

Operational Control of Coagulation and Filtration Processes

MANUAL OF WATER SUPPLY PRACTICES

M37



Third Edition



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AWWA MANUAL M37

Third Edition



**American Water Works
Association**

Manual of Water Supply Practices — M37, Third Edition

Operational Control of Coagulation and Filtration Processes

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Contents

Figures, v

Tables, ix

Acknowledgments, xi

Introduction, xiii

**Chapter 1 Particle and Natural Organic Matter Removal
in Drinking Water Treatment..... 1**

Introduction, 1

Particles, 2

Natural Organic Matter, 6

Particle Stability and Coagulant Chemistry, 9

Particle and NOM Removal Processes, 12

Process Control Strategies, 15

References, 16

Chapter 2 Jar Testing 17

Introduction, 17

Preparing for a Jar Test, 21

Special Applications, 48

References, 57

**Chapter 3 Online Sensors for Monitoring and
Controlling Coagulation and Filtration..... 59**

Introduction, 59

Process Applications of Online Sensors, 59

Turbidimeters: Technical Details, 64

Particle Counters: Technical Details, 80

Streaming Current Monitors: Technical Details, 88

Total Organic Carbon Analyzers: Technical Details, 90

Ultraviolet Absorbance/Transmittance Analyzers: Technical Details, 93

Online Monitoring of pH: Technical Details, 96

References, 99

Chapter 4 Flocculation and Clarification Processes 101

Introduction, 101

Rapid Mix, 103

Flocculation, 105

Clarification, 110

References, 120

Chapter 5 Filtration..... 121

Introduction, 121

Pretreatment, 122

Particle Removal in Rapid Filtration, 123

Filter Operation and Management, 125	
References, 130	
Chapter 6 Pilot Testing for Process Evaluation and Control	131
Introduction, 131	
Determining Piloting Goals, 132	
Processes and Technologies, 134	
Instrumentation, 140	
Quality Control, 142	
Special Testing, 142	
Evaluation of Testing Results, 143	
References, 147	
Chapter 7 Case Studies	149
Case Study 1: Conversion From Alum to Ferric Sulfate at the Addison-Evans Water Treatment Plant, Chesterfield County, Va., 151	
Case Study 2: Jar Test Calibration, 155	
Case Study 3: Relationships Between Coagulation Parameters, Winston-Salem, N.C., 157	
Case Study 4: NOM Measurements for Coagulation Control, 163	
Case Study 5: Net Charge Equals Positive Change, 167	
Case Study 6: Streaming Current Monitor Pilot Study: The Detection of a Ferric Chloride Feed Failure, 171	
Case Study 7: The Application of Simplified Process Statistical Variance Techniques to Improve the Analysis of Real-Time Filtration Performance, 175	
Case Study 8: Online Monitoring Aids Operations at Clackamas River Water, 179	
Case Study 9: Palm Beach County Water Utilities Water Treatment Plant 8 Ferric Chloride Addition, 183	
Appendix: Examples of Standard Operating Procedures, 189	
Index, 217	
List of AWWA Manuals, 225	

Figures

- 1-1 Particulates present in source and finished water, 6
- 1-2 Coagulation (destabilization) mechanisms for particulate contaminants, 12
- 1-3 Treatment train (from coagulation to filtration), 13

- 2-1 Use of jar tests to determine optimum flash mix conditions, 19
- 2-2 Example use of jar tests: Settled turbidity versus settling time, 21
- 2-3 Example use of graph for determining velocity gradient for jar test based on full-scale, 23
- 2-4 Example jar test unit, 24
- 2-5 Example jar test units, 4-jar and 6-jar systems, 24
- 2-6 Example jar test unit, 25
- 2-7 Example jar test unit, 25
- 2-8 Laboratory *G* curve for magnetic jar tester with gator jar, 27
- 2-9 Laboratory *G* curve for flat paddle in the gator jar, 28
- 2-10 Laboratory *G* curve for marine propeller in either the Hudson or gator jar, 29
- 2-11 Wooden holder for six dosing cups, 30
- 2-12 Septa bar, 30
- 2-13 Expressing coagulant doses in molar metal concentrations, 32
- 2-14 Example of micropipettes capable of dispensing 0.1 μL to 2,500 μL , 33
- 2-15 Example jar testing data sheet, 42
- 2-16 Example correlation between jar test results and full-scale plant performance, 45
- 2-17 Use of the jar test to select coagulant aids: Turbidity versus settling time, 45
- 2-18 Use of the jar test to optimize the coagulation pH: UV-254 versus alum dose, 46
- 2-19 Example use of the jar test: Flocculation time versus settled turbidity, 46
- 2-20 Use of the jar test to determine the optimum polymer dose: Turbidity versus dose and settling time, 47
- 2-21 Alum dose, ozone dose, THMFP topograph, 47
- 2-22 Filter Index Test apparatus, 51
- 2-23 Jar test equipment for DAF testing, 55

- 3-1 Basic design of a nephelometer, 67
- 3-2 Diagrams illustrating the difference between in-situ and sidestream turbidimeters, 72
- 3-3 Typical portable turbidimeter, 73
- 3-4 Laboratory turbidimeter commonly used in drinking water plants, 74
- 3-5 Optical geometry for a basic ratio system involving two detectors, 75
- 3-6 Theory of operation for a light obscuration particle counter, 81
- 3-7 Filtered water particle count data prepared to provide percentile analysis, 85
- 3-8 Particle count data for duration of filter run, 85
- 3-9 Schematic diagram of streaming current monitor, 89
- 3-10 Typical online TOC instruments, 91
- 3-11 Block diagram summary of TOC sample preparation, 92
- 3-12 Typical TOC prefiltration apparatus, 93
- 3-13 Examples of single-beam UV absorbance analyzers, 94

- 4-1 Effect of sequence of chemical addition on alum coagulation, 104
- 4-2 Effect of rapid-mixing time on settled turbidity, 105
- 4-3 Crossflow baffling configuration for horizontal flocculators, 107
- 4-4 Top view of plug flow baffling configuration for horizontal flocculators, 107
- 4-5 Seasonal variation in treatment for different flocculation configurations, 109
- 4-6 Flocculator/clarifier, 112
- 4-7 Blanket clarifier, 113
- 4-8 Tube settler installed in sedimentation basin, 114
- 4-9 Contact adsorption clarifier and multimedia gravity filter in series, 115
- 4-10 DAF process train, 118
- 4-11 In-filter DAF treatment train, 119

- 5-1 Size range of various filter types, 122
- 5-2 Particle removal in a granular filter, 123
- 5-3 Calculated clean-bed single-collector removal efficiency as a function of particle size for two filtration velocities according to Tufenjki and Elimelech 2004 ($d_c = 0.5$ mm, $V = 5$ and 20 m/hr, $T = 20^\circ\text{C}$, $\rho_p = 1,050$ kg/m³, $\epsilon_0 = 0.4$, $H = 1.0 \times 10^{-20}\text{J}$), 124
- 5-4 Typical filter breakthrough curve, 126

- 6-1 Example of pilot-scale flocculation basins, 135
- 6-2 Schematic of the Superpulsator® solids contact clarifier process, 137
- 6-3 Schematic of the Actiflo® ballasted flocculation clarification process, 138
- 6-4 Example of a pilot-scale DAF basin with scraper-type sludge removal, 139
- 6-5 Example of pilot filter gallery showing dedicated turbidimeters and differential pressure transmitters sending data to a central data acquisition system, 140

- 7.1-1 Effect of conversion from alum to ferric sulfate on TOC removal at Chesterfield County, Va., 152
- 7.1-2 Settled turbidity contours for ferric sulfate at Chesterfield County, Va., 152
- 7.1-3 Effect of conversion from alum to ferric sulfate on THM formation at Chesterfield County, Va., 153
- 7.1-4 Effect of conversion from alum to ferric sulfate on HAA5 formation at Chesterfield County, Va., 153
- 7.3-1 Effect of pH and alum dose on zeta potential contours (case 1), 159
- 7.3-2 Effect of pH and alum dose on Filter Index contours (case 1), 159
- 7.3-3 Effect of pH and alum dose on settled turbidity (case 1), 160
- 7.3-4 Effect of pH and alum dose on zeta potential contours (case 2), 160
- 7.3-5 Relation between UV_{254} and zeta potential (case 2), 161
- 7.3-6 UV_{254} -ZP data from multisource, multiseason testing at Winston-Salem, N.C., 161
- 7.3-7 Shift in zero zeta potential curves in relation to ZP- UV_{254} slope, 162
- 7.4-1 Relationship between raw water quality parameters and coagulant dose for the Glenmore WTP, 165
- 7.5-1 Kamloops streaming current monitor (SCM) configuration, 169
- 7.5-2 Optimum plant performance, 169
- 7.6-1 SCM, pH, and settled water turbidity data during coagulant feed pump failure, 173
- 7.6-2 SCM and filter effluent turbidity data during coagulant feed pump failure, 174
- 7.7-1 Measurement of turbidity and the variability of the turbidity measurement from the effluent stream of a granular anthracite dual-media filter, 177
- 7.9-1 Turbidity before addition of ferric chloride, August 2006, 186
- 7.9-2 Turbidity after addition of ferric chloride, September 2006, 187

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Tables

1-1	Regulatory requirements for particle and NOM removals, 4
1-2	Guidelines on the nature of NOM and expected DOC removals, 8
1-3	Summary of coagulant solubility, 10
2-1	Settling velocity conversion factors for clarification basins, 20
2-2	Factors for determining molar metal dosage, 31
3-1	Typical online sensors used in coagulation and filtration applications, 60
3-2	Common turbidimeter problems and troubleshooting approaches, 79
3-3	Appropriate application for given turbidimeter technologies, 80
4-1	Multiplier factors to convert horsepower/1,000 gal to G at various temperatures, 103
6-1	Example pilot treatment goals, 133
6-2	Example evaluation criterion for a hypothetical pilot testing program, 145
7.2-1	Example calibration testing sequence, 156
7.4-1	Analytical instrumentation used at the Glenmore WTP for monitoring raw water quality, 164
7.9-1	Water quality characteristics before ferric addition, 184
7.9-2	Customer complaints showing reduction after 2005, 185
7.9-3	Water quality characteristics after ferric addition, 185
7.9-4	Sludge analysis for land application purposes, 186

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Introduction

The first successful practice of water filtration in the United States involved use of slow sand filters in which raw water was applied directly to large sand beds, but these filters were not suitable for treatment of muddy river waters like those found in the Ohio, Mississippi, and Missouri River valleys and their tributaries. In the 1890s and very early 1900s, George Fuller's filtration tests in Louisville and Cincinnati and Alan Hazen's testing program in Pittsburgh showed that turbid waters could be treated successfully by addition of coagulant chemical, clarification, and rapid sand filtration. The capability of a process train consisting of coagulation, mixing, flocculation, sedimentation, and rapid sand filtration to treat raw water having a wide range of turbidity resulted in widespread acceptance of this process train, which came to be called conventional treatment in the United States. Adoption of conventional treatment by a large number of water systems and of chlorination by even more water systems resulted in a very large decrease in the number of cases and number of deaths caused by typhoid fever in the early decades of the twentieth century.

Prior to World War II the focus on water treatment was on disinfecting water and providing clear water to drink. Coagulation and filtration had been shown to remove a substantial fraction of bacteria from water, and combined with chlorination, conventional treatment provided a double barrier against passage of pathogenic bacteria into drinking water. With the realization that viruses also could be transmitted by drinking water, the microbiological challenge broadened. Conventional treatment was found to be capable of removal of polioviruses in the 1960s, and in the 1980s and 1990s removal of protozoan cysts was shown to be within the capabilities of coagulation and filtration when these processes are managed properly. Results of studies on removal of asbestos fibers by coagulation and filtration proved that this process could remove both microbes and inorganic particles in a very wide range of sizes, from considerably less than 1 μm to tens of μm .

Regulatory requirements related to turbidity of filtered water have become more stringent over the decades, but regardless of the regulatory requirement, the drinking water industry has been able to look to some water systems that set their own goals for filtered water turbidity that were considerably more stringent than those set by regulators. This continues to be the case, as at some filtration plants the operating goal is to produce filtered water turbidity of 0.1 ntu or lower. The Partnership for Safe Water encourages the approach of continually striving to improve filtered water quality. Research for removal of viruses, bacteria, protozoan cysts, and asbestos fibers supports the concept that attaining very low filtered water turbidity is an effective means of consistently attaining the best removal of particulate contaminants. Employing proper coagulation chemistry is fundamental to successful filtration for controlling particulate contaminants.

In addition to playing such an important role in removal of particles in granular media filtration, coagulation also has had other important applications, and new ones are being identified. For precipitative lime softening plants that do not soften at a high pH and remove magnesium, the calcium carbonate crystals that are precipitated in the softening process carry a negative charge, and use of a positively charged coagulant or polymer aids in effective clarification and filtration. When surface waters are softened in this manner, use of a coagulant is required by the Surface Water Treatment Rule (SWTR). Depending on the nature of natural organic matter (NOM) found in water, chemical coagulation can be effective for removing a substantial fraction of the NOM. Rapid oxidation of reduced iron and arsenic results in floc formation with sorbed arsenic on the iron floc, and this can be an effective approach to arsenic removal. Coagulation has also proven to be useful in pretreatment of some waters for membrane filtration.

With the discovery in the 1970s of the formation of trihalomethanes (THMs) in drinking water because of chlorination, an additional purpose beyond control of turbidity was found for coagulation and filtration. Early studies of THMs indicated that three control strategies could be pursued:

- Change to a disinfectant that did not form trihalomethanes
- Remove NOM that reacts with chlorine to form THMs
- After THMs are formed, treat water to remove them

Treating water to remove THMs generally was not practical, so much of the effort to control these compounds focused on changing to a disinfectant that would not form THMs and removing NOM prior to chlorination. Removing the NOM by applying coagulation and clarification in a more effective manner, combined with delaying the introduction of chlorine into water until after clarification was completed, was shown to be an economical means of lowering the concentration of THMs in some waters. Thus the benefits of effective coagulation and clarification were extended beyond removal of turbidity-causing particles and removal of microorganisms.

With the passage of increasingly stringent regulations on the concentration of disinfection by-products (DBPs) in drinking water, removal of NOM has become a regulation-driven goal for many water utilities that depend upon surface water sources and even for some that treat groundwater. For many utilities, meeting both surface water treatment regulatory requirements for filtered water turbidity and the requirements for DBPs can be challenging. NOM often provides an important contribution to the negative surface charges found on both organic and mineral particles, so the nature of NOM and its concentration in water can have a strong influence on the type and dosage of coagulant needed for optimizing coagulation, clarification, and filtration.

More recently, as the merits of the microfiltration and ultrafiltration processes have been recognized and costs of the process equipment have become more affordable, ways have been sought to extend the use of these processes that simply strain particulate matter out of water but do not remove dissolved constituents. Again chemical coagulation has been recognized as a process that could pretreat water prior to membrane filtration and thus extend the range of water quality that can be treated this way. Coagulation for removal of NOM, when the NOM is susceptible to removal by this technique, has proven to be an excellent pretreatment for use in conjunction with membrane filtration to control both particulate contaminants and organic matter that can serve as the precursor to DBPs.

Coagulation is important for many goals of water treatment, so chapter 1, “Particle and Natural Organic Matter Removal in Drinking Water Treatment,” deals extensively with this topic. The influence of NOM on coagulation is explained, along with the role of pH and solubility of metal coagulants.

Determining the appropriate chemical conditions, coagulant, and sometimes polymer dosages for coagulation and flocculation is a necessary step at plants where coagulation is practiced. Chapter 2, “Jar Testing,” presents extensive information on procedures for using jar tests to determine the conditions needed for successful treatment full-scale.

Chapter 3, “Online Sensors for Monitoring and Controlling Coagulation and Filtration,” was prepared because numerous measurements, both chemical and physical, are needed in water treatment plants on a daily basis. This is especially so for plants treating surface water, as the Surface Water Treatment Rule and its subsequent modifications have imposed a significant regulatory requirement for monitoring. In addition, the quality of some surface waters can change substantially over one working shift, or even more rapidly. To maintain the careful process control over chemical coagulation and subsequent treatment steps, online monitoring devices are available and can greatly reduce the burden on operators who would otherwise have to perform many analytical procedures manually. With the convenience of online monitoring, however, comes the necessity to maintain an excellent quality control program so the operations staff and management know that they can have confidence in the results being obtained from the online instruments. Online monitoring can be especially helpful in plants that employ high-rate clarification processes or direct filtration, as the residence time in such plants is often much shorter than the residence time in conventional water filtration plants. For continuing effective water treatment at plants with shorter residence times, online monitoring is needed

to alert operators to any adverse changes in raw or treated water quality so prompt corrective action can be taken or so operators can verify that management of chemical feeds by online instrumentation has been done correctly and treated water quality goals continue to be met.

Treatment of coagulated water to create floc growth and to remove suspended solids by clarification is discussed in chapter 4, “Flocculation and Clarification Processes.” Information is presented on a wide range of traditional and newer clarification processes in this chapter.

Even as new applications are found for coagulation, the main purpose for which it is used is to condition water for clarification followed by filtration in rapid rate granular media filters. Even if coagulation is done properly, mismanagement of granular media filters still can result in impaired filtered water quality. In order to optimize filter performance, operators need to understand how to manage tasks such as filter backwashing, returning filters to service, and imposing rate increases on filters. These topics are addressed in chapter 5, “Filtration,” along with a discussion of particle removal mechanisms in granular media filters and biological filtration.

Chapter 6, “Pilot Testing for Process Evaluation and Control,” presents information for those who are considering undertaking pilot filter column or pilot plant water treatment studies to evaluate process modifications or new treatment approaches on an existing water source or to explore treatment options for a new source of water. This chapter also presents a description of the use of pilot filter columns as an online process control tool for assessing the adequacy of coagulation in the full-scale plant.

Practical examples related to information presented in earlier chapters may be found in chapter 7, “Case Studies.” When the topic of a case study in chapter 7 is relevant to text in an earlier chapter, it is mentioned in the earlier chapter.

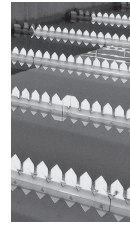
Even with all of the instrumentation, mechanization, and computerization of operations in water treatment plants, the human factor remains vitally important. In a 1989 Awwa Research Foundation (now Water Research Foundation) report entitled *Design and Operation Guidelines for Optimization of the High-Rate Filtration Process: Plant Survey Results*, John L. Cleasby and his co-authors emphasized the human factor. Among their conclusions about the key factors contributing to successful high-rate filtration resulting in low-turbidity finished water were the following:

1. Management must adopt a low turbidity goal, convince the operators that this is a serious goal to be met, and budget adequate funds for whatever chemical dosages are required to achieve the goal. Chemical pretreatment prior to filtration is more critical to success than the physical facilities at the plant. However, good physical facilities may make achievement of the goal easier and more economical. ...
7. Good operator training and the building of operator pride in quality of the treated water are important steps in producing the best filtered water. Some plants utilize 12 hour operating shifts to give more continuity to plant operation, and a short period of shift overlap to provide for intershift communication related to the current treatment strategy.

The advice given by Cleasby and his co-authors is sound. Water treatment plant operators work to produce the drinking water that is supplied to them and their relatives, friends, neighbors, and community in general. The health protection of all in the community is a function of those who operate and oversee water treatment plants. Over the last 100 years or more, the drinking water industry in the United States has made great progress in diminishing health risks related to drinking water. The incidence of waterborne disease is much, much lower than it was in the 1890s, thanks to the many improvements in water treatment that have been implemented in the United States. An important purpose of this manual is to promote the continued improvement in drinking water treatment in future years by providing current information on this topic.

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Cleasby, J.L., A.H. Dharmarajah, G.L. Sindt, and E.R. Baumann. 1989. *Design and Operation Guidelines for Optimization of the High-Rate Filtration Process: Plant Survey Results*. Denver, Colo.: Awwa Research Foundation and AWWA.



Chapter 1

Particle and Natural Organic Matter Removal in Drinking Water

Kwok-Keung (Amos) Au, Scott M. Alpert, and David J. Pernitsky

INTRODUCTION

One of the most basic processes in the treatment of raw source waters to meet drinking water standards is the solid/liquid separation process to remove particulate material. Particulate material originating in raw water or contributed by addition of treatment chemicals is physically separated from source water during drinking water treatment by clarification and filtration processes. These processes target not only removal of particulate material itself but also contaminants that are associated with the particulate material. Clays, sands, colloids, and so on all may comprise typical particulates to be removed; however, removal of other particle classes, such as microorganisms and particulate forms of natural organic matter (NOM), is beneficial for efficient treatment. Further, other contaminants (e.g., arsenic, iron, manganese, or dissolved NOM) may be associated with particulate matter via coprecipitation, sorption, or other physico-chemical mechanisms. Disinfection by-products (DBPs) have been a primary driver for specific focus on NOM removal. In fact, although much research has been devoted to the coagulation of inorganic particles, coagulant dosages for many surface waters are controlled by the NOM concentration rather than by turbidity. During coagulation, dissolved-phase NOM is converted into a solid phase, allowing removal in subsequent clarification/filtration processes. Finally, chemical and/or physical disinfection is also dependent on effective removal of particulate matter that may shield microorganisms from disinfectant contact and/or reduce the effectiveness of disinfection chemicals.

This chapter provides an overview on the removal of particles and NOM by coagulation and filtration processes. These fundamentals serve as a basis for compliance with multiple treatment objectives and prepare the reader for additional detail introduced later in this manual. Specifically, the following are included in this chapter:

- A review of particles and NOM, including the characteristics of these constituents important in their removal
- A discussion of particle surface charge and coagulant chemistry
- An overview of the physical and chemical aspects of coagulation and filtration processes
- A brief discussion of management of multiple processes for effective treatment, including the multiple barrier approach, process control, and membrane filters

PARTICLES

Particles are ubiquitous in all natural waters. Their origins, compositions, and concentrations vary widely. They can be contaminants (as defined here as substances of natural, anthropogenic, or microbiological origin that may be harmful to the public health, adversely affect water quality, and/or affect the aesthetic properties of the finished water) or associated with contaminants and therefore need to be removed. Of the many ways that particles can be characterized, size and surface properties are two of the most important keys related to removal by coagulation and filtration processes. Further, different techniques exist that can be used to quantify or characterize particles. In this section, particle characteristics, quantification, and water quality are discussed.

Origin and Composition of Particles

Based on their underlying composition, particles can be considered as organic, inorganic, or biological (a subset of organic). Particles are introduced into natural waters (i.e., our water supplies) either through natural processes or as a result of anthropogenic (human) activities. An overview of the three major compositions of particles is provided below:

- The majority of organic particles in natural water are the result of degradation of plant and animal materials. These organic constituents may be classified as natural organic matter. However, NOM in natural water consists of more than suspended particles; it also includes dissolved NOM molecules. A separate section of this chapter focuses on NOM and its removal because of its increasing importance to water utilities.
- The majority of inorganic particles in natural water are mineral particles. Most of these particles are derived from the natural weathering of minerals. Examples include clays, iron oxides, aluminum oxides, and calcites. Inorganic particles often enter source water by means of erosion and runoff.
- Biological particles include microorganisms such as viruses, bacteria, and protozoa. These microorganisms enter the water through direct discharge of wastewater, runoff from the watershed, or animal excrement, and some may grow and prosper in the water body. Microorganisms may also be attached to suspended particulate matter. Another type of biological particle is algae, which use mineral nutrients (nitrogen and phosphorus) and photosynthesis to grow.

Particles may result from specific human activity, for example, discharge of municipal or industrial wastewater effluent into a source water. Runoff from land-disturbing activities and property development also introduce particulate matter, into water sources. The composition of these particles is case-specific. The influx of particles into a water body may be driven by natural events such as runoff from snowmelt and precipitation. Depending on the nature of the watershed, particles coming from these events may contain organic, inorganic, and/or biological matter.

In addition to natural particles that occur in water, particles are often added or created in water treatment processes to remove other particles and contaminants. Metal-based coagulants added to water to destabilize particles (as discussed in a later section) may also precipitate as metal hydroxides. These precipitates can then flocculate with particles from the source water and be removed by the solid/liquid separation processes in treatment plants. Bentonite may be added to low turbidity waters to enhance the contact opportunity between particles so that larger and denser flocs are formed for better removal in the settling process. Chlorine may be added to water to oxidize soluble iron (II) species into insoluble iron (III) particles so that these particles can be removed by settling and filtration processes.

Because of their reactivity, pure inorganic or organic particles seldom exist in natural water; that is, all inorganic particles have some kind of organic properties and vice versa. Most inorganic particles have an affinity to and can sorb organic chemicals such as synthetic organic chemicals onto their surfaces. Most inorganic particles in water also react with NOM and form an organic coating on their surfaces. This organic coating plays a significant role on the surface properties of particles, as will be discussed later. Furthermore, NOM, regardless of whether it is in dissolved or particulate form, can chemically bind with many inorganic contaminants such as metals.

The Need to Remove Particles

Particles must be removed from water for both aesthetic and health reasons. The presence of particles may impart color, taste, and/or odor to water, making it less palatable for the customer. More importantly, particles can also be pathogenic or toxic and must be removed to protect public health. Further, particles can shield microbes from disinfectants and reduce the efficiency of the disinfection process. For these reasons, it is essential that coagulation, flocculation, sedimentation, and filtration processes are properly designed and operated to optimize the removal of particles.

Current regulatory requirements for particle removal are based primarily on improved control of microbial pathogens. These requirements are summarized in Table 1-1 and discussed below:

- Removal of particles is regulated indirectly under the Surface Water Treatment Rule (SWTR) and its various revisions. These requirements apply to utilities using surface water or groundwater under the direct influence of surface water.
- Compliance with particle removal criteria is determined by filtered water turbidity, with regulatory limits ranging from 0.3 to 1.0 ntu, depending on the type of filtered water, percentile value, and location of measurement (see Table 1-1).

A utility meeting the turbidity requirements demonstrates that it can consistently provide good removal efficiency of particles and microbes through its coagulation and filtration processes. This, together with properly managed disinfection, ensures that the finished water leaving the treatment plant is of such quality that it minimizes microbial pathogens, has a physical appearance (low turbidity) that is palatable to the consumer, and is safe to drink.

Table 1-1 Regulatory requirements for particle and NOM removals

Constituents	Regulation	Compliance Indicator	Requirements				
Particles	IESWTR ⁽¹⁾⁽³⁾ LT1SWTR ⁽²⁾⁽³⁾	Filtered Water Turbidity	CFWT ⁽⁴⁾	<0.3 ntu 95% of the time			
				<1 ntu any time			
			IFWT ⁽⁵⁾	<0.5 ntu ⁽⁶⁾			
				<1.0 ntu ⁽⁷⁾			
NOM	Stage 1 D/DBPR ⁽⁸⁾	Removal Percentage of Total Organic Carbon (TOC) ⁹	Removal Requirements, %				
			Source Water TOC, mg/L	Source Water Alkalinity, mg/L as CaCO ₃			
				0–60	>60–120	>120	
				>2.0–4.0	35.0%	25.0%	15.0%
				>4.0–8.0	45.0%	35.0%	25.0%
				>8.0	50.0%	40.0%	30.0%

Courtesy of Kwok-Keung Au.

- (1) Interim Enhanced Surface Water Treatment Rule
- (2) Long Term 1 Enhanced Surface Water Treatment Rule
- (3) These requirements apply to utilities using surface water or groundwater under the direct influence of surface water
- (4) Combined filtered water turbidity
- (5) Individual filtered water turbidity
- (6) In any two consecutive measurements taken 15 min apart at the end of the first 4 hr of continuous filter operation after backwash
- (7) In any two consecutive measurements taken 15 min apart
- (8) Stage 1 Disinfectants and Disinfection By-products Rule
- (9) These requirements apply to conventional treatment facilities that use surface water or groundwater under the direct influence of surface water

Particle Quantification

Analytical methods related to the number and size of particles in water are turbidity, particle count, and suspended solids concentration measurements. Each method has advantages and limitations and is used to achieve a different objective. These quantification techniques are discussed below, and turbidity and particle counting are described in detail in chapter 3.

- Turbidity measurement is the most widely used method for assessing particles in water. It does not give a quantitative measure of particles in water but instead indicates the relative clarity of water samples by measuring the amount of light scattered by particles in water samples. The result is reported in nephelometric turbidity units (ntu). The turbidity level of a water sample depends on the physical properties (such as concentration, size, and shape) and the optical properties of the particles contained in the sample. Although the actual relationship among these characteristics is very complicated, the result is sufficient to describe turbidity as a composite measurement based on these properties. Turbidity has been used successfully as a regulatory indica-

tor to assess the removal efficiency of particles and microbes by treatment processes. Turbidity measurements can be performed with grab samples or continuous online instruments.

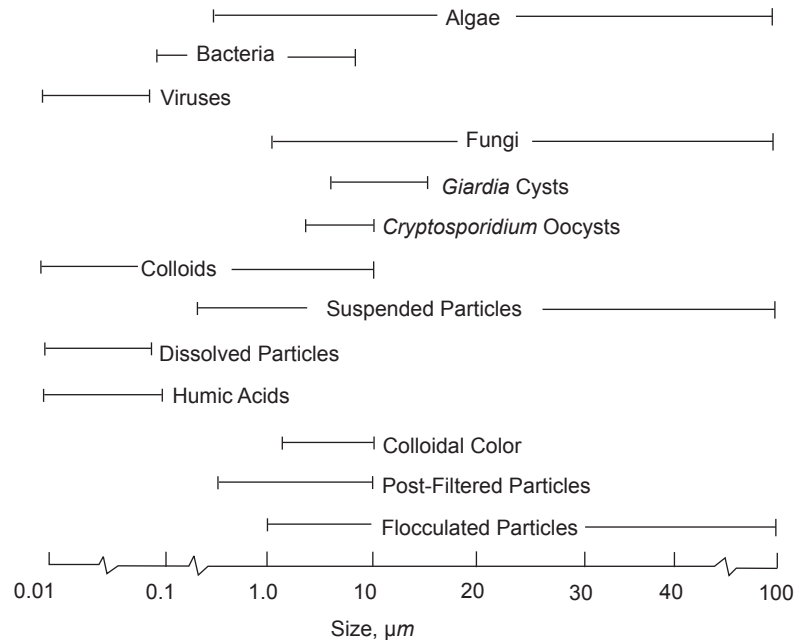
- Particle counts (particle counting) represent the numerical concentration of particles within finite particle diameter ranges. The results are usually reported as cts/mL at different size ranges. Particle counting can be used as a tool to monitor the performance of removal processes. However, because of several limitations in the application of this technique, particle counts are currently not used for regulatory compliance in drinking water. Particle count can be measured by grab samples or continuous online instruments.
- The mass of particles in a water sample can be quantified as the concentration of suspended solids, which is defined as the total mass of particles retained on a glass fiber filter disc through which a measured volume of water sample has been filtered. The result is reported as mg/L. Materials passing through the filter are defined as dissolved solids. Suspended solid measurement is typically not used to assess the removal efficiency of drinking water treatment processes. Instead, because of the exceedingly small mass of suspended solids in filtered drinking water, this analytical method is used by water utilities to estimate the amount of sludge or waste produced from clarification and filtration processes.

Particle Size

The size of particles is an important characteristic affecting their removal in water treatment plants. Particle size may vary by several orders of magnitude. Most inorganic particles have sizes ranging from 0.1 to 5 micrometers (one-millionth of a meter, or μm). Figure 1-1 shows a comparison of sizes that may be encountered in water supplies. Biological particle size is dependent on the classification of the microorganism. Viruses, for example, are the smallest biological particles and have sizes of 3–100 nanometers (one billionth of a meter, or nm). Bacteria are larger than viruses and have sizes from slightly less than 1 μm to over 10 μm . Algae and protozoan cysts are even bigger and have sizes from a few μm to a several hundred μm .

Operators are often familiar with the terms *colloidal/suspended particles* and *suspended/dissolved solids*. These terms are based on particle size and sometimes can be confusing. Colloidal particles are particles with at least one of their dimensions less than about 1 μm or 0.5 μm and generally are not filtered out in the suspended solids test. Dissolved solids contain both colloidal particles and the impurities that are in dissolved form. By definition, colloidal particles do not include constituents that are in true dissolved or molecular form, which typically have sizes of less than 1 nm.

Particle size is important in water treatment because it is one of the key factors in determining the settling characteristics of the particle. For example, the settling velocity of a particle is directly proportional to the square of its diameter. Natural particles in the colloidal size range do not settle quickly enough to be removed in sedimentation basins, so they must be agglomerated together into larger particles, i.e., floc. The size of the floc particle is important for effective settling. Particles passing through the sedimentation process (and flocculated particles in direct filtration treatment plants) may be removed in the filtration process. Again, the size of the particle determines whether the particle will be removed in the top layer of the filter or will penetrate deeper into the filter bed.



Source: McTigue and Cornwell 1988.

Figure 1-1 Particulates present in source and finished water

NATURAL ORGANIC MATTER

Origin and Composition of NOM

Natural organic matter, or NOM, is a complex mixture of natural constituents. The primary sources of NOM are the degradation of vegetation in the watershed area and the growth and decomposition of aquatic organisms such as algae and weeds within the water body. NOM is generally classified into two components: humic substances (HSs) and nonhumic substances (nHSs). HSs are usually the major components of NOM in water with humic acids (HAs) and fulvic acids (FAs) as the major fractions. The major fractions of nHSs are proteins, polysaccharides, and carboxylic acids.

Both humic acids and fulvic acids represent a broad class of heterogeneous organic materials. Because of their complexity and heterogeneity, they cannot be well characterized in terms of a specific chemical structure. The most important properties of these substances are molecular weight, functional groups, and charge behavior. HAs and FAs are macromolecules with molecular weights of several hundred or higher. HAs and FAs carry weakly acidic functional groups such as carboxylic and phenolic groups. Dissociation of these functional groups induces negative charges of HS. The macromolecular nature and charge behavior of HAs and FAs play a significant role in increasing the colloidal stability of particles that bind with NOM and in the removal of NOM from water. The presence of NOM in water will induce an additional demand for coagulant dose. Two mechanisms are usually considered for coagulation of NOM. The first is the neutralization of negative charges of NOM followed by precipitation of the NOM. The second is adsorption of NOM onto precipitates formed from coagulants.

The Need to Remove NOM

Although NOM itself does not impose a direct health threat, removal of NOM from water is becoming more important for aesthetic, health, and operational reasons. The initial driving force for removing NOM was its adverse effect on aesthetic water quality because the color, taste, or odor caused by NOM can make water much less palatable for the consumer. For example, the presence of NOM molecules can make water appear yellow or brown. More importantly, however, NOM is now known to be the major precursor for many disinfection by-products (DBPs). The chemical compounds known as DBPs are formed when an oxidant such as chlorine is added to water that contains organic matter. Removal of NOM to reduce the formation of DBPs has become a major focus for water utilities in the past two decades. A coagulation process that is optimized for both particle removal and NOM reduction is known as enhanced coagulation (EC).

NOM also has adverse impacts on the operation of other treatment processes. By reacting with chemical disinfectants to form DBPs, NOM induces a disinfectant demand. Some NOM molecules contain chemical functional groups that can absorb light in the ultraviolet (UV) range and thus reduce the efficiency of UV disinfection facilities. NOM can foul membranes, reducing flux or increasing operating pressure. Short-chain molecules of NOM (e.g., as a result of oxidation) can serve as a food source for microbial growth in filter beds or the distribution system.

Current regulatory requirements for particle removal and NOM reduction are based on a balance between adequate inactivation of microbial pathogens and minimizing the production of DBPs. These requirements were summarized in Table 1-1 earlier in this chapter and are discussed below:

- NOM is regulated under the Disinfectants and Disinfection By-products Rule (D/DBPR), with reduction related to requirements for minimum removal percentages of TOC between the source and finished water. These removal levels range from 15 percent to 50 percent and are based on TOC levels in the source water and the source water alkalinity (Table 1-1).
- Compliance with NOM removal requirements typically indicates that a utility is effectively using its coagulation and filtration processes to significantly reduce the concentrations of DBP precursors and the formation of DBPs.
- Alternative compliance criteria for NOM removal exist (although not shown Table 1-1). These criteria are designed to provide flexibility to water utilities that use source water either with a proven low potential to form DBPs (indicated by low concentrations of TOC, specific ultraviolet absorbance [SUVA], and DBPs) or that have source waters that are not amenable to significant TOC removal as indicated by site-specific bench-scale jar test results.

The key to meeting the challenges set by new regulations will often be maximizing the removal of NOM while ensuring adequate microbial control by both particle removal and disinfection. For many surface waters, coagulant dosages are controlled by NOM concentration rather than by turbidity (Edzwald and Van Benschoten 1990, Pernitsky and Edzwald 2006). NOM can be removed by coagulation through complexation with positively charged coagulant species forming Al-NOM precipitates or by the adsorption of NOM onto the surface of floc particles, allowing removal in subsequent solids separation processes. The charge density of these NOM functional groups is typically 10 to 100 times greater than the charge density of inorganic particles. For example, a water with 10 mg/L of clay turbidity having a negative charge of 0.5 $\mu\text{eq}/\text{mg}$ will have a positive charge demand of 5 $\mu\text{eq}/\text{L}$. In contrast, a water containing only 3 mg/L dissolved organic carbon (DOC) with a negative charge of 10 $\mu\text{eq}/\text{mg}$ will

have a positive charge demand of 30 µeq/L, which is six times that of the 10 mg/L clay turbidity example (Edzwald and Van Benschoten 1990). The conversion of dissolved NOM to a solid phase happens quickly and is complete prior to the clarification and filtration process.

As mentioned previously, NOM is a mixture of various organic compounds that are present in water as a result of decay of vegetation, runoff from organic soils, and biological activity. As such, NOM from different water sources will have different characteristics. The concept of specific UV absorbance has been developed as an operational indicator of the nature of NOM and the effectiveness of coagulation for removing NOM, DOC, and DBP precursors (Edzwald and Van Benschoten 1990, Edzwald and Tobiason 1999). SUVA values offer a simple characterization of the nature of the NOM, based on measurements of the UV absorbance at 254 nm and DOC. SUVA is defined as the UV absorbance of a water sample normalized with respect to the DOC concentration. SUVA is normally calculated on samples of raw water prior to the addition of any treatment chemicals. Samples must be filtered in the lab to remove turbidity interferences as described in Standard Method 5910 (APHA et al. 2005). It is expressed in units of m^{-1} of absorbance per mg/L of DOC, or $\text{L/mg C} \cdot \text{m}^{-1}$ and also expressed using the units notation of L/mg-m .

$$\text{SUVA (L/mg C} \cdot \text{m}^{-1}) = [\text{UV}_{254}(\text{cm}^{-1}) \times 100 (\text{cm/m})] / \text{DOC (mg/L)}$$

Guidelines for the interpretation of SUVA values are presented in Table 1-2. For supplies with low SUVA (2 or lower), DOC will not control coagulant dosage. For water supplies with SUVA greater than 2, the amount of NOM typically exerts a greater coagulant demand than the amount of particles. For these waters, the required coagulant dosage increases with increasing DOC concentration.

Optimizing treatment processes to remove NOM and particles and also to control microbiological contaminants may involve setting coagulant doses to achieve NOM removal, reducing coagulation pH, improving mixing conditions, and/or using alternative approaches for oxidation of NOM and inactivation of microorganisms. Water treatment operators need effective tools for quick and accurate assessment of treatment performance and evaluations of alternatives. These tools are described in chapters 2 and 3 of this manual.

Table 1-2 Guidelines on the nature of NOM and expected DOC removals

SUVA	Composition	Coagulation	DOC Removals
<2	Mostly nonhumics; low hydrophobicity, low molecular weight	NOM has little influence Poor DOC removals	<25% for alum Potentially higher removals for ferric
2–4	Mixture of aquatic humics and other NOM; mixture of hydrophobic and hydrophilic NOM; mixture of molecular weights	NOM influences DOC removals should be fair to good for these categories	25–50% for alum Potentially higher removals for ferric
>4	Mostly aquatic humics; high hydrophobicity, high molecular weight	NOM controls Good DOC removals	>50% for alum Potentially higher removals for ferric

Source: Edzwald and Tobiason 1999.

PARTICLE STABILITY AND COAGULANT CHEMISTRY

Surface Properties and Colloidal Stability

The surface characteristics of natural particles and their reactions with water and with other solutes in water result in an electrical surface charge being carried by most particles in water. More importantly, the sign of the net charge is usually negative under most conditions in water. The following mechanisms are usually used to explain the charge behavior of particles in water:

Lattice imperfection or isomorphic replacement (intrinsic properties of particles). Lattice imperfection refers to the replacement of atoms in the crystalline lattice (structure) by atoms with different valences. This mechanism is often used to explain the charge behavior of many clay minerals. Clay has a layered structure of silica (SiO_2). During the formation of the structure, if an Al^{3+} atom replaces an Si^{4+} atom, a negative charge develops. Similarly, negative charge develops when an Mg^{2+} atom replaces an Al^{3+} atom in an aluminum oxide crystalline lattice (Al_2O_3).

Ionization of particle surface functional groups (reactions with water). Many particle surfaces contain ionizable functional groups. For example, mineral oxide particles contain surface hydroxyl groups. Biological particles may have surface proteins that contain carboxyl and amino groups. In the presence of water molecules, these surface functional groups can accept or donate protons (H^+), depending primarily on water pH. As a result, the surfaces of particles become charged. In this case, the surface charge is strongly pH dependent, being positive at low pH and negative at high pH. Most natural particles have a negative surface charge at the pH of most natural waters.

Reactions between surface functional groups and other solutes in water (reactions with other solutes). Many cations (such as metals) and anions (such as NOM) in water can react with surface functional groups of particles, resulting in the binding of these ions to the particle surfaces. Interactions other than simple electrostatic interactions are often involved in these processes. Typical examples are hydrophobic interaction, hydrogen bonding, ligand exchange, and covalent bonding. As a result, even anions that have negative charges can bind to negatively charged particles. Binding of cations to a particle makes the particle's surface charge more positive, whereas binding of anions to a particle makes the particle's surface charge more negative. An important example is the binding of NOM onto particle surfaces. Recent research indicated that most particles in water carry some kind of NOM coating on their surfaces, one of the major reasons that most particles in water are negatively charged.

Interactions between particles with similar surface charge result in an electrical repulsive force between them, making them more difficult to aggregate. In colloidal chemistry, a *stable* solution or set of particles is defined as one in which most of the particles have similar charges and thus these particles tend not to aggregate or settle. Chemical pretreatment (coagulation) is therefore needed to reduce or eliminate this repulsion and enhance particle removal by sedimentation and filtration processes. This step is termed *destabilization*.

Use of oxidants to change surface properties of particles. Use of oxidants prior to filtration has been shown to benefit filter performance at numerous plants. Reported benefits include a reduction in filtered water turbidity or particle counts or both, a decrease in turbidity peak during the filter ripening period, and a shorter duration for filter ripening. Oxidants generally used for this purpose are free chlorine and ozone. However, other oxidants such as chlorine dioxide and potassium permanganate exhibit similar benefits. A recent study (Becker et al. 2004) indicated that one of the major mechanisms for these benefits is on the effect of oxidation on particle stability. As mentioned previously, most particles in water carry some kind of NOM coating on their

surfaces. The NOM coating increases particle stability by making the particle's charge more negative and also extending the particle's negative electric field further away from the particle. Mechanistic studies show that oxidation can detach part of the NOM coating from particle surfaces and thereby reduce particle stability. Typically, very low dosages of oxidant and short contact times are enough for these benefits to occur.

At plants where oxidation is an aid to filtration, interruption of oxidation can cause filter performance to deteriorate. Factors to consider related to using oxidants for improving filter performance are cost of the oxidation process, efficacy of the oxidant, and possible detrimental effects of oxidation products, such as formation of assimilable organic matter and bromate by ozone and formation of chlorinated disinfection by-products by chlorine.

Coagulant Chemistry

Aluminum and iron-based coagulants such as aluminium sulfate (alum), polyaluminum chloride (PACl), and ferric chloride react with water to form charged and dissolved metal-hydroxide species, as well as solid-phase metal-hydroxide precipitates (floc particles). These reactions consume alkalinity in the raw water and reduce the pH. Alum and ferric coagulants are more acidic than PACls and therefore result in greater pH depression after addition. For PACls, alkalinity consumption is related to basicity. Higher-basicity PACls will consume less alkalinity than low- or medium-basicity ones.

The charge on the dissolved coagulant species and the relative amount of floc formed are a function of pH. Therefore, the pH at which coagulation occurs is one of the most important parameters for proper coagulation performance. For alum and PACls, the best coagulation performance is generally seen at pH values that are close to the pH of minimum solubility of the coagulant. This controls dissolved Al residuals, as well as maximizing the presence of floc particles. Acid or base addition is often used after coagulant addition to control pH.

The solubility characteristics of various coagulants, and therefore the pH range at which they are most effective, are important properties of the coagulants. Solubility refers to the maximum concentration of dissolved species that can exist in solution before precipitation. This concentration varies with temperature and pH. The pH of minimum solubility represents the pH at which the concentration of dissolved coagulant species is a minimum. This is important from a treatment perspective, as this pH also corresponds to the point at which the maximum amount of solid floc species is formed.

Table 1-3 Summary of coagulant solubility

Coagulant	Minimum Solubility 20°C		Minimum Solubility 5°C	
	pH	µg/L Al	pH	µg/L Al
Alum	6.0	16	6.2	3
Polyaluminum sulfate (PAS)	6.0	28	6.4	6
PACl low-basicity nonsulfated (LBNS)	6.2	27	6.7	4
PACl medium-basicity sulfated (MBS)	6.3	29	6.5	4
PACl high-basicity nonsulfated (HBNS)	6.4	36	6.8	9
PACl high-basicity sulfated (HBS)	6.4	52	6.9	5
Aluminum chlorohydrate (ACH)	6.7	101	7.6	53
FeCl ₃	8.7	0.006	—	—

Source: Pernitsky and Edzwald 2003.

The minimum solubility (concentration) and pH of minimum solubility for several common coagulants are shown in Table 1-3. As can be seen in this table, the minimum solubility and pH of minimum solubility differ for the various chemical coagulants. PACls are more soluble and have a higher pH of minimum solubility than alum. Polyaluminum sulfates have solubility characteristics similar to alum. Ferric coagulants are much less soluble than aluminium-based ones. This means that Fe-based coagulants can be used over a much greater pH range without worrying about dissolved metal concentrations in the finished water. The pH of minimum solubility for Fe(III) is near pH 8.8. However, unlike Al-based coagulants, FeCl_3 is not an effective water treatment coagulant at its pH of minimum solubility because of the weak positive charge of the $\text{Fe}(\text{OH})_2^+$ species present at that pH. Ferric coagulants have, however, been used successfully in secondary clarification of lime softening process basin effluent at softening plants that treat surface waters. More effective performance is seen at lower pH, as low as pH 5.5, where more positively charged species are present. A case study, "Conversion From Alum to Ferric Sulfate at the Addison-Evans Water Treatment Plant, Chesterfield County, Va." is presented in chapter 7.

For all of the metal coagulants, it is important to note that the pH of minimum solubility increases as temperature decreases, as shown in Table 1-3. This is especially important in cold climates because of the wide range in raw water temperatures experienced. For example, the pH of minimum solubility for alum increases from 6.0 at 20°C to 6.2 at 5°C. Over that same range, the pH of minimum solubility for high-basidity PACl changes from 6.4 to 6.8.

Particles can be destabilized through the addition of coagulants/flocculants by three major mechanisms (shown in Figure 1-2).

Adsorption and Charge Neutralization

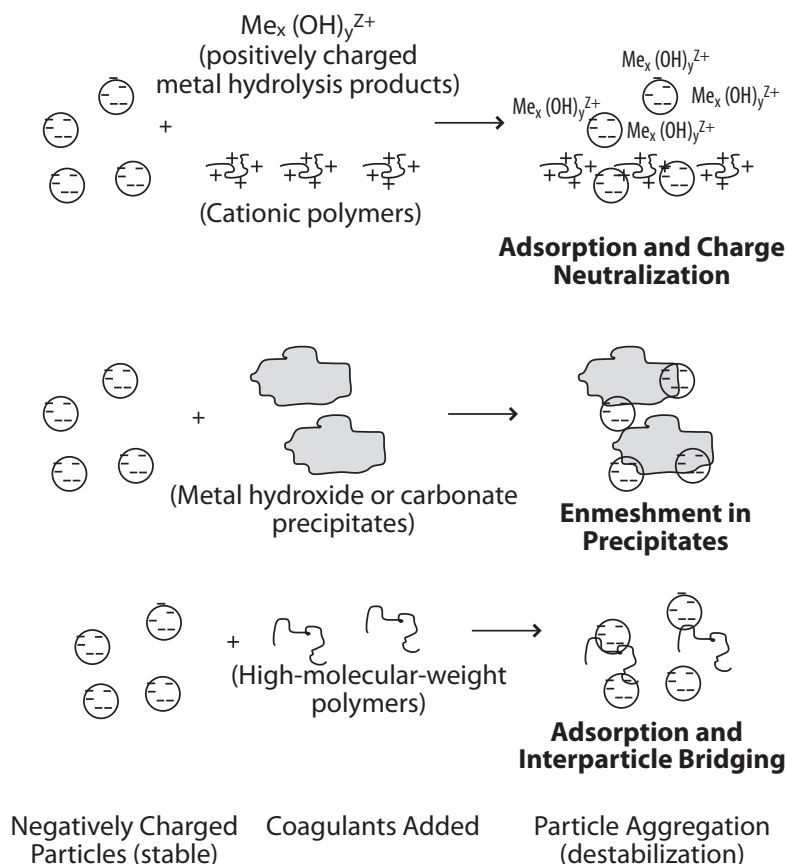
When metal coagulants are added to water, several hydrolysis species are formed. Some of these species are positively charged, depending primarily on water pH. These positively charged species will attach to negatively charged particles and reduce or neutralize the particles' negative charges. This charge neutralization results in a reduction or elimination of the electric repulsion between particles. Cationic polyelectrolytes also can reduce the negative charges and repulsive forces. Note, however, that if the dosage of a cationic polymer is substantially greater than that needed to neutralize the negative charges on particles, then the particles can become positively charged and restabilized, a condition that hinders particle removal.

Enmeshment in a Precipitate (Sweep Floc)

When metal coagulants are added to water, precipitates of metal hydroxide or metal carbonate may form, depending on the dose and water chemistry. Particles can be enmeshed into these amorphous precipitates (coagulant flocs) and subsequently removed by settling and filtration of the flocs. Thus for the sweep floc mechanism, as opposed to the charge neutralization mechanism, the use of dosages of metal coagulants larger than those needed to neutralize the surface charges of particles does not hinder particle removal, because the coagulant will precipitate and can enmesh the particles.

Adsorption and Interparticle Bridging

When high-molecular-weight polymers are added to water, part of the polymeric chains can attach to the surface of one particle with the remaining length of the chains extending into the solution. If these extended chains find other particles with vacant sites not



Courtesy of Kwok-Keung Au.

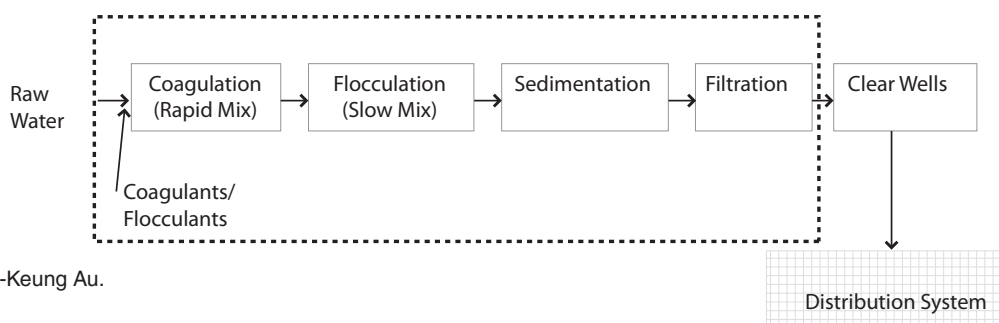
Figure 1-2 Coagulation (destabilization) mechanisms for particulate contaminants

yet attached by other polymeric chains, bridges between particles could form, resulting in particle destabilization and floc formation. Overdose of polymer may result in restabilization because it becomes difficult for the extended polymer molecule to find available vacant sites for adsorption.

Double-layer compression is often cited as the fourth mechanism of coagulation. However, this process is not a dominant mechanism in the chemical coagulation of most raw waters.

PARTICLE AND NOM REMOVAL PROCESSES

The objectives of particle removal and NOM reduction typically cannot be accomplished in a single treatment step. Rather, several plant processes work together to achieve this goal. Specifically, coagulation/mixing, flocculation, sedimentation, and filtration, schematically shown in Figure 1-3, are all interdependent on each other to produce a water of high quality. This section provides a brief overview of each process and describes the mechanisms by which each contributes to particle and NOM removal. These processes are described briefly in this section and in greater detail in chapter 4 (Flocculation and Clarification Processes) and chapter 5 (Filtration).



Courtesy of Kwok-Keung Au.

Figure 1-3 Treatment train (from coagulation to filtration)

Mixing/Coagulation

As described previously, many of the particles that occur in raw water supplies have negative electrical charges and are of such size and density that they will not settle easily in the time available in water treatment plant clarification processes. Therefore, positively charged metal coagulants or polymers are used to decrease the extent of the negative surface charge on the particles so that when they come in contact with each other they can stick together and form larger particles (flocs).

Generally, the chemical reactions associated with coagulation occur very quickly and thus the coagulant must be mixed into the raw water as quickly and efficiently as possible. This initial mixing is often called rapid mixing or flash mixing. The hydraulic retention time in a flash mix process ranges from <1 sec to 30 sec. During this time, the coagulant and any other associated chemicals (e.g., pH and alkalinity control) are dispersed throughout the raw water. The dose of chemicals and the required mixing intensities for optimum coagulation can be determined using bench-scale experiments such as jar tests as described in chapter 2. Rapid mixing is discussed in chapter 4. One exception to the very rapid coagulation reaction is the slower action of alum in very cold water (about 5°C or colder). To accommodate the slower reactions, some water utilities use coagulants other than aluminum sulfate for coagulation of such water (Logsdon et al. 2002).

Flocculation

The next treatment process after coagulation typically is flocculation. The main objective of flocculation is to bring together the particle solids created and/or conditioned in the coagulation step, which ultimately changes the size distribution of the particles. Essentially, a large number of small particles are transformed into a smaller number of larger particles. Traditionally, the objective of flocculation has been to produce particles large enough and dense enough to settle in the clarifier (sedimentation basin). Since the 1980s, several plants have replaced conventional sedimentation with filtration without clarification (direct filtration) or dissolved air flotation (DAF). For these types of treatment processes, the goal of flocculation and floc size production is modified since both of these processes work well with flocs that are considerably smaller than the size of flocs needed for sedimentation. For direct filtration and DAF plants, shorter flocculation times are used as compared to the times employed at plants with conventional sedimentation basins.

Sedimentation/Clarification

After the particles have been preconditioned in the coagulation process and brought together into clumps (flocs) in the flocculation process, physical removal of the solids can be accomplished by sedimentation or by flotation. The hydraulic retention time of a conventional sedimentation basin ranges from 2 to 4 hr. Since the late 1960s, studies of the sedimentation process have led to a variety of approaches that can accomplish sedimentation in times considerably shorter than 2 to 4 hr. Clarification, whether by sedimentation or flotation, is necessary for effective filtration of many source waters because of the excessively high load of solids (particulate matter, including floc formed by coagulant chemical) that would be applied to the filters in the absence of a clarification process.

Filtration

After clarification, water is treated by filtration to remove those particles that were not removed in the clarification process. As water treatment was being developed in the United States, experimental work in Louisville, Ky., and Cincinnati, Ohio, in the late 1890s and early 1900s showed that turbid waters could be treated successfully by chemical coagulation, sedimentation, and rapid sand filtration. About the same time, studies at Pittsburgh, Pa., showed the importance of using an adequate dosage of coagulant chemical to attain successful treatment with rapid sand filters. Coagulation, clarification, and rapid sand filtration became known as conventional water treatment, and this process train was shown to significantly reduce both turbidity and bacteria in water. Today, the performance of granular media filters reflects both source water quality and the changes to the source water induced by added chemicals (pretreatment chemistry). Filtration in drinking water treatment is not just a physical straining process (like that in a coffee filter) by the granular media particles. Attachment of the particles to the filter media is the primary form of target constituent removal. Thus, filtration is a physical and chemical process in which the effectiveness of the particle removal is determined by several variables, including:

- Type of filter media (size, depth, material)
- Water chemistry
- Surface chemistry of the particles (as conditioned by coagulation and flocculation)
- Surface chemistry of the filter media.

During filtration, particles must be transported to the surfaces of the filter media, and the particles must attach to the media surface for removal to occur. Both hydrodynamics and chemistry are important determinants of success. Design criteria most often specify filtration rate, media size, and bed depth. Pretreatment (coagulation) chemistry is the most important factor affecting particle removal in granular media filters. Without proper coagulation, efficient particle removal will not occur.

Plant operators have direct control over the coagulation process (chemical selection and dosing), flocculation (mixing energy), filtration (filter run times, backwashing), and, to some extent, flow rates through each of these processes. Thus, operators have the ultimate responsibility to ensure effective particle and NOM removal.

MULTIPLE BARRIER APPROACH

Multiple treatment processes must be incorporated into a water treatment plant to achieve high-quality finished water. Combined with disinfection, clarification and filtration processes provide multiple barriers to the passage of particles, pathogens, and dissolved constituents into the public water supply. This multiple barrier approach was formally established in the Surface Water Treatment Rule for microbial control and removal of contaminants, and specifically referenced the coagulation/filtration processes, primary disinfection as defined by the CT concept, and maintenance of microbial control through the distribution system. The simple combination of coagulation, sedimentation, filtration, and disinfection constituted an early multiple-barrier approach to microbial control in drinking water technology.

As more contaminants, including pathogens other than bacteria, were discovered in raw water supplies, drinking water treatment objectives were expanded. The drinking water processes of coagulation, flocculation, sedimentation, and filtration must now be optimized to meet multiple treatment objectives. Further, new advanced technologies are being developed and may be incorporated within the conventional treatment process train.

One of the more effective methods of meeting new regulatory requirements is through a “systems approach” that recognizes that all unit processes are interrelated, so what impacts one will also impact the others. Analysis under this systems approach reveals that the conventional treatment processes work together to remove unwanted components from the water, including particles, NOM, color, microorganisms, iron, manganese, and objectionable tastes and odors. Coagulation and flocculation create flocs of suspended particles and convert organic and/or inorganic material from the dissolved phase into the particulate phase. These conditioned particles are subsequently removed by either clarification or filtration.

Much of the effort to optimize conventional treatment focuses on coagulation chemistry as the single most important factor affecting treatment plant performance. This principle is based on the fact that if the pretreatment chemistry is wrong, none of the other downstream processes will work well. Managing the coagulation process to remove both particles and NOM is an example of the challenges that may be encountered when it is necessary to adjust pretreatment chemistry to achieve multiple objectives.

PROCESS CONTROL STRATEGIES

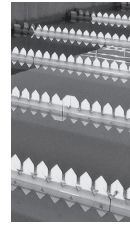
Effective process control strategies are based on theory, experience, practical knowledge of the source water, and performance characteristics of the treatment plant. Water treatment plant operators should be familiar with routine plant operations, special operations (such as startup and shutdown of individual processes), and the preventive maintenance required for each treatment process. On a daily basis, operators may be responsible for monitoring process performance, analyzing water quality (raw, settled, and finished), adjusting process controls, and inspecting plant facilities. Finally, one of the most important operator tasks is record-keeping. Maintaining a daily operation log, including keeping a diary that provides an accurate day-to-day account of plant operations, provides a historical record of events for future reference. Recording all analytical results needed to complete reports that are required by local regulatory agencies supports the regulatory compliance effort and also enables the utility to have long-term records of its water quality. Water quality monitoring for process control is discussed in chapter 3.

Membrane Filtration

Membranes are considered an alternative filtration process and consist of polymeric layers with very small pores that physically strain particles, pathogens, and so on from the influent water. Membranes are classified according to both the pore size and the amount of pressure required to force the water through the membranes. Low-pressure membranes (microfiltration and ultrafiltration) have larger pore sizes and are used for filtration, while high-pressure membranes (nanofiltration and reverse osmosis) have much smaller pore sizes and are used to modify the chemical characteristics of water being treated. Because low-pressure membranes rely on a physical removal process, i.e., straining, the size of the pores determines what contaminants can be removed from the process. Ultrafiltration membranes can remove a portion of the smaller particles that could pass microfiltration membranes. These membranes can be used as a replacement for coagulation, flocculation, sedimentation, and filtration, or can be used as a polishing step behind any combination of these processes. Because microfiltration and ultrafiltration membranes do not remove dissolved constituents such as arsenic or iron in groundwater or NOM in the form of dissolved organic carbon, some form of pretreatment such as coagulation, and perhaps clarification, may be needed prior to microfiltration or ultrafiltration if removal of dissolved substances is necessary. In this situation, information contained in this manual can be helpful for optimizing the pretreatment processes.

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Chapter 2

Jar Testing

Susan Teefy, James Farmerie, and Elizabeth Pyles

INTRODUCTION

The jar test is recognized throughout the water industry as a valuable tool for realistically simulating coagulation, flocculation, and sedimentation at a full-scale treatment plant. Water treatment plant operators as well as consultants, chemical suppliers, and researchers routinely perform this test. It basically involves duplicating, at bench scale, conventional treatment steps that occur in the full-scale plant. The jar test method, while duplicating the chemical treatment processes sufficiently, occasionally has limitations with regard to duplicating more advanced physical treatment processes.

Jar testing may be done for many different reasons. Tests can be performed to evaluate the effects of changes in chemical dosages and points of application; choose alternative coagulants; add polymeric coagulant aids; implement alternative preoxidation strategies; vary mixing intensities and times; and change overflow rates on the removal of particles, natural organic matter (NOM), or other water quality parameters of concern.

It is important that the conditions used in the jar test accurately simulate the full-scale plant conditions. Doing this requires knowledge of the hydraulic characteristics of the treatment steps: initial mixing (also called *rapid* or *flash mixing*), flocculation, and clarification, as well as translation into a batch-testing protocol. The key parameters include:

- Velocity gradient/mixing intensity in the rapid mix and flocculation basins
- Effective retention times in the rapid mix and flocculation basins
- Surface loading rate of the sedimentation basin
- Actual retention time in basins if jar testing is being done to evaluate time-dependent reactions for which full-scale reaction time influences results

However, even when theoretical conditions are matched closely in the jar test procedure, there is often a need to empirically tweak the parameters to make the jar test results match the full-scale results. This is commonly a result of the limitations of the jar test in matching the physical characteristics of the treatment process. Customizing a jar test procedure so it can yield results indicative of plant performance is iterative and can take a lot of time. Operators with successful jar testing procedures have often used the theoretical parameters as a starting point and then made minor adjustments by trial and error until the full-scale plant results are accurately simulated by the jar test. An example of this is presented as a case study, “Jar Test Calibration,” in chapter 7.

Although jar tests are often conducted to help with full-scale plant optimization, they may also be done to meet certain regulatory requirements. Under the Stage 1 Disinfectants and Disinfection By-products Rule (D/DBPR) (1998), jar testing may be conducted as part of the “enhanced coagulation” (EC) requirements. In this case, no attempt is made to simulate the full-scale plant conditions; these EC jar tests must be done under certain predefined conditions and are used to determine alternative total organic carbon (TOC) removal requirements for a particular plant.

Velocity Gradient

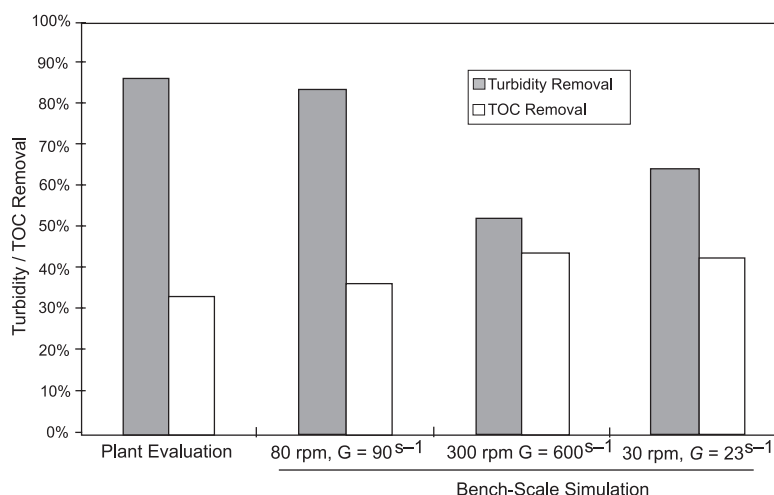
The intensity of mixing is generally quantified by the velocity gradient, G , with units of s^{-1} (seconds to the minus 1 power). The velocity gradient is calculated using the energy dissipation rate in the fluid, or it can be interpolated from calibration curves. In order to attain jar test results that are relevant to the treatment plant, mixing intensities, and therefore velocity gradients, during jar tests should correspond to those in the treatment plant. Commercially available graphs provide velocity gradients in s^{-1} units relative to jar test paddle speed, water temperature, and jar volume, and examples are presented later in the text.

The velocity gradient varies significantly with water temperature (viscosity) independent of the mixing device speed. Jar tests should be conducted with water temperatures the same as or as near as possible to the plant water temperature conditions—see water baths—to simulate plant conditions, and water temperature must be recorded.

One jar test objective is to optimize velocity gradients at the rapid mix and tapered flocculation stages to achieve lower final turbidities with optimum floc development (compatible with sedimentation, direction filtration, dissolved air flotation-filtration, etc.). This should be addressed at least seasonally where significant changes in raw water temperatures occur. When the optimum velocity gradients have been determined by jar test, as depicted in Figure 2-1, the plant mixer(s) and flocculator speed/power can be adjusted according to previously prepared plant-specific information relating flocculator speed, water temperature, and G value, if such information is available. Methods for calculating G for mixing and flocculation basins are presented in chapter 4 of this manual.

Initial Mixing (Rapid Mix)

When a jar test is performed, the rapid mixing time should be equivalent to the retention time of the mixing chamber in the treatment plant, and G values should match the full-scale conditions, if possible. Typical mixing intensities for a well-designed flash mix basin range from 700 to 1,000 s^{-1} , and in a typical jar test, times of 30–60 sec are used, with high paddle speeds of 100–300 rpm. If rapid mixing in the plant is done by in-line mixers or by chemical induction mixers, simulating the full-scale mixing conditions may not be possible using typical 2-L jars and jar test equipment.



Source: AH Environmental Consultants Inc. 1998.

Figure 2-1 Use of jar tests to determine optimum flash mix conditions

G-value testing requires repeated jar tests. Preferably chemical coagulation conditions for alkalinity, pH, and coagulant dosage should be determined first, followed by testing different G values in a series of jars, all of which have received the same chemical treatment and have water at the same temperature as the influent water in the plant.

Flocculation

In jar testing, the retention time and G values of the flocculation basin should correspond to those in the water treatment plant. It may be necessary to vary the mixing speeds, if the plant performs tapered flocculation in different compartments. Typical retention times are approximately 15–30 min, while typical mixing intensities vary from 10 to 40 s^{-1} , with the more intense mixing steps occurring first, followed by the gentler mixing. Users of jar tests for evaluating flocculation need to consider that in jar tests, flocculation is done on a batch basis for a specific retention time, whereas retention times for floc particles in continuous-flow plant-scale flocculation basins vary over a range because of short-circuiting that inevitably occurs in those basins.

Sedimentation

A key jar test objective for evaluating sedimentation processes is to optimize floc development and settleability. The settling velocity of floc must be higher than the surface loading rate of the clarification basin, or the floc will not settle. The surface loading or overflow rate is determined by dividing the basin flow rate by the surface area, commonly expressed in either gallons per day per square foot (gpd/ft^2) or gallons per minute per square foot (gpm/ft^2). A basic unit conversion reveals that the surface loading corresponds to upflow velocity:

$$\text{Surface loading rate} = \frac{\text{Flow rate}}{\text{Surface area}} = \frac{\text{Volume} \div \text{Time}}{\text{Area}} = \frac{\text{Length}}{\text{Time}} \quad (\text{Eq 2-1})$$

or

$$\frac{\text{gpd}}{\text{ft}^2} \times 3,785 \frac{\text{cm}^3}{\text{gal}} \times \frac{1 \text{ day}}{1,440 \text{ min}} \times \frac{1 \text{ ft}^2}{929 \text{ cm}^2} = \frac{\text{cm}}{\text{min}} \quad (\text{Eq 2-2})$$

Table 2-1 Settling velocity conversion factors for clarification basins

Units for Plant Flow Rate/Surface Area	Multiply by	Settling Velocity
mgd/ft ²	2,830	cm/min
gpm/ft ²	4.07	cm/min
gpm/ft ²	2.44	m/hr
gpm/ft ²	1.6	in./min

When sedimentation is used for clarification, an important characteristic of floc is its settling velocity. Typical surface loading rates for conventional sedimentation basins are approximately 0.5 to 1.0 gpm/ft² (1.2 to 2.4 m/hr) or about 2 to 4 cm/min. This can be compared to a “good” jar test sedimentation rate of >2.5 cm/min for metal hydroxide floc formed without polymer.

To calculate the settling velocity from the plant flow rate and the total sedimentation basin area, the conversion factors in Table 2-1 can be used.

Theoretically, a sedimentation basin will remove all particles that exceed this critical velocity for a given overflow rate. This concept is most important for simulating the sedimentation process in a jar test. The retention time of the full-scale settling basin must not be used in the jar test to evaluate settleability of floc. In order to obtain useful results, the jar’s surface loading rate, which corresponds to a settling velocity, should closely match that of the process. In jar testing, this match is accomplished by collecting a sample from the jar at a set depth below the water surface at a given time.

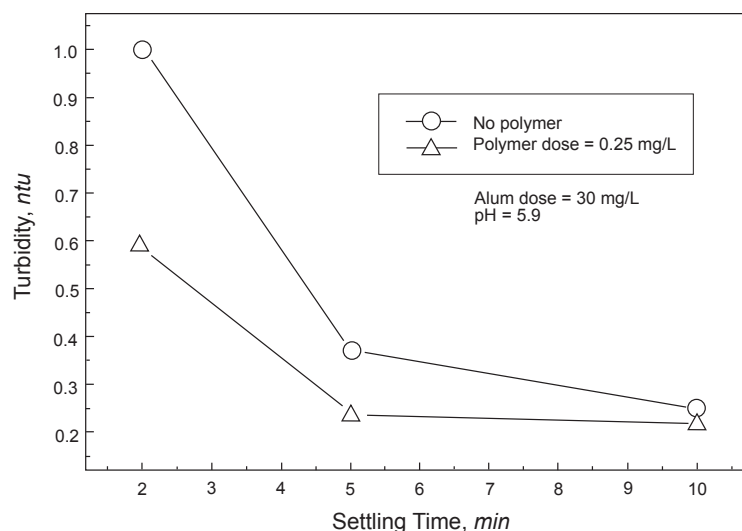
For example, a typical sedimentation basin is designed for an overflow rate of 0.5 gpm/ft². This value corresponds to a particle settling velocity of 2 cm/min. If the sampling port of the jar is 10 cm below the water surface, then all particles that pass the sampling port within 5 min (10 cm divided by 2 cm/min) would be removed. Therefore, samples should be collected 5 min after the flocculation period to simulate the performance of the sedimentation basin. If the jar were sampled on the basis of the settling basin’s retention time (e.g., 120 min), the performance of the basin would be grossly overestimated.

Figure 2-2 illustrates a minimal effect of polymer addition for samples taken after 10 min. When the same plant is operating at a maximum surface loading rate of 1,800 gpd/ft², which corresponds to a sampling time of 2 min, the effect is more pronounced.

Standard jars used in jar tests have sample ports that are 10 cm below the water surface when using the full capacity of the jar (i.e., 2 L in a 2-L jar). For these jars, the sampling time is determined by dividing the 10 cm by the settling velocity, in cm/min. Typical sample collection times in the jar test are between 2 and 5 min.

Points of Chemical Applications

If the purpose of a jar test is to optimize conditions for an existing full-scale plant, chemicals must be added in the same order as in the plant. Alternatively, the same chemicals can be added at different times or in a different order in an attempt to improve the quality of water produced. For example, a jar test might evaluate the potential effect of polymer addition ahead of the primary coagulant or the effect of adding caustic for pH adjustment before adding alum versus after adding alum.



Source: AH Environmental Consultants Inc. 1997.

Figure 2-2 Example use of jar tests: Settled turbidity versus settling time

PREPARING FOR A JAR TEST

The development of a realistic and useful jar test protocol depends on several major steps. These steps require time and effort on the part of the operator, but the benefit will be well worth the effort. A well-planned and organized approach will save time in the long run by reducing guesswork and identifying the critical resources and information needed to ensure that a jar test yields useful data.

Defining Study Goals

Jar tests can be conducted for a number of reasons, so it is critical to define the objective of the test before beginning. The most common use of the jar test is for day-to-day process control, but it may also be used for other reasons. For example, goals might include

- Determining the point of diminishing returns (PODR) or the optimum coagulation pH for TOC removal under the Stage 1 D/DBPR
- Evaluating alternative chemicals such as coagulants (ferric chloride, aluminum sulfate, polyaluminum chloride, etc.), pH controls (lime versus caustic soda), or preoxidants (potassium permanganate, ozone, chlorine dioxide, etc.)
- Assessing additional chemical choices; for example, organic polymers for enhanced solids-liquid separation or effect of powdered activated carbon for taste and odor removal
- Evaluating physical modifications, such as varying mixing intensities and points of chemical application, implementing tapered flocculation, or installing baffles to increase retention times or possible procedures for new physical facilities

Water quality parameters that are commonly used to assess treatment performance include

- Turbidity and color removal

- Dissolved organic carbon (DOC) concentration or ultraviolet absorbance at 254 nm
- Disinfection by-product formation
- Iron and manganese removal
- Taste and odor of the treated water
- Sludge characteristics
- Algae concentrations
- Residual aluminum levels
- pH adjustment

Required Information

The next step in preparing a useful jar test protocol is to gather the necessary information about the physical characteristics of the plant, chemical application points, and current full-scale plant performance. To make valid comparisons between jar test data and actual plant performance data, an operator needs to know the key parameters of the existing or future processes. These factors should include velocity gradients or mixing intensities and detention times for mixing, flocculation, and channels or pipes, as well as overflow rates for sedimentation basins.

Velocity gradient. The design documents or operations and maintenance manual for a water treatment plant should provide data for actual in-plant velocity gradients for the rapid mix and the flocculation basins. Figure 2-3 shows an example of a chart relating velocity gradient to flocculator speed and water temperature. The accuracy of this information is very important for reliable results. If the information is not readily available, use the procedure for calculating velocity gradient described in chapter 4.

Detention times. The theoretical detention or retention time is defined by the following equation:

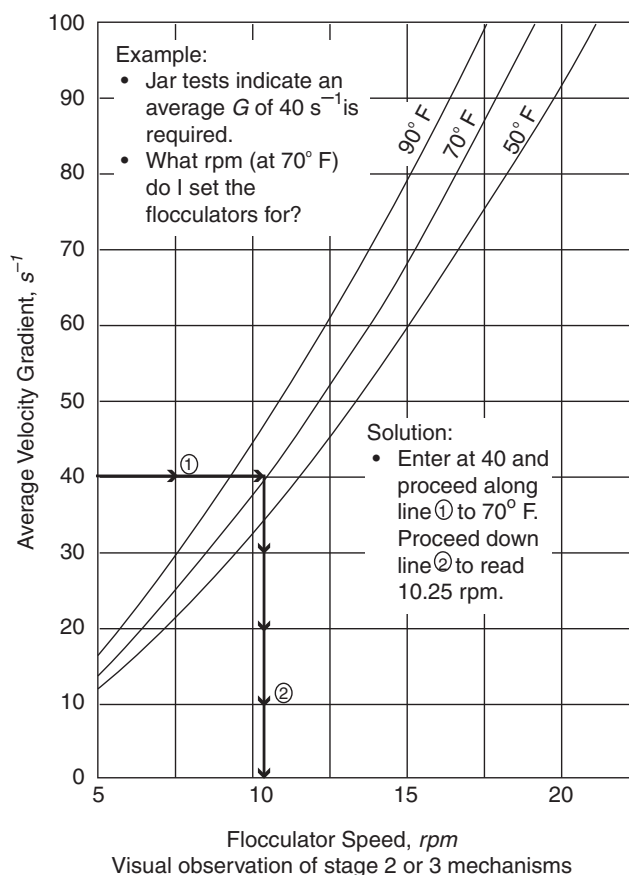
$$\text{Detention time} = \frac{\text{Tank volume}}{\text{Flow rate}} \quad (\text{Eq 2-3})$$

For example, the detention time of a tank with the dimensions 7 ft (2.14 m) × 6 ft (1.83 m) × 10 ft (3.06 m) (depth × width × length) operated at a flow rate of 105 gpm (23.9 m³/h) would be

$$\frac{7 \text{ ft} \times 6 \text{ ft} \times 10 \text{ ft}}{105 \frac{\text{gal}}{\text{min}}} \times 7.48 \frac{\text{gal}}{\text{ft}^3} = 30 \text{ min} \quad (\text{Eq 2-4})$$

$$\frac{2.14 \text{ m} \times 1.83 \text{ m} \times 3.06 \text{ m}}{23.9 \frac{\text{m}^3}{\text{hr}}} \times 60 \frac{\text{min}}{\text{hr}} = 30 \text{ min} \quad (\text{Eq 2-5})$$

In this way, theoretical detention times can be readily calculated from fixed basin dimensions and the flow rates through each basin. However, effective detention times through a plant's basins may be less than half of the theoretical detention



Courtesy of J. Edward Singley and Tim Brodeur.

Figure 2-3 Example use of graph for determining velocity gradient for jar test based on full-scale

times, perhaps because of short-circuiting in the process units. Special studies may need to be done to characterize the effective detention time; see chapter 4 for troubleshooting tips on short-circuiting. Finally, make sure to take into account not only the size of each basin but also the number of basins in service when dividing the volume by the flow rate.

Sedimentation basin overflow rate. The sedimentation basin overflow rate, or surface loading, determines the length of time that the water is allowed to settle in a jar before a sample is taken. Standard practices for jar testing include collection of turbidity samples at various times after stirring has stopped in order to simulate full-scale plant turbidity removal performance. However, the contact time in the full-scale basin may be 2 to 4 hr. The result is that for a given settling velocity, the time of sedimentation in the jar test is about one-hundredth that in the conventional plant. Such short holding times, however, are not adequate for assessing chemical reactions that may be occurring in the basin, such as formation of disinfection by-products or for evaluating the efficacy of powdered activated carbon (PAC). If the purpose of the bench testing procedure is to determine a reaction time-dependent parameter during the treatment process, it will be necessary to hold the jars for the actual retention time in full-scale process basins rather than to take samples at shorter times related to the basin overflow rate.

Chemicals and points of application. Another planning step involves defining which chemicals to use in the jar test. If the objective of the test is to assist in



Source: Phipps & Bird, Inc. Richmond, Va.

Figure 2-4 Example jar test unit



Source: EC Engineering Inc.

Figure 2-5 Example jar test units, 4-jar and 6-jar systems

day-to-day plant optimization, then the chemicals that are currently used in the treatment process should be used in the jars, and in the same order that they are used in the plant. If alternative chemicals are to be evaluated, these must be used in the jars. The operator should have data sheets for each chemical with information about the chemical formula, specific gravity, percent weight, viscosity for liquids, solubility for solids, and safety information. If the chemical being evaluated in a test has never been used in the process, the previous information should be supplemented with data for unit cost, shipping, and storage requirements, as well as a current material safety data sheet (MSDS).

Current treatment performance data. In order to determine how well the jar testing conditions or procedures simulate conditions in the full-scale facility, the operator should obtain treatment plant performance data. This information will be



Source: Boltac Industries, New Zealand.

Figure 2-6 Example jar test unit



Source: Aquagenics Pty Ltd.

Figure 2-7 Example jar test unit

compared to that from the jar tests conducted under the same conditions. Water quality data from the plant's settled water are generally used, such as the settled water turbidity, pH, and TOC or ultraviolet absorbance values.

Equipment

Jar testers. Jar test equipment consists of jars to hold the water, the impeller, a mechanism to turn the impeller, and lab equipment to analyze the results. The following sections describe each of these items and the role of each in the jar test procedure. Examples of typical jar test apparatus are shown in Figures 2-4 through 2-7. Typically, these devices include four or six jars with sample ports and paddle mixers, and can be preprogrammed to stir at particular speeds for particular amounts of time, simulating the coagulation, flocculation, and sedimentation processes.

Types of jars. Various types of jars have been used, including cylindrical 1-L and 2-L glass beakers. The most commonly used jars today are 2-L square beakers.

The square plastic beakers provide better mixing conditions than round beakers; therefore the remainder of this section will focus on these containers. Commercially available square jars are fabricated by cementing together clear acrylic sheets or by injection molding. These jars are often referred to as gator jars (Cornwell and Bishop 1983) because they were developed at the University of Florida. Desirable attributes for the jars include transparency, volume markings, appropriate sampling point, ease of cleaning, and durability.

Stirrer. A stirring mechanism turns the impellers. Two basic types of stirring mechanisms are used: gear-driven and magnetically driven units. A gear-driven unit has a variable-speed motor that turns four to six gears and stirrer shafts. The motor(s) and gears are located above the jar test containers so that the shafts for the impellers extend down into each jar. Units are available that can be controlled from about 10 to 300 rpm. This is the type utilized in the standard jar test apparatus shown in Figure 2-4 through Figure 2-7.

The magnetically driven unit works on the same principle as a magnetic stirrer plate. The paddle contains a magnet that turns as the metal under it rotates. Either type of unit may be used for jar testing. The magnetically driven unit has the advantage of providing open space above the jars to add chemicals. It is also possible to construct a jar stirrer using one or more variable-speed mixers. Units can be purchased that operate over a broad rpm range, allowing for an intensive rapid mix. They offer the advantage of testing different mix intensities simultaneously because the stirrers are individually controlled. It may also be less expensive to buy three or four mixers and mount them on ring stands than to purchase commercially available units.

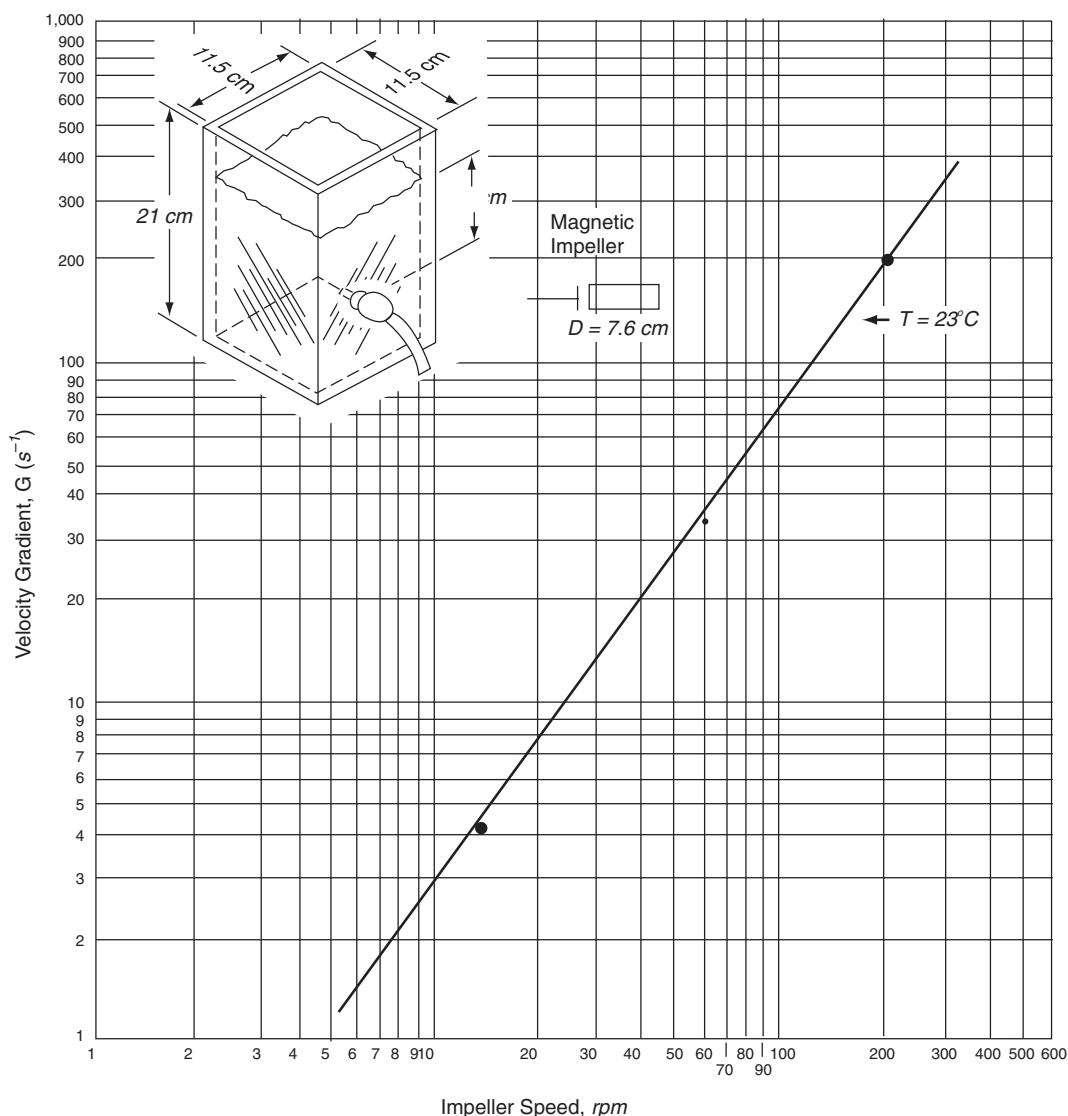
Impellers. Several types of impellers are available: paddle type, turbine, marine, and axial flow. Ideally, the impeller that best simulates the full-scale process should be used. Interchanging impellers requires a stirrer mechanism equipped to allow replacement of the shaft/impeller.

Magnetic stirrers are available only with flat-paddle impellers and would be difficult to retrofit with a different impeller type. They can, therefore, effectively simulate the action of a paddle, walking-beam, or flat-blade turbine types of mixing devices. Figure 2-8 shows the velocity gradients for a standard magnetic stirrer in a 2-L square jar.

Standard top-mounting stirrers are generally provided with flat paddles. However, the shaft and impeller can be changed to allow testing of different impeller types. Figures 2-8 through 2-10 show G values for various combinations of jars and impellers.

Water bath. A water bath is a tank in which the jars sit during the jar test as water circulates around them to maintain the correct water temperature. The use of a water bath is not usually required unless the treated water is very cold and the jar test is to be done in the warm laboratory. A simple test determines if a water bath is necessary: Take a sample of the raw water and immediately run a jar test; take another sample of the same water and let it warm up a few degrees, then conduct the same test and note if the results differ. Cold waters are frequently difficult to treat because lower temperatures result in water that is lower in viscosity, higher in density, and with slower chemical reaction times for flocs to form. Therefore, even a slight temperature increase could make treatment easier than in the full plant, causing misleading results.

Analytical equipment and laboratory ware. A variety of lab equipment is required to prepare standardized solutions and analyze water samples. The most essential analytical equipment includes a turbidimeter, pH meter, and thermometer. Regulatory requirements may require operators to perform more advanced analytical

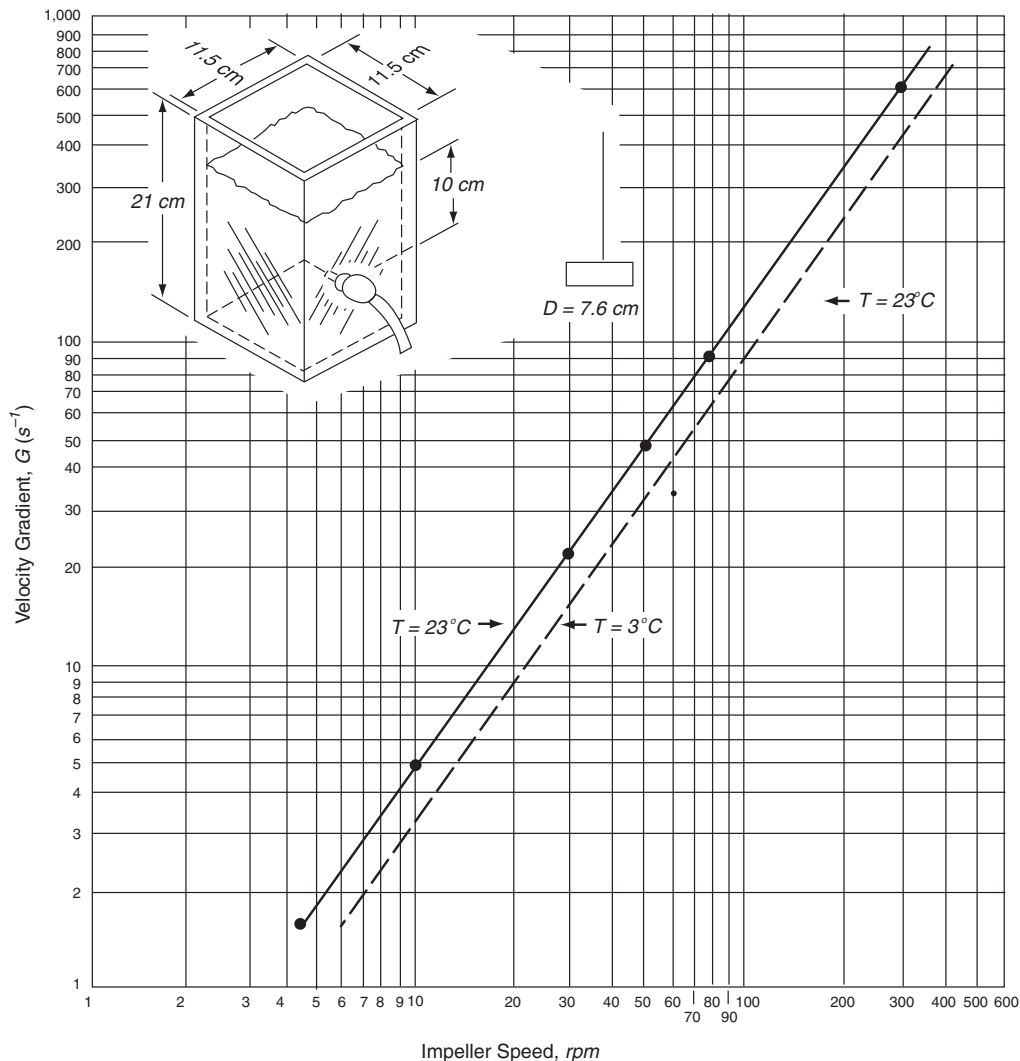


Source: Environmental Engineering & Technology Inc.

Figure 2-8 Laboratory G curve for magnetic jar tester with gator jar

analyses, which may call for the use of a total organic carbon analyzer or ultraviolet (UV) spectrophotometer. If the analytical equipment is not available, the operator must make arrangements with a commercial laboratory for needed tests. The laboratory may also provide suitable sample containers. Zeta potential meters are sometimes used to assess results of the jar test, as are particle counters.

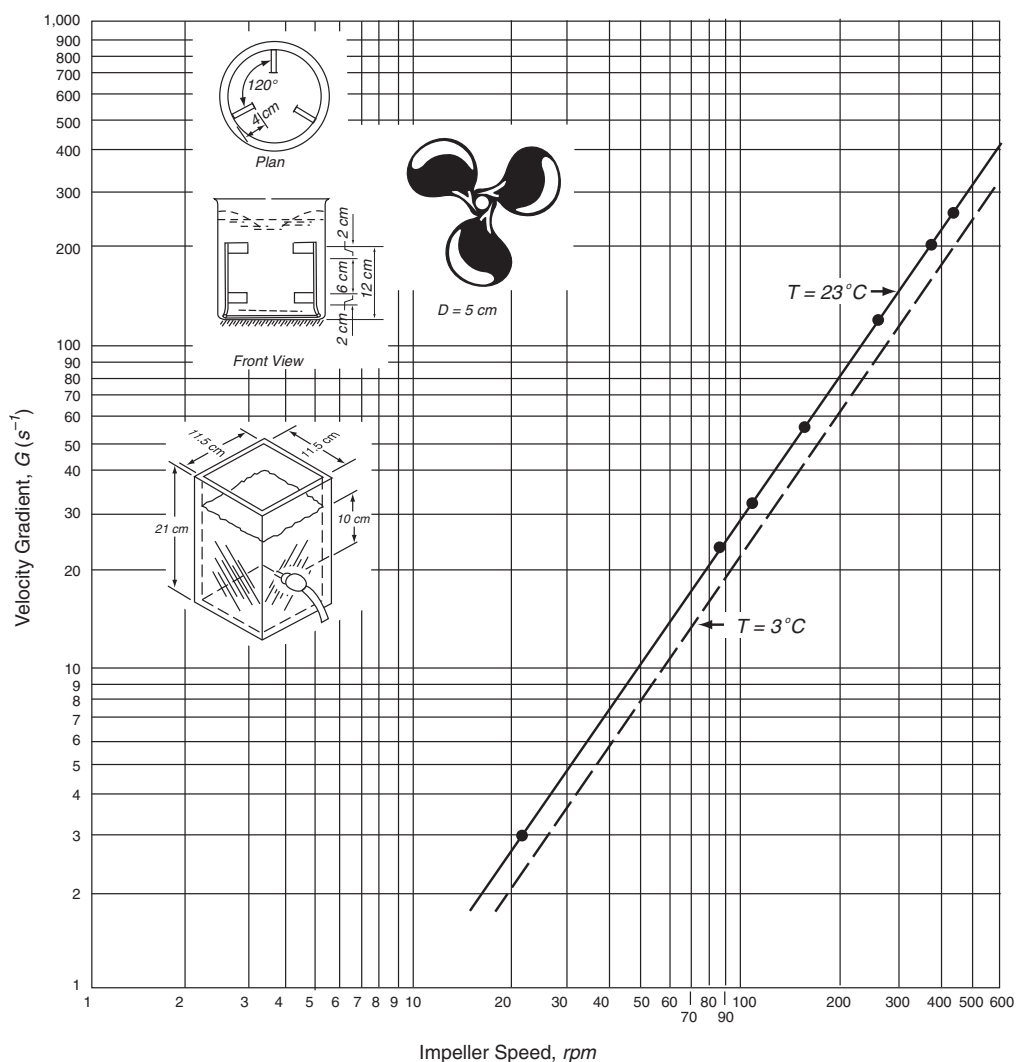
An assortment of pipettes, burettes, syringes, graduated cylinders, volumetric flasks, and a laboratory weight scale may also be required to make the necessary solutions. If chemicals are to be added without dilution, a micropipette is required. Many operators use PTFE septa (small, flat disks originally intended as liners of glass sample bottles) for holding minute volumes of neat chemical until ready for use. When needed, they are simply tossed into the jar along with the neat chemical, where they quickly sink to the bottom as the chemical is being mixed into the water.



Source: Cornwell and Bishop 1983.

Figure 2-9 Laboratory G curve for flat paddle in the gator jar

Tools for simultaneous chemical addition. When comparing various chemical dosages in a jar test, it is necessary to add the chemicals to all jars simultaneously. Under most conditions, manually adding the chemical quickly to each jar is acceptable. However, when small time changes are important, it is necessary to be able to dose all jars at exactly the same time. For example, if a test involves a short mix time of just a few minutes, and it takes 1 min to dose all six jars, the first jar dosed will have a significantly longer reaction time than the last jar. In such cases, operators have built devices such as the cup holder (Figure 2-11) and the septa bar (Figure 2-12) for holding small cups filled with the premeasured chemicals. Such devices allow dosing of all jars simultaneously.



Source: Cornwell and Bishop 1983.

Figure 2-10 Laboratory G curve for marine propeller in either the Hudson or gator jar

Chemicals

The chemicals used for pretreatment processes generally fall into one of four categories:

- Coagulants
- Coagulant aids
- pH controllers
- Oxidants/disinfectants
- Adsorbents (e.g., activated carbon)



Source: Zone 7 Water Agency.

Figure 2-11 Wooden holder for six dosing cups: Small plastic cups fit into each hole drilled in the wood



Figure 2-12 Septa bar: Metal bar to hold multiple septa over jars until ready to dump septa into all jars simultaneously.

In addition to those listed, other chemicals may be needed during and after the jar test. Some of the chemicals listed are available as pure substances of uniform quality. Depending on their origins, others may vary in chemical composition because of their complexity, causing differences in effectiveness. Polymers are an example. In order to achieve useful results, jar testing must use treatment chemicals that are being used or will be used at the full-scale plant and are certified for use in drinking water treatment (NSF/ANSI 60 [NSF International and American National Standards Institute 2005]).

Coagulants. Coagulants and how they work are discussed in detail in chapter 1. The most commonly used coagulants include

- Aluminum sulfate (alum)
- Ferric salts (ferric chloride and ferric sulfate)
- Ferrous sulfate
- Polymeric inorganic coagulants (partially neutralized metal salts such as polyaluminum chloride)

Expressing coagulant concentrations. When a jar test is performed, the correct dosages of chemicals must be applied. The operator must understand whether the applied dosage is stated “as product” or “as ingredient” basis. One way to avoid confusion is to express dosages/concentrations in terms of the molar amount of active ingredient, i.e., the moles of iron or aluminum per liter of solution. This convention is of even greater importance for jar tests comparing different coagulants. Equimolar dosages of aluminum and iron contain the same number of atoms. To determine the molar metal dosage applied at the full-scale treatment plant, data for the plant flow rate, bulk chemical feed rate, and the chemical data sheet are needed. The data sheets for most liquid aluminum or iron-based coagulants report values for the specific gravity and percent Al_2O_3 or percent Fe. To convert to molar metal dosage, apply the formula:

$$\text{Dosage, } \frac{\mu\text{mol}}{\text{L}} = \frac{\text{Chemical feed rate, } \frac{\text{lb}}{\text{day}}}{\text{Plant flow rate, mgd} \times 8.34} \times \text{Factor} \quad (\text{Eq 2-6})$$

The “factor” depends on the coagulant used, as shown in Table 2-2. The molar metal dose at the full-scale plant obtained in this way can then be used as a baseline value for the jar test.

Table 2-2 Factors for determining molar metal dosage

Coagulant	Factor
Dry alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$)	3.365
Liquid aluminum product (alum, PACl , etc.)	$\%\text{Al}_2\text{O}_3 \text{ by weight} \div 5.1$
Dry ferric chloride (anhydrous, FeCl_3)	6.165
Dry ferric sulfate (anhydrous, $\text{Fe}_2(\text{SO}_4)_3$)	5.004
Dry ferrous sulfate (anhydrous, FeSO_4)	6.579
Liquid iron product (ferric sulfate, polyferric chloride, etc.)	$\%\text{Fe by weight} \div 5.58$

Example: A treatment plant feeds 5,000 lb (2,270 kg) of liquid alum per day at a flow rate of 5 mgd (19 ML/d). According to the data sheet, the product contains 8.3 percent Al_2O_3 by weight. Therefore the molar-equivalent dosage equals:

$$\frac{5,000}{(5 \times 8.34)} \times \frac{8.3}{5.1} = 195 \mu\text{M} \left(\frac{\mu\text{mol}}{\text{L}} \right) \text{ as Al} \quad (\text{Eq 2-7})$$

If the operator were to test ferric chloride as an alternative coagulant, a comparable dosage to the currently applied alum would be 195 μM as Fe. Note that 195 μM as Al corresponds to 58 mg/L as alum; ferric chloride at a dosage of 58 mg/L as Fe would be five times the molar Al concentration. Figure 2-13 illustrates the relationship of molar metal concentration to alum or iron concentration in mg/L.

Making up stock solutions from the dry chemical. During jar testing, it is often inconvenient to feed a dry chemical to the jars. To test dry metal salts, stock solutions should be made up according to the following instructions:

Dry alum: Dissolve 10.0 g of dry aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$) in distilled or deionized water and dilute to the 1,000-mL mark in a volumetric flask. The

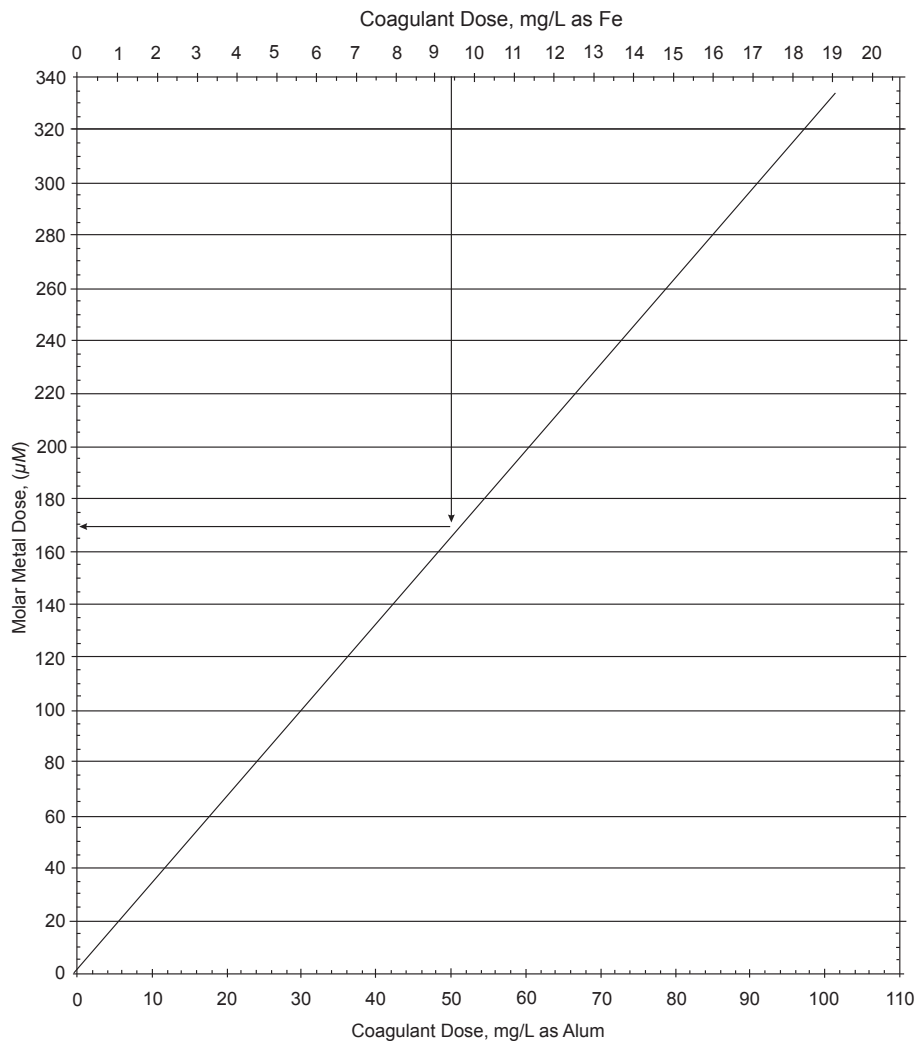


Figure 2-13 Expressing coagulant doses in molar metal concentrations

resulting solution contains 10,000 mg/L alum, which corresponds to 0.17 percent Al_2O_3 by weight. Adding 1.0 mL of this stock solution to a 2-L jar results in a dose of 5 mg/L as alum or 17 μM as Al.

Dry ferric chloride (anhydrous). Dissolve 2.93 g of dry ferric chloride (anhydrous, FeCl_3) in distilled or deionized water and dilute to the 1,000-mL mark in a volumetric flask. The resulting solution has a concentration of 1,000 mg/L or 0.10 percent Fe by weight. Therefore, adding 1.0 mL of stock solution to a 2-L jar results in 0.50 mg/L or 9.0 μM as Fe.

Dry ferric sulfate (anhydrous). Dissolve 3.57 g of dry ferric sulfate (anhydrous) in distilled or deionized water and dilute to the 1,000-mL mark in a volumetric flask. The resulting solution has a concentration of 1,000 mg/L or 0.10 percent Fe by weight. Adding 1.0 mL of stock solution to a 2-L jar results in 0.50 mg/L or 9.0 μM as Fe.

Dry ferrous sulfate (anhydrous). Ferrous sulfate works in much the same way as ferric sulfate, except that it provides a bivalent iron ion (Fe^{2+}) when dissolved in water. Generally, the ferrous iron is oxidized to the trivalent form (Fe^{3+}) through chlorination prior to use. To oxidize ferrous sulfate to ferric iron, add 0.13 mg of chlorine for each milligram of ferrous sulfate. To prepare a stock solution, dissolve 2.7 g of ferrous sulfate (anhydrous) in distilled water and dilute to 1,000 mL. The resulting solution has a concentration of 1,000 mg/L or 0.10 percent Fe by weight. Adding 1 mL of stock solution to a 2-L jar results in 0.50 mg/L or 9.0 μM as Fe.

Polymeric inorganic coagulants. Note that the effectiveness of dry and liquid coagulants varies with dilution, and highly diluted stock solutions may degrade over time. Thus, new stock solutions must be prepared every day. Polymeric inorganic coagulants such as polyaluminum chloride can degrade very quickly and should not be diluted but used neat.

Working with liquid coagulants. Dilution of liquid coagulants is usually not required if the necessary volume can be added to test jars with a micropipette, an



Source: Eppendorf North America.

Figure 2-14 Example of micropipettes capable of dispensing 0.1 μL to 2,500 μL