facilities were inadequately sized. The major unit process evaluation, however, showed that these processes were capable to handle the plant's current peak flows.

A review of the plant's operation procedures revealed that the poor performance was caused by the operator adding coagulants at excessive dosages, leading to formation of a pin floc that was difficult to settle and filter. The operators did not have an adequate process control program or equipment to allow them to identify and set the proper

chemical doses. Additionally, the plant was being operated at its peak capacity for only 8 hours each day, further aggravating the washout of solids from the sedimentation basins.

The CPE evaluators assessed that by implementing proper process control of the plant (e.g., jar testing for coagulant control, calibration and proper adjustment of chemical feed) and operating the plant at a lower flow rate for a longer time period would allow the plant to continuously achieve the desired performance.

When the operator and administration were questioned about the reasons that the plant was not operated for longer periods of time, it was identified that it was an administrative decision to limit the plant staffing to one person. This limitation made additional daily operating time as well as weekend coverage difficult.

It was concluded that three major factors contributed to the poor performance of the plant:

1. **Application of Concepts and Testing to Process Control:** Inadequate operator knowledge existed to determine proper coagulant doses and to set chemical feed pumps to apply the correct chemical dose.
2. **Administrative Policies:** A restrictive administrative policy existed that prohibited hiring an additional operator to allow increased plant operating time at a reduced plant flow rate.
3. **Process Control Testing:** The utility had inadequate test equipment and an inadequate sampling program to provide process control information.

In this example, pursuing the perceived limitation regarding the need for additional sedimentation and filtration capacity would have led to improper corrective actions. Completing a plant expansion without correction of the operation and administrative factors probably would not have solved the performance problems. The limitations in process control would have remained even with a new plant. Administrative policies that led to insufficient staffing of the old plant could have remained with a new plant. The CPE, however, indicated that addressing the identified operational and administrative factors would allow the plant to achieve the desired performance on a continuous basis without major expenditures for construction. The funds that initially were directed towards construction could then be directed towards other factors that truly are limiting the plant's performance.

This example illustrates that a comprehensive analysis of a performance problem is essential to identify the actual performance limiting factors. The CPE emphasis of assessing factors in the broad categories of administration, design, operation, and maintenance helps to ensure the identification of root causes of performance limitations.

6.4 Activities During a CPE

When a plant is required or decides to have a CPE conducted, there are several activities that they should expect to occur. In general, if all of the following activities do not occur,

the plant should question whether the evaluators are following the procedures in the CCP Handbook.

A CPE involves numerous activities conducted within a structured framework. A schematic of CPE activities is shown in Figure 6-5. Initial activities are conducted prior to on-site efforts and involve notifying appropriate plant personnel to ensure that they, as well as other necessary resources, will be available during the CPE. The kick-off meeting, conducted on site, allows the evaluators to describe forthcoming activities, to coordinate schedules, and to assess availability of the materials that will be required.

Following the kick-off meeting, a plant tour is conducted by the superintendent or process control supervisor. During the tour, the evaluators ask questions regarding the plant and observe areas that may require additional attention during data collection activities. For example, an evaluator might make a mental note to investigate more thoroughly the flow splitting arrangement prior to flocculation basins if one basin appeared to receive more flow than the other units (e.g., flooding).

Following the plant tour, data collection activities begin. Depending on team size, the evaluators split into groups to facilitate simultaneous collection of the administrative, design, operations, maintenance, and performance data. Appropriate forms are provided in Appendix F of the CCP Handbook to facilitate the data collection activities. After data are collected, the performance assessment and the major unit process evaluation are conducted. It is noted that often the utility can provide the performance data prior to the site visit. In this case the performance graphs can be completed prior to the on-site activities. However, it is important to verify the sources of the samples and quality of the data during field efforts.

Field evaluations are also conducted to continue to gather additional information regarding actual plant performance and confirm potential factors. This activity may typically include a special study focusing on an individual filter or filters. Once all of this information is collected, a series of interviews are completed with the plant staff and administrators. Initiating these activities prior to the interviews provides the evaluators with an understanding of current plant performance and plant unit process capability, which allows interview questions to be more focused on potential factors.

After all information is collected, the evaluation team meets at a location isolated from the utility personnel to review findings. At this meeting, factors limiting performance of the plant are identified and prioritized. The prioritized list of factors, performance data, field evaluation results, and major unit process evaluation data are then compiled and copied for use as handouts during the exit meeting.

An exit meeting is held with appropriate operations and administration personnel where all evaluation findings are presented and the plant staff are given the opportunity to ask questions. **The evaluation team answers clarifying questions during the exit meeting but does not make recommendations or offer solutions to the factors identified.** A CPE report is then generated off-site by the CPE providers which formalizes the information presented in the exit meeting. **It is intended that all of the CPE findings**

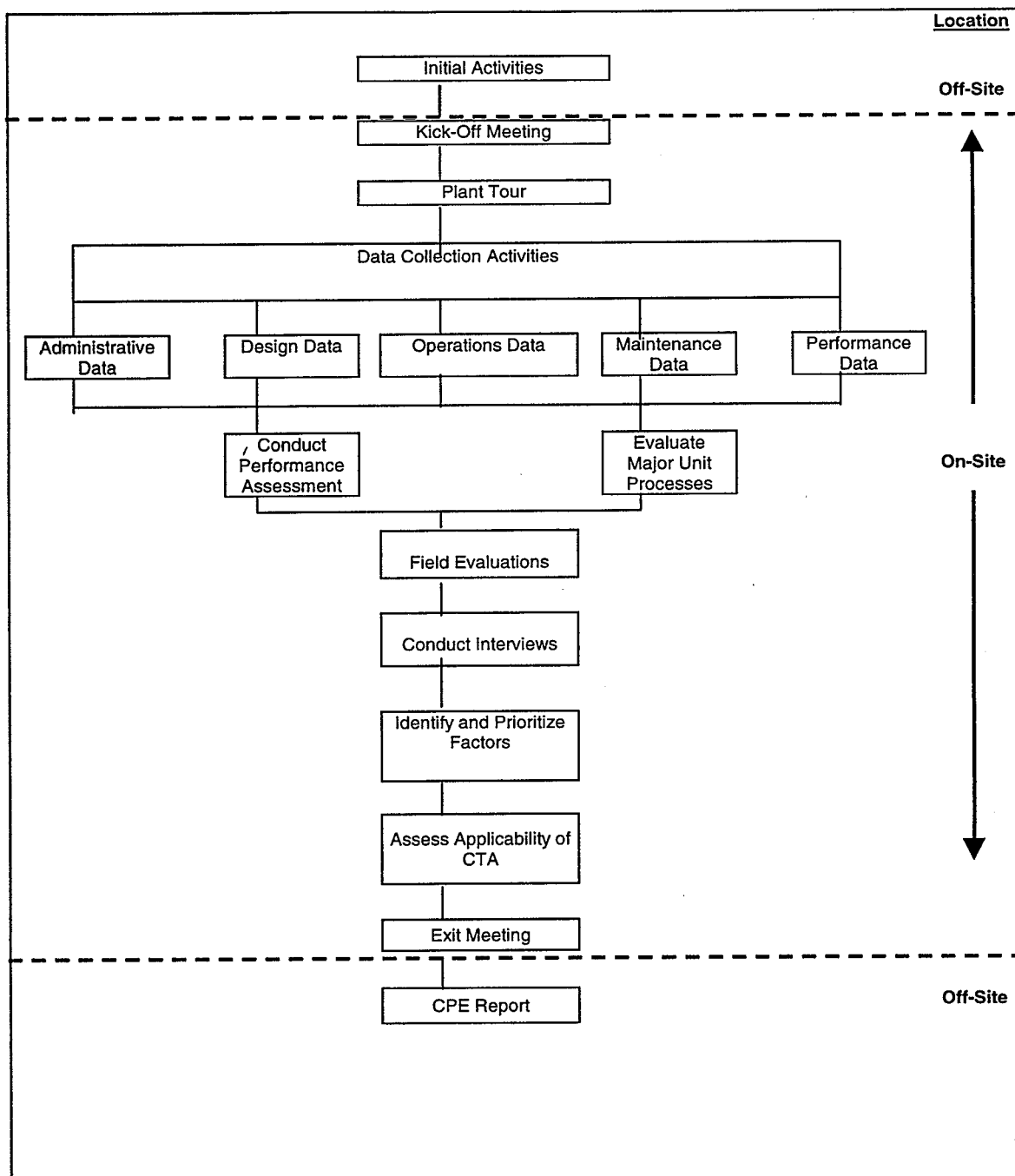


Figure 6-5. Activities During a CPE

are presented in the exit meeting and it is critical that the report not present any additional findings. The CPE provider should not save any controversial findings for the report.

A CPE is typically conducted over a three to five-day period by a team consisting of at least two personnel. A team approach is necessary to allow a facility to be evaluated in a reasonable time frame, and for evaluation personnel to jointly develop findings on topics requiring professional judgment. Professional judgment is critical when evaluating subjective information obtained during the on-site CPE activities. For example, assessing administrative versus operational performance limiting factors often involves the evaluators' interpretation of interview results. The synergistic effect of two people making this determination is a key part of the CPE process.

Because of the wide range of areas that are evaluated during a CPE, the evaluation team needs to have a broad range of available skills. This broad skills range is another reason to use a team approach in conducting CPEs. Specifically, persons should have capability in the areas shown in Table 6-2.

Table 6-2. Evaluation Team Capabilities

| Technical Skills/Knowledge | Leadership Skills |
|---|--|
| • Water treatment plant design | • Communication (presenting, listening, interviewing) |
| • Water treatment operations and process control | • Organization (scheduling, prioritizing) |
| • Regulatory requirements | • Motivation (involving people, recognizing staff abilities) |
| • Maintenance | • Decisiveness (completing CPE within time frame allowed) |
| • Utility management (rates, budgeting, planning) | • Interpretation (assessing multiple inputs, making judgments) |

Regulatory agency personnel with experience in evaluating water treatment facilities, consulting engineers who routinely work with plant evaluation, design and start-up, and utility personnel with design and operations experience represent the types of personnel with appropriate backgrounds to conduct CPEs. Other combinations of personnel can be used if they meet the minimum experience requirements outlined above. Although teams composed of utility management and operations personnel associated with the CPE facility can be established, it is often difficult for an internal team to objectively assess administrative and operational factors. The strength of the CPE is best represented by an objective third party review.

6.5 CPE Quality Control

It is important for CPE providers and recipients of CPEs to be aware of appropriate CCP concepts and expectations of the process. The providers should maintain the integrity of the program and the recipients should make sure they receive the full benefit of the CPE.

This is accomplished by following the protocols described in the CCP Handbook. However, to assure effective and consistent CPE results, quality control considerations have been developed. Table 6-3 presents a checklist for CPE providers and recipients to assess the adequacy of a CPE relative to the guidance provided in the CCP Handbook. The following discusses some of the key areas of concern in more detail.

Table 6-3. Quality Control Checklist for Completed CPEs

| Checklist |
|---|
| <ul style="list-style-type: none"> Findings demonstrate emphasis on achievement of compliance and/or optimized performance goals (i.e., performance emphasis is evident in the discussion of why prioritized factors were identified). |
| <ul style="list-style-type: none"> Lack of bias associated with the provider's background in the factors identified (e.g., all design factors identified by a provider with a design background or lack of operations or administrative factors identified by the utility personnel conducting a CPE). |
| <ul style="list-style-type: none"> Emphasis in the CPE results to maximize the use of existing facility capability. |
| <ul style="list-style-type: none"> All components of the CPE completed and documented in a report (i.e., performance assessment, major unit process evaluation, identification and prioritization of factors, and assessment of CTA application). |
| <ul style="list-style-type: none"> Fewer than 15 factors limiting performance identified (i.e., excessive factors indicates lack of focus for the utility). |
| <ul style="list-style-type: none"> Specific recommendations are not presented in the CPE report, but rather, clear examples that support the identification of the factors are summarized. |
| <ul style="list-style-type: none"> Identified limitations of operations staff or lack of site-specific guidelines instead of a need for a third party-prepared operation and maintenance manual. |
| <ul style="list-style-type: none"> Findings address administrative, design, operation and maintenance factors (i.e., results demonstrate provider's willingness to identify/present all pertinent factors). |

A challenging area for the CPE provider is to maintain the focus of the evaluation on performance and public health protection. Often, a provider will tend to identify limitations in a multitude of areas which may not be related to the performance criteria. Typical areas may include poor plant housekeeping practices, lack of preventive maintenance, or lack of an operation and maintenance manual. Limitations in these areas are easily observed and do not challenge the capability of the operations staff. While they demonstrate a thoroughness by the provider to identify all issues, their identification may cause the utility to focus resources on these areas while ignoring areas more critical to achievement of performance goals. The evaluator should be aware that a utility may take the CPE results and only address those factors that are considered relatively easy to correct without consideration of priority or the inter-relatedness of the factors.

Another significant challenge in conducting an effective CPE is the tendency for providers to identify limitations that are non-controversial rather than real factors that may challenge the plant personnel's roles and responsibilities. For example, it is often

easy to identify a design limitation, since the utility could not be expected to achieve desired performance with inadequate facilities. It is much more difficult to identify "lack of administrative support" or an operator's "inability to apply process control concepts" as the causes of poor performance. This may be especially a problem when the CPE findings tend to criticize the administrators that have hired the CPE providers. Failing to appropriately identify these difficult factors is a disservice to all parties involved. **A common result of this situation is the utility addressing a design limitation without addressing existing administrative or operational issues.** Ultimately, these administrative and operational issues remain and impact the utility's ability to achieve desired performance. Understanding this concept allows the CPE provider to present the true factors, even though they may not be well received at the exit meeting. CPE recipients should be suspicious when a plant has a performance problem and no operations or administrative factors are identified.

A final consideration when implementing a CPE, is to understand the importance that specific recommendations involving plant modifications or day-to-day operational practices should not be made by the CPE provider or accepted without question by the recipient. For example, direction on changing coagulants or chemical dosages is not appropriate during the conduct of a CPE. These types of changes should be evaluated to determine if they are truly appropriate for the specific plant. A coagulant that worked for the CPE provider at one plant may not work for the plant being evaluated; causing unnecessary costs and/or poor performance. There is a strong bias for providers to give specific recommendations and for recipients to want specific checklists to implement. CPE providers should focus their observations during the evaluation on two key areas:

1. Identification of factors limiting the facility from achieving desired performance goals (compliance or optimized); and
2. Providing specific examples to support these factors.

Recipients should, also, not request specific guidance from the providers and, if this guidance is provided, they should make sure that the information provided is truly appropriate to their plant.

6.6 Next Steps

The results of the CPE provide systems and States with a thorough evaluation of processes at a treatment plant. CPE results identify factors which may be limiting performance and subsequently causing compliance problems. The CPE affords systems the opportunity to achieve improvements largely through administrative and operational changes. Most systems can implement any necessary changes through a self-improvement program, but if assistance is necessary facilities should work closely with EPA, the States, and technical assistance programs geared towards improving treatment plant performance.

The second phase of the CCP, the Comprehensive Technical Assistance (CTA), may be used to improve performance in a more formal and structured setting. During the CTA

phase, the system, with assistance from the State, identifies and systematically addresses plant-specific factors. The CTA is a combination of utilizing CPE results as a basis for follow-up, implementing process control priority-setting techniques, and maintaining long-term involvement to systematically train staff and administrators.

6.7 References

1. USEPA. 1998. *Handbook: Optimizing Water Treatment Plant Performance Using the Composite Correction Program*. EPA/625/6-91/027.

7. IMPORTANCE OF TURBIDITY

7.1 Overview

Section 2 of this guidance manual is included to present an overview on the definition and sources of turbidity. Understanding turbidity, its causes and sources, and the significance to human health will provide the background on which the new turbidity standards are based.

7.2 Turbidity: Definition, Causes, and History as a Water Quality Parameter

Turbidity is a principal physical characteristic of water and is an expression of the optical property that causes light to be scattered and absorbed by particles and molecules rather than transmitted in straight lines through a water sample. It is caused by suspended matter or impurities that interfere with the clarity of the water. These impurities may include clay, silt, finely divided inorganic and organic matter, soluble colored organic compounds, and plankton and other microscopic organisms. Typical sources of turbidity in drinking water include the following (see Figure 7-1):

- Waste discharges;
- Runoff from watersheds, especially those that are disturbed or eroding;
- Algae or aquatic weeds and products of their breakdown in water reservoirs, rivers, or lakes;
- Humic acids and other organic compounds resulting from decay of plants, leaves, etc. in water sources; and
- High iron concentrations which give waters a rust-red coloration (mainly in ground water and ground water under the direct influence of surface water).
- Air bubbles and particles from the treatment process (e.g., hydroxides, lime softening)

Simply stated, turbidity is the measure of relative clarity of a liquid. Clarity is important when producing drinking water for human consumption and in many manufacturing uses. Once considered as a mostly aesthetic characteristic of drinking water, significant evidence exists that controlling turbidity is a competent safeguard against pathogens in drinking water.

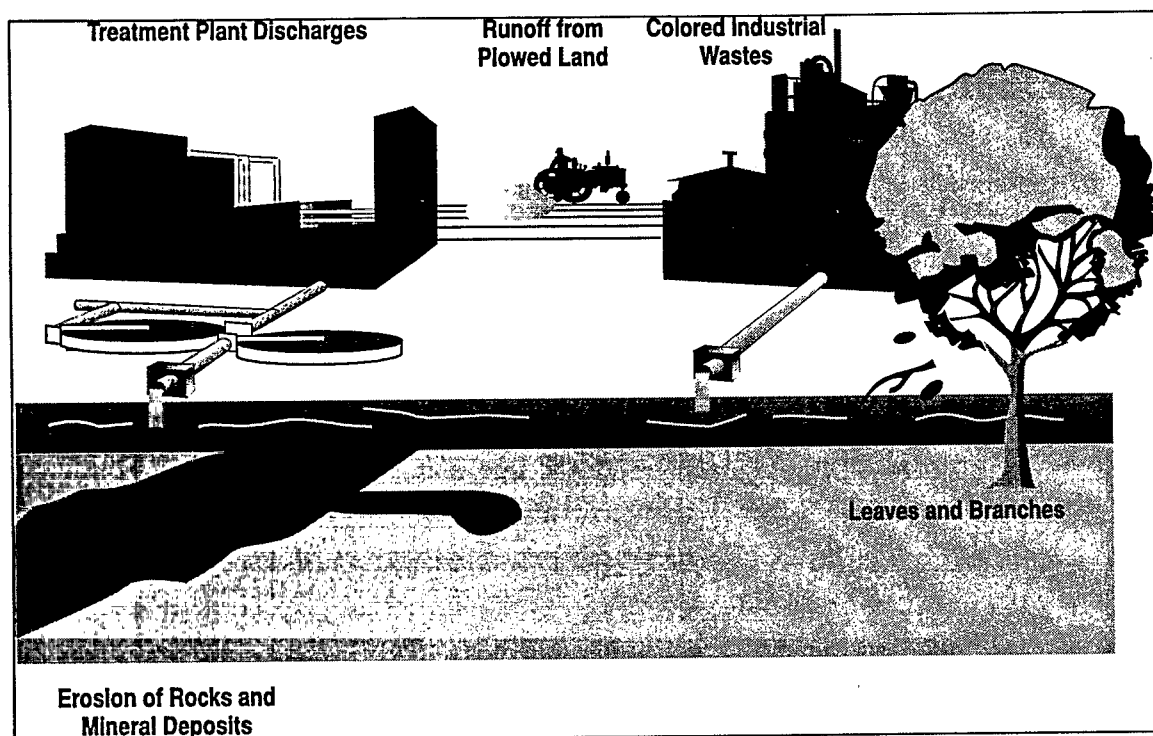
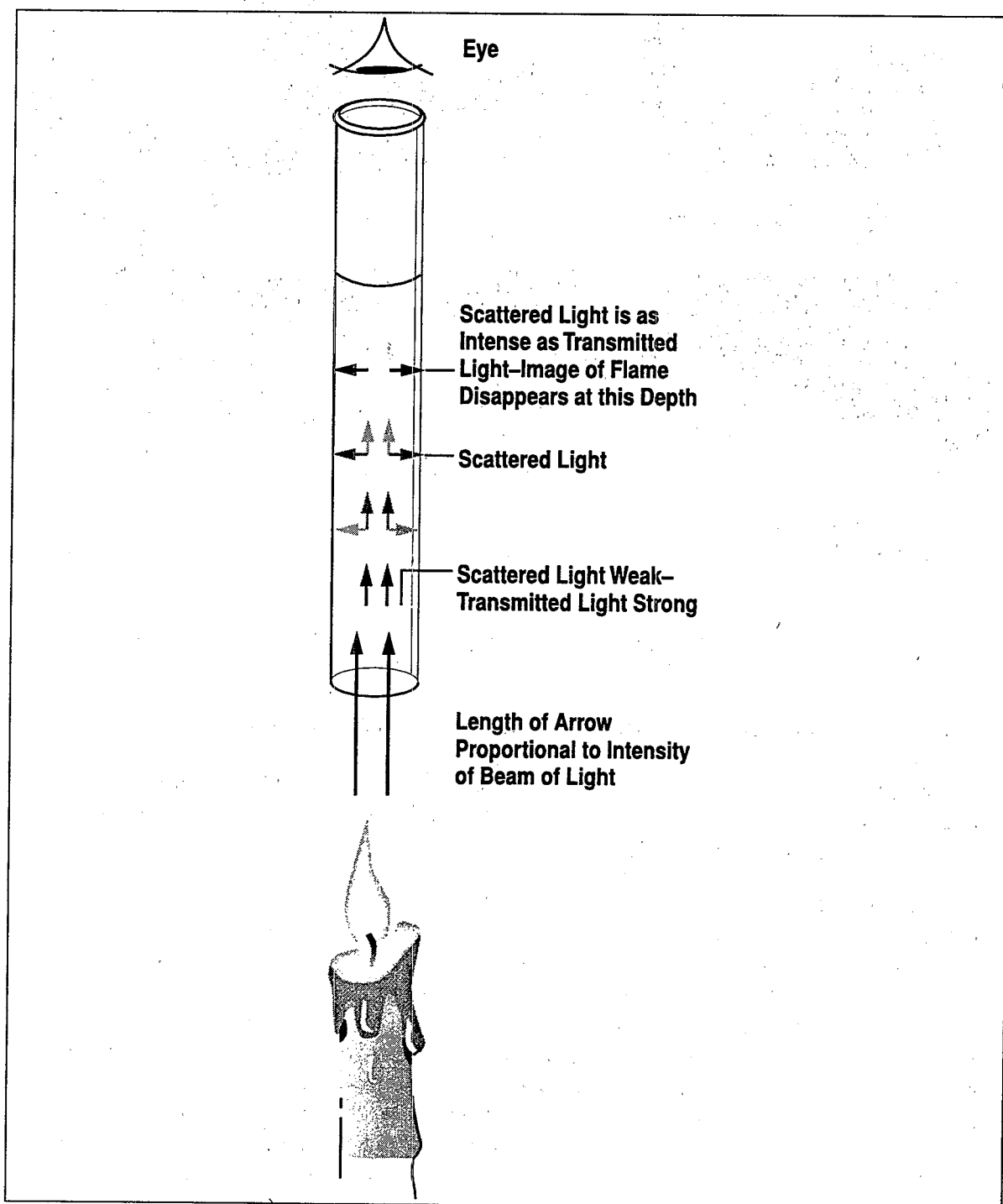


Figure 7-1. Typical Service of Turbidity in Drinking Water

The first practical attempts to quantify turbidity date to 1900 when Whipple and Jackson developed a standard suspension fluid using 1,000 parts per million (ppm) of diatomaceous earth in distilled water (Sadar, 1996). Dilution of this reference suspension resulted in a series of standard suspensions, which were then used to derive a ppm-silica scale for calibrating turbidimeters.

The standard method for determination of turbidity is based on the Jackson candle turbidimeter, an application of Whipple and Jackson's ppm-silica scale (Sadar, 1996). The Jackson candle turbidimeter consists of a special candle and a flat-bottomed glass tube (Figure 7-2), and was calibrated by Jackson in graduations equivalent to ppm of suspended silica turbidity. A water sample is poured into the tube until the visual image of the candle flame, as viewed from the top of the tube, is diffused to a uniform glow. When the intensity of the scattered light equals that of the transmitted light, the image disappears; the depth of the sample in the tube is read against the ppm-silica scale, and turbidity was measured in Jackson turbidity units (JTU). Standards were prepared from materials found in nature, such as Fuller's earth, kaolin, and bed sediment, making consistency in formulation difficult to achieve.



Source: Sadar, 1996.

Figure 7-2. Jackson Candle Turbidimeter

In 1926, Kingsbury and Clark discovered formazin, which is formulated completely of traceable raw materials and drastically improved the consistency in standards formulation. Formazin is a suitable suspension for turbidity standards when prepared accurately by weighing and dissolving 5.00 grams of hydrazine sulfate and 50.0 grams of hexamethylenetetramine in one liter of distilled water. The solution develops a white hue after standing at 25°C for 48 hours. A new unit of turbidity measurement was adopted called formazin turbidity units (FTU).

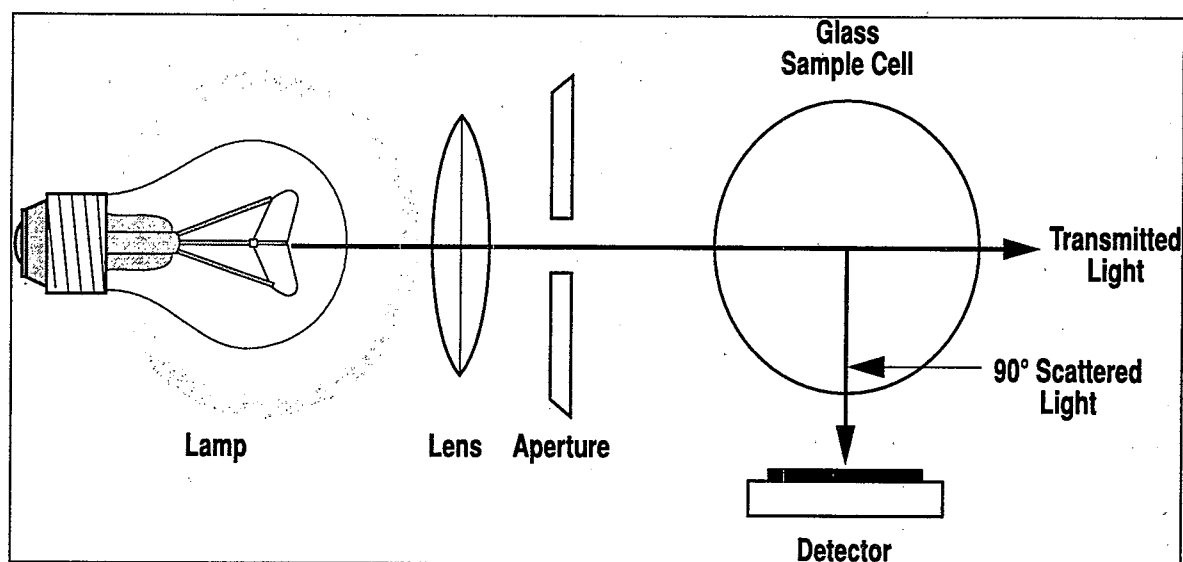
Even though the consistency of formazin improved the accuracy of the Jackson Candle Turbidimeter, it was still limited in its ability to measure extremely high or low turbidity. More precise measurements of very low turbidity were needed to define turbidity in samples containing fine solids. The Jackson Candle Turbidimeter is impractical for this because the lowest turbidity value on this instrument is 25 JTU. The method is also cumbersome and too dependent on human judgement to determine the exact extinction point.

Indirect secondary methods were developed to estimate turbidity. Several visual extinction turbidimeters were developed with improved light sources and comparison techniques, but all were still dependent of human judgement. Photoelectric detectors became popular since they are sensitive to very small changes in light intensity. These methods provided much better precision under certain conditions, but were still limited in ability to measure extremely high or low turbidities.

Finally, turbidity measurement standards changed in the 1970's when the nephelometric turbidimeter, or nephelometer, was developed which determines turbidity by the light scattered at an angle of 90° from the incident beam (Figure 7-3). A 90° detection angle is considered to be the least sensitive to variations in particle size. Nephelometry has been adopted by *Standard Methods* as the preferred means for measuring turbidity because of the method's sensitivity, precision, and applicability over a wide range of particle size and concentration. The nephelometric method is calibrated using suspensions of formazin polymer such that a value of 40 nephelometric units (NTU) is approximately equal to 40 JTU (AWWARF, 1998). The preferred expression of turbidity is NTU.

7.3 Turbidity's Significance to Human Health

Excessive turbidity, or cloudiness, in drinking water is aesthetically unappealing, and may also represent a health concern. Turbidity can provide food and shelter for pathogens. If not removed, turbidity can promote regrowth of pathogens in the distribution system, leading to waterborne disease outbreaks, which have caused significant cases of gastroenteritis throughout the United States and the world. Although turbidity is not a direct indicator of health risk, numerous studies show a strong relationship between removal of turbidity and removal of protozoa.



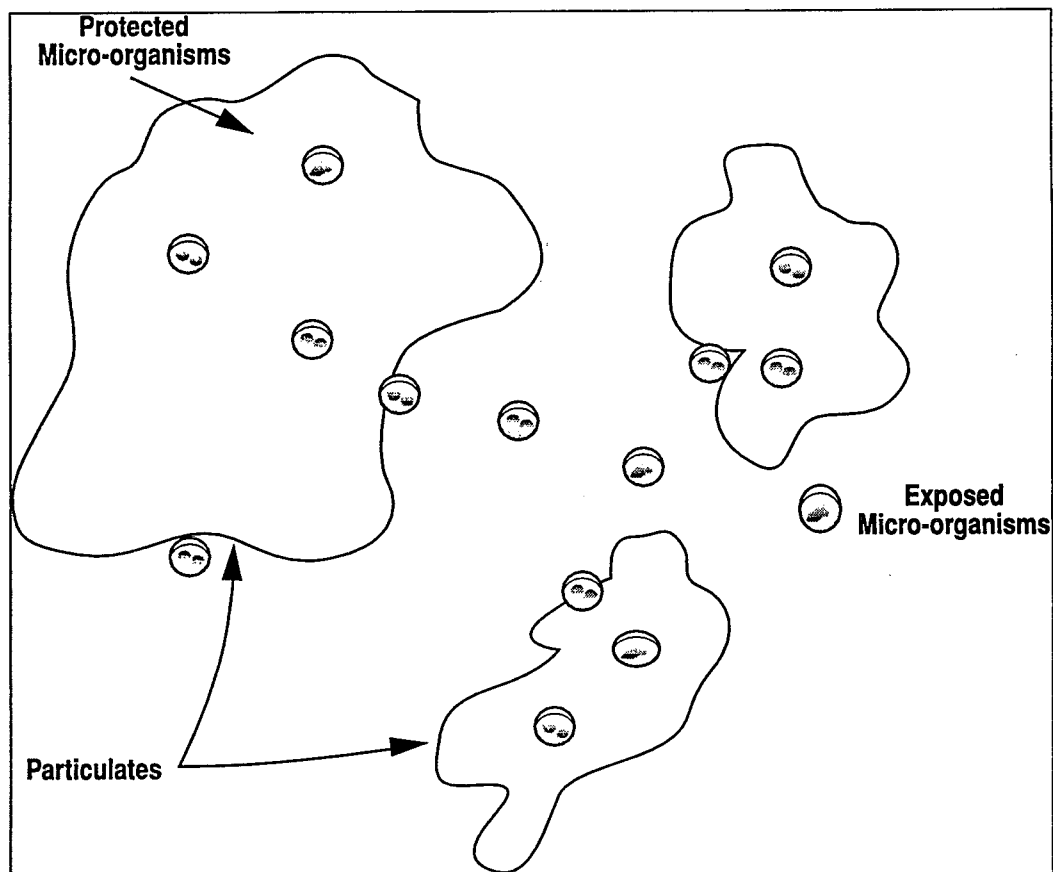
Source: Sadar, 1996; photo revised by SAIC, 1998.

Figure 7-3. Nephelometric Turbidimeter

The particles of turbidity provide “shelter” for microbes by reducing their exposure to attack by disinfectants (Figure 7-4). Microbial attachment to particulate material or inert substances in water systems has been documented by several investigators (Marshall, 1976; Olson et al., 1981; Herson et al., 1984) and has been considered to aid in microbe survival (NAS, 1980). Fortunately, traditional water treatment processes have the ability to effectively remove turbidity when operated properly.

7.3.1 Waterborne Disease Outbreaks

Notwithstanding the advances made in water treatment technology, waterborne pathogens have caused significant disease outbreaks in the United States and continue to pose a significant problem. Even in developed countries, protozoa have been identified as the cause of half of the recognized waterborne outbreaks (Rose et al., 1991). The most frequently reported waterborne disease in the United States is acute gastrointestinal illness, or gastroenteritis (Huben, 1991). The symptoms for this disease include fever, headache, gastrointestinal discomfort, vomiting, and diarrhea. Gastroenteritis is usually self-limiting, with symptoms lasting one to two weeks in most cases. However, if the immune system is suppressed, as with the young, elderly and those suffering from HIV or AIDS, the condition can be very serious and even life threatening. The causes are usually difficult to identify but can be traced to various viruses, bacteria, or protozoa.



Source: LeChevallier and Norton, 1991.

Figure 7-4. Particles of Turbidity May Provide Protection for Microorganisms

Giardia and *Cryptosporidium* are the two most studied organisms known to cause waterborne illnesses. These two protozoa are believed to be ubiquitous in source water, are known to occur in drinking water systems, have been responsible for the majority of waterborne outbreaks, and treatments to remove and/or inactivate them are known to be effective for a wide range of waterborne parasites (LeChevallier and Norton, in Craun, 1993). *Giardia* and *Cryptosporidium* have caused over 400,000 persons in the United States to become ill since 1991, mostly due to a 1993 outbreak in Milwaukee, Wisconsin.

Giardia and viruses are addressed under the 1989 SWTR. Systems using surface water must provide adequate treatment to remove and/or inactivate at least 3-log (99.9%) of the *Giardia lamblia* cysts and at least 4-log (99.99%) of the enteric viruses. However, *Cryptosporidium* was not addressed in the SWTR due to lack of occurrence and health effects data. In the mid-1980's, the United States experienced its first recognized waterborne disease outbreak of cryptosporidiosis (D'Antonio et al., 1985). It was soon discovered that the presence of *Cryptosporidium* in drinking water, even in very low concentrations, could be a significant health hazard (Gregory, 1994). In 1993, a major outbreak of cryptosporidiosis occurred even though the system was in full compliance with the SWTR. Several outbreaks caused by this pathogen have been reported (Smith et

al., 1988; Hayes et al., 1989; Levine and Craun, 1990; Moore et al., 1993; Craun, 1993). The ESWTR's primary focus is to establish treatment requirements to further address public health risks from pathogen occurrence, and in particular, *Cryptosporidium*.

Table 7-1 displays several instances of past outbreaks of cryptosporidiosis in systems using surface water as a source, along with general information about the plant and turbidity monitoring. In three out of four of the cases displayed in the table (Milwaukee, Jackson County, and Carrollton), turbidity over 1.0 NTU was occurring in finished water during the outbreaks.

Table 7-1. Cryptosporidium Outbreaks vs. Finished Water Turbidity

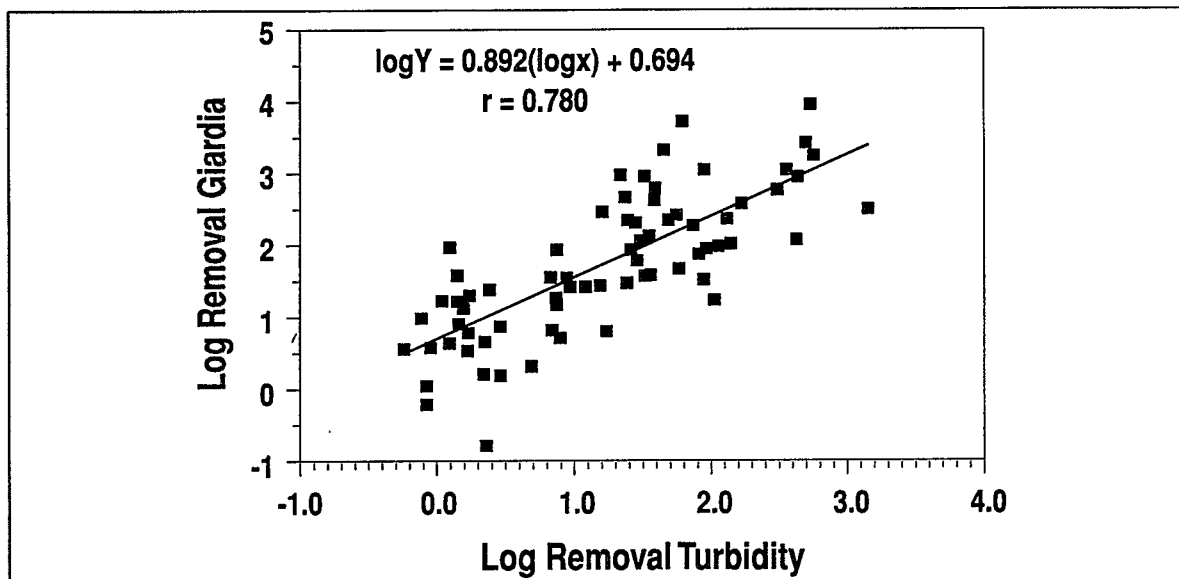
| Location of Outbreak | Year | General Plant Information | Turbidity Information |
|---|-----------|---|---|
| Las Vegas, Nevada (CDC, 1996) | 1993-1994 | No apparent deficiencies or problems with this community system; SWTR compliant; system performed pre-chlorination, filtration (sand and carbon), and filtration of lake water; outbreak affected mostly persons infected with the human immunodeficiency virus (HIV) | The raw water averaged 0.14 NTU between January 1993 and June 1995, with a high of 0.3 NTU; the maximum turbidity of finished water during this time was 0.17 NTU. |
| Milwaukee, Wisconsin (CDC, 1996, Logsdon, 1996) | 1993 | Community system; SWTR compliant; however, deterioration in source (lake) raw-water quality and decreased effectiveness of the coagulation-filtration process | Dramatic temporary increase in finished water turbidity levels; reported values were as high as 2.7 NTU. (Turbidity had never exceeded 0.4 NTU in the previous 10 years.) |
| Jackson County, Oregon (USEPA, 1997) | 1992 | Poor plant performance (excessive levels of algae and debris); no pre-chlorination before filtration | Earlier in the year when outbreak occurred, filtered water had averaged 1 NTU or greater. |
| Carrollton, Georgia (USEPA, 1997, Logsdon, 1996) | 1987 | Conventional filtration plant; sewage overflowed into water treatment intake, followed by operational irregularities in treatment; filters were placed back into service without being backwashed. | Filtered water turbidity from one filter reached 3 NTU about three hours after it was returned to service without being washed. |

7.3.2 The Relationship Between Turbidity Removal and Pathogen Removal

Low filtered water turbidity can be correlated with low bacterial counts and low incidences of viral disease. Positive correlations between removal (the difference between raw and plant effluent water samples) of pathogens and turbidity have also been observed in several studies. In fact, in every study to date where pathogens and turbidity occur in the source water, pathogen removal coincides with turbidity/particle removal (Fox, 1995).

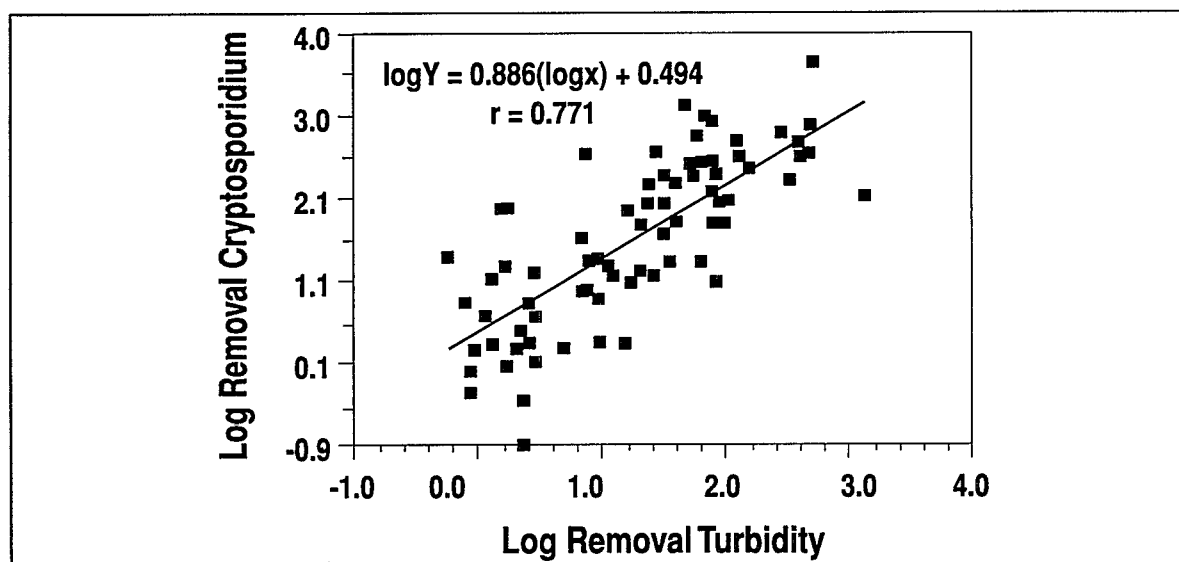
As an example, data gathered by LeChevallier and Norton (in Craun, 1993) from three drinking water treatment plants using different watersheds indicated that for every log removal of turbidity, 0.89 log removal was achieved for the parasites *Cryptosporidium* and *Giardia* (Figures 7-5 and 7-6). Of course, this exact relationship does not hold for all treatment plants. Table 7-2 lists several other studies in addition to LeChevallier and Norton's, and their conclusions on the relationship of turbidity to protozoan removal.

All studies in Table 7-2 show turbidity as a useful predictor of parasite removal efficiency. This evidence suggests that although a very low turbidity value does not completely ensure that particles are absent, it is an excellent measure of plant optimization to ensure maximum public health protection.



Source: LeChevallier and Norton, 1991.

Figure 7-5. Relationship Between Removal of *Giardia* and Turbidity



Source: LeChevallier and Norton, 1991.

Figure 7-6. Relationship Between Removal of *Cryptosporidium* and Turbidity

Table 7-2. Studies on the Relationship between Turbidity Removal and Protozoa Removal

| Reference/Study | Discovery/Conclusion on Turbidity |
|--|---|
| Patania et al., 1995* | Four systems using rapid granular filtration, when treatment conditions were optimized for turbidity and particle removal, achieved a median turbidity removal of 1.4 log and median particle removal of 2 log. The median cyst and oocyst removal was 4.2 log. A filter effluent turbidity of less than 0.1 NTU or less resulted in the most effective cyst removal, by up to 1.0 log greater than when filter effluent turbidities were greater than 0.1 NTU (within the 0.1 to 0.3 NTU range). |
| Nieminski and Ongerth, 1995* | <u>Pilot plant study:</u> Source water turbidity averaged 4 NTU (maximum = 23 NTU), achieving filtered water turbidities of 0.1-0.2 NTU. <i>Cryptosporidium</i> removals averaged 3.0 log for conventional treatment and 3.0 log for direct filtration, while <i>Giardia</i> removals averaged 3.4 log for conventional treatment and 3.3 log for direct filtration. <u>Full scale plant study:</u> Source water had turbidities typically between 2.5 and 11 NTU (with a peak level of 28 NTU), achieving filtered water turbidities of 0.1-0.2 NTU. <i>Cryptosporidium</i> removals averaged 2.25 log for conventional treatment and 2.8 log for direct filtration, while <i>Giardia</i> removals averaged 3.3 log for conventional treatment and 3.9 log for direct filtration. |
| Ongerth and Pecoraro, 1995* | Using very low-turbidity source waters (0.35 to 0.58 NTU), 3 log removal for both cysts were obtained, with optimal coagulation. (With intentionally suboptimal coagulation, the removals were only 1.5 log for <i>Cryptosporidium</i> and 1.3 log for <i>Giardia</i> .) |
| LeChavallier and Norton (in Craun, 1993) | Data gathered from three drinking water treatment plants using different watersheds indicated that for every log removal of turbidity, 0.89 log removal was achieved for <i>Cryptosporidium</i> and <i>Giardia</i> . |
| Nieminski, 1992 | A high correlation ($r^2=0.91$) exists between overall turbidity removal and both <i>Giardia</i> and <i>Cryptosporidium</i> removal through conventional water treatment. |
| Ongerth, 1990 | <i>Giardia</i> cyst removal by filtration of well-conditioned water results in 90% or better turbidity reduction, which produces effective cyst removal of 2-log (99%) or more. |
| LeChavallier et al., 1991* | In a study of 66 surface water treatment plants using conventional treatment, most of the utilities achieved between 2 and 2.5 log removals for both <i>Cryptosporidium</i> and <i>Giardia</i> , and a significant correlation ($p=0.01$) between removal of turbidity and <i>Cryptosporidium</i> existed. |
| LeChavallier and Norton, 1992* | In source water turbidities ranging from 1 to 120 NTU, removal achieved a median of 2.5 log for <i>Cryptosporidium</i> and <i>Giardia</i> at varying stages of treatment optimization. The probability of detecting cysts and oocysts in finished water supplies depended on the number of organisms in the raw water; turbidity was a useful predictor of <i>Giardia</i> and <i>Cryptosporidium</i> removal. |
| Foundation for Water Research, 1994* | Raw water turbidity ranged from 1 to 30 NTU, and <i>Cryptosporidium</i> removal was between 2 and 3 log. Investigators concluded that any measure which reduces filter effluent turbidity should reduce risk from <i>Cryptosporidium</i> . |
| Hall et al., 1994 | Any measure which reduces filtrate turbidity will reduce the risk from <i>Cryptosporidium</i> ; a sudden increase in the clarified water turbidity may indicate the onset of operational problems with a consequent risk from cryptosporidiosis. |
| Gregory, 1994 | Maintaining the overall level of particulate impurities (turbidity) in a treated water as low as possible may be an effective safeguard against the presence of oocysts and pathogens. |
| Anderson et al., 1996 | In a pilot plant study, the removal of particles $> 2\mu\text{m}$ was significantly related to turbidity reduction $r=0.97$ ($p<0.0001$); the removal of <i>Cryptosporidium</i> oocysts may be related to the removal of <i>Giardia</i> , $r=0.79$ ($p<0.14$); the reduction of turbidity may be related to the removal of <i>Giardia</i> cysts, $r=0.67$ ($p<0.13$) and <i>Cryptosporidium</i> oocysts ($p<0.08$) |

as discussed in EPA's Notice of Data Availability (USEPA, 1997)

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8. PARTICLES CONTRIBUTING TO TURBIDITY

8.1 Introduction

To address turbidity removal during treatment processes, an understanding of the physical characteristics and properties of particles in raw water is required. This chapter provides an overview of the inorganic, organic and biotic particles, as well as particles created during typical treatment processes that contribute to turbidity. Because the stability of particles in water is dominated by the electrokinetic properties, a discussion of electrokinetic properties is included to provide information concerning how these properties affect the removal of particle contamination during the treatment process.

8.2 Characteristic Properties of Particles

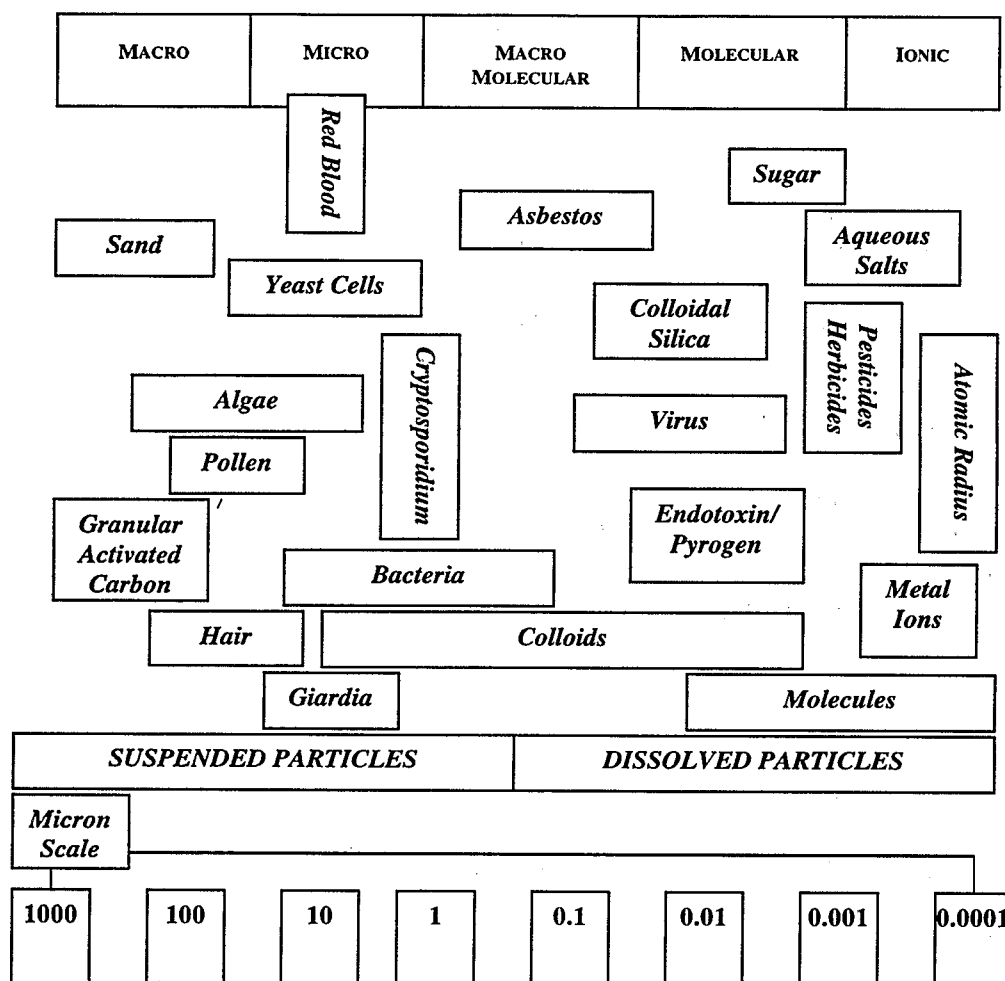
Particles in a raw water supply may be composed of inorganic materials, pathogens, or toxic materials. These particles may also provide sorbent sites for pesticides and other synthetic organic chemicals and heavy metals. Particles are undesirable not only for the cloudy appearance they impart to finished water, but because they also have the ability to shelter microorganisms from inactivation by disinfectants. Consequently, a principal element in supplying quality drinking water is the maximum removal of particles. To establish or optimize a particle removal process, it is important to understand the physical properties of particles.

Particles suspended in water can be categorized into three classes based on their origin:

1. Inorganic materials, such as silt or minerals;
2. Living or dead organic matter; and
3. Biotic material including algae, viruses and bacteria.

Due to the range of small sizes for common particles in water, it is common to find sizes termed in "microns" within the water industry. A micron, or micrometer, is equal to 1×10^{-6} meters, or 0.00004 inches. Generally, particulate contaminants to be removed from a raw water source range from the larger macro sized particles visible to the naked eye, to the ionic particles viewed only by scanning electron microscopes.

Figure 8-1 illustrates some common particles found in raw water sources and indicates where, within the size range, these particles would typically be detected.



Source: Osmonics, Inc., 1996; AWWA, 1990.

Figure 8-1. Particle Size Spectrum

8.2.1 Particle Settling

Particle settling, or sedimentation, may be described for a singular particle by the Newton equation for terminal settling velocity of a spherical particle. A knowledge of this velocity is basic in the design and performance of a sedimentation basin.

The rate at which discrete particles will settle in a fluid of constant temperature is given by the equation:

$$V = [(4g (\rho_s - \rho) d) / (3 C_d \rho)]^{0.5}$$

where

V = terminal settling velocity

g = gravitational constant

ρ_s = mass density of the particle

ρ = mass density of the fluid
 d = particle diameter
 C_d = Coefficient of drag (dimensionless)

The terminal settling velocity is derived by equating the drag, buoyant, and gravitational forces acting on the particle. At low settling velocities, the equation is not dependent on the shape of the particle and most sedimentation processes are designed so as to remove small particles, ranging from 1.0 to 0.5 micron, which settle slowly. Larger particles settle at higher velocity and will be removed whether or not they follow Newton's law, or Stokes' law, the governing equation when the drag coefficient is sufficiently small (0.5 or less) as is the case for colloidal products (McGhee, 1991).

Colloids are very fine solid particles, typically between 10 and 0.001 microns in diameter, which are suspended in solution. Colloidal particles are not visible even with the aid of high-powered microscopes (Sawyer and McCarty, 1978). Colloids will not settle out by gravitational forces and may not be removed by conventional filtration alone. The removal of colloidal particles is typically achieved by coagulation to form larger particles, which then may be removed by sedimentation and/or filtration. Coagulation, as defined by Kawamura (1991), is the "destabilization of (the) charge on colloids and suspended solids, including bacteria and viruses," and is further discussed in Section 8.7, "Electrokinetic Properties of Particles."

8.2.2 Particle Density and Size Distribution

Typically, a large range of particle sizes will exist in the raw water supply. Type 1 settling is the designation given to discrete particles of various sizes, in a dilute suspension, which settle without flocculating. Dilute suspensions of flocculating particles, where heavier particles overtake and coalesce with smaller and lighter particles, are given the designation of Type 2. As there is no mathematical equation which can be applied to the relationships of Type 1 and 2 sedimentation, statistical analysis is applied to predict the settling velocities for particles in water having a broad range of size and density. Particle size distribution analysis (Type 1) or settling-column analysis (Type 1 or 2) is applied and a settling velocity cumulative frequency curve is obtained and used in settling basin design. An excellent resource for understanding the use of settling column analysis, and discrete particle settling is given by Gregory and Zabel (1990).

Type 3a and 3b, or hindered settling, occur when high densities of particles in suspension result in an interaction of particles. The displacement of water produced by the settling of one particle affects the relative velocities of its neighbors (McGhee, 1991). A zone is formed in which more rapidly-settling particles act as a group with a reduced settling velocity. However, even at fairly high concentrations, the reduction in settling velocity is not significant. The following equation from McGhee (1991) gives an estimate of the magnitude for hindered settling:

$$V_h/V = (1 - C_v)^{4.65}$$

where V_h = hindered settling velocity
 V = free settling velocity
 C_v = volume of particles divided by total volume of the suspension.

8.3 Inorganic Particles

Inorganic particles in water are produced by the natural weathering of minerals, including both suspended and dissolved materials. Inorganic particles may consist of iron oxides, salts, sulfur, silts and clays such as bentonite or muscovite. Depending on the concentration of inorganic particles present in raw water sources, human health effects can vary from beneficial to toxic.

8.3.1 Naturally Occurring Minerals

Naturally occurring minerals find their way into raw water sources either naturally through the breakdown of minerals in rock, or through industrial process discharges which have contaminated a raw water source. Industrial contributors can include mining, smelting, coal burning power producers, oil and gas companies, and electroplating operations.

Clays, metal hydroxides, and other particles originating from mineral sources typically vary from several nanometers to several microns in diameter, with a continuous size distribution over this range. In surface waters, the majority of these particles are within a 0.1 to 1 micron size range. As a result of their settling characteristics, particles in this size range have the ability to remain in suspension in moving water. Particles of this size range scatter visible light efficiently, due to the larger surface areas which are created as particles decrease in size. This scattering gives the water a turbid, or cloudy, appearance at very low concentrations. However, Wiesner and Klute (1998) suggest that the real threat of these particles is the adsorptive properties. The large surface areas created by even a small mass concentration of the colloid particles provide abundant adsorption sites for natural and synthetic organic matter, metals, and other toxic substances. Bacteria and viruses can also attach to these particles, and there is some concern that inorganic particulate contamination has the ability to shield microorganisms from inactivation by disinfectants.

Dissolved inorganics known to have adverse health effects on humans when ingested include aluminum, arsenic, cadmium, copper, fluoride, lead, and mercury. The EPA has established maximum contaminant levels (MCLs) for a variety of inorganic contaminants and is in constant review of health advisories to determine the health effects from inorganics ingested in drinking water (Tate and Arnold, 1990). The inorganic materials for which MCLs have been established are toxic to humans in some form.

8.4 Organic Particles

Organic materials are compounds, natural or manmade, having a chemical structure based upon the carbon molecule. Millions of organic compounds containing carbon have been identified and named, including; hydrocarbons, wood, sugars, proteins, plastics, petroleum-based compounds, solvents, pesticides and herbicides.

Both naturally-occurring and synthetic organics are present in surface waters and typically originate from the following sources (Tate and Arnold, 1990):

1. The decomposition of naturally occurring organic materials in the environment;
2. Industrial, agricultural and domestic activities; and
3. Reactions occurring during the treatment and distribution of drinking water.

Organics may have adverse human health impacts, such as toxicity, or as carcinogens when ingested. In addition, naturally occurring organics, most widely referred to as natural organic matter (NOM), can give raw water a characteristic color, taste, or odor. Furthermore, organics in water can be altered by treatment processes resulting in disinfection byproducts (DBPs). In the following sections, a description of the organic constituents in raw water is provided.

8.4.1 Synthetic Organics

Artificial organics, or synthetic organics, can infiltrate raw water supplies through overland flow of contaminated urban and agricultural rainwater; direct discharge from industries and wastewater treatment plants, and, as leachate from contaminated soils. Most contaminants found in water supplies that have adverse health effects are synthetic organics including: herbicides and pesticides; solvents; and, polychlorinated biphenyls commonly known as PCBs (Tate and Arnold, 1990). The EPA has set MCLs for many synthetic substances, both in industrial waste discharge and within the primary drinking water standards.

8.4.2 Natural Organic Matter (NOM)

In the majority of raw water sources, the largest fraction of all organic particles is due to NOM originating from the degradation of plant or animal materials (Wiesner and Klute, 1998). NOM is undesirable in raw water for a variety of reasons, ranging from undesirable color to providing adsorption site for toxic substances. NOM will also adsorb to inorganic particles present in raw water, reducing the settling properties of those particles. Aiken and Cotsaris (1995) recognized numerous studies supporting the importance of NOM in mobilization of hydrophobic organic species; of metals (lead, cadmium, copper, zinc, mercury, and chromium); and radionuclides through the treatment process. Elevated levels of certain NOM constituents require additional coagulation in order to destabilize the particles and remove them in sedimentation and/or filtration basins.

NOM is also present in raw water supplies as colloidal organic carbon in the form of humic materials. Humic substances have generated considerable attention due to their disinfection by-products (DBP) formation potential (Amirtharajah and O'Melia, 1990).

8.4.3 Total Organic Carbon (TOC)

TOC is a composite measure of the overall organic content, in a water sample. TOC is measured by the amount of carbon dioxide produced when a water sample is atomized in a combustion chamber (Standard Methods, 1985). Total organic halogen (TOX) indicates the presence of halogenated organics, and is a proper indication of synthetic chemical contamination. Either of these methods are more economical than testing for any, or all, individual organic compounds likely to be in a raw water supply.

8.4.4 Organic Disinfection By-products (DBPs)

The use of oxidants for disinfection, taste and odor removal, or for decreasing coagulant demand also produces undesirable organic by-products. These by-products are difficult to analyze and remove from the treatment process. Organic contaminants formed during water treatment include trihalomethanes (THMs) and haloacetonitriles. Surveys conducted since the mid-1970s have determined that chloroform and other THMs are the organic chemicals occurring most consistently, and at overall highest concentrations, of any organic contaminant in treated drinking water (Wiesner and Klute, 1998).

THMs are formed in water when chlorine being used as a disinfectant reacts with NOM, such as humic acids from decaying vegetation. Chloroform is one of the most common THMs formed in this type of reaction. The THMs include trichloromethane or chloroform; dibromochloromethane; dichlorobromomethane; and bromoform.

Water chlorination not only produces THMs, but also a variety of other organic compounds. Alternative disinfectants such as, chloramines, chlorine dioxide, and ozone can also react with source water organics to yield organic by-products. Exactly which compounds are formed, their formation pathways, and their health effects are not well known. To complicate matters, many of the DBPs are not susceptible to even highly sophisticated methods of extraction and analysis.

8.5 Particles of Biotic Origin

Four categories of waterborne microorganisms exist as particles contributing to the turbidity of raw water:

- Protozoans;
- Enteric viruses;
- Algae; and
- Bacteria.

Microorganisms are living organisms that are invisible or barely visible to the naked eye. While many microorganisms commonly found in source waters do not pose health risk to humans, others such as *Cryptosporidium* can be sources of infectious and communicable diseases.

Isolation and identification of a specific organism such as *Cryptosporidium* may prove difficult due to the volume and variety of other microorganisms in the sample. Most municipal water plant labs do not possess the equipment required for testing and identification of specific pathogens. Indicator organisms are frequently used to assess contamination by a biotic constituent. Total coliforms are the widely used indicator for pathogens. While the presence of coliforms is not proof that the water contains harmful pathogens, the absence of them is often used as evidence that it is free of pathogens.

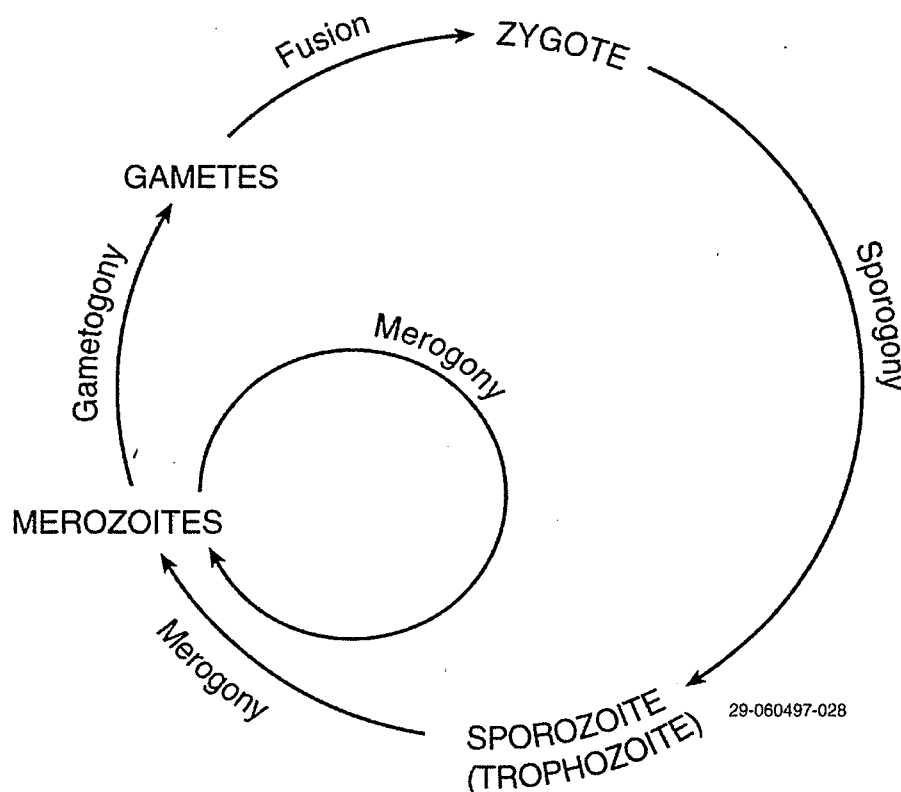
8.5.1 Protozoans

Protozoans are organisms that can exist in colonies or as single cells. Some protozoans are capable of producing spores, a small reproductive body capable of reproducing the organism under favorable conditions. In water, most spores resist adverse conditions that would readily destroy the parent organism.

Of the tens of thousands of species of protozoa, the principal protozoan pathogens of concern in potable water are *Cryptosporidium*, *Giardia lamblia*, and *E. histolytica*. When these organisms are ingested by humans, they can cause symptoms including; stomach cramps, diarrhea, fever, vomiting, and dehydration. These parasites are typically more resistant to traditional chlorine disinfection than coliforms.

Cryptosporidium is a disease-causing protozoan housed in a hard-shelled oocyst (pronounced o-he-sist). The oocyst is typically 2 to 5 microns in diameter, round to egg shaped, colorless and nearly transparent. Human and animal feces are sources of *Cryptosporidium* in surface water. Normally, oocysts are found dormant in the environment. When ingested, the oocyst splits open to release sporozoites. In this new form, a complex reproductive cycle begins. Figure 8-2 describes the lifecycle of *Cryptosporidium*.

The sporozoites invade the lining of the gastrointestinal tract and can cause an illness called Cryptosporidiosis. The disease can be fatal to people with suppressed immune systems, including persons with acquired immune deficiency syndrome (AIDS), those undergoing chemotherapy, children and the elderly (Current and Garcia, 1991). Human Cryptosporidiosis was first reported in 1976, and outbreaks in public water systems have motivated numerous studies and regulatory attention on the effectiveness of filtration and chemical disinfection in the removal and inactivation of these protozoans. Limited data suggests that *Cryptosporidium* oocysts are resistant to disinfection at levels practiced in the U.S. at the time of IESWTR promulgation. While research is underway to identify more appropriate inactivation techniques, removal by filtration is currently the most effective means of dealing with *Cryptosporidium*.



Source: Ewing, 1986.

Figure 8-2. *Cryptosporidium* Life Cycle

Human and animal feces are also sources of *Giardia* in surface waters. *Giardia* exists as either a flagellated trophozoite of approximately 9 to 21 microns, or ovoid cysts, approximately 10 microns long and 6 microns wide. Cysts can survive in water from 1 to 3 months. Objects of this size are easily removed by packed bed filters, provided that coagulation and flocculation pretreatment are properly controlled.

Unlike *Giardia* and *Cryptosporidium*, mammals are not a source of *E. histolytica* to water supplies and potential contamination of surface water is considered to be low (Wiesner and Klute, 1998). The size range for the protozoan is 15 to 25 microns for a trophozoite and 10 to 15 microns for the cyst, and are effectively removed by filtration. Additional information regarding *Cryptosporidium* may be found in *Occurrence Assessment for the Interim Enhanced Surface Water Treatment Rule* (USEPA, 1997).

8.5.2 Viruses

A virus is a parasitic, infectious microbe, composed almost entirely of protein and nucleic acids that can cause disease in humans and other living organisms. Viruses can reproduce

only within living cells, and typically range from 0.004 to 0.1 micron in diameter. The principal viral pathogens of concern in potable water are the Enteric viruses: hepatitis A, Norwalk-type viruses, rotaviruses, adenoviruses, enteroviruses, and reoviruses. Enteric viruses infect the gastrointestinal tracts of humans and are transmitted through public water supplies. It appears that many viruses have an attraction for the surfaces of larger colloidal particles and, if aggregated, may increase the effective size of these pathogens to promote their removal (Wiesner and Klute, 1998).

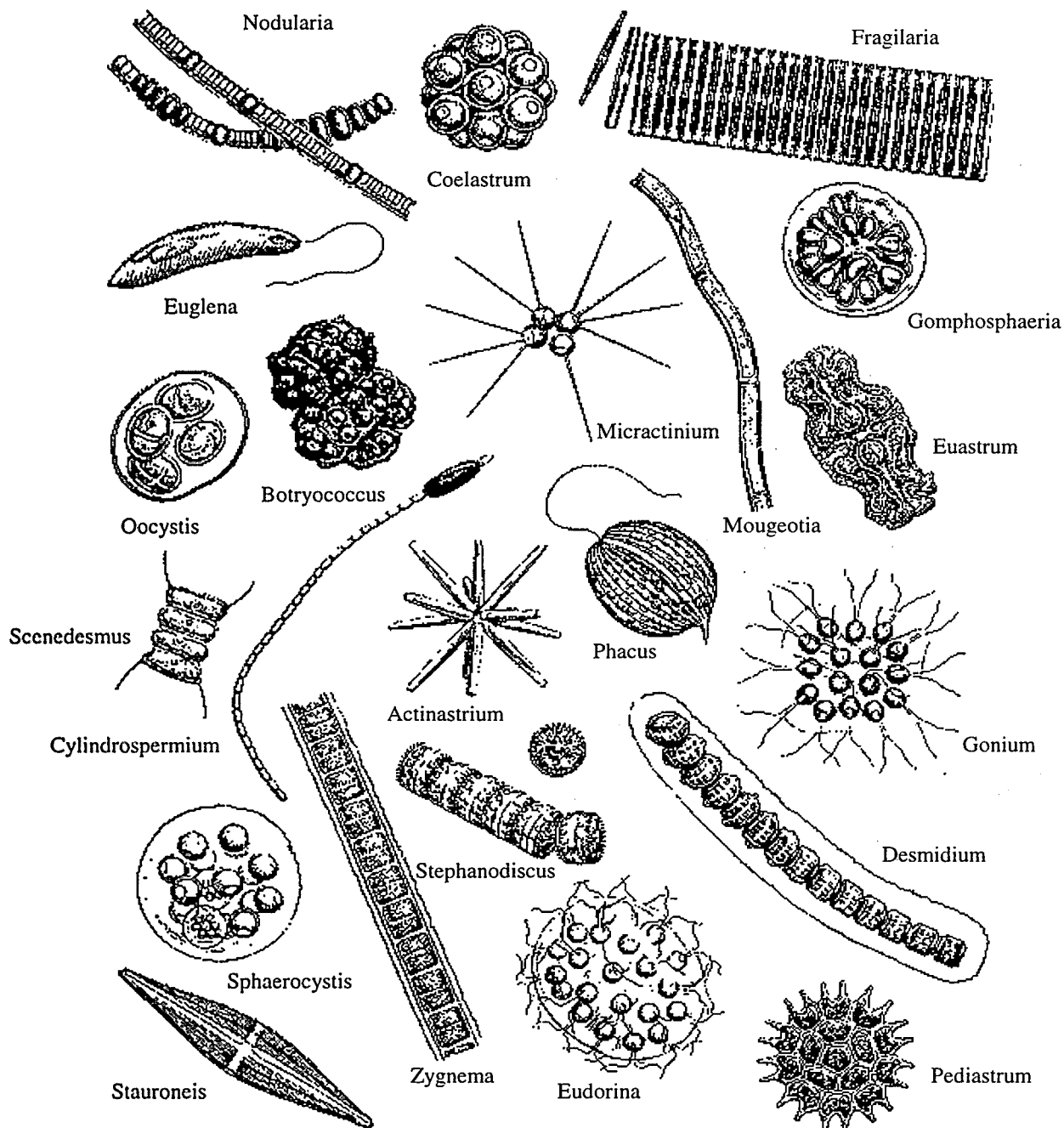
8.5.3 Algae

Algae are common and normal inhabitants of surface waters and are encountered in every water supply that is exposed to sunlight (Tarzwell, undated). Algae typically range in size from 5 to 100 microns. Figure 8-3 presents common types of algae which can be found within source water and in the water treatment process.

Algae are not typically a threat to public health in a drinking water supply. Concerns in potable water treatment arising from the presence of algae include; the ability to create large quantities of organic matter; the production of turbidity, tastes and odors in source water, and; the physical impact on the water treatment plant processes. Some species of blue-green algae are known to produce endotoxins which may affect human health. Algae can clog filters, resulting in reduced run times and an increase in the volume of backwash water needed for cleaning. Examples of filter clogging algae are seen in Figure 8-4. In slow sand filters and biologically active filters, algae will produce oxygen for bacteria that actively degrade organic compounds. They may also release biopolymers that aid in the destabilization of fine colloidal materials (Wiesner and Klute, 1998).

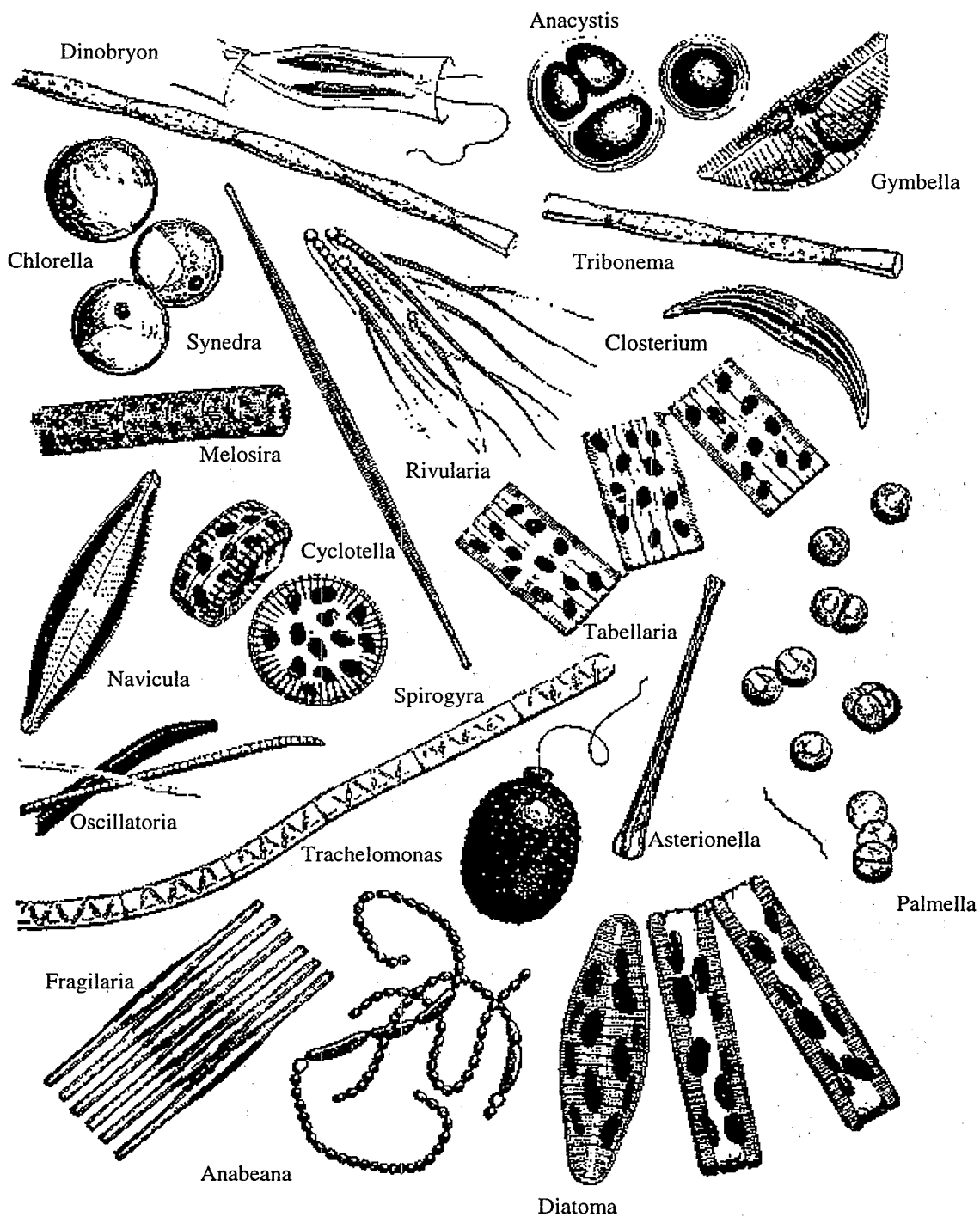
8.5.4 Bacteria

Bacteria are single-celled organisms that lack well-defined nuclear membranes and other specialized functional cell parts. Bacterial cells typically range from 1 to 15 microns in length. They vary in shape from simple spheres to filamentous threads. Figure 8-5 presents various bacterial and fungal forms. Bacteria and fungi are decomposers that break down the wastes and bodies of dead organisms to make their components available for reuse. Bacteria can exist almost anywhere on earth and in almost any medium. Some are beneficial to man while others are harmful, or even fatal. The principal bacterial pathogens of concern in water treatment are the *Salmonella*, *Shigella*, *Yersinia enterocolitica*, enteropathogenic *E. coli*, *Campylobacter jejuni*, *Legionella*, *Vibrio cholerae*, and *Mycobacterium*.



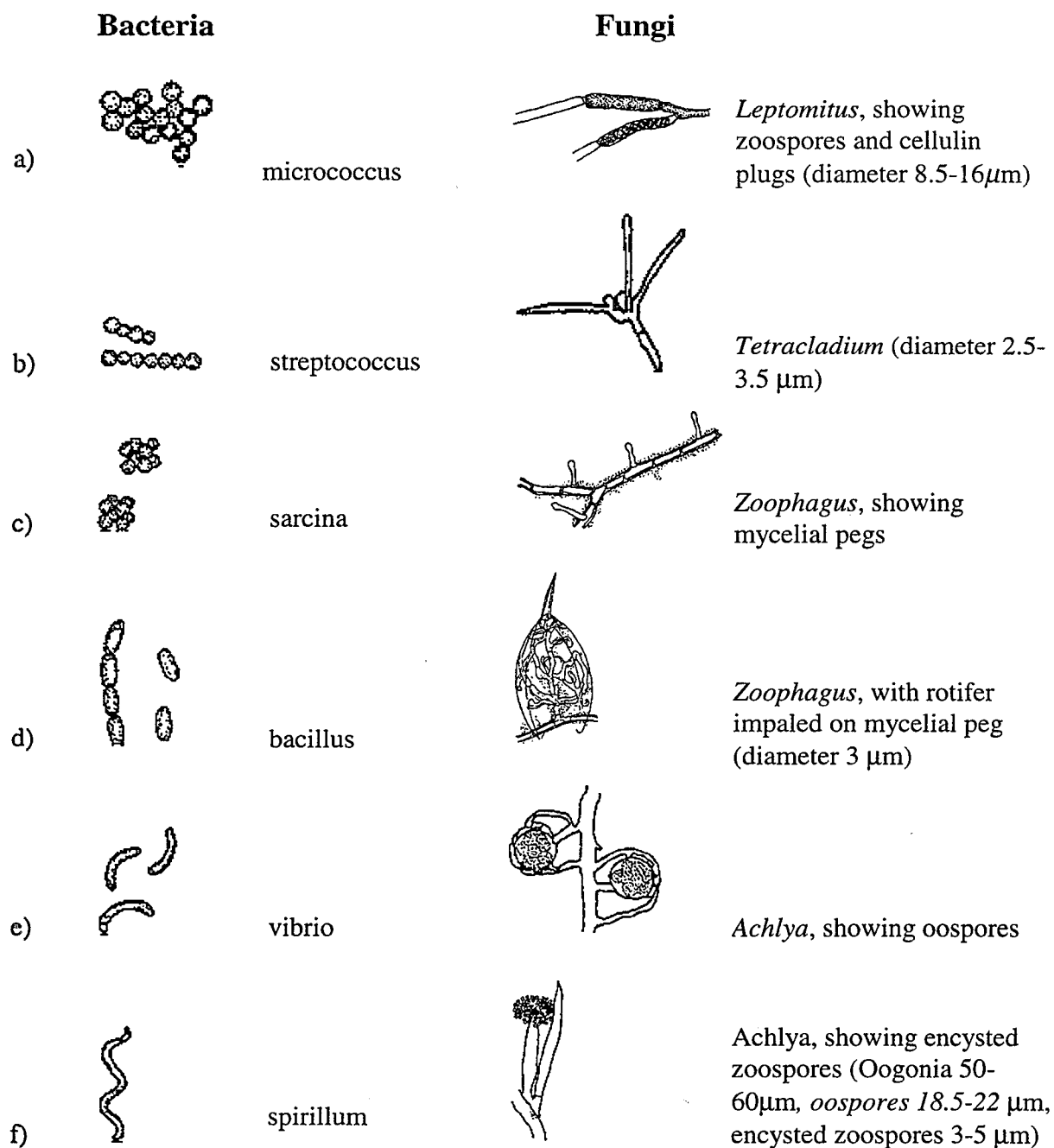
Source: Standard Methods, 1985.

Figure 8-3. Plankton and Other Surface Water Algae



Source: Standard Methods, 1985.

Figure 8-4. Filter Clogging Algae



Source: Standard Methods, 1985.

Figure 8-5. Examples of Bacteria and Fungi Forms

8.6 Particles Added or Created During Treatment

Several steps in the water treatment process may contribute to turbidity. As discussed in Section 10, water treatment is provided to remove undesirable constituents from raw water, and many of these processes are intended to remove suspended solids and reduce turbidity. However, this section identifies those chemicals and practices used in water treatment which are known to increase turbidity. Specifically, the addition of pretreatment chemicals for coagulation-flocculation-sedimentation or filter aids prior to filtration can substantially increase the particulate materials loading of sedimentation basins, filters and other processes used in water treatment. Moreover, increases in turbidity may occur when any aspect of the water treatment process fails.

8.6.1 Coagulants

The coagulation of water generally involves the chemical addition of either hydrolyzing electrolytes or organic polymers for the destabilization of colloids in suspension. Some common coagulants are those based on aluminum, such as aluminum sulfate and alum; and those based on iron, such as ferric and ferrous sulfate. The action of metallic coagulants is complex and is dependent on the fact that colloid particles are charged entities in water solution. More discussion of the electrokinetic properties of colloids is included in section 8-7. Additionally, the use of bentonite, and activated silica for coagulation enhancement will increase the particle loading in the treatment stream (Wiesner and Klute, 1998).

Polymers

Natural and synthetic coagulant aids are known as "polyelectrolytes," because they have characteristics of both polymers and electrolyte. Polyelectrolytes are long-chain, high-molecular-weight molecules which bear a large number of charged groups. The net charge on the molecule may be positive, negative, or neutral. The chemical groups on the polymer are thought to combine with active sites on the colloid, combining them into a larger particles which will then settle by gravitational force. Both the molecular weight of the polymer and charge density influence the effectiveness of polyelectrolytes.

Polyelectrolytes may be used alone or in tandem with metallic coagulants. Optimal doses for polymeric coagulant are typically determined in bench scale or pilot scale plant testing utilizing source water. Use of quantities over the optimal dose will not increase coagulation and instead will create unnecessary loading of particles to be removed.

Lime

Lime is a calcinated chemical material used in lime or lime and soda ash water treatment processes to add alkalinity to the water and adjust the pH. Lime treatment has the incidental benefits to remove iron, aid in clarification of turbid waters, and minimal bactericidal benefit (Logsdon et al., 1994). Lime has a tendency to deposit solids at changes in directions and will precipitate out of solution at areas where velocity decreases

or where changes in velocity occur. The precipitates formed in the lime-soda softening process consist principally of calcium carbonate and magnesium hydroxide with size ranges from 15 to 20 microns. If lime is dosed in quantities greater than the water supply requires, residual lime particles will increase the turbidity in treated water effluent.

8.6.2 Powdered Activated Carbon (PAC)

PAC adsorption is generally used for the removal of organics, radon, color, and taste and odor treatment. Activated carbon is produced from bituminous coal, or cellulose-based substances like wood or coconut shells, by a destructive distillation process that drives off the volatile components of the material. A highly porous, adsorbent material is created which possesses a large surface area per unit volume.

PAC is generally less than 0.075 millimeters in size and has an extremely high ratio of surface area to volume. Nonpolar compounds of high molecular weight are attracted and held, or adsorbed, to this surface. The effectiveness of organic removal by PAC is dependent on the pH, temperature, contaminant concentration, molecular weight of the particles to be adsorbed, type of PAC used, and the contact time of the PAC with the water.

The relative capacity of different carbons to attract and adsorb particles to their surfaces is best assessed by bench or pilot scale testing of the raw water supply. Therefore, the addition of PAC for the removal of organic materials, or to control tastes and odors, creates an additional loading of materials to the downstream processes, as it is slow to settle because of its small size and low density.

8.6.3 Recycle Flows

Filtration treatment processes require frequent, intermittent backwash cycles to remove particles from the media. The backwash water is a concentrate of particles and pretreatment chemicals added prior to the filters. Some plants capture and return this concentrate to a location in the treatment process as a recycled flow. The properties of the backwash concentrate depend on the type and quantity of particles present in the source water, and pretreatment chemicals and treatment processes used earlier in the treatment train. The practice of returning spent backwash water to the treatment system has become a concern due to the potential for returning pathogens to the treatment train.

8.7 Electrokinetic Properties of Particles

Colloidal particles comprise a large portion of the turbidity-producing substances in waters. Examples of colloidal particles include color compounds, clays, microscopic organisms and organic matter from decaying vegetation or municipal wastes. Colloidal

dispersions are stable in water, as they possess a large surface area relative to their weight. Therefore, gravitational forces alone will not remove colloids during sedimentation.

Effective removal of these colloidal dispersions is greatly impacted by the electrokinetic properties on the surface of the colloids.

Each colloid carries a similar electrical charge that produces a force of mutual electrostatic repulsion between adjacent particles. If the charge is high enough, the colloids will remain discrete and in suspension. The addition of coagulants or polymers reduces or eliminates this charge and colloids will begin to agglomerate and settle out of suspension or form interconnected matrices which can then be removed during filtration. This agglomeration causes the characteristics of the suspension to change by creating new particle viscosity, settling rates and effective size properties for the colloids.

Colloids are classified as hydrophobic (resistant to water bonding) or hydrophilic (affinity for water bonding). Hydrophilic colloids are stable because their attraction to water molecules will overcome the slight charge characteristic they possess. This attraction makes hydrophilic colloids difficult to remove from suspension. Examples of hydrophilic colloids include soaps and detergents, soluble starches, soluble proteins and blood serum. On the other hand, hydrophobic particles are dependent on electrical charge for their stability in suspension. The bulk of inorganic and organic matter in a turbid raw water is of this type.

8.7.1 Electrical Potential

Most colloidal particles in water are negatively charged as a result of differences in electrical potential between the water and the particle phases. This charge is due to an unequal distribution of ions over the particle surface and the surrounding solution.

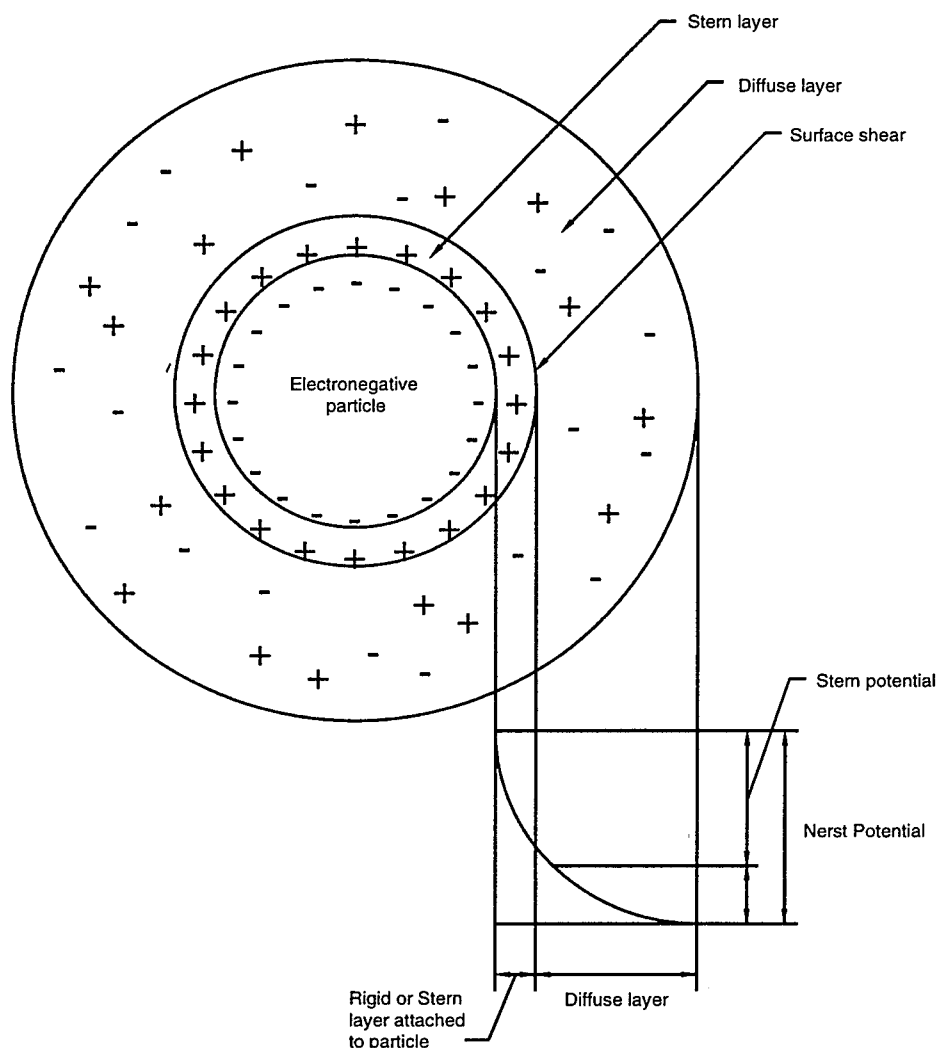
The charge on a colloidal particle can be controlled by modifying characteristics of the water which holds the particles in suspension. Modifications include changing the liquid's pH or changing the ionic species in solution. Another, more direct technique is to use surface-active agents, such as coagulants, that directly adsorb to the surface of the colloid and change its characteristics.

8.7.2 Electrical Double Layer Theory

The double layer model explains the ionic environment surrounding a charged colloid and explains how the repulsive forces are set up around a colloid. Figure 8-6 illustrates the resulting colloidal state.

A single negative colloid will initially attract some of the positive ions in the solution to form a firmly attached layer around the surface of the colloid, known as the *Stern layer*. Additional positive ions are still attracted by the negative colloid, but are also repelled by the Stern layer as well as by other positively charged ions trying to get close to the negatively charged colloid. This constant attraction and repulsion results in the formation of a *diffuse layer* of charged ions surrounding the colloid and Stern layers.

The diffuse layer can be visualized as a charged atmosphere surrounding the colloid. Together, the attached positively charged ions in the Stern layer and the charged atmosphere in the diffuse layer is referred to as the *double layer*. The charge is a



Source: McGhee, 1991.

Figure 8-6. Double Layer Theory (Guoy-Stern Colloidal Model)

maximum at the particle surface and decreases with distance from the surface. The thickness of this layer depends on the type and concentration of ions in solution.

The DLVO Theory (for Derjaguin, Landau, Verwey and Overbeek) is the classic model which describes the balance of forces between charged colloid particles. Amirtharajah and O'Melia (1990) provide a thorough discussion of the electrostatic theory of colloidal stability from the DLVO model and other works.

When two similar colloidal particles with similar primary charge approach each other, their diffuse layers begin to interact. The similar primary charges they possess result in repulsive forces. The closer the particles approach, the stronger the repulsive forces. Repulsive forces which keep particles from aggregating are counteracted to some degree by an attractive force termed *van der Waals* attraction. All colloidal particles possess this attractive force regardless of charge and composition. As van der Waals forces tend to be relatively weak attractions, the force decreases rapidly with an increasing distance between particles.

The balance of the two opposing forces, electrostatic repulsion and van der Waals attraction, explains why some colloidal systems agglomerate while others do not. As particles with similar charge approach one another, the repulsive electrostatic forces increase to keep them separated. However, if they can be brought sufficiently close together to get past this energy barrier, the attractive van der Waals force will predominate, and the particles will remain together. The random motion of colloids caused by the constant collisions with water molecules, termed Brownian Movement, will bring particles in close proximity and aggregation may occur. However, the addition of coagulant and polymers is typically used to lower the energy barriers between particles and provide efficient agglomerations for settling.

Zeta Potential

The Stern layer is considered to be rigidly attached to the colloid, while the diffuse layer is a dynamic layer of charged particles. The *Nernst Potential* is the measurement of voltage (in the order of millivolts) in the diffuse layer. The potential is a maximum at the Stern layer and drops exponentially through the diffuse layer. The *zeta potential* is the electrical potential representing the difference in voltage between the surface of the diffuse layer and the water. It is important to know the magnitude of the zeta potential, as it represents the strength of the repulsion between colloid particles and the distance which must be overcome to bring the particles together.

The primary charge on a colloid cannot be measured directly. However, the zeta potential can be computed from measurements of particle movement within an electrical field (electrophoretic mobility). Therefore, the zeta potential, ζ , is defined by the equation:

$$\zeta = \frac{4\pi\delta q}{D}$$

where

q = charge of the particle

δ = thickness of the zone of influence of the charge on the particle

D = dielectric constant of the liquid

Zeta potential measurements can be made using a high-quality stereoscopic microscope to observe colloidal particles inside an electrophoresis cell (Zeta-Meter 1998). An electric field is created across the cell and charged particles move within the field. Their velocity and direction are then related to the zeta potential. Measurements of zeta potential can

give an indication of the effectiveness of added electrolytes in lowering the energy barrier between colloids, and can direct the optimization of coagulant dose in water treatment.

The destabilization of colloids is accomplished by the reduction of the zeta potential with coagulants such as alum, ferric chloride and/or cationic polymers. Once the charge is reduced or eliminated, no repulsive forces exist. Gentle agitation in a flocculation basin will cause numerous, successful colloid collisions. Chapter 10 further discusses the mechanics of coagulation and flocculation in the water treatment process.

Streaming Current

As discussed in the previous section, a charged particle will move with fixed velocity through a voltage field under the physical phenomenon known as electrophoresis. *Streaming current* is a measurable electric current that is generated when particles in water are temporarily immobilized and the bulk liquid is forced to flow past the particles. A streaming current monitor is a continuous, online sampling instrument which measures the charge on particles. A streaming current detector, or monitor, is a cylinder and piston. The up and downward motion of the piston draws a sample of water into the annular space between the piston and cylinder. An alternating current is read by the electrodes attached to the ends of the cylinder (Amirtharajah and O'Melia, 1990). Charged particles are temporarily immobilized by the piston and cylinder, and the motion of charged particles in the double layer passing these immobilized particles creates the streaming current (ChemTrac, 1997).

8.8 References

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9. TURBIDITY IN SOURCE WATER

9.1 Introduction

The characteristics of turbidity in surface water supplies are a function of many factors. Watershed features, such as geology, human development (i.e., agricultural uses or urban development), topography, vegetation, and precipitation events can all greatly influence raw water turbidity. In addition, reservoirs and ponds can often dampen the impact of increased turbidity events by acting as points in a stream or river where particles can settle before being drawn into the intake of a treatment plant. Wells and infiltration galleries along streams or rivers can also reduce the impact of turbidity increases in streams by their use of a natural aquifer as a filter. This chapter will discuss the turbidity in surface water and ground water under the direct influence (GWUDI) of surface water, and other source water characteristics as they relate to turbidity in raw water supplies.

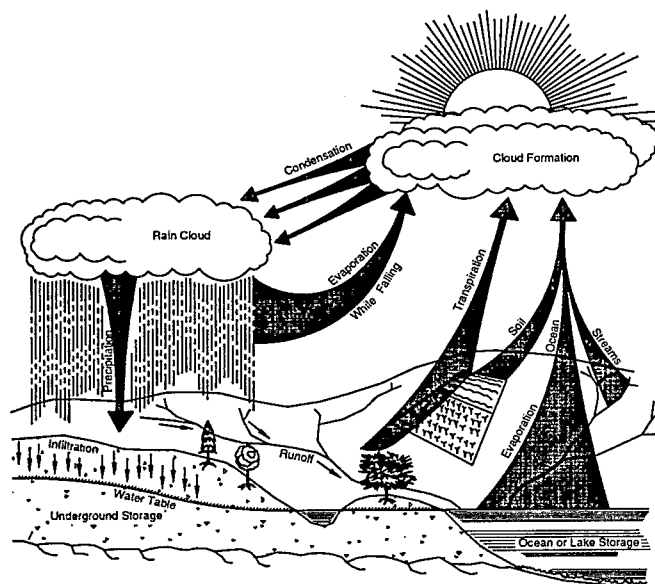
9.2 Occurrence of Turbidity in Surface Water Supplies

There are many natural processes by which turbidity is created and conveyed to a raw water intake for a water treatment plant. The following discussion focuses on the origins of turbidity in surface water supplies including rivers, lakes and reservoirs.

9.2.1 Rivers

The largest component comprising the mix of particles creating turbidity found in rivers is caused by erosion of materials from the contributing watershed. Turbidity may be created from a wide variety of eroded materials, including clay, silt, or mineral particles from soils, or from natural organic matter created by the decay of vegetation. Particles may capture and hide, or mask, other inorganic and organic constituents that are present in the watershed.

To help understand the formation of turbidity in rivers, it is important to understand the natural hydrologic cycle. The diagram shown in Figure 9-1 illustrates the hydrologic cycle. Natural evaporation occurs from water bodies, such as oceans and lakes, and forms clouds, which then condense into precipitation. As precipitation falls to the earth, it first infiltrates the soil and replaces soil moisture and eventually recharges ground water aquifers. Runoff occurs when the rate of precipitation exceeds the rate of water infiltrating the soil. As runoff flows over the land surface, the water can cause soil and other materials to erode, which results in increased turbidity. Runoff then collects in streams and rivers that flow back into water bodies such as lakes and oceans. From there, the hydrologic cycle begins again.



Source: AWWA, 1990.

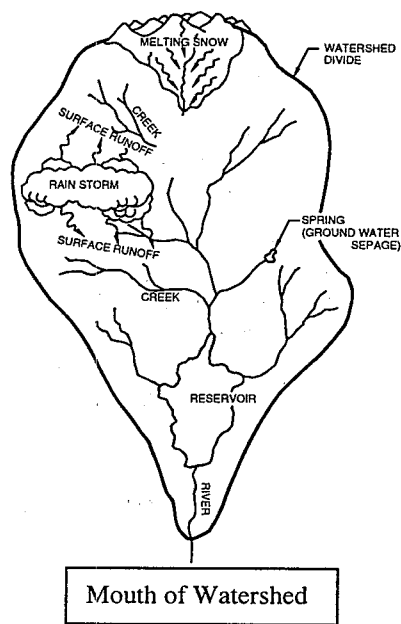
Figure 9-1. The Natural Hydrologic Cycle

Thus, during precipitation events, river turbidities are higher than during periods between precipitation events when the ground water may be supplying nearly all flow to the stream.

Watersheds have great influence on the resulting stream turbidity during a precipitation event. Figure 9-2 illustrates the various components of a watershed. Watersheds can be very large, such as the Mississippi River drainage basin, which drains most of the central United States. A large drainage basin usually consists of runoff that has large amounts of turbidity from the various sources of urban and agricultural runoff and the differing soil types present. Smaller watersheds may be highly urbanized and create high turbidity runoff. However, areas which have been protected from development can produce lower levels of turbidity even during runoff events.

Mountainous watersheds generally contain turbidity particles that are largely colloidal rock matter. In glacial areas, the grinding of mountain glaciers often produces rock particles that add a blue or green color to the mountain rivers. Mountain watersheds that contain little development usually have much lower turbidities than those that may be from an agricultural area in the plains or seacoast areas. Although low in turbidity, these type of watersheds may still be contaminated by *Giardia* and *Cryptosporidium* and other enteric viruses due to wildlife.

Rivers in the plains or coastal areas generally have watersheds which have farming and urban runoff that add turbidity from topsoil and organic matter. The topsoil particles are largely clay, and can hide or carry many different types of contaminants which are a concern to water utilities. These trapped contaminants can include agricultural chemicals and compounds such as fertilizers and pesticides.



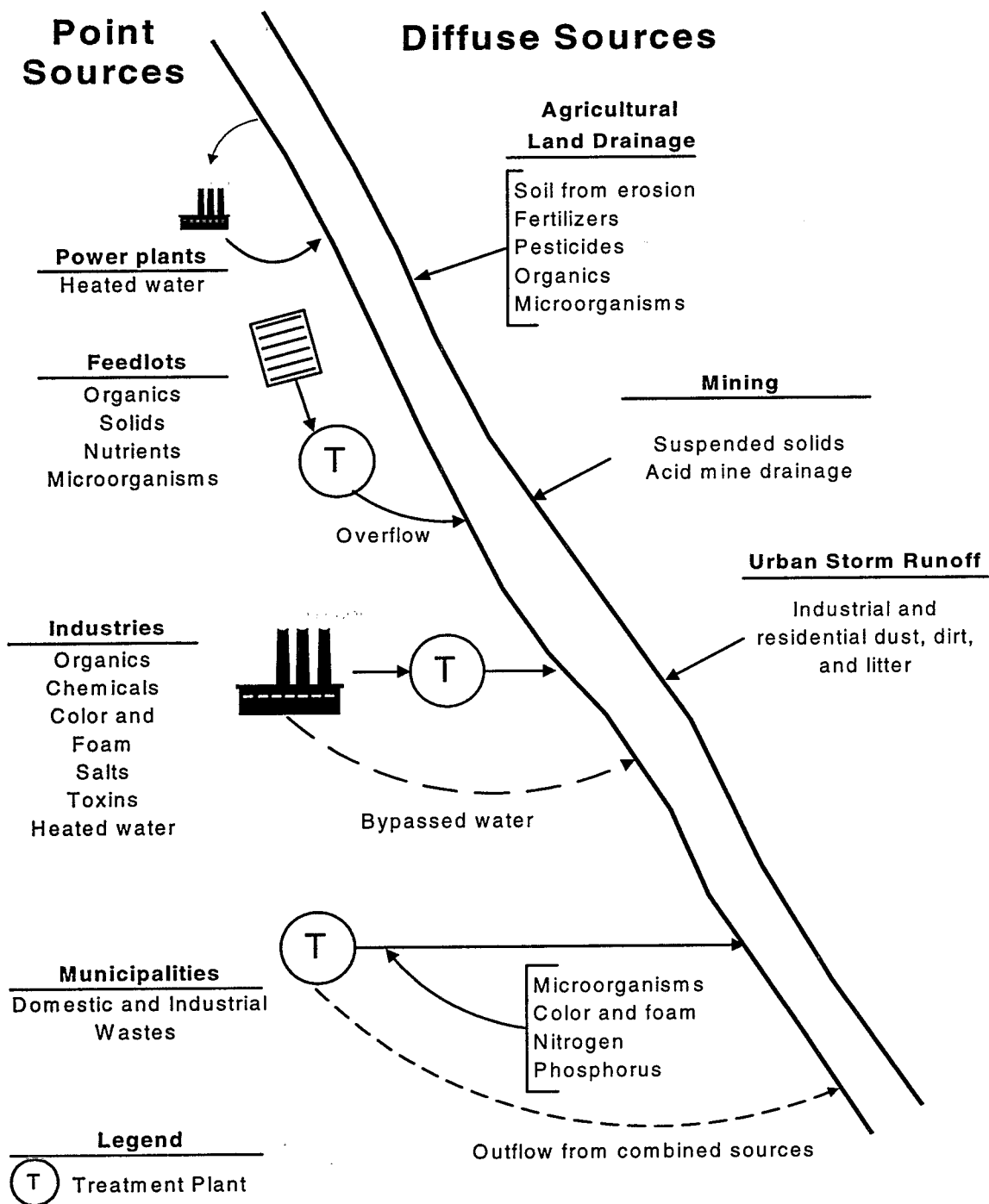
Source: AWWA, 1990.

Figure 9-2. Typical Watershed

One agricultural practice of particular concern is confined animal feeding operations, such as feed lots. This type of development can produce runoff with high concentrations of organic material and nutrients. In addition, many microorganisms, including *Giardia* and *Cryptosporidium* which are known to be present in animal wastes, can be carried downstream.

Because of the high percentage of impermeable surfaces in urban areas, the magnitude of runoff often increases leading to the increased levels of turbidity and related contaminants. In addition to eroded soils, runoff can include domestic and industrial wastes, fertilizers, road de-icing salts, overflows from combined sewers, eroded material from construction sites, and contaminants from roadways and parking lots. Significant industrial development can result in high levels of toxic materials, and power generating facilities can cause elevated water temperatures.

Figure 9-3 shows the possible sources of contaminants that can comprise or be found in turbidity particles.



Source: Hammer, 1997.

Figure 9-3. Sources of Contaminants in Raw Water Supplies

Organic materials reaching the rivers from both undeveloped and urbanized land can serve as a food source for bacteria and other microorganisms. Inorganic nutrients such as nitrogen and phosphorus from wastewater and agricultural runoff can provide nutrients to stimulate the growth of algae, resulting in increased turbidity during low flow times.

The turbidity in streams and rivers is a constantly changing phenomenon. During dry periods, when no precipitation occurs, turbidity levels usually drop to a somewhat stable value for the stream. A precipitation event in the watershed can then bring additional suspended material into the stream and greatly increase the turbidity. Generally, the more intense the precipitation event, the higher the turbidity values experienced in the stream. In addition, turbidity levels are typically found to be higher further downstream in a watershed due to the amount contributed from upstream, the variety of contributing factors it contains, and biological growth that accumulates in the stream as the water moves through the basin.

Low Turbidity in Rivers

Low turbidity streams and rivers (less than 20 NTU) are those which are usually located at the upper reaches of a undeveloped watershed. These watersheds include high mountain areas, as well as those watersheds with little or no development. Characteristics of these watersheds generally include:

- Little or no development;
- No agricultural activity;
- Heavy natural vegetation along streambanks; and
- Little streambank erosion.

Although these streams are usually low in turbidity, Total Organic Carbon (TOC) levels can be high during runoff events resulting in an increase in turbidity from biological growth or the presence of significant natural color. In addition, higher mountain streams with low turbidities are often low in alkalinity due to the lack of natural buffering materials in the water. This makes the treatment of these waters subject to swings in pH with the addition of coagulants. A pH adjustment chemical and the resulting increase in alkalinity is usually needed to achieve good coagulation and produce stabilized water.

High Turbidity in Rivers

High turbidity streams and rivers tend to be located in watersheds which have erodible soils and/or significant agricultural farming activity. They can also be streams which receive runoff from urban and industrialized areas. Large rivers such as the Missouri, Ohio and Mississippi, have consistently high levels of turbidity in the lower reaches of its watersheds.

Rapidly Changing Turbidity Case Study

There are many rivers which experience rapid changes to turbidity in response to precipitation events. One such example of rapidly changing turbidity involves the Metropolitan Utilities District (MUD) of Omaha, Nebraska. The Florence Water Treatment Plant in Omaha is located on the Missouri River. In the spring, the combination of snowmelt and rainwater runoff, can cause turbidity levels in the Missouri River to rise rapidly. The upstream drainage area is largely agricultural with several urban centers. The Florence Water Treatment Plant receives water directly from the Missouri River through a surface intake. The plant has pre-sedimentation using cationic polymer followed by split-treatment with lime softening and alum. Disinfection and filtration complete the treatment.

During the period between March 5th and March 9th of 1995, the plant experienced a severe increase in the raw water turbidity associated with spring precipitation. Turbidity values increased from under 100 NTU on March 5th to over 1,000 NTU on March 8th. A graph of the turbidity increases is shown on Figure 9-4. While the Florence Plant has experienced similar episodes in the past, the 1995 event was one of the largest swings in turbidity due to runoff in recent years.

During the four day time period, the plant operators were able to manage the increasing turbidity levels by increasing chemical dosages while monitoring raw water quality parameters such as color, hardness, and turbidity. Over the years, the plant operators have noticed the raw water color will begin to increase and hardness will begin to drop prior to the arrival of the high turbidity water from snow melts or precipitation events. The increased color results from the suspension of decayed organic matter in the spring runoff. The reduction in hardness experienced is typical of runoff.

By observing color and hardness during a runoff event, the plant adjusted polymers and coagulants slightly ahead of the turbidity event so that optimal treatment could be maintained through the plant. In fact, no appreciable increase in turbidity from the pre-sedimentation basins were recorded throughout the event. The quality of the finished water effluent was unimpacted.

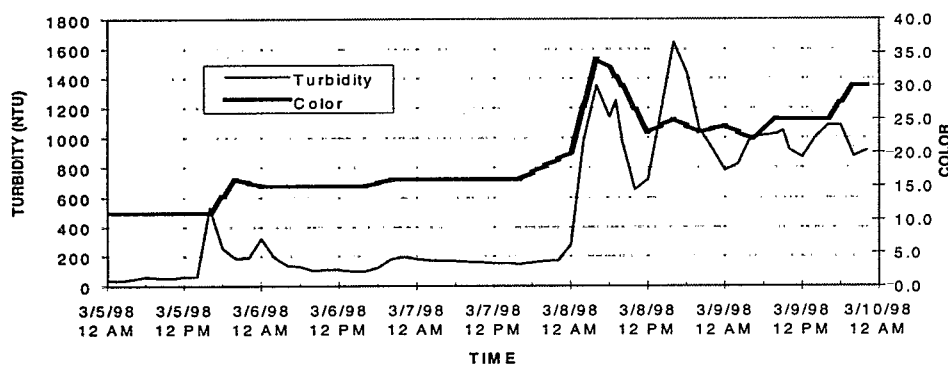


Figure 9-4. Turbidity Increase Event on the Missouri River at Omaha

High turbidity streams and rivers are usually subject to large increases in turbidity as the result of precipitation events. Larger amounts of precipitation cause erosion by bringing topsoil and decaying organic matter into the rivers. Increases in turbidities can sometimes occur within short periods of time as large flushes of precipitation runoff pass through the watershed.

9.2.2 Lakes and Reservoirs

Lakes and reservoirs capture water either naturally or through man-made impoundments through the construction of dams on streams or rivers. Because of the quiescent nature in a reservoir, turbidity levels are generally lower than streams or rivers due to the settling of particles.

Low Turbidity in Lakes and Reservoirs

In general, larger reservoirs or lakes have lower turbidity levels. For example, the Great Lakes usually have turbidity levels below 100 NTU, whereas rivers can have turbidities reaching over 1000 NTU. Lakes and reservoirs provide longer detention times, allowing for adequate settling of the larger turbidity particles and suspended solids. Of course, intakes near a river inlet to the lake may be subject to greater swings in turbidity since they may experience carryover of the river turbidity into the lake before settling can occur.

Low turbidity levels can also be found in smaller reservoirs receiving drainage from higher quality streams serving non-agricultural watersheds such as those found in mountainous areas. These reservoirs have watersheds which have streams carrying low sediment loads due to a great deal of snow melt runoff. They usually produce relatively stable sources of supply with little swings in turbidity. However, because they are small they sometimes do not have the capacity to deal with the extremes caused by severe intense precipitation or destruction of vegetation by fire. Such was the case experienced by the Denver Water Department in the spring of 1996.

High Turbidity in Lakes and Reservoirs

High turbidity events in reservoirs usually occur in smaller reservoirs or lakes that receive water from a agricultural watershed or urban drainage area. Larger reservoirs also experience high turbidity as a result of water quality changes during annual thermal changes in the lake, and may experience high turbidity events associated with severe flooding. During periods of heavy watershed runoff, smaller reservoirs are usually not large enough to effectively settle out the turbidity particles before they reach the intake location of a water treatment plant. In addition, if a reservoir or lake is shallow, wave action created by high winds can stir up sediments from the bottom and re-suspend particles.

Reservoir turbidity events can also be caused by seasonal turnover of the thermal stratification levels which form in the reservoirs. In deep reservoirs (i.e., those over 20

feet) de-stratification often occurs in the fall when the upper levels of the reservoir become cooler and denser, drop to the lower levels, and destroy the stratification. This "overturning" effect can happen quickly and may bring anoxic water that is nutrient-rich from the lower depths to the surface where algae is present. Sudden algal blooms can then severely raise turbidity levels. The resulting impacts on raw water supplies can be minimized through the construction of intake structures with multiple level draw-off points.

Lake Reservoir Turbidity Case Study

A forest fire in the watershed area of Buffalo Creek near Denver has caused some long-lasting impacts on the tributary area turbidities. The Foothills Water Treatment Plant receives water from this watershed via a storage reservoir in Watertown Canyon. In May 1996, the Buffalo Creek watershed experienced a forest fire which destroyed many trees and ground vegetation. Prior to the fire, the highest turbidities observed were around 40 NTU (Denver Water). Usually, the turbidities from the reservoir were less than 20 NTU.

During and after the fire, increased erosion has caused the turbidity to reach as much as 400 NTU during peak runoff events. Figure 9-5 shows a comparison of the maximum average day turbidities before and after the fire. The watershed is still recovering from the fire and so these higher turbidities may still occur during precipitation events. Since the fire, Denver Water Department has installed a turbidimeter on the intake tower at the Strontious Springs Dam, as well as instituting an observation system of spotters who live in Buffalo Creek that will inform the Department when heavy rainfalls are occurring so that appropriate flow and chemical adjustments can be made at the downstream plant so that finished water quality is not effected.

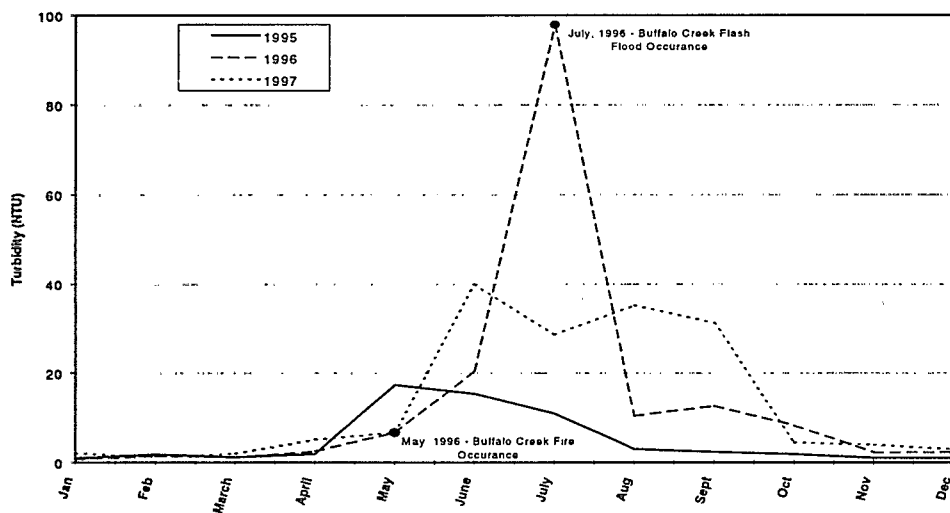


Figure 9-5. Turbidity Increase Due to Forest Fire in Buffalo Creek

9.3 Ground Water Under the Direct Influence (GWUDI)

GWUDI is also a water supply source that can be subject to changes in turbidity. These sources usually consist of a well or infiltration gallery located adjacent to or under a stream, river or lake. However, wells that are located significant distances away from surface water sources can also be influenced by surface water runoff due to geologic conditions that transport water quickly from the ground surface to the well.

The classification of a water source as GWUDI is usually the result of a Microscopic Particulate Analysis (MPA) test that examines the source for certain surface water organisms in the water supply. The presence of these organisms is an indication that the supply is influenced by surface water. In addition, if raw water turbidities or temperatures rise and fall with the source water this can also be an indicator of a connection between the surface water source and the well.

The degree to which these types of raw water sources are subject to changes in turbidity are usually a function of how far the well is from the surface water source and the type of linking aquifer. Wells in very close proximity to a river with a coarse gravel aquifer may mirror the turbidity changes in the river very closely. On the other hand, wells that are several hundred feet from a surface water source in a tight sandy aquifer may not experience noticeable changes in turbidity in response to a surface water turbidity event.

9.4 Additional Watershed Considerations

Water facilities should also be aware of the nature of their watershed and any contamination sources. Some sources of contamination may be present which are not a concern under normal circumstances, but may become a problem during a large precipitation event. For example, some U.S. cities have combined sanitary and storm sewers which can result in surface water contamination during large rain events.

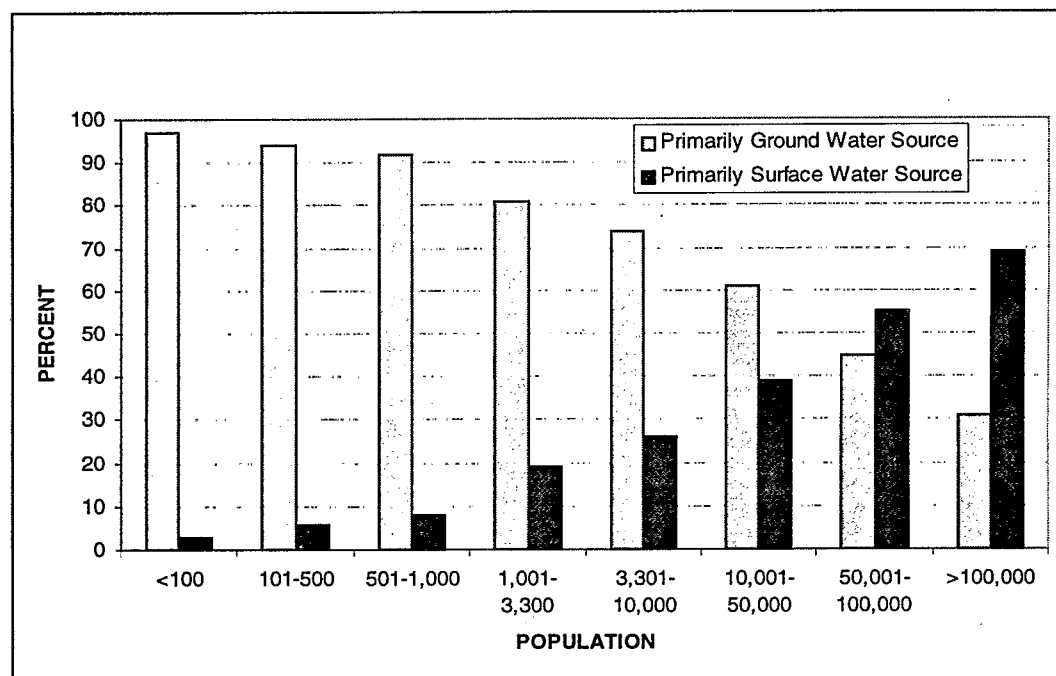
During dry periods, combined sewer systems collect wastewater and convey it to the wastewater treatment plant. However, during periods of high precipitation these systems also collect storm water which also travels to the wastewater treatment plant. When extreme precipitation events occur, wastewater plant can be overloaded by the high combined flows. This causes sewerage to bypass the plant and undergo only preliminary treatment prior to discharge to a river. If flows are extremely high, preliminary treatment may also be bypassed and raw sewage may be discharged directly to the river. These events, termed combined sewer overflows (CSOs), can cause increases in river turbidity. However, at times turbidity levels in the receiving stream may actually drop due to the large amount of sewage flow, but the levels of bacteria and protozoa in the raw water supply may rise significantly.

Another similar situation may exist where water treatment plants are situated immediately downstream of livestock operations. These feeding operations can be sources for runoff containing elevated levels of *Giardia* and *Cryptosporidium* during runoff events. Downstream utilities should be aware of these situations and take the necessary treatment precautions to ensure adequate treatment.

9.5 Water Sources Occurrence in the United States

Turbidity occurrence in raw water supplies is generally associated with surface water sources or GWUDI. An indication of the percentage of utilities using surface water sources of raw water supply was presented in the 1997 *Community Water System Survey* (USEPA, 1997). Figure 9-6 illustrates the percentage of utilities using ground water versus surface water sources by water system size. These percentages were developed from the data presented in the 1997 study, which is a representative sample of systems in the U.S.

The figure indicates that smaller systems typically use ground water while larger systems typically use surface water. Since turbidity occurrence is generally greater with surface water sources, larger water systems may be more concerned with potential difficulties arising from high turbidity levels.



Source: USEPA, 1997.

Figure 9-6. Raw Water Source by Water System Size

9.6 References

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10. TURBIDITY THROUGH THE TREATMENT PROCESSES

10.1 Introduction

In the arena of public water supply, water treatment is provided to remove constituents from raw water which may pose a risk to public health or are undesirable in finished water. Turbidity is a characteristic related to the concentration of suspended solid particles in water and has been adopted as an easy and reasonably accurate measure of overall water quality. Turbidity can be used to measure the performance of individual treatment processes as well as the performance of an overall water treatment system. Common water treatment processes intended to remove suspended solids and reduce turbidity, or aid in this removal and reduction process, include:

- Raw water screening;
- Pre-sedimentation;
- Coagulation;
- Flocculation;
- Sedimentation; and
- Filtration.

This chapter provides a general description of each of these processes and information on the level of turbidity reduction that is commonly achieved through each. A typical water treatment system is shown schematically in Figure 10-1.

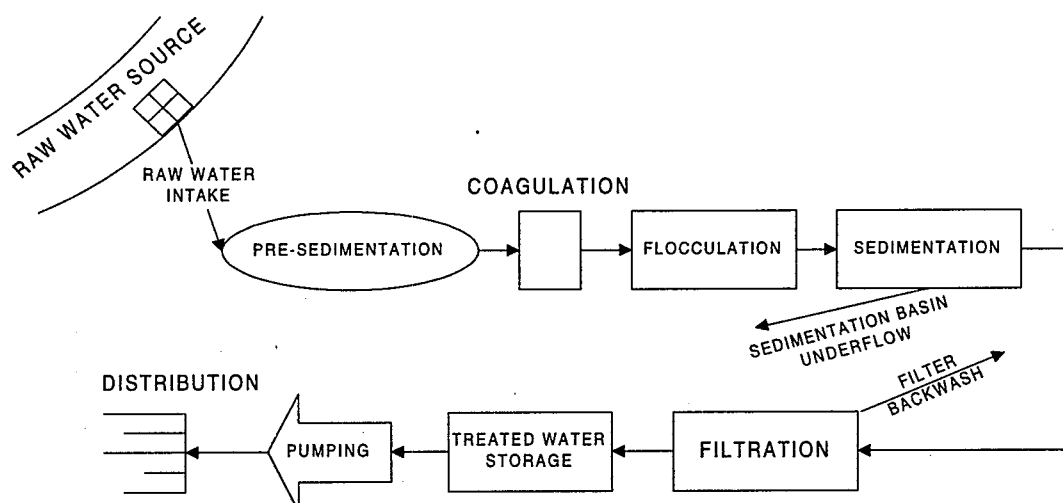


Figure 10-1. A Typical Conventional Water Treatment System

10.2 Intake Facilities/Raw Water Screening

Systems which obtain water from surface supplies such as lakes and rivers employ intake facilities to allow water to be withdrawn from the source. Most surface water intake facilities are equipped with some type of screening device to prevent large rocks, sticks, and other debris from entering the treatment system. Large bar racks with openings of 1 and 3 inches apart are commonly used for this purpose. They are designed specifically to prevent large materials that could damage the intake structure or downstream equipment from entering the treatment system. Bar racks are usually designed for manual cleaning. When the raw water source is a river and a bar rack is used, the rack is usually oriented to take advantage of the hydraulics of the river to keep the rack cleaned. Although trash racks have little effect on turbidity, they do serve an important function in keeping large solids out of the treatment system.

In other cases, intake screens are employed to perform the same function. Intake screens are generally similar to bar racks except they have smaller openings (typically 3/16 to 3/8 inch openings) and are usually equipped with mechanical or hydraulic cleaning mechanisms. Because intake screens remove particles much smaller than those generally removed with bar racks, screens may provide some turbidity reduction by removing larger solids that may be the source of smaller particles further in the treatment train.

10.2.1 Intake Location

Intake facilities are typically the very first process in the water treatment system. When the water source is a lake or reservoir, substantial "pre-sedimentation" may occur within the reservoir itself. This can serve to reduce the turbidity of water entering the treatment system as well as dampen the impact of fluctuations in source water turbidity resulting from storm events and other environmental phenomenon. If the intake facility is located away from the reservoir's water source (i.e., the river feeding the reservoir) this pre-sedimentation may substantially reduce the turbidity of the water entering the treatment system. On the other hand, if the intake facility is located near the point where the supply stream enters the reservoir, the benefit of the pre-sedimentation occurring within the reservoir can be significantly reduced or lost.

When the water source is a river, the quality of water withdrawn may be impacted by the location of the intake in relationship to sources of pollution entering the river. For example, an intake structure located upstream from a municipal or industrial wastewater discharge may supply substantially higher quality water than if it were located downstream from the discharge.

10.2.2 Intake Depth

For many lakes and reservoirs the water surface elevation varies seasonally due to environmental factors or reservoir management practices. In such cases, it is essential to be able to withdraw water from the source under a variety of different water surface level conditions. Even in cases where the source water surface elevation does not vary significantly, the intake structure may be designed to allow withdrawal from the surface,

or from different levels beneath the surface. This capability can have a significant impact on the quality of water entering the treatment system. Many times stratification within a lake or reservoir exists continually or occurs on a seasonal basis. In these cases, the quality of water may vary significantly from near the surface to tens or hundreds of feet below the surface. For example, if algae growth is a problem, water withdrawn from several feet beneath the surface may have substantially lower turbidity than water withdrawn from the surface, as algae needs sunlight to survive and is typically found near the water surface.

10.2.3 Effect on Turbidity

Intake screens are not intended to reduce the turbidity of the water entering the treatment system. The solids removed by intake screens are large enough that they typically do not directly impact turbidity, though subsequent deterioration and break-up of these solids could contribute to increased levels of turbidity later in the treatment process. The physical location of the intake structure and the flexibility it provides for varying the depth from which source water is withdrawn can significantly influence the turbidity of the water entering the treatment system.

10.3 Pre-sedimentation

Pre-sedimentation is commonly used for water supplies where raw water turbidity is continually high, is high on a seasonal basis, or is high sporadically due to storms or other environmental events within the watershed. Pre-sedimentation may also be used in situations where substantial amounts of sand and gravel may be present in the source water. Depending on the purpose of the pre-sedimentation process, the pre-sedimentation basins may be relatively large settling ponds or small concrete basins. When ponds are utilized, they are generally designed to remove large quantities of silt from the raw water and typically provide hydraulic detention times ranging from a few hours to a few days. Smaller concrete basins that provide less than 20 minutes detention time are sometimes used to provide grit removal. The larger settling ponds are generally not equipped with mechanical sludge removal facilities and must be periodically cleaned by dredging or other means. The concrete pre-sedimentation basins may be equipped with mechanical equipment to remove solids from the basin bottom, or they may be designed to promote manual cleaning using a fire hose or other equipment.

When pre-sedimentation is intended to remove silt and other fine suspended solids, chemical addition is often used to enhance process performance. Organic polymers are the chemicals most commonly added prior to pre-sedimentation to enhance solids removal, but alum and ferric chloride are also sometimes used. The chemicals are added to the raw water as it enters the pre-sedimentation basin to promote solid separation.

10.3.1 Effect on Turbidity

Pre-sedimentation facility performance depends largely on facility design. Factors such as the ability to provide low velocity plug flow through the pre-sedimentation facility and the capability to add chemicals are critical to achieving optimal system performance. The

characteristics of the suspended solids in the raw water also play a key role in facility performance. In cases where well-designed pre-sedimentation facilities are available and adequate hydraulic detention times are provided (generally greater than 12 hours), significant turbidity reduction can be achieved through the pre-sedimentation process.

In cases where pre-sedimentation is used primarily to remove grit from the raw water before it enters subsequent treatment processes, detention times are generally limited to 10 to 20 minutes and very little turbidity reduction is achieved.

10.4 Coagulation

Coagulation is the process of conditioning suspended solids particles to promote their agglomeration and produce larger particles that can be more readily removed in subsequent treatment processes. In many cases, dissolved organic substances are adsorbed on the surface of suspended solids particles and effective coagulation can be an effective step in their removal as well (AWWA and ASCE, 1990). The particles suspended in raw water typically vary widely in size. Typical sizes for different types of particles commonly found in water supplies can be seen in Figure 8-1.

Colloidal size particles typically carry an electrical charge (AWWA and ASCE, 1990). When the suspended particles are similarly charged, the resulting repulsive forces between particles tend to "stabilize" the suspension and prevent particle agglomeration. The process of coagulation is complex and may involve several different mechanisms to achieve "destabilization", which allows particle agglomeration and enhances subsequent removal.

Coagulation is typically accomplished through chemical addition and mixing. Following coagulation, the processes of flocculation, sedimentation, and filtration are used to remove the "destabilized" particles from suspension.

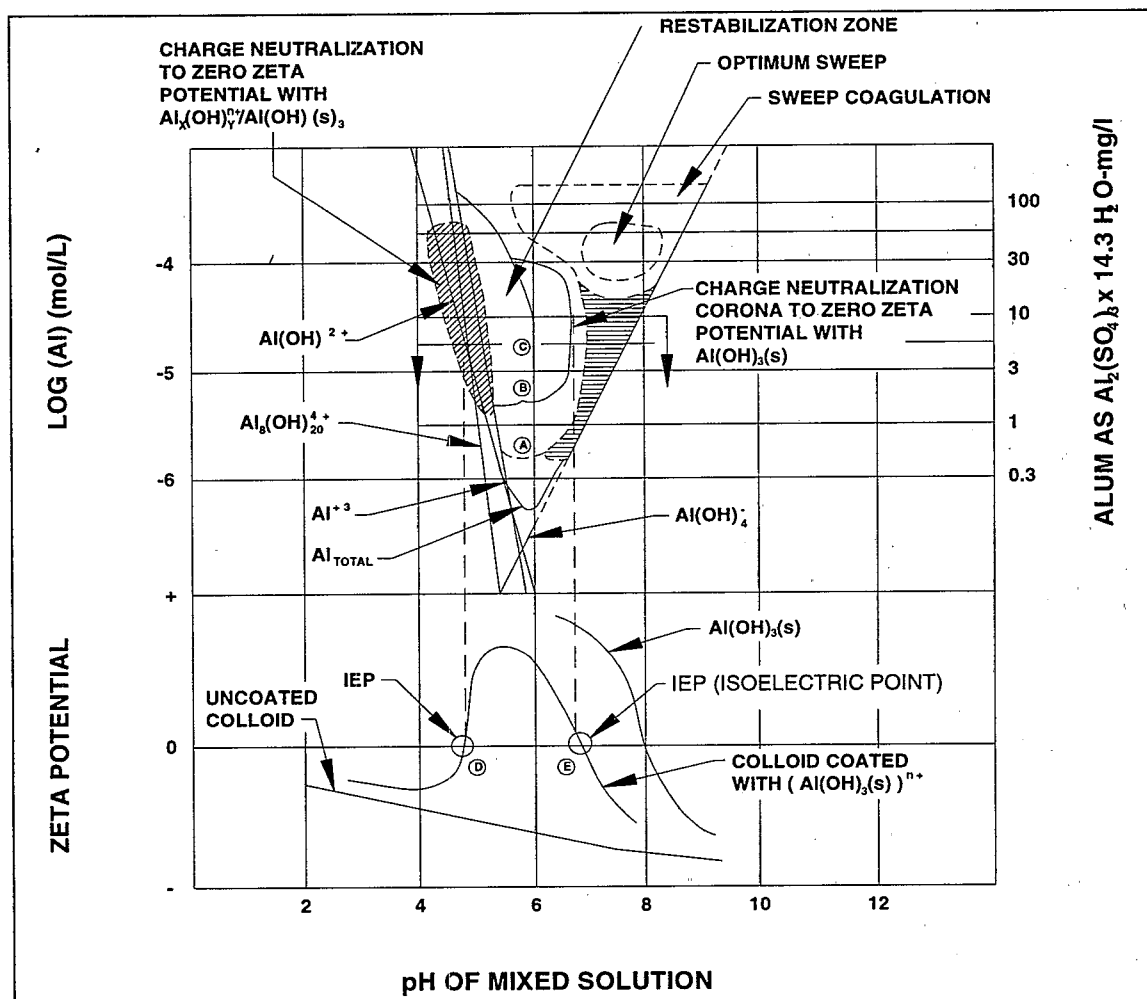
10.4.1 Chemicals

Chemicals commonly used in the coagulation process include aluminum or iron salts and organic polymers. The most common aluminum salt used for coagulation is aluminum sulfate, or alum. Alum may react in different ways to achieve coagulation. When used at relatively low doses (<5 mg/l), charge neutralization (destabilization) is believed to be the primary mechanism involved. At higher dosages, the primary coagulation mechanism is entrapment. In this case, aluminum hydroxide ($\text{Al}(\text{OH})_3$) precipitates forming a "sweep-floc" which tends to capture suspended solids as it settles out of suspension.

Solution pH plays an important role when alum is used for coagulation since the solubility of the aluminum species in water is pH dependent. If the pH value of a mixed solution is between 4 and 5, alum is generally present in the form of positive ions (i.e., $\text{Al}(\text{OH})^{2+}$, $\text{Al}_2(\text{OH})_4^{4+}$, and Al^{3+}). However, optimum sweep and sweep coagulation occur when negatively-charged forms of alum predominate, which occurs when the pH is between 6 and 8. Figure 10-2 depicts the solubility of some of these aluminum species present during a typical coagulation process. Figure 10-2 depicts some of the aluminum

species involved in alum coagulation and the conditions of aluminum concentration and pH under which they occur (AWWA and ASCE, 1990).

When alum is used and charge neutralization is the primary coagulation mechanism, effective flash mixing is critical to the success of the process. When the primary mechanism is entrapment, effective flash mixing is less critical, and flocculation is the more important process.



Source: AWWA and ASCE, 1990.

Figure 10-2. The Alum Coagulation Diagram and Its Relationship to Zeta Potential

Ferric Chloride (FeCl_3) is the most common iron salt used to achieve coagulation. Its reactions in the coagulation process are similar to those of alum, but the relative solubility and pH ranges differ significantly from those of alum.

Both alum and ferric chloride can be used to generate inorganic polymeric coagulants that have been used for coagulation. These coagulants are typically generated by partially

neutralizing concentrated solutions of alum or ferric chloride with a base such as sodium hydroxide prior to their use in the coagulation process (AWWA and ASCE, 1990). The resulting inorganic polymers may have some advantages over alum or ferric chloride in cold waters or in low alkalinity waters.

Organic polymers tend to be large molecules composed of chains of smaller "monomer" groups (AWWA and ASCE, 1990). Because of their large size and charge characteristics, polymers can promote destabilization through bridging, charge neutralization, or both. Polymers are often used in conjunction with other coagulants such as alum or ferric chloride to optimize solids removal.

10.4.2 Rapid Mixing

Mixing is utilized as part of the coagulation process to distribute the coagulant chemicals throughout the water stream. When alum or ferric chloride are used to achieve destabilization through charge neutralization, it is extremely important that the coagulant chemical be distributed quickly and efficiently because it is the intermediate products of the coagulant reaction that are the destabilizing agents. The life of these intermediate species is short and they must contact the solids particles in the water if destabilization is to be achieved. When other mechanisms are predominant in the coagulation process, or when organic polymers are being used as the coagulant chemical, immediate distribution of the coagulant chemical is not as critical and less intense mixing may be acceptable, or even desirable. In some cases, excessive mixing may serve to break-up coagulant molecules or floc particles, thereby reducing the effectiveness of subsequent solids removal processes.

Mixing intensity is typically quantified with a number known as the "velocity gradient" or "G value". The G value is a function of the power input into the mixing process and the volume of the reaction basin. Typical G values for coagulation mixing range from 300 to 8000 sec^{-1} (Hudson, 1981).

The time required to achieve efficient coagulation varies, depending on the coagulation mechanism involved. When charge neutralization is the mechanism involved, the detention time required may be one second or less. When sweep floc or entrapment is the mechanism involved, longer detention times on the order of 1 to 30 seconds may be appropriate (Kawumara, 1991; AWWA and ASCE, 1998; Hudson, 1981).

10.4.3 Effect on Turbidity

Coagulation by itself does not achieve turbidity reduction, in fact turbidity may increase during the coagulation process due to the additional insoluble compounds generated through chemical addition. The subsequent processes of flocculation, sedimentation, and filtration are used in conjunction with coagulation to achieve suspended solids and turbidity reduction.

10.5 Flocculation

Flocculation is the physical process of agglomerating small particles into larger ones that can be more easily removed from suspension. Flocculation is almost always used in conjunction with, and preceded by coagulation. During the coagulation process the repulsive forces between solids particles are reduced or eliminated. Flocculation is the process of bringing the destabilized particles into contact with one another to form larger "floc" particles. These larger particles are more readily removed from the water in subsequent processes.

Flocculation is generally accomplished by mixing the destabilized suspension to provide the opportunity for the particles to come into contact with one another and stick together.

10.5.1 Slow Mixing

Mixing is a key aspect of the flocculation process. Often the intensity of mixing is reduced as the water proceeds through the flocculation process to achieve optimum performance.

At the beginning of the process, the mixing is fairly intense to maximize the particle contact opportunities. Mixing intensity values (G values) in this area are typically in the range of 60 to 70 sec^{-1} (Kawamura, 1996).

Toward the end of the flocculation process, mixing intensity is generally reduced to minimize the potential for breaking up the floc particles that have begun to form. In this portion of the process, G values are commonly in the 10 to 30 sec^{-1} range (Kawamura, 1996). Many times mixing intensity is tapered through several different stages of the flocculation process to optimize process effectiveness.

A wide variety of flocculation mixing mechanisms have been used in water treatment. These include vertical shaft mechanical mixers, horizontal shaft mechanical mixers, and hydraulic mixing systems.

10.5.2 Detention Time

The amount of time the water spends in the flocculation process is a key performance parameter. Adequate time must be provided to allow generation of particles sufficiently large to allow their efficient removal in subsequent treatment processes. The optimum particle size may vary significantly depending on the downstream treatment processes utilized. For example, when sedimentation is used, large floc particles are typically desirable because they tend to settle out of suspension readily. If filtration directly follows the flocculation process, smaller floc particles may be the most desirable since they tend to be stronger and less susceptible to break-up by the shear forces encountered within the filters. Overall detention time in the flocculation process typically ranges from 10 to 30 minutes and is generally provided in several different basins or basin segments. This allows the mixing intensity to be varied through the process.

10.5.3 Effect on Turbidity

As with coagulation, the purpose of the flocculation process is not to directly reduce turbidity or suspended solids levels, but rather to prepare the solids for subsequent removal. The reduction in number of suspended solids particles in suspension is typically achieved in the flocculation process as the smaller particles are combined to form larger ones. This process may, or may not result in a reduction in turbidity.

10.6 Sedimentation/Clarification

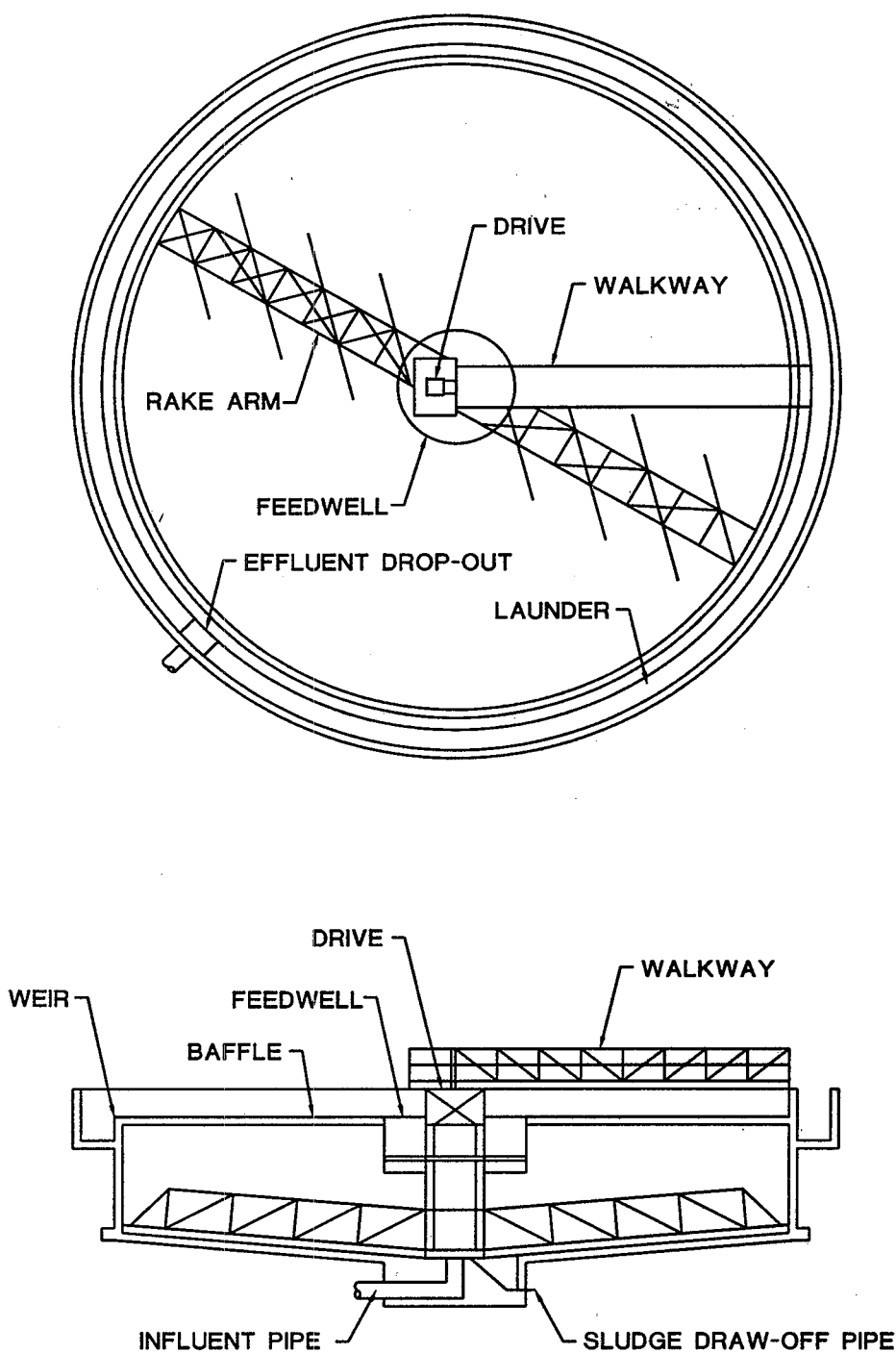
Sedimentation is the process by which solids are removed from the water by means of gravity separation. In the sedimentation process, the water passes through a basin in which relatively quiescent conditions prevail. Under these conditions, the floc particles formed during flocculation settle to the bottom of the basin while the "clear" water passes out of the basin over an effluent baffle or weir. As shown in Figure 10-3, the solids collect on the basin bottom and are removed, typically by a mechanical "sludge collection" device. The sludge collection device scrapes the solids (sludge) to a collection point within the basin from which it is pumped directly to disposal or to a sludge treatment process.

Conventional sedimentation typically involves one or more basins. These "clarifiers" are relatively large open tanks, either circular or rectangular in shape. In properly designed clarifiers, velocity currents are reduced to the point where gravity is the predominant force acting on the water/solids suspension. Under this condition, the difference in specific gravity between the water and the solids particles causes the solids particles to settle to the bottom of the basin.

High rate sedimentation is similar to conventional sedimentation except that the sedimentation basin has been modified through the addition of some mechanical or other device to aid in the settling process. These mechanical devices typically consist of plates or tubes intended to reduce the distance the solids particles must settle through the water before they reach the bottom of the basin and can be removed. Figure 10-4 illustrates a plate settler used for high rate sedimentation.

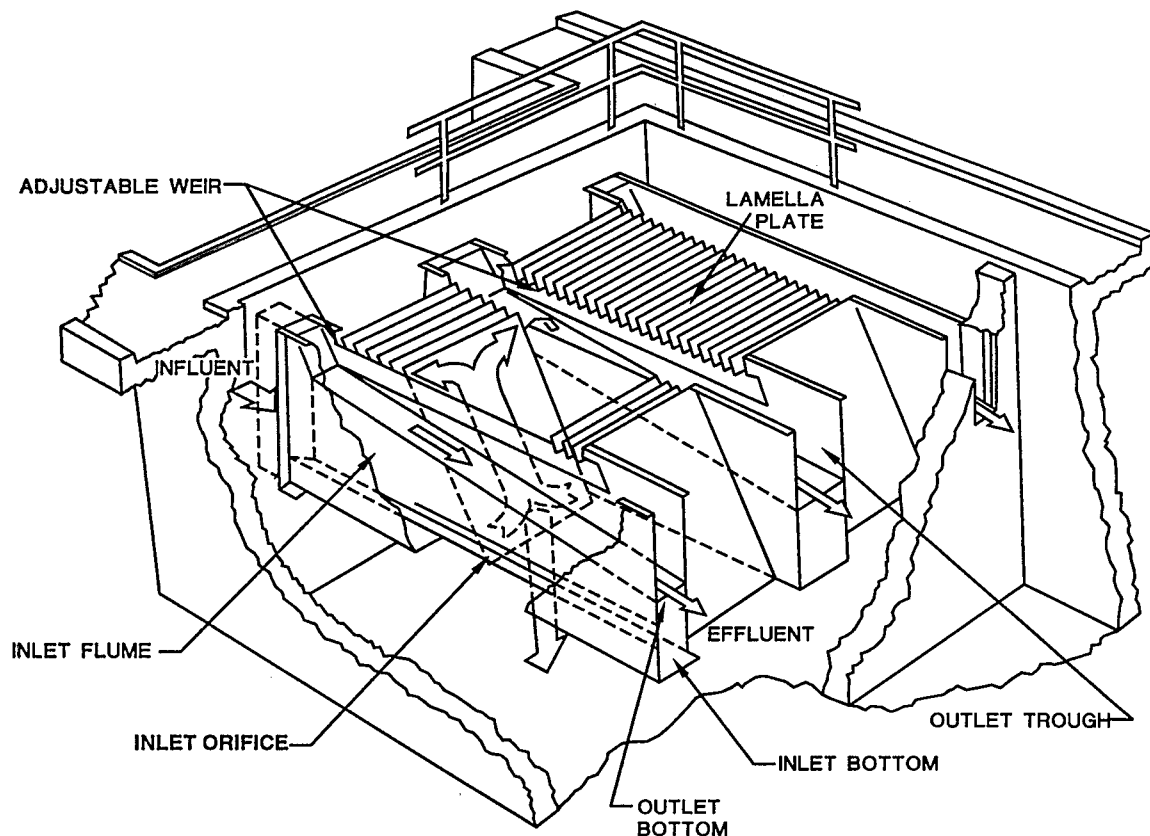
Another high rate clarification process employs an "adsorption clarifier" and is designed to provide flocculation and clarifications within a single process. These clarifiers consist of a basin filled with adsorption media, generally small particles of either plastic or rock, about the size of pea gravel. As the water passes through the media, hydraulic mixing promotes flocculation and the flocculated particles adhere to the surface of the media particles. The media is cleaned periodically using an air or air and water backwash process to remove the solids.

Solids Contact clarifiers represent an entirely different approach to high rate clarification. They consist of a basin similar to that used for a conventional clarifier but with a sludge recycle system to promote development of a dense sludge blanket as depicted in Figure 10-5.



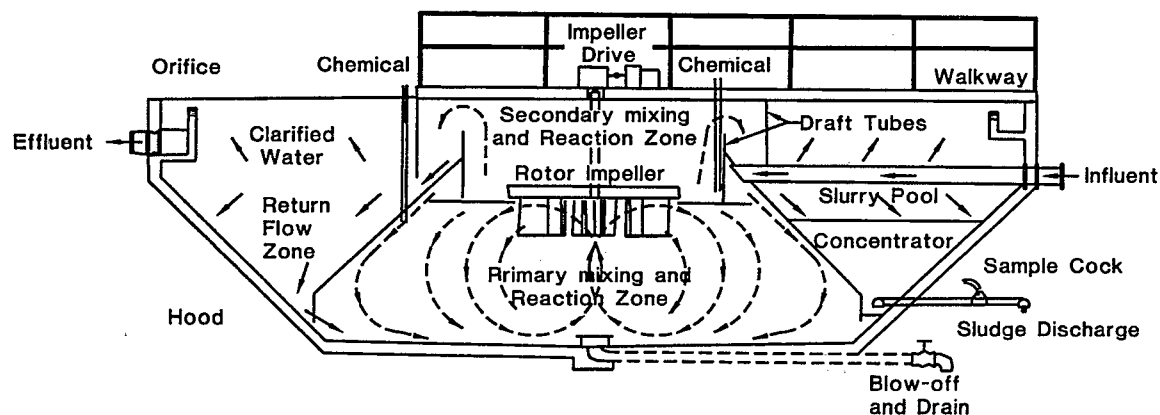
Source: AWWA and ASCE, 1990.

Figure 10-3. Circular Radial-flow Clarifier



Source: AWWA and ASCE, 1998.

Figure 10-4. Plate Settlers Used for High Rate Sedimentation



Source: AWWA and ASCE, 1998.

Figure 10-5. Accelerator Solids Contact Unit

As the water enters the bottom of the basin and passes upward through the sludge blanket, the flocculated solids in the blanket tend to contact and capture or adsorb the solids from the water.

10.6.1 Effect on Turbidity

Suspended solids removal and turbidity reduction rates achieved through sedimentation may range from about 50 to 90 percent, depending on the nature of the solids, the level of pretreatment provided, and the design of the clarifiers. Common values are in the 60 to 80 percent range (Hudson, 1981). A primary function of the sedimentation or clarification process is to reduce the load of solids going to the filters. Optimization of the clarification process will minimize the solids loading on the filters and contribute to enhanced filter performance and better overall treated water quality.

10.7 Filtration

Like clarification, filtration is a process in which solids are removed from water and substantial turbidity removal is achieved. Optimization used prior to the filtration process will control loading rates while allowing the system to achieve maximum filtration rates. In fact, filtration is the final step to achieve turbidity reduction in most water treatment operations. The water leaving the filtration process should be well within turbidity limits.

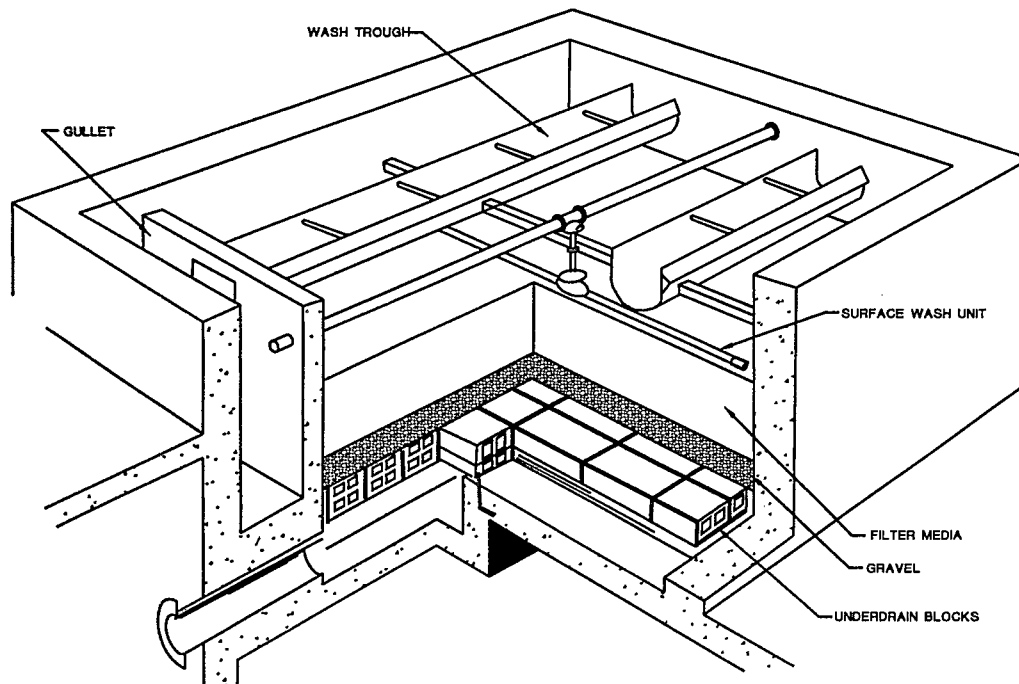
In the filtration process, the water passes through a bed of granular filter media or other filtering material and solids are physically retained on the media. After passing through the filter media, the "filtered" water is collected and removed from the filter. The solids retained on the media are also periodically collected and removed. As with the sedimentation process, the performance of most filters depends largely on the preparatory treatment processes of coagulation and flocculation. Without effective use of these processes, only marginal filter performance can be expected.

Filters are classified according to the type of media used and the operational conditions employed. The primary types of filters used in domestic water treatment include:

- Rapid Sand Filters;
- Pressure Filters;
- Slow Sand Filters; and
- Precoat Filters.

10.7.1 Conventional Rapid Sand Filters

Rapid sand filters are the most commonly used type of filters in water treatment systems today. They get their name from the type of media employed (sand) and from the rate at which they are hydraulically loaded. A sectional drawing of a typical rapid sand filter is shown in Figure 10-6.



Source: AWWA and ASCE, 1998.

Figure 10-6. Typical Rapid Sand Filter

Water enters the filter unit above the media and flows by gravity downward through the filter media to the underdrain or collection system, where it is removed from the filter. When the filter media becomes clogged with solids it is cleaned through a “backwash” process. In the backwash process water, and in some instances, air is introduced to the filter at a relatively high rate through the underdrain system. The water and air flow upward through the media, expanding the media bed and creating a scrubbing or scouring action which removes solids accumulated on the media surface and in inter-particle sites within the media bed. After passing through the media bed, the backwash water and the solids it contains are removed from the filter with a series of collection troughs.

Media

A variety of different types of media are used in rapid sand filters. As the name implies, the primary media is sand. In some cases all of the sand is the same size, but more commonly the media consists of particles of varying composition, size, and density. Filters with more than one type and size of media are referred to as dual media, mixed media, or multi-media filters, depending on the media provided. As the backwashing process in these filters concludes and the media particles settle back into position in the filter bed, the particles become stratified due to their differing sizes and densities. The largest and least dense media particles accumulate near the top of the media bed and the smallest and most dense particles migrate to the bottom. With this media stratification, when the filter is placed back into service and the water passes down through the bed of media, it first encounters large particles and then finer and finer sand until it reaches the

underdrain system. This stratification tends to minimize the "blinding" effect that occurs when solid particles accumulate at the very top of the media bed. It also provides a much greater volume for solids storage within the filter bed, which allows longer filter runs between backwash operations.

The top, or coarsest layer of media is often composed of anthracite coal rather than sand. The relatively light coal remains at the top of the filter bed after filter cleaning (backwashing), even though its particle sizes are relatively large. Conversely, high density garnet sand is used for the smallest layer of filter media. The high density of this material causes it to settle quickly to the bottom of the filter bed following backwash operations, even though its particles are relatively small.

Hydraulics

Filter performance is affected significantly by its hydraulic characteristics. Typical rapid sand filter loading rates range from 2 to 8 gallons per minute per square foot of filter bed surface area. As the filter bed becomes dirty and clogged with solids, the resistance to flow increases. Ultimately flow will cease when the resistance to flow is greater than the gravitational force compelling it. As the "head" required to push water through the filter increases, the rate of flow tends to decrease and solids particles are pushed further and further into the bed of media. Ultimately, if sufficient head is available, solids will be driven completely through the bed and appear in the filtered water, a condition known as "breakthrough". The filter run should be terminated and backwash initiated before breakthrough occurs.

Controls

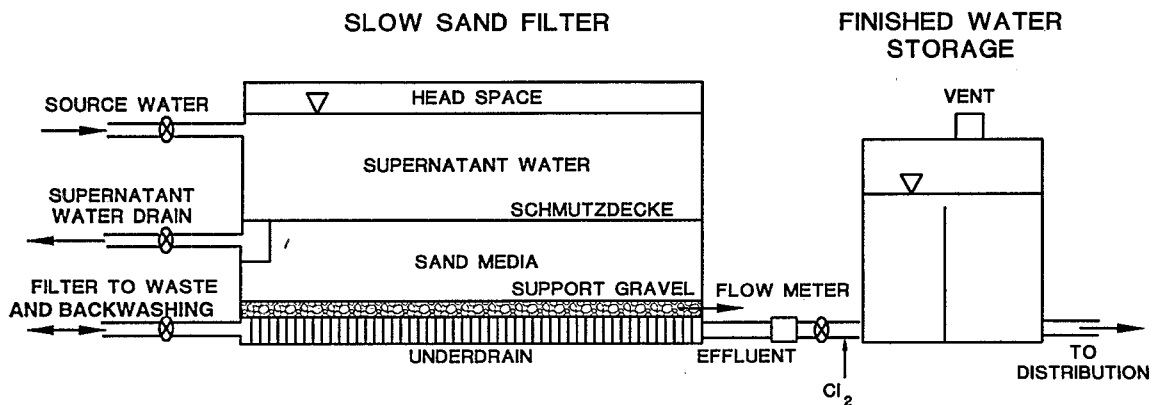
Typical filter control parameters include:

- Filter loading rate;
- Filter run length;
- Headloss;
- Filtered water turbidity;
- Backwash rate; and
- Backwash duration.

Control of these parameters gives the operator a great deal of influence in determining the performance of a filter. Often, however, there are conflicting objectives associated with filter operation. For example, the goal of maximizing water production may conflict with the objective of minimizing treated water turbidity. The operator must use good judgement in establishing operational goals and exercising process control to achieve optimal finished water quality and production.

10.7.2 Slow Sand Filters

Slow sand filters have been used for nearly two centuries and have been proven to an effective “low-tech” method of treating some waters (AWWA and ASCE, 1990). A slow sand filter consists of a bed of uniform, relatively fine grain sand underlain by an underdrain system as depicted in Figure 10-7.



Source: AWWA and ASCE, 1998.

Figure 10-7. Typical Covered Slow Sand Filter Installation

Water is introduced at the top of the bed and under the influence of gravity it passes downward through the bed to the underdrain system. Slow sand filters are loaded at much lower rates than rapid sand filters, with typical hydraulic loading rates ranging from 0.04 to 0.1 gallons per minute per square foot of filter bed area (AWWA and ASCE, 1998). Since the sand used in slow sand filters is relatively uniform in size and fine grained, most of the solids removal and turbidity reduction occurs at the very top of the sand bed. As operation of the filter continues, a layer of dirt and micro-organisms builds up at the surface of the bed. This layer is known as the “schmutzdecke” and contributes to the effectiveness of the filter in removing suspended solids and reducing turbidity. After a period of operation the headloss through the filter becomes excessive and the filter must be cleaned. Cleaning is accomplished by letting the water level drop below the top of the filter media and then physically removing the schmutzdecke along with the top 0.8 to 1.2 inches of sand. Typical slow sand filter runs between cleaning are one to six months (Kawamura, 1996).

Generally slow sand filters are not preceded by coagulation or flocculation processes, making them one of the simplest water filtration processes available. However, relatively large land areas are required and, with their simplicity comes little operational flexibility. The only basic operational controls available to the slow sand filter operator are hydraulic loading and frequency of cleaning.

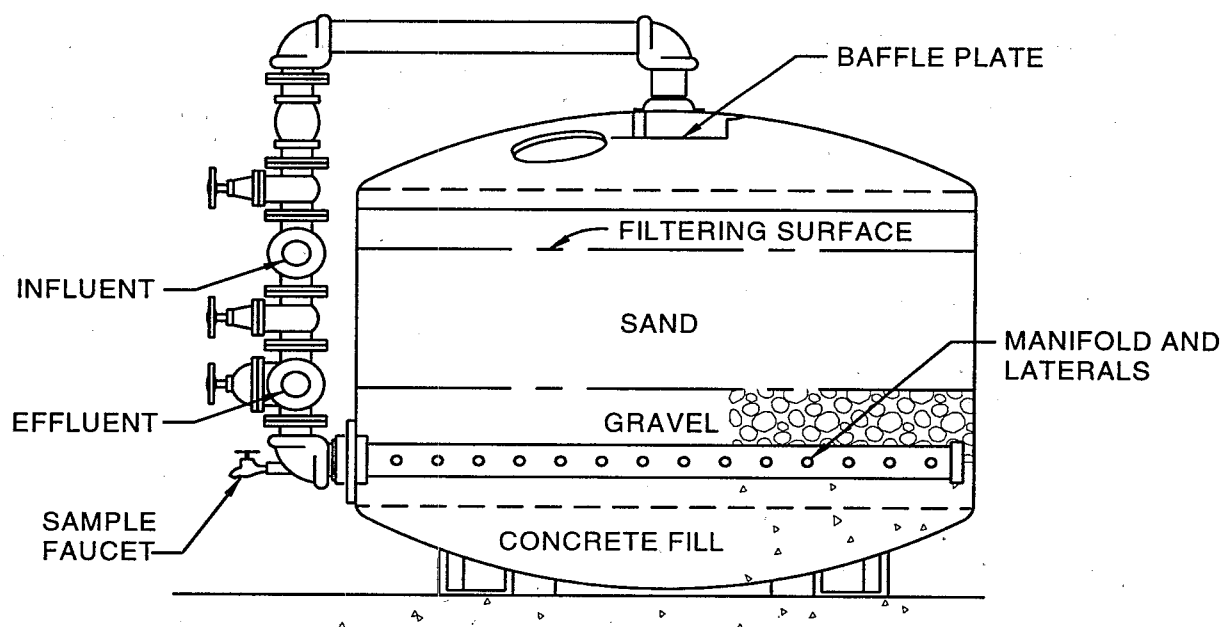
Slow sand filters can be very effective in removing suspended solids and reducing turbidity, depending on the nature of the solids particles involved, however, they have been found to be limited in their capability to remove clay particles and color (AWWA and ASCE, 1990).

10.7.3 Pressure Filters

Pressure filters are essentially a variation of the conventional rapid sand filter. They employ the same types of media and function in much the same way. The primary difference is that pressure filters are contained within a pressurized vessel, usually made of steel, and pressure is used to push the water through the filter bed rather than gravity as depicted in Figure 10-8.

Since pressure filters function much like conventional rapid sand filters, their capability to remove suspended solids and reduce turbidity is similar.

The primary advantage of pressure filters is that they do not require the vertical space for several feet of water above the filter bed and the water leaves the filter under pressure, thus eliminating the potential for air binding associated with conventional rapid sand filters. Disadvantages include the lack of access for visual observation of the filter bed and the possibly greater potential to experience turbidity "breakthrough" due to the higher pressure of force driving the filtration process.



Source: AWWA and ASCE, 1990.

Figure 10-8. Cross Section of a Typical Pressure Filter

10.7.4 Precoat/Diatomaceous Earth Filters

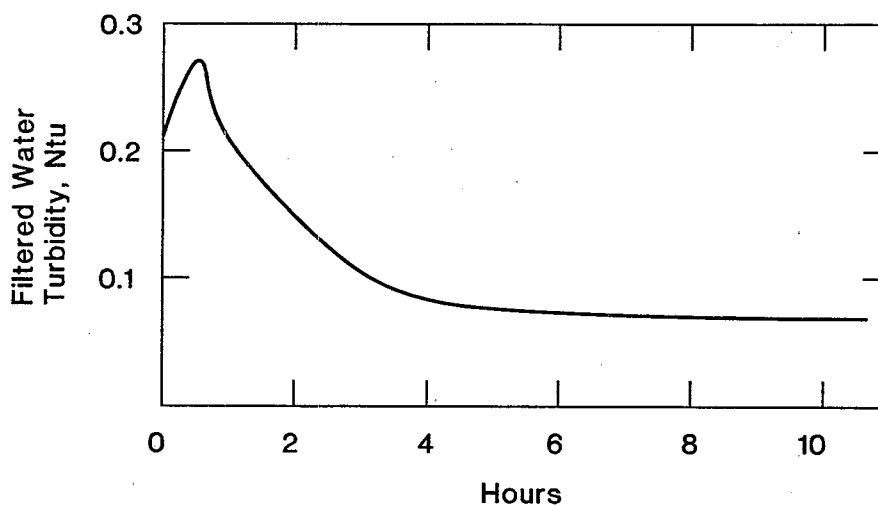
Precoat filters represent an entirely different kind of filtration mechanism. Instead of using sand or other granular material as the filtration medium, precoat filters use a thin layer of "diatomaceous earth" or similar material to form a thin layer of filter media over a supporting fabric or "septum", which in turn is supported by a rigid filter support structure. The filter coat material is applied in a slurry before the filtration cycle begins. When water passes through the filter under pressure, usually supplied by a pump but sometimes by gravity, the solids in the water are captured on the surface of the filter media. As the filtration process proceeds, additional filter media is added to the water going to the filter. This supplemental media or "body feed", like the suspended solids in the water, accumulates on the surface of the filter coat, increasing the depth of the media and preventing the surface blinding effect that would otherwise occur. When the pressure loss through the filter becomes excessive, filtration is discontinued and the filter media coat is washed off through a backwash process, a new pre-coat is applied, and the filtration process begins again.

Precoat filters have the capability to remove particles down to about one micron in size. Hydraulic loading rates are typically in the range of 0.5 to 2 gallons per minute per square foot of coated filter surface (ASCE, 1990). Advantages include relatively low capital cost and no need for the preliminary processes of coagulation and flocculation. Disadvantages include the inability to handle high turbidity water, the potential for particle pass-through if the precoat process is not effective or cracking occurs during filter operation, and the relatively poor capability to remove color and taste and odor causing compounds.

10.7.5 Effect on Turbidity

Conventional and direct filtration processes have the capability of producing water with turbidity below the proposed SDWA turbidity of 0.3 NTU and even below the 0.1 NTU Partnership for Safe Water finished water optimization goal if properly operated and maintained.

Filter performance depends largely on the characteristics of the solids particles entering the filter and on the characteristics of the filter itself. Generally treated water turbidity will be relatively high for a short period immediately following the backwash cycle of rapid sand filter operation, commonly known as post backwash turbidity spiking, but will then improve rapidly to a level near the highest quality level the filter can produce. The filter will then operate at or near this level for an extended period. Figure 10-9 shows typical filtered water turbidity as a function of filter run time.



Source: Hudson, 1981.

Figure 10-9. Typical Filter Run Showing Progress of Floc Penetration and Effluent Turbidity

A variety of strategies may be used to minimize the impact of post backwashing turbidity spikes on finished water quality. These include routing the post backwash, high turbidity, water to waste or adding organic polymers to the backwash water during the final stages of the backwash process.

The performance of other types of filters is similar to that of rapid sand filters, except that some may not experience the higher turbidity levels following filter cleaning operations.

A filter run is typically terminated after a pre-set period of time, when a certain pre-established headloss is reached, or treated water turbidity deteriorates to a set level.

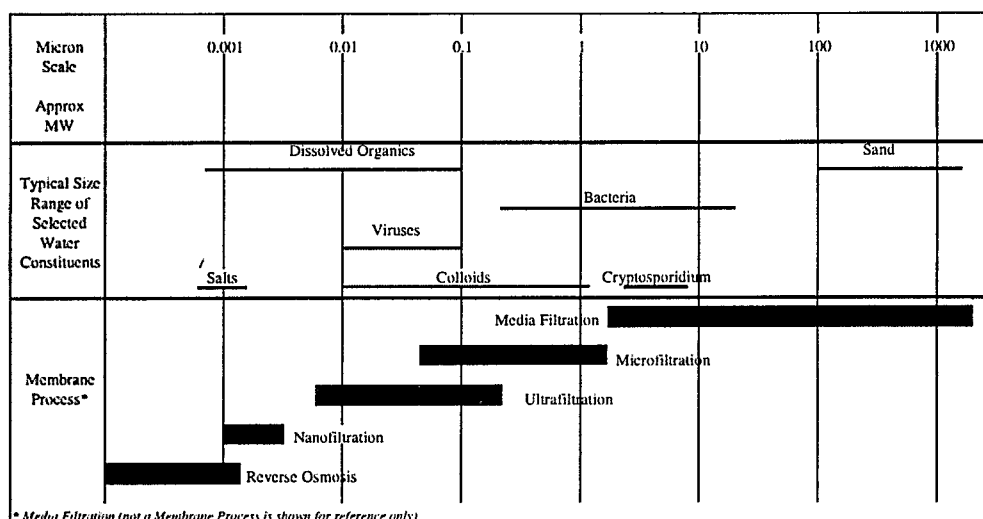
10.8 Membrane Processes

Membrane processes are processes in which the water is passed through a semi-permeable membrane to accomplish solids removal. They are much like other filtration processes except the membrane is used in place of the filter media. An additional benefit that may be realized with membrane processes is the removal of dissolved organic or inorganic constituents. Membrane technology has been in use for many years but recent technological advances coupled with increased concern for particulate removal have brought its use to the forefront of potable water treatment technology.

Membranes are made of a variety of different materials and membrane processes are typically classified according to the driving force involved and the size of particles that pass through the membrane (AWWA and ASCE, 1998). For most systems commonly used in larger water treatment operations, the water is forced through the membrane by applying pressure to one side creating a pressure differential across the membrane. The four general classifications of pressure membrane process are:

- Microfiltration;
- Ultrafiltration;
- Nanofiltration; and
- Reverse Osmosis.

Figure 10-10 shows the size of particles generally removed by these different membrane processes.



Source: AWWA and ASCE, 1998.

Figure 10-10. Pressure-Driven Membrane Process Application Guide

Table 10-1 provides information on the typical pressure operating ranges for the different types of pressure-driven membrane processes. Most pressure driven membrane processes utilize either cellulose acetate or synthetic organic polymer membranes (AWWA and ASCE, 1998). Standard pressure membrane configurations include spiral wound membrane units and hollow fiber membrane units. Figures 10-11, 10-12, and 10-13 show the standard membrane configurations commonly used for potable water treatment systems.

Table 10-1. Typical Feed Pressures for Pressure Driven Membrane Processes

| Membrane Process | Typical Feed Pressure (psi) |
|--|-----------------------------|
| Reverse Osmosis - Brackish Water Application | |
| Low Pressure | 125 to 300 |
| Standard Pressure | 350 to 600 |
| Reverse Osmosis - Seawater Application | 800 to 1,200 |
| Nanofiltration | 50 to 150 |
| Ultrafiltration | 20 to 75 |
| Microfiltration | 15 to 30 |

Source: AWWA and ASCE, 1998.

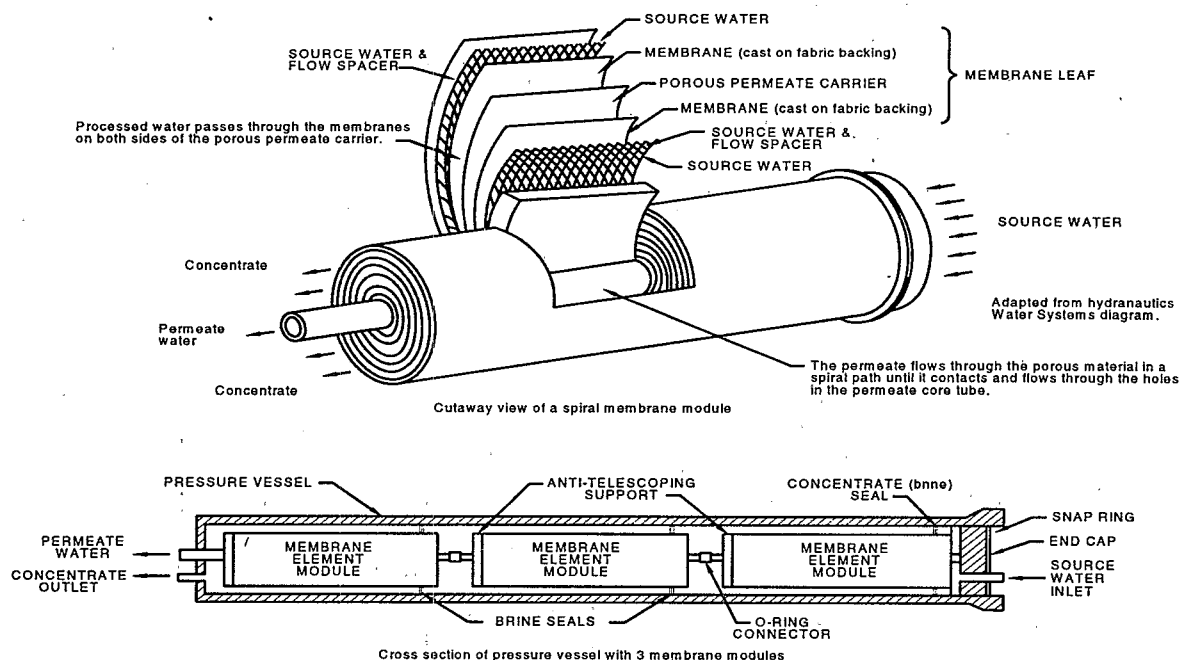


Figure 10-11. Typical Spiral-Wound Reverse Osmosis Membrane

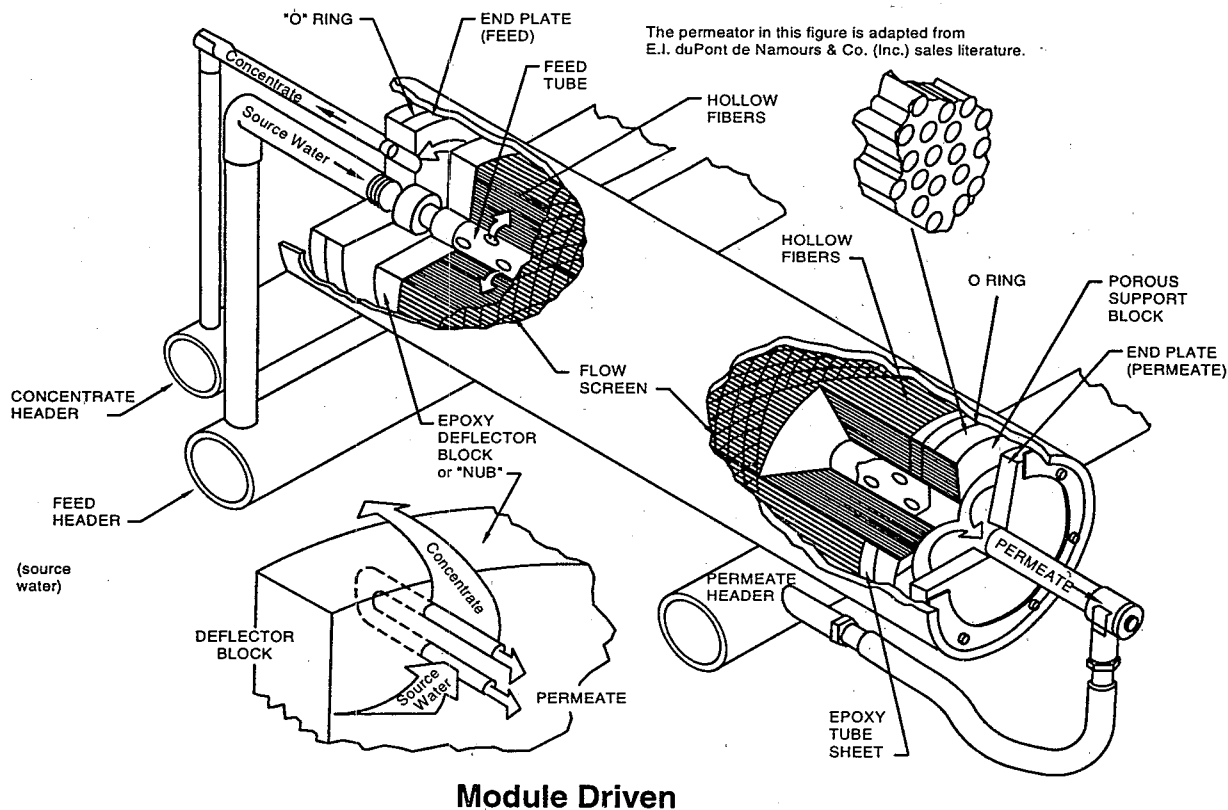
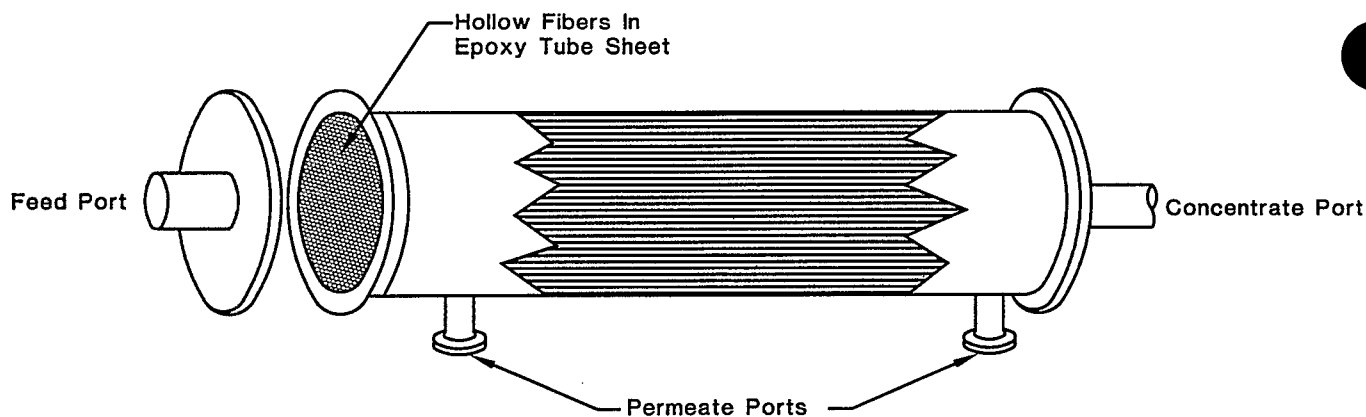


Figure 10-12. Typical Hollow Fine-Fiber Reverse Osmosis Membrane Module



Source: AWWA and ASCE, 1998.

Figure 10-13. Representation of Hollow-fiber UF Module

10.8.1 Effect on Turbidity

Membrane systems provide a positive barrier to particles of a size larger than will pass through the membrane. Consequently, the turbidity of water produced by membrane treatment systems is usually well below 0.3 NTU. The size of particles that will pass through the membrane depends on the structure of the membrane itself. Figure 10-10 contains information on the sizes of particles removed by different types of membrane systems. As shown in Figure 10-10 all conventional membrane processes will effectively remove bacteria and other large organisms such as *Giardia* and *Cryptosporidium*. Only the more restrictive membranes are effective for removing viruses, small colloids, and dissolved constituents. Many times membrane system performance is determined not by treated water turbidity but by the level of other constituents such as total dissolved solids that may be of concern in a particular situation. Please note that this assessment is based on absolute pore sizes outlined in Figure 10-10. It does not reflect microbe pass-through resulting from nominal pore size membranes or membrane failures (e.g., rupture, seal leakage).

10.9 Recycle Streams

Recycle streams are waste streams generated during the water treatment process that are returned to the treatment train with or without prior treatment. Though they are not related to one particular treatment process, recycle streams may have a deleterious impact on treated water quality, including turbidity. Consequently, proper management of recycle streams is an important part of optimizing turbidity reduction in water treatment. Any discharges of recycle streams must comply with Federal and State regulations, including the National Pollution Discharge Elimination System (NPDES) program (40 CFR 122) and the Pretreatment program (40 CFR 403).

Waste streams may be handled in several different ways. Historically it was a common practice to discharge waste streams directly to surface waters. In some cases this may still be acceptable but state or federal regulations have largely curtailed the practice of

discharging water treatment waste streams directly to surface water. If a waste stream is to be discharged to a surface water, an NPDES permit must be obtained from the appropriate permitting authority prior to any discharge occurring. Due to these new regulatory requirements, or to conserve water and reduce wastes, waste streams are now recycled by many systems, with or without treatment, or discharged to a sanitary sewer system.

10.9.1 Sources of Recycle Streams

The most common recycle streams found in potable water treatment systems include:

- Filter backwash water;
- Sludge thickener supernatant;
- Filter to waste flow; and
- Sedimentation basin underflow.

These recycle streams can represent concentrated waste flows and contain high levels of contaminants. The continued recycle of these contaminants may affect treated water quality. Impacts may include higher turbidity as well as higher concentrations of pathogens and other contaminants in the plant influent. Because of its potential impact to finished water quality, the handling of recycle streams should be carefully considered during design and upgrade of all water treatment systems.

10.9.2 Recycle Stream Quantity and Quality

The quantity and quality of recycle streams varies considerably depending on the quality of the raw water, the treatment processes employed and their efficiencies, and the type and amount of chemicals used during treatment. Generally, the composite of all waste streams generated in a conventional complete treatment system employing coagulation, flocculation, sedimentation, and filtration will be in the neighborhood of 2 to 10 percent of the total volume of water treated. Contaminants present in recycle streams may include:

- Suspended solids;
- Organics;
- Inorganics; and
- Microorganisms.

Reported quality parameters associated with sludges generated from alum coagulation include (Culp and Culp, 1974):

- BOD – 40 to 150 mg/l
- COD – 340 to 5000 mg/l
- TSS – 1100 to 14,000 mg/l
- VSS – 600 to 4000 mg/l

- pH — near neutral

Levels of *Cryptosporidium* oocysts ranging from 2,900 to 47,000 counts per mL have been reported in recycle streams from sedimentation and filtration processes after settling (Cornwell and Lee, 1994). Reported values of spent filter backwash water turbidity typically range from 30 to 400 NTU (Kawamura, 1991; Cornwell and Lee, 1993).

Waste streams generated from membrane processes such as reverse osmosis may also contain significant levels of other contaminants such as dissolved solids and salts.

10.9.3 Point of Recycle Stream Return

The point at which a recycle stream is introduced to the treatment train is also important. Recycle streams should be introduced at the plant headworks or as close to the beginning of the treatment system as possible to provide the maximum level of recycle stream treatment. The point of introduction should also be one where effective mixing is provided to thoroughly disperse the recycled flow in the raw water stream before it enters subsequent treatment processes. Studies have shown that the timing or regularity of the recycle stream introduction is also very important in determining its impact on the performance of the treatment process (Goldgrabe-Brewen, 1995). The continuous and steady introduction of an equalized recycle stream will have much less negative impact on the water treatment process than sporadic introduction of larger volume recycle flows that vary in quantity and quality.

10.9.4 Effect on Turbidity

When waste streams are recycled they may have an impact on the amount of solids loaded to the treatment system. A model, developed by Cornwell and Lee (1993) to predict the impact of recycled spent filter backwash water on the concentration of *Giardia* cysts and *Cryptosporidium* cysts on water entering a treatment system, demonstrates the significant impact recycle streams can have on water quality, even when a relatively high level of treatment is provided for the recycle flow before it is returned to the main flow stream. The model predicts a greater than three-fold increase in cyst concentration in the water entering the treatment process as a result of the recycle practice, even when 70 percent of the cysts initially present in the recycle stream are removed through treatment. Similar impacts on turbidity can be expected.

10.10 References

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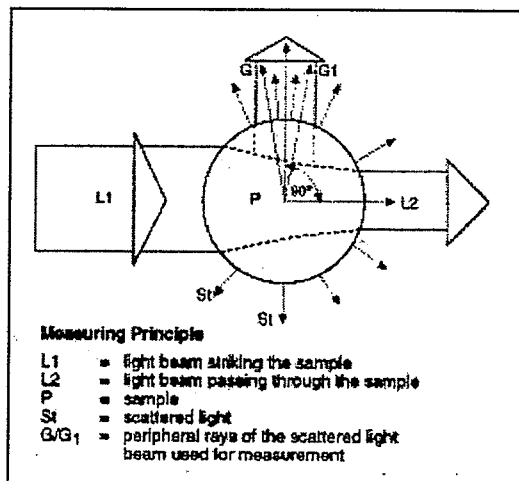
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11. BASIC TURBIDIMETER DESIGN AND CONCEPTS

11.1 Introduction

Turbidity is described in the *Standard Methods for the Examination of Water and Wastewater* Method 2130B (EPA Method 180.1) for turbidity measurement as, “an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample” (Standard Methods, 1995). This chapter includes a detailed summary of the various types of instruments used to measure turbidity and includes descriptions of the physical properties associated with the measurements of turbidity and design configurations.

As shown in Figure 11-1, modern turbidimeters use the technique of nephelometry, which measures the amount of light scattered at right angles to an incident light beam by particles present in a fluid sample. In general, all modern turbidimeters utilize the nephelometric measurement principals, but instrument manufacturers have developed several different meter designs and measurement configurations.



Source: GLI, undated.

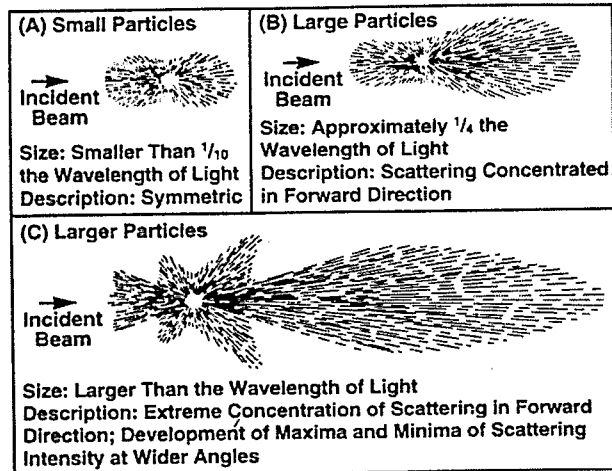
Figure 11-1. Scattered Light at 90°

11.2 Turbidimeter Measuring Principles

As light passes through ‘absolutely pure’ water, the light beams travel along relatively undisturbed paths. However, some distortion occurs as light is scattered by molecules present in the pure fluid. As shown in Figure 11-1, when light passes through a fluid containing suspended solids, the light beam interacts with the particles, and the particles absorb the light energy and re-radiate light in all directions.

Particle size, configuration, color, and refractive index determine the spatial distribution of the scattered light intensity around the particle. As shown in Figure 11-2, particles much smaller than the wavelength of the incident light, which is typically expressed in nanometers (nm), scatter light of approximately equal intensity in all directions. However, particles larger than the wavelength of the incident light, form a spectral pattern that results in greater light scattering in the forward direction (away from the incident light) than in the other directions. This scattering pattern and intensity of the light beam

transmitted through the sample can also be affected by the particles absorbing certain wavelengths of the transmitted light (Sadar, 1996).



Source: Sadar, 1996.

Figure 11-2. Angular Patterns of Scattered Light from Particles of Different Sizes

reading to turbidity. This angle is considered very sensitive to light scatter by particles in the sample. As described later in this chapter, additional light sensors are also sometimes added to detect light scattered at other angles in order to improve the instrument range and remove errors introduced by natural colors and lamp variability.

11.2.1 Light Source

The basic turbidimeter instrument contains a light source, sample container or cell, and photodetectors to sense the scattered light. The most common light source used is the tungsten filament lamp. The spectral output (band of wavelength light produced) of these lamps is generally characterized by "color temperature," which is the temperature that a black body radiator must be operated to produce a certain color. The tungsten filament lamps are incandescent lamps and are termed "polychromatic," since they have a fairly wide spectral band that includes many different wavelengths of light, or colors. The presence of the various wavelengths can cause interference in the turbidity measurements as natural color and natural organic matter in the sample can absorb some specific wavelengths of light and reduce the intensity of the scattered light (King, 1991).

The tungsten filament lamp is also highly dependent on the voltage of the lamp power supply. The voltage applied to the lamp determines the spectral output characteristics produced, making a stable power supplies a necessity. In addition, as with any incandescent lamp, the output from the lamp decays with time as the lamp slowly "burns out," making recalibration of the instrument a frequent and necessary requirement.

To overcome some of the incandescent lamp limitations, some turbidimeter designs utilize monochromatic light sources, such as light emitting diodes (LEDs), lasers,

Since the light scattered in the forward direction is variable depending on particle size, the measurement of the light transmitted through the sample yields variable results. In addition, the change in transmitted light is very slight and difficult to distinguish from electronic noise when measuring low turbidities. High turbidity samples are also difficult to measure using transmitted light due to multiple scatter of the light by many particles in the fluid. To solve these problems, turbidimeters primarily measure the scatter of light at a 90 degree angle to the incident beam and relate this

mercury lamps, and various lamp filter combinations. Monochromatic light has a very narrow band of light wavelengths (only a few colors). By selecting light wavelengths that are not normally absorbed by organic matter, the monochromatic light source can be less susceptible to interference by sample color. However, some of these alternate light sources respond differently to particle size, and are not as sensitive to small sized particles as the tungsten filament lamp.

11.2.2 Sample Volume

Grab samples are typically introduced into bench top turbidimeter instruments through a transparent sample cell made of glass. These sample cells, or cuvettes, are usually about 30 milliliters in capacity. Some on-line turbidimeters utilize the glass sample cell, but most designs use a flow-through chamber with the light source located outside the sample. Sample chambers in on-line instruments range from 30 milliliters to over two liters.

11.2.3 Photodetector

In turbidimeters, photodetectors detect the light produced from the interaction of the incident light and the sample volume and produce an electronic signal that is then converted to a turbidity value. These detectors can be located in a variety of configurations depending on the design of the instrument. The four types of detectors commonly used include photomultiplier tubes, vacuum photodiodes, silicon photodiodes, and cadmium sulfide photoconductors (Sadar, 1992).

Each of the four types of detectors vary in their response to certain wavelengths of light. Therefore, if a polychromatic light source is used, the spectral output of the light source has a direct bearing on the type and design of photodetector selected for an instrument. The specification of the photodetector is not nearly as critical when a monochromatic light source is used. In general, with the polychromatic tungsten filament lamp as a light source, the photomultiplier tube and the vacuum photodiode are more sensitive to the shorter wavelength light in the source, making them more sensitive to the detection of smaller particles. Conversely, the silicon photodiode is more sensitive to longer wavelengths in the light source, making it more suited for sensing larger particles. The sensitivity of the cadmium sulfide photoconductor is between the sensitivity of the photomultiplier tube and the silicon photodiode.

11.3 Turbidimeter Design Configurations

Several instrument design standards have been developed by various organizations to attempt to standardize instrument designs and achieve test results that are accurate and repeatable. These standards govern the design of the various turbidimeter configurations available today, which include the single beam design, modulated four beam design, surface scatter design, and transmittance design. Only the single beam design, ratio design, and modulated four beam design are approved by EPA.

11.3.1 Design Standards

The requirements stated in *Standard Methods* 2130B (see Appendix D) are similar to the requirements of EPA Method 180.1 (see Appendix C) for turbidity measurement. The EPA Method 180.1 lists the following design requirements for turbidimeters:

- "Light Source: Tungsten-filament lamp operated at a color temperature between 2200 and 3000 degree K.
- Distance traversed by incident light and scattered light within the sample tube not to exceed 10 cm.
- Angle of light acceptance by detector: Centered at 90 degrees to the incident light path and not to exceed +/- 30 degrees from 90 degrees. The detector, and filter system if used, shall have a spectral property between 400 and 600 nm (Standard Methods, 1995)."

EPA has recognized one additional standard for turbidimeter design called GLI Method 2. Like EPA Method 180.1, this standard is applicable for turbidities in the 0 to 40 NTU range, but may be used for higher turbidities by diluting the sample. The GLI Method 2 standard requires that instruments utilize basic nephelometric concepts, but requires the use of two light sources with a photodetector located at 90-degrees from each source. This concept, which is often called a modulated four beam design, pulses the two light sources on and off and utilizes a portion of the scattered light as a reference signal to arithmetically cancel errors. A full description of the modulated four beam design is included later in this Chapter.

The specific apparatus requirements listed in the GLI Method 2 standard are as follows:

- The wavelength of the incident radiation shall be 860 nanometers.
- The spectral bandwidth of the incident radiation shall be less than or equal to 60 nanometers.
- There shall be no divergence from parallelism of the incident radiation and any convergence shall not exceed 1.5 degrees.
- There shall be two light sources and two detectors.
- The measuring angle between the optical axis of the incident radiation and that of the diffused radiation for light pulsed through the sample by either light source shall be 90 +/- 2.5 degrees.

An additional turbidimeter design standard was developed by the International Organization for Standardization. ISO 7027 defines the requirements for a turbidimeter light source with stricter requirements attempting to produce instruments that have good repeatability and compare well with other instruments. The specification reads:

"Any apparatus may be used provided that it complies with the following requirements:

- The wavelength, λ , of the incident radiation shall be 860 nm;
- The spectral bandwidth, $\Delta\lambda$, of the incident radiation shall be less than or equal to 60 nm;
- There shall be no divergence from parallelism of the incident radiation and any convergence shall not exceed 2.5 degrees;
- The measuring angle (tolerance on deviation of the optical axis) shall be ± 2.5 degrees
- The aperture angle, Ω_0 , should be between 10 and 20 degrees in the water sample (ISO, 1990)."

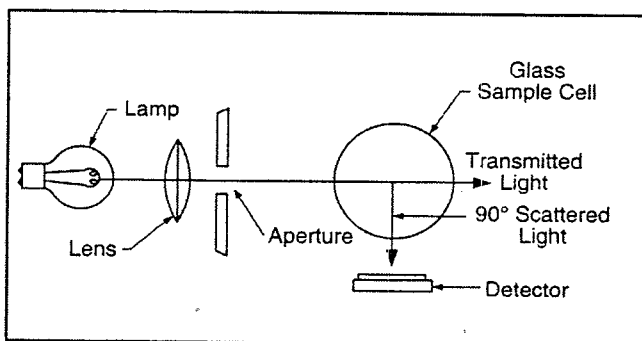
ISO 7027 requires the use of monochromatic light sources such as tungsten lamps fitted with monochromators and filters, diodes, or lasers. However, the standard recognizes that many older instruments have polychromatic light sources, and allows their use for water treatment monitoring and control, but not for comparison to readings from other turbidimeters.

The tighter definition of the light source in ISO 7027 eliminates many of the variables inherent to the polychromatic sources used in the other standards. However, ISO 7027 does not eliminate the effects of light source decay or electronic gains and drifts inherent in monochromatic sources such as LEDs (Lex, 1994). **ISO 7027 is not accepted by EPA for turbidity analysis for compliance with the IESWTR.**

11.3.2 Single Beam Design

The single beam design configuration, shown in Figure 11-3, is the most basic turbidimeter design using only one light source and one photodetector located at 90 degrees from the incident light. The single beam design is the oldest of the modern nephelometers and typically is used with a polychromatic tungsten filament lamp. The design is still in wide used today and yields accurate results for turbidity under 40 NTU, provided that samples have little natural color. In fact, many on-line instruments in use today still utilize the single beam design.

The single beam design does, however, have limited accuracy at higher turbidities. As



Source: Sadar, 1996.

Figure 11-3. Basic Nephelometer

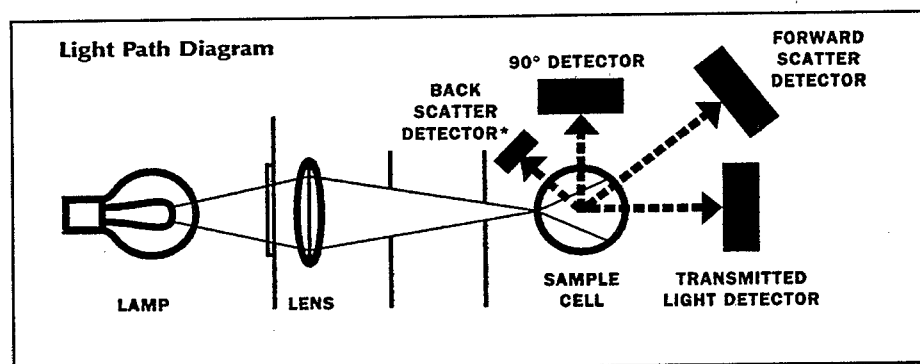
turbidity increases and the amount of scattered light increases, multiple scattering can occur when light strikes more than one particle as it reacts with the sample fluid. The resulting scattered light intensity reaching the 90 degree detector can diminish as the instrument effectively "goes blind." For this reason, a single beam design conforming strictly to EPA 180.1 does not typically demonstrate

stable measurement capability at high turbidities and is generally only applicable for turbidity readings from 0 to 40 NTU.

The design of the single beam instrument is also limited by the need for frequent recalibration of the instrument due to the decay of the incandescent light source. Because of the polychromatic nature of the light source, these instruments also can demonstrate poor performance with samples containing natural color. Since most treated water samples have low or no color, use of the single beam design is appropriate.

11.3.3 Ratio Design

The ratio turbidimeter design expands upon the single beam concept, but includes additional photodetectors located at other angles than 90 degrees from the incident light. As shown in Figure 11-4, the ratio design utilizes a forward scatter detector, a transmitted light detector, and for very high turbidity applications, a back scatter detector. The signals from each of these detectors are mathematically combined to calculate the



Source: Sadar, 1996.

Figure 11-4. Ratio Turbidimeter

turbidity of the sample. A typical ratio mathematical algorithm is as follows (Standard Methods, 1995):

$$T = I_{90} / (d_0 * I_t + d_1 * I_{fs} + d_2 * I_{bs} + d_3 * I_{90})$$

Where:

- T = Turbidity in NTU
- d_0, d_1, d_2, d_3 = Calibration Coefficients
- I_{90} = 90 Degree Detector Current
- I_t = Transmitted Detector Current
- I_{fs} = Forward Scatter Detector Current
- I_{bs} = Back Scatter Detector Current

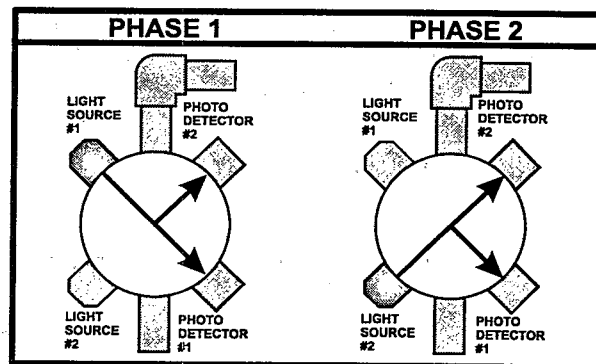
The use of multiple photodetectors and the ratio algorithm gives the instrument much better performance with colored samples. The transmitted light and the 90-degree scattered light are affected almost equally by the color of the sample because they travel

nearly the same distance through the sample volume. When the ratio of the two readings is taken, the effects of color absorption on the two readings tend to cancel mathematically.

11.3.4 Modulated Four Beam Design

Unlike the single beam and ratio turbidimeters, the modulated four-beam instrument design utilizes two light sources and two photo detectors. The two sources and the two detectors are used to implement theory of ratio measurements to cancel errors. As shown in Figure 11-5, the light sources and detectors are located at 90 degrees around the sample volume (Great Lakes Instruments, undated).

This design takes two measurements every 0.5 seconds. In the first phase, light from source #1 is pulsed directly into photodetector #2. Simultaneously, photodetector #1 measures the light scattered from this pulse at a 90 degree angle. In the second phase, light from source #2 is pulsed directly into photodetector #1. Simultaneously, photodetector #2 measures the light scattered from this pulse at a 90 degree angle. In both phases, the signal from the photodetector receiving the direct light signal is the active signal, while the signal from photodetector measuring scattered light is called the reference signal. The two phase measurements provide four measurements from two light sources: two reference signals and two active signals.



Source: GLI, undated.

Figure 11-5. Modulated Four-Beam Turbidimeter

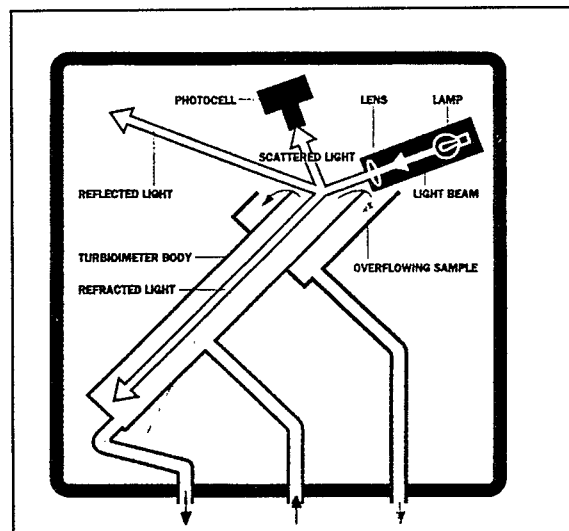
The turbidity of the sample is calculated from the four independent measurements taken from the two light sources using a mathematical algorithm similar to the algorithm used by the ratio instrument design. The result is that errors resulting from sample color appear in both the numerator and denominator of the mathematical algorithm, and the errors are mathematically canceled.

Like the ratio design, the mathematical algorithm used in the four beam design allows for more sensitivity in highly turbid samples and extends the range of the instrument to about 100 NTU. The error cancellation achieved by the ratio algorithm also makes the instrument very accurate in the 0 to 1 NTU range.

11.3.5 Surface Scatter Design

As turbidity increases, light scattering intensifies and multiple scattering can occur as light strikes more than one particle as it interacts with the fluid. Light absorption by particles can also significantly increase. When particle concentration exceeds a certain point, the amount of transmitted and scattered light decreases significantly due to multiple scattering and absorption. This point is known as the optical limit of an instrument.

The surface scatter design utilizes a light beam focused on the sample surface at an acute angle. As shown in Figure 11-6, light strikes particles in the sample and is scattered toward a photodetector that is also located above the sample surface. As turbidity increases, the light beam penetrates less of the sample, thus shortening the light path and compensating for interference from multiple scattering. The reported range of surface scatter instruments is about 0 to 9999 NTU, although these instruments are best suited for measuring high turbidities such as are present in raw water and recycle streams (Hach Corporation, 1995). These designs are not approved by EPA.



Source: Hach Corporation, 1995.

Figure 11-6. Surface Scatter Turbidimeter

11.3.6 Transmittance Design

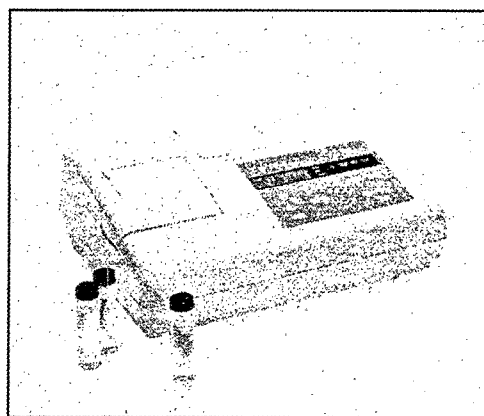
Instruments utilizing a transmittance design are often referred to as turbidimeters, but these instruments do not measure true turbidity of water in NTUs. These instruments are better termed "absorptometers" as they measure the amount of light transmitted through a sample rather than the amount of light scattered by a sample. Light transmittance is measured by introducing a light source to a sample volume and measuring the relative amount of light transmitted through the sample volume to a photodetector located opposite the light source. Transmittance values are reported as 0 to 100 percent of the incident light source transmitted through the sample. The use of absorptometers in water treatment has generally been restricted to monitoring spent filter backwash water to determine relative cleanliness of the filter media (Hach Corporation, 1995). These designs are not approved by EPA.

11.4 Types of Turbidimeters

There are three common types of turbidimeters employed today. These are referred to as bench top, portable, and on-line instruments. Bench top and portable turbidimeters are used to analyze grab samples. Bench top units are typically used as stationary laboratory instruments and are not intended to be portable. On-line instruments are typically installed in the field and continuously analyze a sample stream spilt off from a unit process. Measurement with these units requires strict adherence to the manufacturer's sampling procedure to reduce errors from dirty glassware, air bubbles in the sample, and particle settling.

11.4.1 Bench Top Turbidimeters

Most bench top turbidimeters are designed for broad applications and have the capability to measure highly colored samples as well as samples with high turbidities. The most popular bench top turbidimeters used today utilize the ratio design, but may have options for back scatter detectors or monochromatic light sources. Many ratio bench top instruments also have the capability to turn off the ratio calculation so that measurements can be made using the single beam design. Older bench top instruments may be of the single beam design, and some have analog rather than digital displays. Bench top units are used exclusively for grab samples and require the use of glass cuvettes for holding the sample volume.

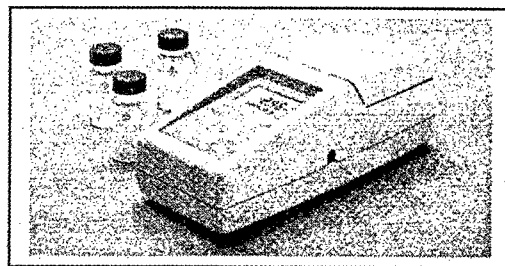


Source: Hach Corporation, 1995.

Figure 11-7. Bench Top Turbidimeter

11.4.2 Portable Turbidimeters

Portable turbidimeters are similar to the bench top units, except that they are designed for portable use and are battery operated. Portable turbidimeters are available in a variety of designs, including the single beam and ratio designs. The accuracy of portable instruments is comparable to the bench top units, but the resolution of low turbidity reading may only be 0.01 NTU as compared to the 0.001 NTU resolution of bench top units (Hach Corporation, 1995).



Source: Hach Corporation, 1995.

Figure 11-8. Portable Turbidimeter

Portable turbidimeters are designed for use in the field with grab samples. These instruments are designed to be rugged and capable of withstanding the affects of moving the instrument as well as variable field conditions. However, since these instruments are inherently susceptible to damage or disturbance from dropping, abuse, or environmental conditions such as dust, these units are not appropriate for the process monitoring and reporting tasks normally accomplished by bench top units or on-line turbidimeters.

However, portable instruments are useful for measuring turbidity at remote locations such as at sampling points in the watershed upstream of a water treatment plant, or at a remote raw water intake location. Portable instruments are also useful for conducting special process studies, such as backwash recycle characterization or distribution system analysis that may be accomplished more readily and accurately in the field rather than conducting analysis after transporting a sample to a laboratory.

11.4.2 On-Line Turbidimeters

The on-line instruments used in the water treatment industry typically utilize the single beam or modulated four beam design. On-line ratio turbidimeters are also available, but their use has not been as extensive as the single beam and modulated four beam designs. On-line surface scatter turbidimeters are often used for raw water monitoring and transmittance-type absorptometers have been used for filter backwash monitoring.

On-line instruments typically sample a side stream split off from the treatment process. The sample flows through the on-line instrument for measurement and then is wasted to a drain or recycled through the treatment process. Supervisory Control and Data Acquisition (SCADA) instrumentation and remote telemetry can also be connected to on-line instruments to collect data for trending analysis or to control automated treatment actions based on the turbidities measured. The use of SCADA with turbidity measurement is discussed in Chapter 4.

Typical sample flow rates through on-line instruments range from about 0.1 to 1.0 liter per minute. Some single beam on-line turbidimeters do not contain a glass sample container. The light source is located above the sample volume, which has an optically flat surface as it flows over a weir. The photodetector is submerged within the sample volume and requires frequent cleaning to prevent fouling. Most on-line four beam instruments used in the water industry contain a sealed flow-through sample volume with windows at each of the light sources and photodetectors. These surfaces must also be cleaned frequently to prevent fouling.

Most on-line instruments contain bubble traps to eliminate air bubbles from the sample that might interfere with the turbidity readings. Bubble traps are typically baffled chambers that allow air bubbles to rise to the sample surface prior to the sample entering the measurement chamber. The volume of the sample chamber varies significantly between the single beam and four beam design due mostly to the design of the bubble trap. Single beam devices typically include a bubble trap within the sample chamber, making the sample volume in excess of two liters. Several other on-line instruments use sample volumes as small as 30 milliliters.



Source: GLI, undated.

Figure 11-9. On-Line Turbidimeter

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APPENDIX A. LIST OF DEFINITIONS

A.1 List of Definitions

accuracy. How closely an instrument measures the true or actual value of the process variable being measured or sensed.

acidic. The condition of water or soil which contains a sufficient amount of acid substances to lower the pH below 7.0.

activated carbon. Adsorptive particles or granules of carbon usually obtained by heating carbon (such as wood). These particles or granules have a high capacity to selectively remove certain trace and soluble organic materials from water.

air binding. A situation where air enters the filter media. Air is harmful to both the filtration and backwash processes. Air can prevent the passage of water during the filtration process and can cause the loss of filter media during the backwash process.

alarm contact. A switch that operates when some pre-set low, high or abnormal condition exists.

algae. Microscopic plants which contain chlorophyll and live floating or suspended in water. They also may be attached to structures, rocks or other submerged surfaces. They are food for fish and small aquatic animals. Excess algal growths can impart tastes and odors to potable water. Algae produce oxygen during sunlight hours and use oxygen during the night hours. Their biological activities appreciably affect the pH and dissolved oxygen of the water.

alkaline. The condition of water or soil which contains a sufficient amount of alkali substances to raise the pH above 7.0.

alkalinity. The capacity of water to neutralize acids. This capacity is caused by the water's content of carbonate, bicarbonate, hydroxide and occasionally borate, silicate, and phosphate. Alkalinity is expressed in milligrams per liter of equivalent calcium carbonate. Alkalinity is not the same as pH because water does not have to be strongly basic (high pH) to have a high alkalinity. Alkalinity is a measure of how much acid can be added to a liquid without causing a great change in pH.

analog. The readout of an instrument by a pointer (or other indicating means) against a dial or scale.

Association of Boards of Certification. An international organization representing over 150 boards which certify the operators of waterworks and waste water facilities. For

information on ABC publications regarding the preparation of and how to study for operator certification examinations, contact ABC, 4261/2 Fifth Street, P.O. Box 786, Ames, Iowa 50010-0786.

available expansion. The vertical distance from the sand surface to the underside of a trough in a sand filter. This distance is also called FREEBOARD.

back pressure. A pressure that can cause water to backflow into the water supply when a user's water system is at a higher pressure than the public water system.

backflow. A reverse flow condition, created by a difference in water pressures, which causes water to flow back into the distribution pipes of a potable water supply from any source or sources other than an intended source. Also see backsiphonage and cross-connection.

backsiphonage. A form of backflow caused by a negative or below atmospheric pressure within a water system. Also see backflow and cross-connection.

backwashing. The process of reversing the flow of water back through the filter media to remove the entrapped solids.

bacteria. Singular: bacterium. Microscopic living organisms usually consisting of a single cell. Bacteria can aid in pollution control by consuming or breaking down organic matter in sewage, or by similarly acting on oil spills or other water pollutants. Some bacteria in soil, water or air may also cause human, animal and plant health problems.

baffle. A flat board or plate, deflector, guide or similar device constructed or placed in flowing water or slurry systems to cause more uniform flow velocities, to absorb energy, and to divert, guide, or agitate liquids (water, chemical solutions, slurry).

best available technology (BAT). The best technology treatment techniques, or other means which the Administrator finds, after examination for efficacy under field conditions and not solely under laboratory conditions, are available (taking cost into consideration). For the purposes of setting MCLs for synthetic organic chemicals, any BAT must be at least as effective as granular activated carbon.

best management practices (BMPs). Structural, nonstructural and managerial techniques that are recognized to be the most effective and practical means to control nonpoint source pollutants yet are compatible with the productive use of the resource to which they are applied. BMPs are used in both urban and agricultural areas.

bias. An inadequacy in experimental design that leads to results or conclusions not representative of the population under study.

breakthrough. A crack or break in a filter bed allowing the passage of floc or particulate

matter through a filter. This will cause an increase in filter effluent turbidity. A breakthrough can occur: 1) when a filter is first placed in service, 2) when the effluent valve suddenly opens or closes, and 3) during periods of excessive head loss through the filter (including when the filter is exposed to negative heads).

calcium carbonate (CaCO_3) equivalent. An expression of the concentration of specified constituents in water in terms of their equivalent value to calcium carbonate. For example, the hardness in water which is caused by calcium, magnesium and other ions is usually described as calcium carbonate equivalent.

calibration. A procedure which checks or adjusts an instrument's accuracy by comparison with a standard or reference.

capital costs. Costs (usually long-term debt) of financing construction and equipment. Capital costs are usually fixed, one-time expenses which are independent of the amount of water produced.

carcinogen. Any substance which tends to produce cancer in an organism.

clarifier. A large circular or rectangular tank or basin in which water is held for a period of time, during which the heavier suspended solids settle to the bottom. Clarifiers are also called SETTLING BASINS and SEDIMENTATION BASINS.

clear well. A reservoir for the storage of filtered water of sufficient capacity to prevent the need to vary the filtration rate with variations in demand. Also used to provide chlorine contact time for disinfection.

coagulant aid. Any chemical or substance used to assist or modify coagulation.

coagulants. Chemicals that cause very fine particles to clump together into larger particles. This makes it easier to separate the solids from the water by settling, skimming, draining or filtering.

coagulation. The clumping together of very fine particles into larger particles caused by the use of chemicals (coagulants). The chemicals neutralize the electrical charges of the fine particles and cause destabilization of the particles. This clumping together makes it easier to separate the solids from the water by settling, skimming, draining, or filtering.

cohesion. Molecular attraction which holds two particles together.

colloids. Very small, finely divided solids (particles that do not dissolve) that remain dispersed in a liquid for a long time due to their small size and electrical charge. When most of the particles in water have a negative electrical charge, they tend to repel each other. This repulsion prevents the particles from clumping together, becoming heavier, and settling out.

combined sewer. A sewer that transports surface runoff and human domestic wastes (sewage), and sometimes industrial wastes. Wastewater and runoff in a combined sewer may occur in excess of the sewer capacity and cannot be treated immediately. The excess is frequently discharged directly to a receiving stream without treatment, or to a holding basin for subsequent treatment and disposal.

community water system (CWS). A public water system which serves at least 15 service connections used by year round residents or regularly serves at least 25 persons year-round

residents. Also see non-community water system, transient water system and non-transient non-community water system.

complete treatment. A method of treating water which consists of the addition of coagulant chemicals, flash mixing, coagulation - flocculation, sedimentation and filtration. Also called CONVENTIONAL FILTRATION.

continuous sample. A flow of water from a particular place in a plant to the location where samples are collected for testing. This continuous stream may be used to obtain grab or composite samples. Frequently, several taps (faucets) will flow continuously in the laboratory to provide test samples from various places in a water treatment plant.

conventional filtration. A method of treating water to remove particulates. The method consists of the addition of coagulant chemicals, flash mixing, coagulation - flocculation, sedimentation and filtration. Also called COMPLETE TREATMENT. Also see direct filtration and in-line filtration.

conventional filtration treatment. A series of processes including coagulation, flocculation, sedimentation, and filtration resulting in substantial particulate removal.

cross connection. Any actual or potential connection between a drinking (potable) water system and an unapproved water supply or other source of contamination. For example, if you have a pump moving nonpotable water and hook into the g water system to supply water for the pump seal, a cross-connection or mixing between the two water systems can occur. This mixing may lead to contamination of the drinking water. Also see backsiphonage and backflow.

CT or CTcalc. The product of "residual disinfectant concentration" (C) in mg/l determined before or at the first customer, and the corresponding "disinfectant contact time" (T) in minutes, i.e., "C" x "T". If a public water system applies disinfectants at more than one point prior to the first customer, it must determine the CT of each disinfectant sequence before or at the first customer to determine the total percent inactivation or "total inactivation ratio". In determining the total inactivation ratio, the public water system must determine the residual disinfectant concentration of each disinfection sequence and corresponding contact time before any subsequent disinfection

application point(s). "CT99.9" is the CT value required for 99.9 Percent (3-log) inactivation of *Giardia lamblia* cysts. CT99.9 a variety of disinfectants and conditions appear in Tables 1.1- 1.6, 2.1, and 3.1 of section 141.74(b)(3) in the code of Federal Regulations. CT99.9 is the inactivation ratio. The sum of the inactivation ratios, or total inactivation ratio shown as $E = (CT \text{ calc}) / (CT99.9)$ is calculated by adding together the inactivation ratio for each disinfection sequence. A total inactivation ratio equal to or greater than 1.0 is assumed to provide a 3-log inactivation of *Giardia lamblia* cysts.

degasification. A water treatment process which removes dissolved gases from the water. The gases may be removed by either mechanical or chemical treatment methods or a combination of both.

degradation. Chemical or biological breakdown of a complex compound into simpler compounds.

diatomaceous earth filtration (DE filtration). A filtration method resulting in substantial particulate removal, that uses a process in which: 1) a "precoat" cake of diatomaceous earth filter media is deposited on a support membrane (septum), and 2) while the water is filtered by passing through the cake on the septum, additional filter media, known as "body feed," is continuously added to the feed water to maintain the permeability of the filter cake.

direct filtration. A filtration method of treating water which consists of the addition of coagulant chemicals, flash mixing, coagulation, minimal flocculation, and filtration. The flocculation facilities may be omitted, but the physical-chemical reactions will occur to some extent. The sedimentation process is omitted. Also see conventional filtration and in-line filtration.

effective range. That portion of the design range (usually upper 90 percent) in which an instrument has acceptable accuracy. Also see range and span

effective size (E.S.). The diameter of the particles in a granular sample (filter media) for which 10 percent of the total grains are smaller and 90 percent larger on a weight basis. Effective size is obtained by passing granular material through sieves with varying dimensions of mesh and weighing the material retained by each sieve. The effective size is also approximately the average size of the grains.

effluent. Water or some other liquid-raw, partially or completely treated-flowing from a reservoir, basin, treatment process or treatment plant.

end point. Samples are titrated to the end point. This means that a chemical is added, drop by drop, to a sample until a certain color change (blue to clear, for example) occurs. This is called the END POINT of the titration. In addition to a color change, an end point may be reached by the formation of a precipitate or the reaching of a specified pH. An end point may be detected by the use of an electronic device such as a pH meter.

enteric. Of intestinal origin, especially applied to wastes or bacteria.

entrain. To trap bubbles in water either mechanically through turbulence or chemically through a reaction.

EPA. United States Environmental Protection Agency.

epidemic. Widespread outbreak of a disease, or a large number of cases of a disease in a single community or relatively small area. Disease may spread from person to person, and/or by the exposure of many persons to a single source, such as a water supply.

filtration. A process for removing particulate matter from water by passage through porous media.

finished water. Water that has passed through a water treatment plant; all the treatment processes are completed or "finished". This water is ready to be delivered to consumers. Also called PRODUCT WATER.

floc. Clumps of bacteria and particulate impurities that have come together and formed a cluster. Found in flocculation tanks and settling or sedimentation basins.

flocculation. The gathering together of fine particles in water by gentle mixing after the addition of coagulant chemicals to form larger particles.

garnet. A group of hard, reddish, glassy, mineral sands made up of silicates of base metals (calcium, magnesium, iron and manganese). Garnet has a higher density than sand.

gastroenteritis. An inflammation of the stomach and intestine resulting in diarrhea, with vomiting and cramps when irritation is excessive. When caused by an infectious agent, it is often associated with fever.

Giardia lamblia. Flagellate protozoan which is shed during its cyst stage into the feces of man and animals. When water containing these cysts is ingested, the protozoan causes a severe gastrointestinal disease called giardiasis.

giardiasis. Intestinal disease caused by an infestation of Giardia flagellates.

grab sample. A single sample collected at a particular time and place which represents the composition of the water only at that time and place.

ground water under the direct influence (GWUDI) of surface water. Any water beneath the surface of the ground with: 1) significant occurrence of Insects or other macroorganisms algae, or large-diameter pathogens such as Giardia lamblia or, 2) significant and relatively rapid shifts in water characteristics such as turbidity, temperature, conductivity, or pH which closely correlate to climatological or surface

water conditions. Direct influence must be determined for individual sources in accordance with criteria established by the State. The State determination of direct influence may be based on site-specific measurements of water quality and/or documentation of well construction characteristics and geology with field evaluation.

hardness, water. A characteristic of water caused mainly by the salts of calcium and magnesium, such as bicarbonate, carbonate, sulfate, chloride and nitrate. Excessive hardness in water is undesirable because it causes the formation of soap curds, increased use of soap, deposition of scale in boilers, damage in some industrial processes, and sometimes causes objectionable tastes in drinking water.

head. The vertical distance (in feet) equal to the pressure (in psi) at a specific point. The pressure head is equal to the pressure in psi times 2.31 ft/psi.

head loss. The head, pressure or energy (they are the same) lost by water flowing in a pipe or channel as a result of turbulence caused by the velocity of the flowing water and the roughness of the pipe, channel walls or restrictions caused by fittings. Water flowing in a pipe loses head, pressure or energy as a result of friction losses.

humus. Organic portion of the soil remaining after prolonged microbial decomposition, hydrogeologic cycle. The natural process recycling water from the atmosphere down to (and through) the earth and back to the atmosphere again.

influent. Water or other liquid-raw or partially flowing INTO a reservoir, basin, treatment process or treatment plant.

in-line filtration. The addition of chemical coagulants directly to the filter inlet pipe. The chemicals are mixed by the flowing water. Flocculation and sedimentation facilities are eliminated. This pretreatment method is commonly used in pressure filter installations. Also see conventional filtration and direct filtration.

jar test. A laboratory procedure that simulates a water treatment plant's coagulation/flocculation units with differing chemical doses and also energy of rapid mix, energy of slow mix, and settling time. The purpose of this procedure is to ESTIMATE the minimum or ideal coagulant dose required to achieve certain water quality goals. Samples of water to be treated are commonly placed in six jars. Various amounts of chemicals are added to each jar, and the settling of solids is observed. The dose of chemicals that provides satisfactory settling removal of turbidity and/or color is the dose used to treat the water being taken into the plant at that time. When evaluating the results of a jar test, the operator should also consider the floc quality in the flocculation area and the floc loading on the filter.

legionella. A genus of bacteria, some species of which have caused a type of pneumonia called Legionnaires Disease.

linearity. How closely an instrument measures actual values of a variable through its effective range; a measure used to determine the accuracy of an instrument.

microbial growth. The activity and growth of microorganisms such as bacteria, algae, diatoms, plankton and fungi micrograms per liter (mg/L) One microgram of a substance dissolved in each liter of water. This unit is equal to parts per billion (ppb) since one liter of water is equal in weight to one billion micrograms.

micron. A unit of length. One millionth of a meter or one thousandth of a millimeter. One micron equals 0.00004 of an inch.

microorganisms. Living organisms that can be seen individually only with the aid of a microscope.

milligrams per liter (mg/L). A measure of concentration of a dissolved substance. A concentration of one mg/L means that one milligram of a substance is dissolved in each liter of water. For practical purposes, this unit is equal to parts per million (ppm) since one liter of water is equal in weight to one million milligrams. Thus a liter of water containing 10 milligrams of calcium has 10 parts of calcium per one million parts of water, or 10 parts per million (10 ppm).

mudballs. Material that is approximately round in shape and varies from pea-sized up to two or more inches in diameter. This material forms in filters and gradually increases in size when not removed by the backwashing process.

National Environmental Training Association (NETA). A professional organization devoted to serving the environmental trainer and promoting better operation of waterworks and pollution control facilities. For information on NETA membership and publications, contact NETA, 8687 Via de Ventura, Suite 214, Scottsdale, AZ 85258

nephelometric. A means of measuring turbidity in a sample by using an instrument called a nephelometer. A nephelometer passes light through a sample and the amount of light deflected (usually at a 90-degree angle) is then measured.

nephelometric turbidity unit (NTU). The unit of measure for turbidity.

non-transient non-community water system (NTNCWS). A public water system that regularly serves at least 25 of the same nonresident persons per day for more than six months per year.

non-community water system (NCWS). A public water system that is not a community water system. There are two types of NCWSs: transient and non-transient.

operation and maintenance costs. The ongoing, repetitive costs of operating a water system; for example, employee wages and costs for treatment chemicals and periodic

equipment repairs.

organic. Substances that come from animal or plant sources. Organic substances always contain carbon. (Inorganic materials are chemical substances of mineral origin.)

organics. 1) A term used to refer to chemical compounds made from carbon molecules. These compounds may be natural materials (such as animal or plant sources) or man-made materials (such as synthetic organics). 2) Any form of animal or plant life.

overflow rate. One of the guidelines for the design of settling tanks and clarifiers in treatment plants. Used by operators to determine if tanks and clarifiers are hydraulically (flow) over- or underloaded. $\text{Overflow Rate (GPD/sq ft)} = \text{Flow (GPD)} / \text{Surface Area (sq ft)}$ particle count. The results of a microscopic examination of treated water with a special "particle counter" which classifies suspended particles by number and size.

particulate. A very small solid suspended in water which can vary widely in size, shape, density, and electrical charge. Colloidal and dispersed particulates are artificially gathered together by the processes of coagulation and flocculation.

pathogenic organisms. Organisms, including bacteria, viruses or cysts, capable of causing diseases (typhoid, cholera, dysentery) in a host (such as a person). There are many types of organisms which do NOT cause disease. These organisms are called non-pathogenic.

pathogens. Microorganisms that can cause disease in other organisms or in humans, animals and plants. They may be bacteria, viruses, or parasites and are found in sewage in runoff from animal farms or rural areas populated with domestic and/or wild animals, and in water used for swimming. Fish and shellfish contaminated by pathogens, or the contaminated water itself, can cause serious illnesses.

performance evaluation sample. A reference sample provided to a laboratory for the purpose of demonstrating that the laboratory can successfully analyze the sample within limits of performance specified by the Agency. The true value of the concentration of the reference material is unknown to the laboratory at the time of the analysis.

pH. pH is an expression of the intensity of the basic or acid condition of a liquid. Mathematically, pH is the logarithm (base 10) of the reciprocal of the hydrogen ion concentration, $[H^+]$. $pH = \text{Log } (1/H^+)$ The pH may range from 0 to 14, where 0 is most acid, 14 most basic, and 7 neutral. Natural waters usually have a pH between 6.5 and 8.5.

plug flow. A type of flow that occurs in tanks, basins or reactors when a slug of water moves through a tank without ever dispersing or mixing with the rest of the water flowing through the tank.

polymer. A chemical formed by the union of many monomers (a molecule of low

molecular weight). Polymers are used with other chemical coagulants to aid in binding small suspended particles to larger chemical flocs for their removal from water. All polyelectrolytes are polymers, but not all polymers are polyelectrolytes.

pore. A very small open space in a rock or granular material.

precision. The ability of an instrument to measure a process variable and to repeatedly obtain the same result. The ability of an instrument to reproduce the same results.

public water system. A system for the provision to the public of piped water for human consumption. If such system has at least fifteen service connections or regularly least 60 days out of the year. Such term includes: 1) any collection, treatment, storage, and distribution facilities under control of the operator of such system and used primarily in connection with such system, and 2) any collection or pretreatment storage facilities not under such control which are used primarily in connection with such system. A public water system is either a "community water system" or a "non-community water system."

range. The spread from minimum to maximum values that an instrument is designed to measure. Also see span and effective range.

recarbonation. A process in which carbon dioxide is bubbled into the water being treated to lower the pH. The pH may also be lowered by the addition of acid. Recarbonation is the final stage in the lime-soda ash softening process. This process converts carbonate ions to bicarbonate ions and stabilizes the solution against the precipitation of carbonate compounds.

reservoir. Any natural or artificial holding area used to store; regulate, or control water.

reverse osmosis. The application of pressure to a concentrated solution which causes the passage of a liquid from the concentrated solution to a weaker solution across a semipermeable membrane. The membrane allows the passage of the solvent (water) but not the dissolved solids (solutes). The liquid produced is a demineralized water.

Safe Drinking Water Act (SDWA). Commonly referred to as SDWA. An Act passed by the U.S. Congress in 1974. The Act establishes a cooperative program among local, state and federal agencies to insure safe drinking water for consumers.

sand. Soil particles between 0.05 and 2.0 mm in diameter.

sand filters. Devices that remove some suspended solids from sewage. Air and bacteria decompose additional wastes filtering through the sand so that cleaner water drains from the bed.

sedimentation. A water treatment process in which solid particles settle out of the water being treated in a large clarifier or sedimentation basin.

slow sand filtration. A process involving passage of raw water through a bed of sand at low velocity (generally less than 0.4 m/h) resulting in substantial particulate removal by physical and biological mechanisms.

standard. A physical or chemical quantity whose value is known exactly, and is used to calibrate or standardize instruments.

Standard Methods for the Examination of Water and Wastewater. A joint publication of the American Public Health Association, American Water Works Association, and the Water Pollution Control Federation which outlines the procedures used to analyze the impurities in water and wastewater.

standardize. To compare with a standard. 1) In wet chemistry, to find out the exact strength of a solution by comparing it with a standard of known strength. 2) To set up an instrument or device to read a standard. This allows you to adjust the instrument so that it reads accurately, or enables you to apply a correction factor to the readings.

State. The agency of the State or Tribal government which has jurisdiction over public water systems. During any period when a State or Tribal government does not have primary enforcement responsibility pursuant to Section 1413 of the Safe Drinking Water Act, the term "State" means the Regional Administrator, U.S. Environmental Protection Agency.

surface water. All water naturally open to the atmosphere (rivers, lakes, reservoirs, streams, impoundments, seas, estuaries, etc.) and all springs, wells, or other collectors which are directly influenced by surface water.

surfactant. Abbreviation for surface-active agent. The active agent in detergents that possesses a high cleaning ability.

suspended solids. 1) Solids that either float on the surface or are suspended in water or other liquids, and which are largely removable by laboratory filtering. 2) The quantity of material removed from water in a laboratory test, as prescribed in STANDARD METHODS FOR THE EXAMINATION OF WATER AND WASTEWATER.

transient water system. A non-community water system that does not serve 25 of the same nonresident persons per day for more than six months per year. Also called a transient non-community water system (TNCWS).

tube settler. A device that uses bundles of small bore (2 to 3 inches or 50 to 75 mm) tubes installed on an incline as an aid to sedimentation. The tubes may come in a variety of shapes including circular and rectangular. As water rises within the tubes, settling solids fall to the tube surface. As the sludge (from the settled solids) in the tube gains weight, it moves down the tubes and settles to the bottom of the basin for removal by conventional sludge collection means. Tube settlers are sometimes installed in

sedimentation basins and clarifiers to improve particle removal.

turbid. Having a cloudy or muddy appearance.

turbidimeter. A device that measures the amount of suspended solids in a liquid.

turbidity. The cloudy appearance of water caused by the presence of suspended and colloidal matter. In the waterworks field, a turbidity measurement is used to indicate the clarity of water. Technically, turbidity is an optical property of the water based on the amount of light reflected by suspended particles. Turbidity cannot be directly equated to suspended solids because white particles reflect more light than dark-colored particles and many small particles will reflect more light than an equivalent large particle.

urban runoff. Stormwater from city streets and adjacent domestic or commercial properties that may carry pollutants of various kinds into the sewer systems and/or receiving waters.

virus. The smallest form of microorganisms capable of causing disease. Especially, a virus of fecal origin that is infectious to humans by waterborne transmission.

waterborne disease outbreak. The significant occurrence of acute infectious illness, epidemiologically associated with the ingestion of water from a public water system that is deficient in treatment, as determined by the appropriate local or state agency.

water supplier. A person who owns or operates a public water system.

water supply system. The collection, treatment, storage, and distribution of potable water from source to consumer.

zeta potential. In coagulation and flocculation procedures, the difference in the electrical charge between the dense layer of ions surrounding the particle and the charge of the bulk of the suspended fluid surrounding this particle. The zeta potential is usually measured in millivolts.

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APPENDIX B. DETERMINATION OF TURBIDITY BY NEPHELOMETRY

METHOD 180.1

DETERMINATION OF TURBIDITY BY NEPHELOMETRY

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Revision 2.0
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180.1-1

1.0 SCOPE AND APPLICATION

- 1.1 This method covers the determination of turbidity in drinking, ground, surface, and saline waters, domestic and industrial wastes.
- 1.2 The applicable range is 0 to 40 nephelometric turbidity units (NTU). Higher values may be obtained with dilution of the sample.

2.0 SUMMARY OF METHOD

- 2.1 The method is based upon a comparison of the intensity of light scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension. The higher the intensity of scattered light, the higher the turbidity. Readings, in NTUs, are made in a nephelometer designed according to specifications given in sections 6.1 and 6.2. A primary standard suspension is used to calibrate the instrument. A secondary standard suspension is used as a daily calibration check and is monitored periodically for deterioration using one of the primary standards.
 - 2.1.1 Formazin polymer is used as a primary turbidity suspension for water because it is more reproducible than other types of standards previously used for turbidity analysis.
 - 2.1.2 A commercially available polymer primary standard is also approved for use for the National Interim Primary Drinking Water Regulations. This standard is identified as AMCO-AEPA-1, available from Advanced Polymer Systems.

3.0 DEFINITIONS

- 3.1 CALIBRATION BLANK (CB) - - A volume of reagent water fortified with the same matrix as the calibration standards, but without the analytes, internal standards, or surrogates analytes.
- 3.2 INSTRUMENT PERFORMANCE CHECK SOLUTION (IPC) - - A solution of one or more method analytes, surrogates, internal standards, or other test substances used to evaluate the performance of the instrument system with respect to a defined set of criteria.
- 3.3 LABORATORY REAGENT BLANK (LRB) - - An aliquot of reagent water or other blank matrices that are treated exactly as a sample including exposure to all glassware, equipment, solvents, reagents, internal standards, and surrogates that are used with other samples. The LRB is

used to determine if method analytes or other interferences are present in the laboratory environment, the reagents, or the apparatus.

- 3.4 LINEAR CALIBRATION RANGE (LCR) - - The concentration range over which the instrument response is linear.
- 3.5 MATERIAL SAFETY DATA SHEET (MSDS) - - Written information provided by vendors concerning a chemical's toxicity, health hazards, physical properties, fire, and reactivity data including storage, spill, and handling precautions.
- 3.6 PRIMARY CALIBRATION STANDARD (PCAL) - - A suspension prepared from the primary dilution stock standard suspension. The PCAL suspensions are used to calibrate the instrument response with respect to analyte concentration.
- 3.7 QUALITY CONTROL SAMPLE (QCS) - - A solution of the method analyte of known concentrations that is used to fortify an aliquot of LRB matrix. The QCS is obtained from a source external to the laboratory, and is used to check laboratory performance.
- 3.8 SECONDARY CALIBRATION STANDARDS (SCAL) - - Commercially prepared, stabilized sealed liquid or gel turbidity standards calibrated against properly prepared and diluted formazin or styrene divinylbenzene polymers.
- 3.9 STOCK STANDARD SUSPENSION (SSS) - - A concentrated suspension containing the analyte prepared in the laboratory using assayed reference materials or purchased from a reputable commercial source. Stock standard suspension is used to prepare calibration suspensions and other needed suspensions.

4.0 INTERFERENCES

- 4.1 The presence of floating debris and coarse sediments which settle out rapidly will give low readings. Finely divided air bubbles can cause high readings.
- 4.2 The presence of true color, that is the color of water which is due to dissolved substances that absorb light, will cause turbidities to be low, although this effect is generally not significant with drinking waters.
- 4.3 Light absorbing materials such as activated carbon in significant concentrations can cause low readings.

5.0 SAFETY

- 5.1 The toxicity or carcinogenicity of each reagent used in this method has not been fully established. Each chemical should be regarded as a potential health hazard and exposure should be as low as reasonably achievable.
- 5.2 Each laboratory is responsible for maintaining a current awareness file of OSHA regulations regarding the safe handling of the chemicals specified in this method. A reference file of Material Safety Data Sheets (MSDS) should be made available to all personnel involved in the chemical analysis. The preparation of a formal safety plan is also advisable.
- 5.3 Hydrazine Sulfate (7.2.1) is a carcinogen. It is highly toxic and may be fatal if inhaled, swallowed, or absorbed through the skin. Formazin can contain residual hydrazine sulfate. Proper protection should be employed.

6.0 EQUIPMENT AND SUPPLIES

- 6.1 The turbidimeter shall consist of a nephelometer, with light source for illuminating the sample, and one or more photo-electric detectors with a readout device to indicate the intensity of light scattered at right angles to the path of the incident light. The turbidimeter should be designed so that little stray light reaches the detector in the absence of turbidity and should be free from significant drift after a short warm-up period.
- 6.2 Differences in physical design of turbidimeters will cause differences in measured values for turbidity, even though the same suspension is used for calibration. To minimize such differences, the following design criteria should be observed:
 - 6.2.1 Light source: Tungsten lamp operated at a color temperature between 2200-3000°K.
 - 6.2.2 Distance traversed by incident light and scattered light within the sample tube: Total not to exceed 10 cm.
 - 6.2.3 Detector: Centered at 90° to the incident light path and not to exceed $\pm 30^\circ$ from 90°. The detector, and filter system if used, shall have a spectral peak response between 400 and 600 nm.
- 6.3 The sensitivity of the instrument should permit detection of a turbidity difference of 0.02 NTU or less in waters having turbidities less than 1 unit. The instrument should measure from 0 to 40 units turbidity. Several ranges may be necessary to obtain both adequate coverage and sufficient sensitivity for low turbidities.

6.4 The sample tubes to be used with the available instrument must be of clear, colorless glass or plastic. They should be kept scrupulously clean, both inside and out, and discarded when they become scratched or etched. A light coating of silicon oil may be used to mask minor imperfections in glass tubes. They must not be handled at all where the light strikes them, but should be provided with sufficient extra length, or with a protective case, so that they may be handled. Tubes should be checked, indexed and read at the orientation that produces the lowest background blank value.

6.5 Balance -- Analytical, capable of accurately weighing to the nearest 0.0001 g.

6.6 Glassware -- Class A volumetric flasks and pipettes as required.

7.0 REAGENTS AND STANDARDS

7.1 Reagent water, turbidity-free: Pass deionized distilled water through a 0.45 μ pore size membrane filter, if such filtered water shows a lower turbidity than unfiltered distilled water.

7.2 Stock standard suspension (Formazin):

7.2.1 Dissolve 1.00 g hydrazine sulfate, $(\text{NH}_2)_2\text{H}_2\text{SO}_4$, (CASRN 10034-93-2) in reagent water and dilute to 100 mL in a volumetric flask.
CAUTION -- CARCINOGEN

7.2.2 Dissolve 10.00 g hexamethylenetetramine (CASRN 100-97-0) in reagent water and dilute to 100 mL in a volumetric flask. In a 100 mL volumetric flask, mix 5.0 mL of each solution (7.2.1 + 7.2.2). Allow to stand 24 hours at $25 \pm 3^\circ\text{C}$, then dilute to the mark with reagent water.

7.3 Primary calibration standards: Mix and dilute 10.00 mL of stock standard suspension (7.2) to 100 mL with reagent water. The turbidity of this suspension is defined as 40 NTU. For other values, mix and dilute portions of this suspension as required.

7.3.1 A new stock standard suspension (7.2) should be prepared each month. Primary calibration standards (7.3) should be prepared daily by dilution of the stock standard suspension.

7.4 Formazin in commercially prepared primary concentrated stock standard suspension (SSS) may be diluted and used as required. Dilute turbidity standards should be prepared daily.

7.5 AMCO-AEPA-1 Styrene Divinylbenzene polymer primary standards are available for specific instruments and require no preparation or dilution prior to use.

7.6 Secondary standards may be acceptable as a daily calibration check, but must be monitored on a routine basis for deterioration and replaced as required.

8.0 SAMPLE COLLECTION, PRESERVATION AND STORAGE

8.1 Samples should be collected in plastic or glass bottles. All bottles must be thoroughly cleaned and rinsed with turbidity free water. Volume collected should be sufficient to insure a representative sample, allow for replicate analysis (if required), and minimize waste disposal.

8.2 No chemical preservation is required. Cool sample to 4°C.

8.3 Samples should be analyzed as soon as possible after collection. If storage is required, samples maintained at 4°C may be held for up to 48 h.

9.0 QUALITY CONTROL

9.1 Each laboratory using this method is required to operate a formal quality control (QC) program. The minimum requirements of this program consist of an initial demonstration of laboratory capability and analysis of laboratory reagent blanks and other solutions as a continuing check on performance. The laboratory is required to maintain performance records that define the quality of data generated.

9.2 INITIAL DEMONSTRATION OF PERFORMANCE.

9.2.1 The initial demonstration of performance is used to characterize instrument performance (determined of LCRs and analysis of QCS).

9.2.2 Linear Calibration Range (LCR) - - The LCR must be determined initially and verified every 6 months or whenever a significant change in instrument response is observed or expected. The initial demonstration of linearity must use sufficient standards to insure that the resulting curve is linear. The verification of linearity must use a minimum of a blank and three standards. If any verification data exceeds the initial values by $\pm 10\%$, linearity must be reestablished. If any portion of the range is shown to be nonlinear,

sufficient standards must be used to clearly define the nonlinear portion.

- 9.2.3 Quality Control Sample (QCS) - - When beginning the use of this method, on a quarterly basis or as required to meet data-quality needs, verify the calibration standards and acceptable instrument performance with the preparation and analysis of a QCS. If the determined concentrations are not within $\pm 10\%$ of the stated values, performance of the determinative step of the method is unacceptable. The source of the problem must be identified and corrected before continuing with on-going analyses.

9.3 ASSESSING LABORATORY PERFORMANCE

- 9.3.1 Laboratory Reagent Blank (LRB) - - The laboratory must analyze at least one LRB with each batch of samples. Data produced are used to assess contamination from the laboratory environment.
- 9.3.2 Instrument Performance Check Solution (IPC) - - For all determinations, the laboratory must analyze the IPC (a midrange check standard) and a calibration blank immediately following daily calibration, after every tenth sample (or more frequently, if required) and at the end of the sample run. Analysis of the IPC solution and calibration blank immediately following calibration must verify that the instrument is within $\pm 10\%$ of calibration. Subsequent analyses of the IPC solution must verify the calibration is still within $\pm 10\%$. If the calibration cannot be verified within the specified limits, reanalyze the IPC solution. If the second analysis of the IPC solution confirms calibration to be outside the limits, sample analysis must be discontinued, the cause determined and/or in the case of drift the instrument recalibrated. All samples following the last acceptable IPC solution must be reanalyzed. The analysis data of the calibration blank and IPC solution must be kept on file with the sample analyses data. NOTE: Secondary calibration standards (SS) may also be used as the IPC.
- 9.3.3 Where additional reference materials such as Performance Evaluation samples are available, they should be analyzed to provide additional performance data. The analysis of reference samples is a valuable tool for demonstrating the ability to perform the method acceptably.

10.0 CALIBRATION AND STANDARDIZATION

- 10.1 Turbidimeter calibration: The manufacturer's operating instructions should be followed. Measure standards on the turbidimeter covering the range of interest. If the instrument is already calibrated in standard turbidity units, this procedure will check the accuracy of the calibration scales. At least one standard should be run in each instrument range to be used. Some instruments permit adjustments of sensitivity so that scale values will correspond to turbidities. Solid standards, such as those made of lucite blocks, should never be used due to potential calibration changes caused by surface scratches. If a pre-calibrated scale is not supplied, calibration curves should be prepared for each range of the instrument.

11.0 PROCEDURE

- 11.1 Turbidities less than 40 units: If possible, allow samples to come to room temperature before analysis. Mix the sample to thoroughly disperse the solids. Wait until air bubbles disappear, then pour the sample into the turbidimeter tube. Read the turbidity directly from the instrument scale or from the appropriate calibration curve.

- 11.2 Turbidities exceeding 40 units: Dilute the sample with one or more volumes of turbidity-free water until the turbidity falls below 40 units. The turbidity of the original sample is then computed from the turbidity of the diluted sample and the dilution factor. For example, if 5 volumes of turbidity-free water were added to 1 volume of sample, and the diluted sample showed a turbidity of 30 units, then the turbidity of the original sample was 180 units.

- 11.2.1 Some turbidimeters are equipped with several separate scales. The higher scales are to be used only as indicators of required dilution volumes to reduce readings to less than 40 NTU.

NOTE 1: Comparative work performed in the Environmental Monitoring Systems Laboratory - Cincinnati (EMSL-Cincinnati) indicates a progressive error on sample turbidities in excess of 40 units.

12.0 DATA ANALYSIS AND CALCULATIONS

- 12.1 Multiply sample readings by appropriate dilution to obtain final reading.
- 12.2 Report results as follows:

| NTU | Record to Nearest |
|-------------|-------------------|
| 0.0 – 1.0 | 0.05 |
| 1 – 10 | 0.1 |
| 10 – 40 | 1 |
| 40 – 100 | 5 |
| 100 – 400 | 10 |
| 400 – 1,000 | 50 |
| > 1,000 | 100 |

13.0 METHOD PERFORMANCE

- 13.1 In a single laboratory (EMSL-Cincinnati), using surface water samples at levels of 26, 41, 75 and 180 NTU, the standard deviations were ± 0.60 , ± 0.94 , ± 1.2 and ± 4.7 units, respectively.
- 13.2 The interlaboratory precision and accuracy data in Table 1 were developed using a reagent water matrix. Values are in NTU.

14.0 POLLUTION PREVENTION

- 14.1 Pollution prevention encompasses any technique that reduces or eliminates the quantity or toxicity of waste at the point of generation. Numerous opportunities for pollution prevention exist in laboratory operation. The EPA has established a preferred hierarchy of environmental management techniques that places pollution prevention as the management option of first choice. Whenever feasible, laboratory personnel should use pollution prevention techniques to address their waste generation. When wastes cannot be feasibly reduced at the source, the Agency recommends recycling as the next best option.
- 14.2 The quantity of chemicals purchased should be based on expected usage during its shelf life and disposal cost of unused material. Actual reagent preparation volumes should reflect anticipated usage and reagent stability.
- 14.3 For information about pollution prevention that may be applicable to laboratories and research institutions, consult "Less is Better: Laboratory Chemical Management for Waste Reduction," available from the American Chemical Society's Department of Government Regulations and Science Policy, 1155 16th Street, N.W., Washington, DC 20036, (202) 872-4477.

15.0 WASTE MANAGEMENT

- 15.1 The U.S. Environmental Protection Agency requires that laboratory waste management practices be conducted consistent with all applicable rules and regulations. Excess reagents, samples and method process wastes should be characterized and disposed of in an acceptable manner. The Agency urges laboratories to protect the air, water and land by minimizing and controlling all releases from hoods, and bench operations, complying with the letter and spirit of any waste discharge permit and regulations, and by complying with all solid and hazardous waste regulations, particularly the hazardous waste identification rules and land disposal restrictions. For further information on waste management consult the "Waste Management Manual for Laboratory Personnel," available from the American Chemical Society at the address listed in Sect. 14.3.

16.0 REFERENCES

1. American Society for Testing and Materials (ASTM). 1993. *Annual Book of ASTM Standards, Volume 11.01*. Water (1), Standard D1889-88A, p. 359. West Conshohocken, PA,
2. Standard Methods. 1992. *Standard Methods for the Examination of Water and Wastewater*. Eighteenth Edition, pp. 2-9, Method 2130B. APHA, AWWA, and WEF. Port City Press, Baltimore, MD.

17.0 TABLES, DIAGRAMS, FLOWCHARTS AND VALIDATION DATA

Table 1. Interlaboratory Precision And Accuracy Data

| Number of Values Reported | True Value (T) | Mean (X) | Residual for X | Standard Deviation (S) | Residual for S |
|---------------------------------|-------------------|-------------|-------------------|------------------------------|-------------------|
| 373 | 0.450 | 0.4864 | 0.0027 | 0.1071 | -0.0078 |
| 374 | 0.600 | 0.6026 | -0.0244 | 0.1048 | -0.0211 |
| 289 | 0.65 | 0.6931 | 0.0183 | 0.1301 | 0.0005 |
| 482 | 0.910 | 0.9244 | 0.0013 | 0.2512 | 0.1024 |
| 484 | 0.910 | 0.9919 | 0.0688 | 0.1486 | -0.0002 |
| 489 | 1.00 | 0.9405 | -0.0686 | 0.1318 | -0.0236 |
| 640 | 1.36 | 1.3456 | -0.0074 | 0.1894 | 0.0075 |
| 487 | 3.40 | 3.2616 | -0.0401 | 0.3219 | -0.0103 |
| 288 | 4.8 | 4.5684 | -0.0706 | 0.3776 | -0.0577 |
| 714 | 5.60 | 5.6984 | 0.2952 | 0.4411 | -0.0531 |
| 641 | 5.95 | 5.6026 | -0.1350 | 0.4122 | -0.1078 |

Regressions: $X = 0.955T + 0.54$, $S = 0.074T + 0.082$

APPENDIX C. TURBIDITY STANDARD METHOD

2130 TURBIDITY*

2130 A. Introduction

1. Sources and Significance

Clarity of water is important in producing products destined for human consumption and in many manufacturing operations. Beverage producers, food processors, and potable water treatment plants drawing from a surface water source commonly rely on fluid-particle separation processes such as sedimentation and filtration to increase clarity and insure an acceptable product. The clarity of a natural body of water is an important determinant of its condition and productivity.

Turbidity in water is caused by suspended and colloidal matter such as clay, silt, finely divided organic and inorganic matter, and plankton and other microscopic organisms. Turbidity is an expression of the optical property that causes light to be scattered and absorbed rather than transmitted with no change in direction or flux level through the sample. Correlation of turbidity with the weight or particle number concentration of suspended matter is difficult because the size, shape, and refractive index of the particles affect the light-scattering properties of the suspension. When present in significant concentrations, particles consisting of light-absorbing materials such as activated carbon cause a negative interference. In low concentrations these particles tend to have a positive influence because they contribute to turbidity. The presence of dissolved, color-causing substances that absorb light may cause a negative interference. Some commercial instruments may have the capability of either correcting for a slight color interference or optically blanking out the color effect.

2. Selection of Method

Historically, the standard method for determination of turbidity has been based on the Jackson candle turbidimeter; however, the lowest turbidity value that can be measured directly on this device is 25 Jackson Turbidity Units (JTU). Because turbidities of water treated by conventional fluid-particle separation processes usually fall within the range of 0 to 1 unit, indirect secondary methods were developed to estimate turbidity. Electronic nephelometers are the preferred instruments for turbidity measurement.

Most commercial turbidimeters designed for measuring low turbidities give comparatively good indications of the intensity of light scattered in one particular direction, predominantly at right angles to the incident light. Turbidimeters with scattered-light detectors located at 90° to the incident beam are called nephelometers. Nephelometers are relatively unaffected by small differences in design parameters and therefore are specified as the standard instrument for measurement of low turbidities. Instruments of different make and model may vary in response.† However, interinstrument variation may be effectively negligible if good measurement techniques are used and the characteristics of the particles in the measured suspensions are similar. Poor measurement technique can have a greater effect on measure-

† Nephelometers that instrument manufacturers claim meet the design specifications of this method may not give the same reading for a given suspension, even when each instrument has been calibrated using the manufacturer's manual. This differential performance is especially important when measurements are made for regulatory purposes. Consult regulatory authorities when selecting a nephelometer to be used for making measurements that will be reported for regulatory purposes.

* Approved by Standard Methods Committee, 1964.

ment error than small differences in instrument design. Turbidimeters of nonstandard design, such as forward-scattering devices, may be more sensitive than nephelometers to the presence of larger particles. While it may not be appropriate to compare their output with that of instruments of standard design, they still may be useful for process monitoring.

An additional cause of discrepancies in turbidity analysis is the use of suspensions of different types of particulate matter for instrument calibration. Like water samples, prepared suspensions have different optical properties depending on the particle size distributions, shapes, and refractive indices. A standard reference suspension having reproducible light-scattering properties is specified for nephelometer calibration.

Its precision, sensitivity, and applicability over a wide turbidity

range make the nephelometric method preferable to visual methods. Report nephelometric measurement results as nephelometric turbidity units (NTU).

3. Storage of Sample

Determine turbidity as soon as possible after the sample is taken. Gently agitate all samples before examination to ensure a representative measurement. Sample preservation is not practical; begin analysis promptly. Refrigerate or cool to 4°C, to minimize microbiological decomposition of solids, if storage is required. For best results, measure turbidity immediately without altering the original sample conditions such as temperature or pH.

2130 B. Nephelometric Method

1. General Discussion

a. Principle: This method is based on a comparison of the intensity of light scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension under the same conditions. The higher the intensity of scattered light, the higher the turbidity. Formazin polymer is used as the primary standard reference suspension. The turbidity of a specified concentration of formazin suspension is defined as 4000 NTU.

b. Interference: Turbidity can be determined for any water sample that is free of debris and rapidly settling coarse sediment. Dirty glassware and the presence of air bubbles give false results. "True color," i.e., water color due to dissolved substances that absorb light, causes measured turbidities to be low. This effect usually is not significant in treated water.

2. Apparatus

a. Laboratory or process nephelometer consisting of a light source for illuminating the sample and one or more photoelectric detectors with a readout device to indicate intensity of light scattered at 90° to the path of incident light. Use an instrument designed to minimize stray light reaching the detector in the absence of turbidity and to be free from significant drift after a short warmup period. The sensitivity of the instrument should permit detecting turbidity differences of 0.02 NTU or less in the lowest range in waters having a turbidity of less than 1 NTU. Several ranges may be necessary to obtain both adequate coverage and sufficient sensitivity for low turbidities. Differences in instrument design will cause differences in measured values for turbidity even though the same suspension is used for calibration. To minimize such differences, observe the following design criteria:

1) Light source—Tungsten-filament lamp operated at a color temperature between 2200 and 3000°K.

2) Distance traversed by incident light and scattered light within the sample tube—Total not to exceed 10 cm.

3) Angle of light acceptance by detector—Centered at 90° to the incident light path and not to exceed $\pm 30^\circ$ from 90°. The detector and filter system, if used, shall have a spectral peak response between 400 and 600 nm.

b. Sample cells: Use sample cells or tubes of clear, colorless glass or plastic. Keep cells scrupulously clean, both inside and out, and discard if scratched or etched. Never handle them where the instrument's light beam will strike them. Use tubes with sufficient extra length, or with a protective case, so that they may be handled properly. Fill cells with samples and standards that have been agitated thoroughly and allow sufficient time for bubbles to escape.

Clean sample cells by thorough washing with laboratory soap inside and out followed by multiple rinses with distilled or deionized water; let cells air-dry. Handle sample cells only by the top to avoid dirt and fingerprints within the light path.

Cells may be coated on the outside with a thin layer of silicone oil to mask minor imperfections and scratches that may contribute to stray light. Use silicone oil with the same refractive index as glass. Avoid excess oil because it may attract dirt and contaminate the sample compartment of the instrument. Using a soft, lint-free cloth, spread the oil uniformly and wipe off excess. The cell should appear to be nearly dry with little or no visible oil.

Because small differences between sample cells significantly impact measurement, use either matched pairs of cells or the same cell for both standardization and sample measurement.

3. Reagents

a. Dilution water: High-purity water will cause some light scattering, which is detected by nephelometers as turbidity. To obtain low-turbidity water for dilutions, nominal value 0.02 NTU, pass laboratory reagent-grade water through a filter with pore size sufficiently small to remove essentially all particles larger than 0.1 μm ;^{*} the usual membrane filter used for bacteriological examinations is not satisfactory. Rinse collecting flask at least twice with filtered water and discard the next 200 mL.

Some commercial bottled demineralized waters have a low turbidity. These may be used when filtration is impractical or a good grade of water is not available to filter in the laboratory. Check turbidity of bottled water to make sure it is lower than the level that can be achieved in the laboratory.

^{*} Nuclepore Corp., 7035 Commerce Circle, Pleasanton, Calif., or equivalent.

b. Stock primary standard formazin suspension:

1) Solution I—Dissolve 1.000 g hydrazine sulfate, $(\text{NH}_2)_2\cdot\text{H}_2\text{SO}_4$, in distilled water and dilute to 100 mL in a volumetric flask.

CAUTION: Hydrazine sulfate is a carcinogen; avoid inhalation, ingestion, and skin contact. Formazin suspensions can contain residual hydrazine sulfate.

2) Solution II—Dissolve 10.00 g hexamethylenetetramine, $(\text{CH}_2)_6\text{N}_4$, in distilled water and dilute to 100 mL in a volumetric flask.

3) In a flask, mix 5.0 mL Solution I and 5.0 mL Solution II. Let stand for 24 h at $25 \pm 3^\circ\text{C}$. This results in a 4000-NTU suspension. Transfer stock suspension to an amber glass or other UV-light-blocking bottle for storage. Make dilutions from this stock suspension. The stock suspension is stable for up to 1 year when properly stored.

c. Dilute turbidity suspensions: Dilute 4000 NTU primary standard suspension with high-quality dilution water. Prepare immediately before use and discard after use.

d. Secondary standards: Secondary standards are standards that the manufacturer (or an independent testing organization) has certified will give instrument calibration results equivalent (within certain limits) to the results obtained when the instrument is calibrated with the primary standard, i.e., user-prepared formazin. Various secondary standards are available including: commercial stock suspensions of 4000 NTU formazin, commercial suspensions of microspheres of styrene-divinylbenzene copolymer,[†] and items supplied by instrument manufacturers, such as sealed sample cells filled with latex suspension or with metal oxide particles in a polymer gel. The U.S. Environmental Protection Agency¹ designates user-prepared formazin, commercial stock formazin suspensions, and commercial styrene-divinylbenzene suspensions as "primary standards," and reserves the term "secondary standard" for the sealed standards mentioned above.

Secondary standards made with suspensions of microspheres of styrene-divinylbenzene copolymer typically are as stable as concentrated formazin and are much more stable than diluted formazin. These suspensions can be instrument-specific; therefore, use only suspensions formulated for the type of nephelometer being used. Secondary standards provided by the instrument manufacturer (sometimes called "permanent" standards) may be necessary to standardize some instruments before each reading and in other instruments only as a calibration check to determine when calibration with the primary standard is necessary.

All secondary standards, even so-called "permanent" standards, change with time. Replace them when their age exceeds the shelf life. Deterioration can be detected by measuring the turbidity of the standard after calibrating the instrument with a fresh formazin or microsphere suspension. If there is any doubt about the integrity or turbidity value of any secondary standard, check instrument calibration first with another secondary standard and then, if necessary, with user-prepared formazin. Most secondary standards have been carefully prepared by their manufacturer and should, if properly used, give good agreement with formazin. Prepare formazin primary standard only as a last resort. Proper application of secondary standards is specific for each make and model of nephelometer. Not all secondary standards have to be discarded when comparison with a primary standard

and shows that their turbidity value has changed. In some cases, the secondary standard should be simply relabeled with the new turbidity value. Always follow the manufacturer's directions.

4. Procedure

a. General measurement techniques: Proper measurement techniques are important in minimizing the effects of instrument variables as well as stray light and air bubbles. Regardless of the instrument used, the measurement will be more accurate, precise, and repeatable if close attention is paid to proper measurement techniques.

Measure turbidity immediately to prevent temperature changes and particle flocculation and sedimentation from changing sample characteristics. If flocculation is apparent, break up aggregates by agitation. Avoid dilution whenever possible. Particles suspended in the original sample may dissolve or otherwise change characteristics when the temperature changes or when the sample is diluted.

Remove air or other entrained gases in the sample before measurement. Preferably degas even if no bubbles are visible. Degas by applying a partial vacuum, adding a nonfoaming-type surfactant, using an ultrasonic bath, or applying heat. In some cases, two or more of these techniques may be combined for more effective bubble removal. For example, it may be necessary to combine addition of a surfactant with use of an ultrasonic bath for some severe conditions. Any of these techniques, if misapplied, can alter sample turbidity; *use with care*. If degassing cannot be applied, bubble formation will be minimized if the samples are maintained at the temperature and pressure of the water before sampling.

Do not remove air bubbles by letting sample stand for a period of time because during standing, turbidity-causing particulates may settle and sample temperature may change. Both of these conditions alter sample turbidity, resulting in a nonrepresentative measurement.

Condensation may occur on the outside surface of a sample cell when a cold sample is being measured in a warm, humid environment. This interferes with turbidity measurement. Remove all moisture from the outside of the sample cell before placing the cell in the instrument. If fogging recurs, let sample warm slightly by letting it stand at room temperature or by partially immersing it in a warm water bath for a short time. Make sure samples are again well mixed.

b. Nephelometer calibration: Follow the manufacturer's operating instructions. Run at least one standard in each instrument range to be used. Make certain the nephelometer gives stable readings in all sensitivity ranges used. Follow techniques outlined in *§s 2b* and *4a* for care and handling of sample cells, degassing, and dealing with condensation.

c. Measurement of turbidity: Gently agitate sample. Wait until air bubbles disappear and pour sample into cell. When possible, pour well-mixed sample into cell and immerse it in an ultrasonic bath for 1 to 2 s or apply vacuum degassing, causing complete bubble release. Read turbidity directly from instrument display.

d. Calibration of continuous turbidity monitors: Calibrate continuous turbidity monitors for low turbidities by determining turbidity of the water flowing out of them, using a laboratory-model nephelometer, or calibrate the instruments according to manufacturer's instructions with formazin primary standard or appropriate secondary standard.

5. Interpretation of Results

Report turbidity readings as follows:

| Turbidity Range NTU | Report to the Nearest NTU |
|------------------------|---------------------------------|
| 0-1.0 | 0.05 |
| 1-10 | 0.1 |
| 10-40 | 1 |
| 40-100 | 5 |
| 100-400 | 10 |
| 400-1000 | 50 |
| >1000 | 100 |

When comparing water treatment efficiencies, do not estimate turbidity more closely than specified above. Uncertainties and discrepancies in turbidity measurements make it unlikely that results can be duplicated to greater precision than specified.

6. Reference

1. U.S. ENVIRONMENTAL PROTECTION AGENCY. 1993. Methods for Determination of Inorganic Substances in Environmental Samples.

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2150 ODOR*

2150 A. Introduction

1. Discussion

Odor, like taste, depends on contact of a stimulating substance with the appropriate human receptor cell. The stimuli are chemical in nature and the term "chemical senses" often is applied to odor and taste. Water is a neutral medium, always present on or at the receptors that perceive sensory response. In its pure form, water cannot produce odor or taste sensations. Man and other animals can avoid many potentially toxic foods and waters because of adverse sensory response. These senses often provide the first warning of potential hazards in the environment.

Odor is recognized¹ as a quality factor affecting acceptability of drinking water (and foods prepared with it), tainting of fish and other aquatic organisms, and esthetics of recreational waters. Most organic and some inorganic chemicals contribute taste or odor. These chemicals may originate from municipal and industrial waste discharges, from natural sources such as decomposition of vegetable matter, or from associated microbial activity, and from disinfectants or their products.

The potential for impairment of the sensory quality of water has increased as a result of expansion in the variety and quantity of waste materials, demand for water disposal of captured air pollutants, and increased reuse of available water supplies by a growing population. Domestic consumers and process industries such as food, beverage, and pharmaceutical manufacturers require water essentially free of tastes and odors.

Some substances, such as certain inorganic salts, produce taste without odor and are evaluated by taste testing (Section 2160). Many other sensations ascribed to the sense of taste actually are odors, even though the sensation is not noticed until the material is taken into the mouth. Because some odorous materials are detectable when present in only a few nanograms per liter, it is usually impractical and often impossible to isolate and identify the odor-producing chemical. The ultimate odor-testing device is the human nose. Odor tests are performed to provide qualitative descriptions and approximate quantitative measurements of odor intensity. The method for intensity measurement presented here is the *threshold odor* test, based on a method of limits.² This procedure, while not universally preferred,³ has definite strengths.⁴

Sensory tests are useful as a check on the quality of raw and finished water and for control of odor through the treatment process. They can assess the effectiveness of different treatments and provide a means of tracing the source of contamination.

Section 6040B provides an analytical procedure for quantifying several organic odor-producing compounds including geosmin and methylisoborneol.

2. References

1. U.S. ENVIRONMENTAL PROTECTION AGENCY. 1973. Proposed Criteria for Water Quality. Vol. 1, Washington, D.C.
2. AMERICAN SOCIETY FOR TESTING AND MATERIALS COMMITTEE E-18. 1968. STP 433. Basic principles of sensory evaluation; STP 434, Manual on sensory testing methods; STP 440. Correlation of subjective-

* Approved by Standard Methods Committee, 1991.

APPENDIX D. TURBIDITY GLI METHOD 2

Revision Date: November 2, 1992

1. SCOPE AND APPLICATION

- 1.1 This method is applicable to drinking water samples in the range of turbidity from 0 to 40 nephelometric units (NTU). Higher values may be obtained with dilution of the sample. A method detection limit of .100 NTUs is recommended for this procedure.

NOTE 1: NTUS are considered comparable to the previously reported Formazin Turbidity Units (FTU).

2. SUMMARY OF METHOD

- 2.1 The method is based upon a comparison of the intensity of light scatters by the sample under defined conditions with the intensity of the light scattered by a standard reference suspension. The higher the intensity of the scattered light, the higher the turbidity. Readings, in NTUs, are made in a nephelometer designed according to the specifications outlined in Apparatus. A standard suspension of Formazin, prepared under closely defined conditions, is used to calibrate the instrument.

2.1.1 Formazin polymer is used as the turbidity reference suspension for water because it is more reproducible than other types of standards previously used for turbidity standards.

3. SAMPLE HANDLING AND PRESERVATION

- 3.1 Collect each sample in a soft or hard plastic, or soft or hard glass container. Immediately refrigerate or ice the sample to 4°C and analyze within 48 hours.

4. Physical Characteristics

- 4.1 The presence of floating debris and coarse sediments which settle out rapidly will give low readings. Finely divided air bubbles will affect the results in a positive manner.
- 4.2 The presence of color, that is the color of water which is due to dissolved substances which absorb light, will cause turbidities to be low, although this effect is generally not significant.

5. APPARATUS

- 5.1 The turbidimeter shall consist of a nephelometer with two light sources for illuminating the sample and two detectors with a readout device to indicate the intensity of light scattered at right angles to the path of the incident light. The turbidimeter shall accomplish two measurement phases every 0.5 seconds.

In the first phase, light source shall pulse a beam of light directly into photodetector two. Simultaneously, photodetector one shall measure the light scattered at a 90 degree angle. Diffused light measured by photodetector two shall be called the reference signal while scattered light measured by photodetector one shall be called an active signal.

In the second phase, light source two shall pulse a beam of light directly into photodetector one. Simultaneously, photodetector two shall measure the light scattered at a 90 degree angle. This time, the diffused light measured by photodetector one shall be called a reference signal and scattered light measured by photodetector two shall be called an active signal. The two phase measurement shall provide four independent measurements from the two light sources; two reference signals and two active signals. A ratiometric algorithm will then be used to calculate the turbidity value from these four readings.

The turbidimeter should be designed that little stray light reaches the detector in the absence of turbidity and should be free from significant drift after a short warm-up period.

- 5.2 The sensitivity of the instrument should permit detection of a turbidity difference of 0.02 unit or less in waters with turbidities less than 1 unit. The instrument should measure from 0 to 40 units turbidity. Several ranges will be necessary to obtain both adequate coverage and sufficient sensitivity for low turbidities.
- 5.3 The sample tubes to be used with the available instrument must be of clear, colorless optical glass. They should be kept scrupulously clean, both inside and out, and discarded when they become scratched or etched. They must not be handled at all where the light strikes them, but should be provided with sufficient extra length, or with a protective case, so that they may be handled.
- 5.4 Any apparatus may be used provided that it complies with the following requirements:
- 5.4.1 the wavelength of the incident radiation shall be 860 nm;

- 5.4.2 the spectral bandwidth of the incident radiation shall be less than or equal to 60 nm;
- 5.4.3 there shall be no divergence from parallelism of the incident radiation and any convergence shall not exceed 1.5 degrees;
- 5.4.4 There shall be two light sources and two detectors
- 5.4.5 the measuring angle between the optical axis of the incident radiation and that of the diffused radiation for light pulsed through the sample by light source one shall be 90 ± 2.5 degrees;
- 5.4.6 the measuring angle between the optical axis of the incident radiation and that of the diffused radiation for light pulsed through the sample by light source two shall be 90 ± 2.5 degrees;

The narrow definition of the light source makes it unnecessary to specify sensitivity of the photodetector.

6. REAGENTS

- 6.1 Turbidity-free water: Pass distilled water through a membrane filter having precision-sized holes of $0.2 \mu\text{m}$; the usual membrane filter used for bacterial examinations is not satisfactory (Sec. 3.1, EPA-approved Standard Method 214A, 16th edition).
- 6.2 Stock formazin turbidity suspension:
Solution 1: Distilled 1.00 g hydrazine sulfate $(\text{NH}_2)_2\text{H}_2\text{SO}_4$, in distilled water and dilute to 100 ml in a volumetric flask.
Solution 2: Dissolve 10.00 g hexamethylenetetramine in distilled water and dilute to 100 ml in a volumetric flask. In a 100 ml volumetric flask, mix 5.0 ml Solution 1 with 5.0 ml Solution 2. Allow to stand 24 hours at $24 \pm$ degrees C, then dilute to the mark and mix.
- 6.3 Standard formazin turbidity suspension: Dilute 10.00 ml stock turbidity suspension to 100 ml with turbidity-free water. The turbidity of this suspension is defined as 40 units. Dilute portions of the standard turbidity suspension with turbidity-free water as required.

7. PROCEDURE

- 7.1 Turbidimeter calibration: The manufacturer's operating instructions should be followed. Measure standards on the turbidimeter covering the range of interest. If the instrument is already calibrated in standard turbidity units, this procedure will check the accuracy of the calibration scales. At least one standard should be run in each instrument range to be used. Some instruments permit adjustments of sensitivity so that scale is not supplied, then calibration curves should be prepared for each range of the

instrument.. If a pre-calibrated scale is not supplied, then calibration curves should be prepared for each range of the instrument.

- 7.2 Turbidities less than 40 units: Shake the sample thoroughly to disperse the solids. Wait until air bubbles disappear then pour the sample into the turbidimeter tube . Read the turbidity directly from the instrument scale or from the appropriate calibration curve.
- 7.3 Turbidities exceeding 40 units: Dilute the sample with one or more volumes of turbidity-free water until the turbidity falls below 40 units. The turbidity of the original sample is then computed from the turbidity of the diluted sample and the dilution factor. For example if five volumes of turbidity-free water were added to 1 volume of sample, and the diluted sample showed a turbidity of 30 units, then the turbidity of the original sample was 180 units.

8. CALCULATIONS

- 8.1 Nephelometric turbidity units (NTU)

$$= \frac{A \times (B + C)}{C}$$

where: A = NTU found in the diluted sample
B = volume of the dilution water, mL and
C = sample volume taken for dilution, mL

- 8.2 Report results as follows:

| NTU | Record to Nearest |
|-----------|-------------------|
| 0.0–1.0 | 0.05 |
| 1–10 | 0.1 |
| 10–40 | 1 |
| 40–100 | 5 |
| 100–400 | 10 |
| 400–1,000 | 50 |
| >1,000 | 100 |

9. PRECISION AND ACCURACY

9.1 In a single laboratory, using surface waters filtered to minimum turbidity with 0.04 μ filters and dosed with formazin to levels of 0.47, 0.91, 5.6, 9.8, 39.3, 82.7 and 99.4 NTU, the \pm standard deviations were 0.007, 0.014, 0.1, 0.22, 0.45, and 0.83 units respectively.

9.2 Accuracy of the great Lakes Turbidity Method

The range of the mean percent recoveries of turbidity from 10 fortified drinking water samples, each analyzed in triplicate by the Great Lakes Instruments Turbidity Method, was as follows:

| Turbidity Added to Sample | Range of Percent Recovery |
|---------------------------|---------------------------|
| 4.5 | 98.1–112.2 |
| 9.5 | 96.8–111.1 |
| 34.5 | 93.7–114.3 |

PRECISION OF THE GREAT LAKES TURBIDITY METHOD

The range of the standard deviations and percent relative standard deviations (or percent coefficient of variations) associated with the triplicate observations of the total theoretical concentration of 10 fortified drinking water samples by the Great Lakes Instruments turbidity Method were as follows:

| Total Theoretical Turbidity (NTU) | Standard Deviation (NTU) | Relative Standard Deviation (%) |
|-----------------------------------|--------------------------|---------------------------------|
| 0.5 | 0.01–0.06 | 1.1–10.7 |
| 5.0 | 0.00–0.10 | 0.0–2.0 |
| 10.0 | 0.00 | 0.0–5.6 |
| 35.0 | 0.00–0.58 | 0.0–1.8 |

9.3 Accuracy and precision should be checked on a routine basis to monitor the overall performance of the instrument. A series of reagent blanks and check standards should be run to validate the quality of sample data. These checks should occur at frequency that is required for regulatory compliance.

10. SAFETY

- 10.1 Operators handling reagents should wear safety glasses, rubber gloves and appropriate protective clothing. Consult the Material Safety Data Sheets for additional safety information before working with reagents.

11. QUALITY ASSURANCE

- 11.1 Each laboratory using this method in regulated environmental monitoring is required to operate a formal quality assurance/control program. The minimum initial requirements of this program consist of the demonstration of the laboratory's capability with this method. On a continuing basis, the laboratory should check its performance (accuracy and precision) by analyzing reagent blanks and check standards, fortified blanks, and/or fortified samples, preferably at a minimum frequency of 10% of the total samples analyzed by the method. The laboratory should maintain the performance records that define the quality of the data generated with the method.

12. POLLUTION PREVENTION

- 12.1 Solution samples should be used, collected and disposed of in accordance with all Federal, state and local regulations.

13. WASTE MANAGEMENT

- 13.1 In case of spill or release: Dilute with water. Dispose of in accordance with all Federal, state, and local regulations.

14. REFERENCES

1. *Book of ASTM Standards*. 1976. Part 31. "Water." Standard D1889-71.
2. *Methods for the Examination of Water and Wastewater*. 1975. Fourteenth Edition. Method 214A.
3. Standard, Ref. No. ISO 7027-1984 (E).
4. *Methods for the Examination of Water and Wastewater*. Sixteenth Edition. Method 214A.
5. "Standard Methods for the Certification of Laboratories Analyzing Drinking Water: Criteria and Procedures, Quality Assurance." 1990. EPA/570/9-90/008.