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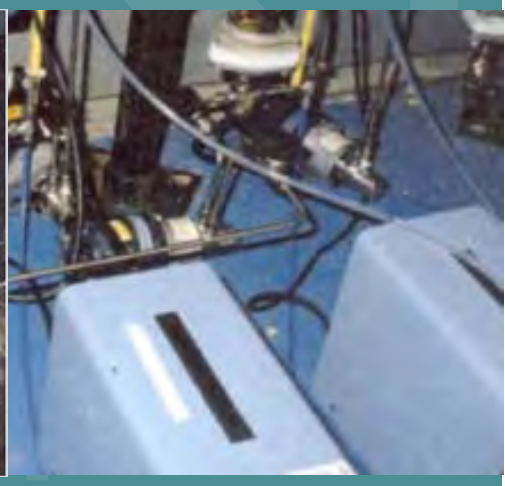
Water Treatment Pilot Plant Design Manual:
Low Flow Conventional/Direct Filtration Water Treatment Plant for Drinking Water Treatment Studies





Office of Research and Development
Water Supply and Water Resources Division

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Low Flow Conventional/Direct Filtration Water Treatment Plant for Drinking Water Treatment Studies

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, EPA is tasked with formulating and implementing actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of NRMRL's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments, and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

Abstract

Pilot plant systems are generally designed to reflect conditions of a particular full-scale system for the purpose of studying the impact of drinking water treatment changes, effectiveness for the removal of contaminants and the addition of new unit processes and practices. Pilot testing potential mitigation strategies is a recommended procedure to research optimal water quality treatment variables and avoid implementing a strategy that may not work for unforeseen reasons. This document is a comprehensive design manual that summarizes the activities and experiences of an EPA research team which was assembled to address *Cryptosporidium* contamination of drinking water, as well as other research needs. All of the team members had significant experience with filtration studies or in designing, fabricating, or operating pilot plant systems. The team concluded that the best, most meaningful way to conduct the needed research was to design, build, and operate a 'mini pilot plant.' The team designed and constructed a prototype 450 milliliter per minute conventional flocculation, sedimentation, and filtration facility. Final design specifications of individual processes were summarized and compared to other pilot- and full-scale systems. While originally designed for *Cryptosporidium* research, the system was built to allow relatively simple, fast, and inexpensive modifications for other studies.

Acronyms and Abbreviations

ρ	density
μ	dynamic viscosity
ν	kinematic viscosity
alum	aluminum sulfate
As(III)	arsenite
AWBERC	Andrew W. Breidenbach Environmental Research Center
BSC	biohazard safety cabinet
CSTR	continuous-flow stirred tank reactor
CT	contact time
d	diameter
DOC	dissolved organic carbon
EBCT	empty bed contact time
EFL	
EPA	Environmental Protection Agency
ESWTR	Enhanced Surface Water Treatment Rule
Fe(II)	ferrous iron
G	velocity gradient
H	height
KCL	potassium chloride
LR	loading rate
NRMRL	National Risk Management Research Laboratory
ORD	Office of Research and Development
P	power
PMAA	polymethyl methacrylate
PTFE	polytetrafluoroethylene
Q	flow rate
r	
SLR	surface loading rate
t	retention time
TTEB	Treatment Technology Evaluation Branch
TOC	total organic carbon
V	volume
v	inlet velocity
W	width
WSWRD	Water Supply and Water Resources Division

Units of Measure

°	degree
%	percent
cm	centimeter
ft	foot/feet
ft^2	square feet
gal	gallons/gallons
gpd	gallons per day
gpm	gallon per minute
gpm/ft^2	gallons per minute per square foot
H	height
hp	horsepower
in	inch/inches
L	liter
L/min	liters/minute
lb	pound
m/hr	meters per hour
min	minutes
mL	milliliter
mL/min	milliliters per minute
mm	millimeter
oocysts/mL	oocysts per milliliter
oocysts/min	oocysts per minute
rpm	revolutions per minute
sec	seconds
µm	micrometer

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Chapter 1 – Introduction

1.1 Background

Pilot plant systems are generally designed to reflect conditions of a particular full-scale system for the purpose of studying the impact of drinking water treatment changes, effectiveness for the removal of contaminants and the addition of new unit processes and practices. Pilot testing potential mitigation strategies is a recommended procedure to research optimal water quality treatment variables and avoid implementing a strategy that may not work for unforeseen reasons. This document is a comprehensive design manual that summarizes the activities and experiences of a research team, consisting of engineers, scientists, and technicians from the U.S. Environmental Protection Agency's (EPA) Office of Research and Development, which was assembled to address *Cryptosporidium* contamination of drinking water, as well as other research needs in the mid-1990s. All of the team members had significant experience with filtration studies or in designing, fabricating, or operating pilot plant systems. The team concluded that the best, most meaningful way to conduct the needed research was to design, build, and operate a 'mini pilot plant.'

The team designed and constructed a prototype 450 milliliter per minute (mL/min) conventional flocculation, sedimentation, and filtration pilot plant at EPA's Andrew W. Breidenbach Environmental Research Center (AWBERC) in Cincinnati, Ohio. A series of shakedown tests, tracer studies, and preliminary experimental runs were conducted to hydraulically characterize the system, identify operational problems, and evaluate treatment performance. Several modifications to the prototype plant's design were made to remedy problems identified during the shakedown period. Final design specifications of individual processes were summarized and compared to other pilot plants and full-scale systems (Tables A1 to A4, Appendix A).

1.2 Highlights

This manual highlights the project constraints and concerns, and includes detailed design calculations and system schematics. The plant is based on engineering design principles and practices, previous pilot plant design experiences, and professional experiences and may serve as design guide for similar scale systems.

While originally designed for *Cryptosporidium* research, the system was built to allow relatively simple, fast, and inexpensive modifications for other studies. The initial system design was guided by

the flow rate, an important design restriction to achieve the desired concentration of micro-organisms for a given period of time. The plant was designed for ease of use and to minimize number of staff required for operation, reduce water needs, and to create a flexible, modular design that can be modified to meet the system requirements for various future experimental needs, including arsenic removal studies, iron removal studies, etc.

1.3 Initial Pathogen Studies

Although this pilot plant was initially designed to conduct pathogen studies, specifically the removal of *Cryptosporidium* oocysts from drinking water, the design principles established for pathogen studies can be modified to perform other water quality studies. The need to study the removal of *Cryptosporidium* oocysts from drinking water is driven by a number of waterborne cryptosporidiosis outbreaks[1-5], including the United States' largest outbreak in the City of Milwaukee during the spring of 1993[6, 7]. Due to the widespread publicity and concern over these events, the water industry and water utilities reexamined their treatment practices. In response, research was being conducted to study the removal of *Cryptosporidium* oocysts from drinking water under various conditions and to explore the use of surrogate parameters (i.e., particle counts, aerobic bacterial endospores, etc.) for monitoring the effectiveness of treatment processes and fine-tuning treatment conditions.

When this project began, EPA was developing the Enhanced Surface Water Treatment Rule (ESWTR), which established a regulatory limit for *Cryptosporidium* oocysts in drinking water. The information gained from the research studies involved in this project may have, in part, supported the development of the regulation. Specifically, the experimental studies that provided useful information for developing log removal credit guidance for various filtration scenarios (e.g., coagulant type, filter media, etc.) under the ESWTR and establishing achievable *Cryptosporidium* oocyst removal boundaries. Filtration studies were also useful in identifying surrogate parameters for evaluating overall treatment performance, and identifying correlations between turbidity, surrogate parameters, and *Cryptosporidium* oocyst removal. The impact of plant operational practices (e.g., filter loading rate, filter backwashing protocol, etc.) on oocyst levels and water quality were also evaluated. Finally, the studies were useful in determining whether the physical rigors of a water treatment plant damages the outer walls of oocysts, consequently rendering them more susceptible to disinfection.

Every pilot-scale research study that has evaluated the removal of *Cryptosporidium* oocysts from drinking water, including those conducted at AWBERC, has been conducted by spiking *Cryptosporidium* oocysts into the source water over a relatively brief time frame (minutes to hours). "Slug-spiking" is practiced because of constraints imposed by the amount of *Cryptosporidium* oocysts available and by flow conditions of the plant. This method, however, is not representative of the true environmental conditions under which a water treatment plant operates. In addition, experimental sampling through the treatment process to precisely catch the spike peak is difficult to accomplish.

This difficulty is exacerbated because a ceiling is usually placed on the number of samples that can be taken during a test run. Another problem is the frequent inability to calculate statistically significant log removals of oocysts due to filtered water oocyst levels below the detection limit. As a result, log removal data is frequently reported as a "greater-than" value based on some detection limit threshold. To avoid such problems, high concentrations of oocysts must reach the filter to increase the chance that measurable amounts will be present in the filter effluent.

A number of jar tests and pilot plant runs were conducted by the research team using *Cryptosporidium parvum* oocysts. The effects of a number of initial water quality conditions and coagulant types and dosages on the removal of the protozoan were examined. The general conclusion that can be drawn from all of the data collected, thus far, is that *Cryptosporidium* oocyst removal paralleled the removal of particles, turbidity, and aerobic bacterial endospores. Typically, when optimum removal of these parameters was achieved, optimal removal of *Cryptosporidium* oocysts was coincidently observed.

Chapter 2 – Safety Considerations

Safety issues should be incorporated into the planning process of any pilot plant study/experiment. These plans should include a description of procedures and equipment required to handle the equipment, chemicals, pathogens, etc. used for experiments. Safety and precision in a laboratory setting is critical not only for the health and wellness of the researchers, technicians, and operators, but it is also critical to the accuracy and validity of the study and data results. The biosafety practices outlined here are by no means exhaustive or all encompassing; they are meant to indicate standard best practices and necessary considerations when dealing with potentially harmful or toxic materials. The excerpts below come from the Center for Disease Control's Biosafety Level 2 resource, *Biosafety in Microbiological and Biomedical Laboratories, 5th Edition* [8]:

Biosafety Level 2 practices, equipment, and facility design and construction are applicable to clinical, diagnostic, teaching, and other laboratories in which work is done with the broad spectrum of indigenous moderate-risk agents that are present in the community and associated with human disease of varying severity. With good microbiological techniques, these agents can be used safely in activities conducted on the open bench, provided that the potential for producing splashes and aerosols is low.

Primary hazards to personnel working with these agents relate to accidental percutaneous or mucous membrane exposures, or ingestion of infectious materials. Extreme caution should be taken with contaminated needles or sharp instruments. Even though organisms routinely manipulated at BSL-2 are not known to be transmissible by the aerosol route, procedures with aerosol or high splash potential that may increase the risk of such personnel exposure must be conducted in primary containment equipment, or in devices such as biological safety cabinets or safety centrifuge cups.

Personal protective equipment should be used as appropriate, such as splash shields, face protection, gowns, and gloves. Secondary barriers, such as hand washing sinks and waste decontamination facilities, must be available to reduce potential environmental contamination.

Standard Microbiological Practices

- Access to the laboratory is limited or restricted by the laboratory director when work with infectious agents is in progress.
- Work surfaces are decontaminated at least once a day and after any spill of viable material.
- All infectious liquid or solid wastes are decontaminated before disposal.

- Mechanical pipetting devices are used; mouth pipetting is prohibited.
- Eating, drinking, smoking, and applying cosmetics are not permitted in the work area. Food may be stored in cabinets or refrigerators designated and used for this purpose.
- Persons wash their hands after handling infectious materials and animals when they leave the laboratory.
- All procedures are performed carefully to minimize the creation of aerosols.

Special Practices

- Contaminated materials that are to be decontaminated at a site away from the laboratory are placed in a durable leak-proof container which is closed before removal from the laboratory.
- The laboratory director/operator limits access to the laboratory in general. Persons who are at increased risk of acquiring infection or for whom infection may be unusually hazardous are not allowed in the laboratory or animal rooms. The director/operator has the final responsibility for assessing each circumstance and determining who may enter or work in the laboratory.
- The laboratory director establishes policies and procedures whereby only persons who have been advised of the potential hazard and meet specific entry requirements (e.g., immunization) enter the laboratory or animal rooms.
- When the infectious agent in use in the laboratory requires special provisions for entry (e.g., vaccination), a hazard warning sign, incorporating the universal biohazard symbol is posted on the access door to the laboratory work area. The hazard warning sign identifies the infectious agent, lists the name and telephone number of the laboratory director or other responsible person(s), and indicates the special requirement(s) for entering the laboratory.
- An insect and rodent control program is in effect.
- Laboratory coats, gowns, smocks, or uniforms are worn while in the laboratory. Before leaving the laboratory for non-laboratory areas (e.g., cafeteria, library, administrative offices), this protective clothing is removed and left in the laboratory or covered with a clean coat not used in the laboratory.
- Animals not involved in the work being performed are not permitted in the laboratory.
- Special care is taken to avoid skin contamination with infectious materials; gloves should be worn when handling infected animals and when skin contact with infectious materials is unavoidable.
- All wastes from laboratories and animal rooms are appropriately decontaminated before disposal.

Chapter 3 – Materials

When considering the property of the material used to build the rapid mix, flocculation, and sedimentation chambers, the most important was the material's inertness, especially with respect to organic leaching. Although it was not a necessary component, a clear material was used to obtain a visual observation and description of what occurs in the chambers. Glass is difficult to work with in terms of construction and breakability; thus, polymethyl methacrylate (PMMA)[1] is recommended. The major concern associated with the use of PMMA is the potential release of organics from the joint cement or binding material.

PMMA, ¼-inch (in) thickness, was constructed into a square container with 1-foot (ft) long sides. A bonding agent consisting of methylene chloride, methyl methacrylate monomer, and trichloroethylene was used. A leaching study was done to determine the extent to which the binding agent contributes contaminants to the water, and if continuous water flow would rinse away any residue. The container was filled with deionized water[2] (before being rinsed or cleaned in any manner) and allowed to sit stagnant for seven days. After seven days, the water was analyzed for methylene chloride and trichloroethane; the container was allowed to air dry for nearly two days, after which the container was again filled with deionized water[3] and allowed to sit for six days before analysis began. And, finally, the water was allowed to continually flow into the container at a rate of approximately 100 ml/min periodically over a two-week time frame, and was sampled twice during that time (Table 1).

Table 1. Results of polymethyl methacrylate (PMMA) leaching study.

Date	Description	Duration (days)	Methylene chloride (µg/L)	Trichloroethene (µg/L)
10-3-1996	batch	7 standing	2524	27
10-9-1996	batch	6 standing	138	2.7
10-18-1996	flow	16 flowing	< 0.1	< 0.1
10-21-1996	flow	18 flowing	< 0.1	< 0.1

µg/L = micrograms/liter

[1] PMMA is also known as acrylic glass or by the name brand Plexiglas®.
[2] NANOpure® deionized water was used.
[3] NANOpure® deionized water was used.

The results of the leaching study clearly demonstrated that with little effort and time, any materials left from the binding procedure can easily be removed. Therefore, these materials will not likely become a source for contamination.

Chapter 4 – Pilot Plant Design Principles

4.1 Design Considerations

Using accepted engineering practice, the processes in the following sections have been designed to reflect hydraulic conditions and treatment effectiveness of the 1.6-gallons per minute (gpm), or 6056-mL/min, organics control pilot plant [9-11]. Two identical parallel mini pilot plants were built and each treatment train consisted of coagulation, flocculation, and sedimentation processes followed by filtration. The sections to follow outline the governing design considerations and the final design of each system component. While the design considerations were specific to the initial needs of the pathogen study, system modifications can be easily made to support other water quality studies (See Chapter 8 – System Modifications).

The design of the pilot plant for studies to evaluate *Cryptosporidium* oocyst removal was primarily governed by two restrictions: *Cryptosporidium* oocyst availability and flow rate. First, the number of oocysts available for the studies had to be identified by the microbiological support staff. Second, a desirable flow rate had to be calculated to produce necessary raw water oocyst concentrations that would meet the project objectives.

The quantity of *Cryptosporidium parvum* oocysts available for pilot studies was limited by staff availability. The oocysts were harvested in mice within AWBERC by EPA microbiologists and were available for use by the research team. The oocyst production rate for this project was identified as approximately 1×10^9 oocysts/week.

Accurately observing large reductions of *Cryptosporidium* oocysts in any setting (i.e., full-scale, pilot plant, etc.) requires that large numbers of oocysts be measured in the influent water while maintaining measurable levels in the effluent stream. Filtration studies using the existing 1.5-gpm (5678 mL/min) conventional/direct filtration pilot plant would have required enormous numbers of oocysts illustrated by the following example:

If a 3-log (99.9%) oocyst reduction through the pilot plant is expected, and measurable amounts of oocysts are seen in the effluent stream, then the raw water must be spiked with at least 1,000 oocysts/milliliter (oocysts/mL) and the filter effluent must contain at least one measured oocyst/mL. Therefore, oocysts must be spiked into the raw water at a rate of 5.68×10^6 oocysts/minute (oocysts/min). In only three hours, the entire weekly limit of 1.0×10^9 oocysts would be used.

This example is an ideal case scenario. In reality, analytical limitations and unexplained losses of oocysts throughout the treatment plant must be considered, after requiring an increase in the number of oocysts needed. Research was conducted by the EPA team to define any losses.

Nearly all studies involving *Cryptosporidium* oocyst research based on short-term spiking or 'slugging' were primarily due to the resource constraints described above. In natural systems, however, a treatment facility would be more likely challenged with oocysts over an extended period of time. Therefore, a long spike period in a pilot setting would be more representative of field conditions with respect to exposure duration. The number of oocysts available, the need to spike continuously over an extended period, and the oocyst concentration required in the raw water made the current pilot plant too large to meet the research needs. The only solution to the identified problems was to design a smaller scale, low-flow, conventional filtration pilot plant.

4.1.1 System Specifications

The following limitations served as the primary pilot plant design parameters:

- Supply of 1 x 10^9 oocysts/week
- Raw water oocyst concentration 1,000 to 10,000 oocysts/mL
- Minimum 1.5-in filter diameter (A_s) to minimize wall effects
- Filter surface loading rate of 2 gpm per square foot (gpm/ft^2)
- Design flow rate (Q) through the rapid mix chamber of 450 mL/min
- Retention time (t) in rapid mix chamber of 1.5 minutes (min)

4.1.2 Raw Water Storage

EPA has the ability to truck water in using its 5,300-gallon (gal), or 20,000-liter (L) tanker trailer. The tanker trailer can be gravity drained using a series of 3-in diameter hoses to an existing 5,500-gal (20,800 L) 304 stainless steel rectangular water storage tank. Water is continuously recirculated through the tank by a 3/4 horsepower (hp) pump to reduce particle settling. In addition, a submersible pump has been lowered into the tank to provide additional mixing.

Water from the storage reservoir is pumped up to a covered 100-gal, 304 stainless steel cylindrical constant head tank. A series of ¾-in diameter, 304 stainless steel pipes and valves and a 1/5 hp pump is used to feed the tank. The tank is not intended to be used for pre-sedimentation or chemical feed. The tank provides a constant volume of water with a constant head, from which raw water is pumped at a regulated rate to downstream processes. The tank is continuously filled, and its level is maintained 16 inches above the pilot plant feed pump by a 1-in diameter, 304 stainless steel overflow line that recirculates the water back to the 5,500-gal tank. A ¼-in diameter polytetrafluoroethylene (PTFE) [4] line from a tee in the overflow line leads to a micro pump that feeds the pilot plant at a constant rate.

[4] PTFE is commonly known by the name brand Teflon®.

To avoid a build-up of algae and sludge at the bottom of the tank, it is drained when the pilot plant is not in operation.

4.1.3 Flow Rate Calculations

The flow rate (Q) through the system had to be adjusted so that the supply of *Cryptosporidium parvum* oocysts (or other pathogens) could be continuously spiked into a raw water supply ahead of the plant inlet for extended time periods (at least 24 hours). The concentration of oocysts in the influent water needed to be high, and measurable numbers of oocysts needed to pass the filters in order to reliably calculate 3 to 4-log removals. The following calculations are approximations for the prototype pilot plant. Detailed calculations will be presented in the following sections. The surface area (A_s) of a 1.5-in diameter (d) filter is

$$A_s = \frac{\pi \cdot d^2}{4} = \frac{\pi (1.5\,\text{in}/12\,\text{in}/1\,\text{ft})^2}{4} = 0.0122\,\text{ft}^2$$

Q per each A_s based on an initial filter loading rate (LR) of 2 gpm/ft^2, 4.9 meters per hour (m/hr), is

$$Q = LR \cong A_s$$

$$= 2.0\ \text{gpm/ft}^2 \cong 0.0122\ \text{ft}^2 = 0.0244\ \text{gpm} \cong 0.2642\ \text{liters/min. (L/min)/gpm} = 0.092\ \text{L/min}$$

$$= 92\ \text{mL/min}$$

Rounding Q and adding a filter overflow (50 mL/min for design) to bring the design Q per filter of 150 mL/min. The pilot plant is designed to operate with up to three parallel filters, which result in a total design Q of 450 mL/min.

The theoretical raw water oocyst concentration based on design flow must be determined to indicate whether the primary design criteria can realistically be met:

$$\text{Concentration (oocysts/mL)} = \frac{\text{total oocysts available}}{450\,\text{mL/min} \cdot \text{spike duration (min)}}$$

This equation can be used to calculate the theoretical oocyst concentrations for a number of spiking conditions as shown in Table 2.

Table 2. Theoretical oocyst concentrations at maximum design flow.

Spike duration (available oocysts/wk)	Raw water concentration (oocysts/mL)
24 hr spike, 1 x 10^9 oocysts	1543
48 hr spike, 1 x 10^9 oocysts	772
24 hr spike, 2 x 10^9 oocysts	3086
48 hr spike, 2 x 10^9 oocysts	1544

Table 2 suggests that it may be possible to fall within the desirable raw water oocyst concentration range under the maximum design flow rate. However, it must also be pointed out that *Cryptosporidium* oocysts are known to be highly adhesive to many surfaces. Consequently, actual concentrations may be significantly lower in practice than calculated estimates.

4.1.4 Mixing

The design Q through the rapid mix chamber and retention time (t) were predetermined to be 450 mL/min and 1.5 min, respectively, based upon recommended guidelines and reported design practice (see section 4.1). The retention time was based upon recommended guidelines [12, 13] and reported design practice. Also, adequate retention time was needed to size a mixing chamber that could accommodate a reasonably-sized mixer paddle. The mix chamber was square in shape and does not contain baffles. These design parameters were used to size the rapid mix chamber:

$$V = Q \cdot t = (450\ \text{mL/min})\,(1.5\ \text{min}) = 675\ \text{mL} = 0.675\ \text{L} \cdot \frac{0.0353\ \text{ft}^3}{\text{L}} = 0.0238\ \text{ft}^3 = 41.13\ \text{in}^3$$

Where,

V = volume of chamber

The dimensions of the chamber, assuming that the water height (H) is equal to 1.25 times the width (W) [13], are

V = (W) (W) (H) = 40.96 in^3,
So, W = 3.2" and H = 4.0"

A 3.5-in freeboard was added to the design height for a total height of 7.5 inches. Figure B1 (Appendix B) is a schematic of the rapid mix chamber. The water level was controlled by a ½-in, 304 stainless steel overflow line connecting the rapid mix chamber to the flocculation chamber at the 4-inch water height. This was accomplished by a ½-inch PTFE bulkhead fitting and hose nozzle located as shown in Figure B1 (Appendix B). The water travels through (1) a ½-inch stainless steel tubing to a 90° elbow, 8-inch drop through ½-inch tubing, (2) then through another 90° elbow to a short 3-inch run of ½-inch

stainless steel tubing, (3) and then into the flocculation basin through a ¾-in PTFE bulkhead fitting (Figures B4a to B4d, Appendix B).

Paddle design was based on previous pilot plant design experiences and targeted to meet acceptable values for the mean velocity gradient (G). The dimensions of the final paddle design allow for reasonable clearance between paddle tip and chamber walls/water surface.

The mean velocity gradient, G (sec^{-1}), was calculated as follows [15]:

$$G = \sqrt{\frac{P}{V \cdot \mu}}$$

where,

P = power, ft ≅ pound/second (lb/sec)
V = volume of water in rapid mix chamber, ft^3
μ = dynamic (absolute) viscosity of water, lb ≅ seconds (sec)/ft^2

$$P = \frac{C_d \cdot A \cdot \rho \cdot v_p^3}{2}$$

where,

C_d = drag coefficient (unitless)
A = total cross sectional area of paddles, ft^2
P = density of water, lb ≅ sec^2/ft^4
v_p= velocity of paddles relative to water, ft/sec, = 0.75 ≅ π · r · n / 60, where
r = length of paddle blade (in ft)
n = revolutions per minute (rpm)

Therefore, based on design calculations, G can be calculated as a function of revolutions of the paddle by substituting the following:

V = 0.0238 ft^3
μ = 1.90 x 10^{-5} lb_f ≅ sec/ft^2 @ 75°F
C_d = 1.2
ρ = 62.4 lb_m/ft^3 / 32.2 lb_m ≅ ft/sec^2 = 1.938 lb ≅ sec^2/ft^4
v_p = (0.75 · 2π · r · [1'/12"] · n) / 60 = 0.006545 · r · n ft/sec

where,

lb_f = pound-force

lb_m = pound-mass

and, substituting into the equation of P,

$$P = 1.2 \cdot A \cdot (1.938\ lb \cong sec^2/ft^4)\ (0.006545 \cdot r \cdot n\ ft/sec)^3 / 2$$
$$P = 2.264 \times 10^{-9} \cdot A \cdot r^3 \cdot n^3$$

and, substituting in for G,

$$G = [2.264 \times 10^{-9} \cdot A \cdot r^3 \cdot n^3 / (0.0238\ ft^3)\ (1.90 \times 10^{-5}\ lb_f \cong sec/ft^2)]^{½}$$

which simplifies to

$$G = 7.08 \times 10^{-2} \cong (A)^{0.5} \cong (r^3)^{0.5} \cong (n^3)^{0.5}$$

where,

A = total area of all paddles (in^2)
r = paddle radius (in)
n = paddle speed (rpm).

The final equation is based on a temperature of 25°C, and conversions from feet to inches have been incorporated.

The mixer paddles consist of two pairs of flat, rectangular blades located above one another and rotated at right angles (Figure B2, Appendix B). The design was chosen because of previous design experiences, ease of fabrication, and simplicity. Spreadsheet calculations of G for several potential paddle blade sizes (1.0-in radius and 1.9-in depth, 1.1-in radius and 1.3-in depth, and 1.2-in radius and 0.9-in depth) and mixing speeds are included in Tables C1 to C3 (Appendix C). One option for the mix paddle dimensions and blade positioning is shown in Figure B2 (Appendix B). The paddles are fabricated from approximately 1.5 mm thick 316 stainless steel and welded to 1-foot long, ¼-inch diameter, 304 stainless steel rods using 316 stainless steel welding. The ease of paddle fabrication and low cost will easily permit all paddle sizes to be interchanged if necessary.

Figure C1 (Appendix C) shows the calculated G for the paddle designs and various mixing speeds at 25°C. Since all mixer blade dimensions produce nearly identical G values for a given mixer speed, the 1.1 x 1.3-in blades were initially incorporated into the construction of the pilot plant based upon their ease of fabrication and ability to fit within the mixing chamber. The initial mixer speed was 100 rpm, which translates to a G of 195 sec^{-1}. This G value is below recommended values [13, 16], as illustrated in Table A1 (Appendix A). However, the relatively long retention time should provide sufficient mixing. Mixing speed should be adjusted if the proposed conditions are demonstrated to be insufficient.

A dual-shaft mixer with a remote speed controller (0 to 333 rpm) that resembles a blender was used. The mixer motor was suspended above the chamber by a metal frame[5] so the bottom blade was suspended approximately one and one-half inches above the bottom of the chamber. The frame was adjustable so that the blade depth may be raised or lowered.

Raw water and coagulant entered the mix chamber through $^1/_4$-in PTFE and $^1/_8$-in plastic tubing[6], respectively. The lines are held in place by channels (½-inch diameter tube cut vertically) fastened to the corners of the mix chamber. The inlet levels are adjustable and the final water level was experimentally determined. The coagulant feed line extends beyond the channel to allow the coagulant to freely disperse into the chamber at the mixer blade. Figure B3 (Appendix B) is a picture of the rapid mix chamber.

4.1.5 Flocculation

The system has a cross-flow or horizontal flow flocculation unit with four rectangular chambers or cells. The flocculation unit was separated from the clarifier, or sedimentation, unit. The t through the entire flocculation unit was 60 min (15 min per chamber) based upon recommended guidelines [12,13,16] and previous experience. Evenly spaced baffles separated each chamber and forced water flow to take an under-over route. The volume of the total chamber, V, was calculated as follows:

$$V = Q \cdot t = (450\ \text{mL/min})(60\ \text{min}) = 27000\ \text{mL} = 27.0\ \text{L} \cdot \frac{0.0353\ \text{ft}^3}{\text{L}} = 0.95\ \text{ft}^3 = 1647\ \text{in}^3$$

Dividing the volume by four chambers gives a resulting size per chamber of 0.238 ft^3 (6.75 L). The internal tank design dimensions used were 7.5-in x 7.0-in x 28.75-in (Height x Width x Length). A 4-in freeboard was added to the water height to bring the chamber height to 11.5 inches. A sampling port was located on a side wall of the last chamber. Figures B4a and B4b show the flocculation unit design. Mixing motors are mounted above each chamber on the same or similar frame as that used to support the rapid mixer. This design permits easy access to motors, shafts and paddles, and eliminates the need to drain the system in the case of motor repairs. G values tapered through successive chambers. Velocity gradients of 30, 20, 15, and 10 sec^{-1}, for the respective chambers, were initially evaluated based on recommended guidelines [12,16] and previous experience, but were subject to change following experimentation. Similar to the derivation of G for rapid mixing, the following equation can be used to calculate G (sec^{-1}) for individual flocculation chambers:

$$G = 2.238 \times 10^{-2} \cong (A)^{0.5} \cong (r^3)^{0.5} \cong (n^3)^{0.5}$$

where,

A = Total area of all paddles (in^2)
r = Paddle radius (in)
n = Paddle speed (rpm)

[5] Unistrut® metal frame was used.
[6] Nalgene® brand tubing was used.

The final equation was based on a temperature of 25°C, and conversions from feet to inches were incorporated.

As with the rapid mix design, the mixer paddles consisted of two pairs of flat, rectangular mixer blades located above one another at right angles. The bottom blades were supported approximately 1.5 inches from the basin bottoms. Spreadsheet calculations of G for several potential paddle blade sizes (2.5-in radius and 1.5-in depth; 2.0-in radius and 3.0-in depth, and 3.0-in radius and 0.75-in depth) and mixing speeds are included in Tables C4 to C6 (Appendix C). The paddle dimensions and positioning are shown in Figure B2 (Appendix B). The paddles were fabricated from 304 stainless steel and rotated on a ¼-in 304 stainless steel shaft. The ease of fabrication and low cost allowed all previously mentioned paddle sizes to be evaluated if necessary. Figure C2 (Appendix C) shows the calculated velocity gradient, G, for the paddle designs and various mixing speeds at 25°C.

Since all mixer blade dimensions produce nearly identical G values for a given mixer speed (Figure C1, Appendix C), the 2.5 x 1.5-in blades were initially incorporated into the construction of the pilot plant based upon their ease of fabrication and geometry within the mixing chamber. The mixer speeds were adjusted to the appropriate settings to achieve the desired G values (Table C5, Appendix C). Mixing speed was adjusted if the proposed conditions were demonstrated to be insufficient.

The flocculation basin was connected to the sedimentation basin by a ¼-in PTFE bulkhead. This connection will limit the distance floc particles travel and minimize shearing forces. Photographs of the flocculation chambers are shown in Figures B4c and B4d (Appendix B).

4.1.6 Sedimentation

A cross or horizontal clarifier was not employed for this study and plate or tube settlers were not incorporated. Based upon the design Q of 450 mL/min, clarifier design specifications were developed for a number of conditions. A 3-hour detention time was selected as being typical. Design calculations are given for one condition as follows:

$$V = (3 \times 450 \times 60)\,\text{mL} = 81{,}000\,\text{mL} = 81\,\text{L}$$

$$t = \frac{V}{Q} = 3\,\text{hrs} = \frac{V\,\text{mL}\,\text{min}}{450\,\text{mL}}\,\frac{\text{hr}}{60\,\text{min}}$$

$$V = \frac{21.4\,\text{gal}\,\text{ft}^3}{7.48\,\text{gal}} = 2.86\,\text{ft}^3$$

$$V = \frac{21.4\,\text{gal}\,\text{ft3}}{7.48\,\text{gal}} = 2.86\,\text{ft}^3$$

Based on this volume, if depth (D) of the clarifier is 1.0 ft, then the cross sectional area (A_s) is 2.86 ft^2, and if the length ($\mathcal{L}$) is 2.86 ft, then the width (W) will be 1.0 ft.

Like flocculation, sedimentation was difficult to scale down because the geometry of the basin can be reduced, but the size of the discrete and flocculated particles cannot. While surface loading rates (SLRs) for full-scale sedimentation basins are typically greater than 500 gallons per day (gpd)/ft^2 [12], they are much smaller in small systems and in pilot systems in order to avoid extremely deep basins.

$\mathcal{L}$:W ratios are typically in the 2:1 to 5:1 range. Using a 1-ft depth and a $\mathcal{L}$:W = 2.86:1, then

$$SLR = \frac{gpd}{ft^2} = \frac{450\ mL}{min} \cdot \frac{\frac{1440\ min}{day}}{2\ ft} \cdot \frac{gal}{3785\ mL} = \frac{60\ gpd}{ft}$$

The settling velocity, v_s, is proportional to the SLR:

$$v_s = 60\ gpd/ft^2 \cdot \frac{4.74 \times 10^{-5}\ cm/sec}{gpd/ft^2} = 0.002\ cm/sec$$

The horizontal velocity, v_o, is defined by the flow rate, Q, = 450 mL/min and the W x D:

$$v_0 = \frac{Q}{W \times D} = \frac{450\ mL}{min\ (1 \times 1)\ ft^2} \cdot \frac{gal}{3785\ mL} \cdot \frac{ft^3}{7.48\ gal} = 0.016\ fpm$$

In full-scale basins, v_o ranges from approximately 0.5 to 3-ft/min; the v_o range is appreciably smaller in pilot systems.

The Reynolds number, R_e, is a function of the horizontal velocity, the viscosity and the hydraulic radius, R. The hydraulic radius is the cross sectional area (W x D) divided by the wetted perimeter (W+2D). At 10°C, the viscosity, $v_1 = 1.41 \times 10^{-5}$ ft^2/sec. for the 1-ft x 1-ft cross section is as follows:

$$R = \frac{A}{P} = \frac{(1\times 1)\,ft^2}{(1+1+1)\,ft} = 0.33\,ft$$

$$v_0 = \frac{0.016\,ft}{min} \cdot \frac{min}{60\,sec} = \frac{0.000265\,ft}{sec}$$

$$R_e = \frac{v_0}{\nu} = \frac{0.000265\,ft}{sec} \cdot 0.33 \cdot \frac{sec}{1.41\times 10^{-5}} = 6.2$$

The suggested Reynolds numbers for full-scale basins are below 2,000 [12]. A $R_e = 6.2$ is very laminar, but consistent with attempts to settle full-sized flocculated particles in very small and very shallow basins. Using temperatures of either 20°C or 5°C (unlikely to occur with an indoor pilot plant) has an insignificant impact on R_e.

The previous calculations were repeated for a number of scenarios and are shown in Tables C7 and C8 (Appendix C). The final design size was 1-ft x 1-ft x 34.25-in (H x W x L). A 3-in freeboard was added to the depth for a total of fifteen inches. The final design is shown in Figure B5a (Appendix B). A deflector shield and adjustable perforated baffle (Figure B5b) will be inserted in the settling basin as shown in Figures B5a and B5b (Appendix B). L = 2.85 ft and is approximately 34 inches, as shown in Figure B5a (Appendix B). Two baffle walls are utilized; their location was determined by trial and error. The closest baffle wall separator, SB1, was intended as a deflector to prevent floc from short circuiting across the basin, although the bulkhead fitting at the entry to the basin was large enough that the velocity should minimize short circuiting and not shear the floc. It is recommended that the G value through the bulkhead should not be greater than the velocity gradient within the last flocculation[12]. Because no reference on how to calculate G values for such fittings could be found, the issue of floc shearing was indirectly examined by calculating the inlet velocity (v) through the bulkhead:

$$v = \frac{Q}{A} = \left(\frac{450\,mL/min}{(0.75/12)^2\,ft^2\,(\pi/4)}\right) \cdot \frac{ft^3}{7.48\,gal} \cdot \frac{gal}{3785\,mL} \cdot \frac{min}{60\,sec} = 0.09\,ft/sec$$

In full-scale basins, inlet velocities are typically 0.5 to 5 ft/sec [12, 17, 18] to maintain floc in suspension. Since the calculated velocity was well below recommended values, the velocity was also presumed to be too low to create shearing of the floc.

The other baffle wall was intended to distribute the 450 mL/min over the cross section of the basin. Similarly, 15 holes of $^3/_8$-inch diameter will not produce velocities that will shear the floc (v = 0.023 ft/sec).

The sedimentation basin weir design was subject to experimental testing, because the weir design was complicated by the low flow conditions. The simplest design consisted of a standpipe situated at the end of the sedimentation basin at the desired water level. A ½-in diameter, stainless steel tube will set the water depth to 12 inches. The tube was located approximately ½-in from the exit wall of the basin. Based on the pipe perimeter, the weir loading rate may be calculated as

$$450\,\text{mL/min} \cdot 1440\,\text{min/day} \cdot \text{gal}/3785\,\text{mL} \cdot \frac{1}{(0.5/12\,\text{ft})\,\pi} = 1300\,\text{gpd/ft}$$

Full-scale plant weir loading rates range from 11,000 to 22,000-gpd/ft weir length [12]. A photograph of the sedimentation basin is shown in Figure B5c.

Water flowed directly downward to the filter distribution manifold. The number of elbows and length of tubing was minimized to reduce particle shearing. An air brake was introduced in the line to reduce air bubbles that can block the standpipe opening or interfere with water flow to the filters. The water was then distributed amongst the three filters.

4.1.7 Filtration

The sedimentation basin was followed by a set of three parallel cylindrical glass filter columns. Column design and operation was based on previous experiences. Dual-media, anthracite over silica sand was initially used.

Filter diameter was minimized to match flow restrictions, but not so much that it introduced complications associated with wall effects. Numerous studies have examined the D_c/D_p ratio (column-to-particle diameter ratio) needed to avoid wall effects. Generally, ratios greater than 20:30 have been considered acceptable [19-21]. For original pathogen studies, anthracite filter media was used with an effective size of approximately 1.0-millimeters (mm) – an effective size is one that exceeds the representative sample weight by 90 percent (%) – and silica sand with an effective size of 0.4 to 0.55-mm (actual sizes may vary depending upon supplier). Based upon ratio criteria (for sand), a column would have to be greater than 8 to 16.5-mm (0.31 to 0.65-in) to minimize wall effects. Previous EPA pilot plant studies have incorporated 1.5-in (38-mm) diameter columns without experiencing wall effects.

The data shown in Table 3 compares 6-in diameter and 1.5-in diameter dual media filters by their ability to remove organic contaminants from the test water; the removal efficiencies are calculated as percentages. The data was collected during a 220-day pilot study with the filters operating with a loading rate (LR) of 2-gpm/ft^2. Each filter received identical ozonated, aluminum sulfate (alum) coagulated, and settled Ohio River water. Paired t-tests showed no statistically significant difference in

any of the parameters at 95% confidence. Based upon these data and design limitations, 1.5-inch diameter columns were used.

Each filter consisted of a 6-ft high glass column and a 9-in high glass tee (all 1.5-in in diameter). The bottom three media layers (4-in of #3 gravel, 4-in of #4 gravel, and 4-in coarse sand) were used for structural support and retained by a PTFE plate as shown in Figure B6a (Appendix B). A 30-in media layer sits on top of the structural support layers. Initially, a dual media filter was assembled that consisted of a 15-in layer of anthracite over a 15-in layer of fine sand. A summary of the filter media properties is given in Table 4, and sieve analysis results are shown in Figures D1 to D3 (Appendix D). A schematic of the filter column is shown in Figure B6b (Appendix B).

Table 3. Performance comparison data between 1.5-inch (in) and 6-in filters' ability to remove organic contaminants**.**

Organic Contaminants	Percent Removal*			
	F3 (6-in diameter)		F4 (1.5-in diameter)	
formaldehyde	88 ± 5	n = 25	89 ± 5	n = 25
AOC- NOX	48 ± 12	n = 19	54 ± 10	n = 25
TOXFP	25 ± 8	n = 15	26 ± 3	n = 25
HAA6FP	36 ± 6	n = 22	41 ± 5	n = 25
THMFP	21 ± 8	n = 13	18 ± 7	n = 25
TOC	20 ± 8	n = 17	22 ± 7	n = 25
UV254	5 ± 6	n = 78	6 ± 6	n = 25
HPC(R2A)/mL (geometric mean)	93,900	n = 20	76,300	n = 20
turbidity, NTU	0.087 ± 0.024	n = 254	0.090 ± 0.027	n = 252

* Percent removal by mean percentage +/- the standard deviation.

Table 4. Filter media properties.

Layer	Depth (in)	Effective Size (mm)	Uniformity Coefficient	Size Range (mm)
Anthracite	15	0.97	1.309	—
Fine sand	15	0.45	1.544	0.45 - 0.55
Coarse sand	4	0.79	1.481	0.80 - 1.20
#3 gravel	4	—	—	3.17 - 6.35
#4 gravel	4	—	—	6.35 - 12.7

Using a 1.5-in diameter filter, the surface area, A_s, is

$$A_s = (1.5/12)^2 \cdot (\pi/4) = 0.0123\ \text{ft}^2$$

If Q is 2 gpm/ft^2, then the flow rate, Q, is

$$Q = 2\ \text{gpm/ft}^2 \cdot 0.0123\ \text{ft}^2 \cdot 3785\ \text{mL/gal} = 93\ \text{mL/min}\ (4.9\ \text{m/hr})$$

Using a 30-in media depth (not considering structural support), the empty bed contact time (EBCT), or t, is

$$t = \frac{V}{Q}$$

$$V = 0.0123\ \text{ft}^2 \cdot 2.5\ \text{ft} \cdot 7.48\ \text{gal/ft}^3 \cdot 3785\ \text{mL/gal} = 871\ \text{mL}$$

$$t = \frac{871\ \text{mL}}{93\ \text{mL/min}} = 9.4\ \text{min}$$

Values of the Q and EBCT for different loading rates are calculated in Table C9 (Appendix C).

Water was transferred to the filters from a ½-in horizontal stainless steel splitter tube through a series of $^1/_4$-in and ½-in stainless steel valves, fittings and tubing as shown in Figure B6c (Appendix B). A valve was installed at the end of the splitter tube as a filter by-pass or for periodically flushing-out settled material in the tube. The height of standing water above the media was approximately 2.5 ft. This depth was sufficient to allow for 50% bed expansion during backwashing (i.e., 15 in or 1.25 ft). The overflow port was at the 9-in glass tee located 2.5 ft above the media. Water enters each filter column at a location three inches below the overflow port. This feature prevents air bubbles from blocking filter feed lines and stopping flow to individual filters. A settled water sampling port installed in the ½-in stainless steel line connecting the sedimentation standpipe to the splitter tube at four inches above the splitter tube and seven inches below the filter overflow level (Figure B6c, Appendix B). An appropriate flushing protocol was established before sampling from this port. Photographs of various aspects of filter design are shown in Figures B6d to B6f (Appendix B).

The filters operate at a constant level mode. Pumps and valves were used to maintain a constant flow of 93 mL/min through the filter, while the head increased over time. A flow rate of approximately 450

mL/min was delivered to up to three parallel filters at a time. Overflow conditions for various filter configurations and flow rates are shown in Table C10 (Appendix C). Studies have been done to evaluate the effects of filter loading rates on pathogen removal and other studies. Hydraulic conditions may be evaluated in future pilot plant studies.

Filters operated in either normal mode or backwash mode by adjusting valve settings and operating pumps. Figure B7a (Appendix B) is a schematic of the filter flow control system and shows the pump and valve settings during normal filter operation. All tubing and fitting connections following the filter were ¼-in diameter, 304 stainless steel. Filter effluent water flowed through the effluent tubing line, past a rotameter, and would freefall from a port into a funnel and down a drain line at a height of 55 inches above the filter base. The drain lines fed individual clearwells. Filter effluent samples were collected at the freefall port. The filter pump was sized for a flow of 93 mL/min plus at least 50% (140 ml/min) at a LR of 2 gpm/ft^2. Gear pumps with digital flow controllers are used to meet desired flow. A $^1/_4$-inch plastic tubing[7] line was inserted at the base of the tube and runs along the filter height to monitor headloss.

Figure B7b (Appendix B) shows the pump and valve settings during filter backwash mode. Filter backwashing was based on one of the following: headloss, turbidity, flow rate, time, or a combination of them. Bed expansion is 50% of the bed depth, while the backwash pump has the capacity to achieve at least 100% expansion. The pump was capable of producing a flow of at least 1,400 mL/min plus 50% (2100 mL/min). Air scour is not used to break up surface accumulations due to filter size constraints. Filters are backwashed for ten minutes after 50% bed expansion is achieved, although time may be adjusted as needed. The backwash Q is 1.3 to 1.5 L/min to achieve bed expansion. Previous experience has found that desired bed expansion without losing media typically takes approximately two minutes. Adding ten minutes at 50% expansion (for a total of twelve minutes of backwashing) and multiplying by an average backwash Q of 1.4 L/min gives the volume of water, 16.8 L (4.4 gal), needed for backwashing. To accommodate this volume, clearwell volume should be at least ten gallons (37.9 L). The filters could be backwashed at least every 24 to 48 hours depending on the requirements of the study and the associated water quality parameters.

4.1.8 Clearwell (Backwash Water Storage Reservoirs)

Each filter effluent stream was initially plumbed to an independent 40-gal clearwell[8] using $^1/_4$-in stainless steel; water entered the clearwells from the top. Two ports are located at the base of the tank, one for draining the tank and the other for delivering backwash water. An overflow line controls the water level in the tank. A photograph of the clearwells is shown in Figure B8a (Appendix B).
The clearwell design was later modified to accommodate disinfection research. Ten gallon clearwells, constructed of either stainless steel or PMAA, were fabricated as shown in Figure B8b (Appendix B). The clearwells operated in upflow mode to provide sufficient residence time. Disinfectant feed and

[7] Nalgene® brand tubing was used.
[8] Nalgene® brand plastic clearwell was used.

static mixers were incorporated into the feed line (from filter effluent). Additional feed lines for NH_3, pH adjustment, and others may be added as well. Static mixers were tested to assure complete chemical mixing. A number of other sized units can be built. Table C11 (Appendix C) gives dimensions for a number of clearwell sizes. Consideration was given to make the clearwells interchangeable.

4.2 Process Considerations

All pilot plant components are modular so that they can be configured in any sequence or easily removed and replaced to satisfy the needs of various research studies (i.e., arsenic removal by iron removal studies, filter media studies, pathogen studies, etc.). Minor design changes may be necessary based upon research needs and desired outcomes. Since PMMA is relatively inexpensive and fabrication is simple, modular design easily accommodates such alterations.

4.2.1 Flow Control

Flow control throughout the pilot plant is achieved by either overflow devices such as weir boxes, pumps in combination with valves, or pumps with digital flow controllers. Valves are maintained manually. Flow rate measurements are made manually on a regular basis using a stopwatch and graduated cylinder, or by reading in-line rotameters.

4.2.2 Sludge Removal

Sludge removal was not considered in the design because continuous plant operation is unlikely to exceed one week. Sludge build-up has not been a concern for any study conducted to date. Sludge is appropriately removed from each process between runs. Similarly, none of the units other than the filters have overflow capacity. The system should be operating 24 hours a day when running a test.

4.3.3 Coagulant and Feed Systems

Coagulant solution was pumped from a 2-L glass graduated cylinder through $^1/_4$-inch PTFE tubing directly into the rapid mix chamber using a peristaltic pump. The tubing was inserted into a channel at a corner of the rapid mix chamber. The tubing was positioned so that the coagulant was dispensed at the tip of the mixer blades.

In the original pathogen pilot studies, a solution containing *Cryptosporidium parvum* oocysts was pumped from a glass flask through a 0.03-in diameter tubing into the raw water feed line between the constant head tank and the rapid mix chamber (Figure B9, Appendix B) using a peristaltic pump. A $^1/_4$-inch static mixer was added to the raw water line after the feed location for mixing. Both *Cryptosporidium parvum* oocyst and coagulant feed solutions were continuously mixed by magnetic stirrers and stirrer bars.

Chapter 5 – Operation

The pilot plant operated continuously over four- to seven-day periods (24 hours per day) in the conventional mode, although the plant has been operated in the direct filtration mode in subsequent studies. For the original pathogen study, each test run was dedicated to the study of the removal of *Cryptosporidium parvum* oocysts and other microbiological parameters from drinking water under differing water quality and pilot plant operating conditions. The impact of a number of variables was explored. These variables included, but were not limited to, coagulant type (alum, ferric chloride, polymeric coagulants), pH (enhanced coagulation), and possibly source water. The pilot plant operated to achieve optimal turbidity reduction.

Optimal coagulant dose was based on jar testing. When considering operation under enhanced coagulation, operating conditions were based on total organic carbon (TOC) removal guidelines described under the proposed Enhanced Surface Water Treatment Rule [22]. In addition, the pilot plant intentionally operated under non-ideal conditions to examine relationships between plant failure and oocyst removal. Statistical correlations between potential surrogate parameter removals such as particle counts, bacterial endospores, and *Cryptosporidium* oocyst removal were tested.

Chapter 6 – Data Collection

The most difficult and uncertain task associated with this project dealt with water quality sampling. The problem with sampling was the low flow through the system. Sampling may lead to significant draw down in the system, which can create operational concerns. The sampling protocol for any study should be well planned. For example, sampling should start from the end of the plant and move forward. If possible, on-line instrumentation should be used to gauge temperature, pH, turbidity, and particle counting. In order to develop a detailed sampling protocol, first a shakedown and test runs should be completed. A list of proposed samples and ideal sample sites is summarized in Table 5. The frequency of sampling will change with study objectives and analytical capacity.

Table 5. Proposed sample types and sites.

Sample Type and Size (bottle)	Sample Location (s)	Sample Time (hours)
ICP metals, 30 mL (Nalgene®)	raw, settled, filtered	every 8
pH, 30 mL (glass vial)	raw, settled, filtered	every 4
TIC, 30 mL (glass vial)	raw, settled, filtered	every 8
Wet chemistry (alkalinity, Cl, NO_3, NH_3, PO_4), 250 mL (Nalgene®)	raw, settled, filtered	every 8
Turbidity, 30 mL (glass vial)	raw, settled, filtered	every hour
Particle counting, 150 mL, (glass bottle)	raw, settled, filtered	every 2
Microbiological (aerobic bacterial endospores, etc.)	raw, settled, filtered	every 4 to 8
Cryptosporidium parvum	raw, settled, filtered	every 4 to 8
Organics	raw, settled, filtered	every 8

Chapter 7 – Prototype Pilot Plant System

7.1 Purpose

A prototype pilot plant system consisting of all unit processes was constructed in stages for test and evaluation purposes. The prototype system was based on an earlier design. Problems discovered during its operation have led to several modifications. The final pilot plant design described in previous sections incorporated all changes made during operation of the prototype system.

The 1.1 x 1.3-in and 2.5 x 1.5-in paddles were used for the rapid mix and flocculation chambers, respectively. The system was operated on a number of occasions at various stages of construction under real conditions, using Ohio River water and alum coagulation. Alum levels were determined through jar testing and were based on turbidity reduction. The jar test protocol was designed to simulate mixing conditions within the pilot plant and is outlined in Table A5 (Appendix A). A six paddle stirrer jar test apparatus[9] with 1.5-L rectangular PMMA jars was used.

7.2 Preliminary Tests

The first test run was conducted over a brief, five-hour period with the filters offline. The turbidity, pH, and temperature of both raw and settled waters were measured and recorded every 30 minutes (average raw water quality is shown in Table A6 [Appendix A]). An alum dose of 30 mg/L as $Al_2(SO_4)_3 \cong 14H_2O$ was used, and the system was started with the sedimentation basin drained to a level of four inches above the bottom. As the water cascaded into the sedimentation basin from the flocculation chamber, sediment at the bottom of the basin that had settled over previous trial runs was stirred-up. Monitoring results showed that settled turbidity levels continued to decrease after five hours of operation (Figure B10, Appendix B), while pH dropped by approximately one unit in response to alum addition. Two conclusions were drawn from the test run results:

(1) Five hours was not enough operation time for the system to reach equilibrium, and

(2) The system should be started when the sedimentation basin is full to reduce disturbing previously settled material.

[9] Coffman Industries, Westford, MA.

The second test run was conducted over an 11.5-hour period, and was initiated with a full sedimentation tank and an alum dose of 30 mg/L (filters were not on-line). Raw water quality data (Table A6, Appendix A) showed a considerable settling problem in the 5,500-gal storage reservoir, despite the existing operation of a recirculation pump intended for mixing. Raw water turbidity had dropped from 12.9 to 4.50 nephelometric turbidity units (NTU) over a 3-day period. Test run results showed that settled pH and turbidity values had leveled off after about seven hours of operation, which suggested that the system had reached equilibrium (Figure B11, Appendix B). Visual examination of the system showed an expected development of floc through the flocculation chambers, and a realistic floc settling pattern through the sedimentation basin. Settled turbidity levels (1 to 2 NTU) were well within expectations and representative of full-scale operation.

The third test run was conducted continuously over a 36-hour period and was the most extensive run conducted without the filters online. Turbidity, pH, particle counts, and temperature were monitored hourly, while TOC, aerobic spore forming bacteria, and heterotrophic bacteria were measured every eight hours. A detailed record log and monitoring checklist consisting of water quality measurements and pilot plant operational parameters was established. The checklist was incorporated into a log book and the data gathered during the run was later transferred to a computer spreadsheet (Table A7, Appendix A). Graphs of raw and settled water quality fluctuations over the test run are shown in Figures B12 to B16 (Appendix B). A submersible pump was placed into the storage reservoir six hours into the test run to provide additional mixing. The addition of the pump immediately increased particulate parameters, which then remained relatively steady for the remainder of the study run (see Table A5, Appendix A, for raw water quality). A small fluctuation in temperature that corresponded to building heating and cooling schedules was noted. Results showed excellent removals (>92%) for all parameters (Table A8, Appendix A). TOC removal was also within the expected range at 20%.

7.3 Tracer Studies

A step input tracer study [23] focusing on the rapid mix chambers, flocculation chambers, and sedimentation basin was conducted to hydraulically define the prototype system. Potassium chloride (KCl) was chosen as the tracer because it was readily available, non-reactive, and could be easily monitored. Total dissolved solid (TDS) concentration was used to monitor salt movement through the pilot plant. TDS provided an instantaneous surrogate measurement of KCl and was measured with a hand-held TDS meter[10].

KCl was fed at the rapid mix chamber in place of alum. The spiked KCl concentration met several criteria: (1) the salt feed rate was insignificant relative to water flow rate, (2) the resulting TDS

[10] Myron L Company, Carlsbad, CA.

contribution was significantly higher than background water level, (3) the resulting TDS concentration was lower than the upper limit of the TDS meter (2000 ppm), and (4) KCl feed solution was under-saturated. A KCl concentration of 800 mg/L was experimentally determined (Figure B17, Appendix B) to meet these criteria. This level contributed an approximately 5-fold TDS increase relative to the raw water (Ohio River water) of 200 ppm. A 72 g/L KCl feed solution was prepared in deionized water and fed into the rapid mix chamber at a rate of 5 mL/min.

The pilot plant was operated for one theoretical detention time (four hours) prior to the addition of tracer in order to establish normal flow patterns. Two sets of data were collected: one for the rapid mix chamber and flocculation chambers and one for the rapid mix chamber, flocculation chambers, and sedimentation basin. The sampling duration was three to four times the theoretical detention times, during which time, at least 30 samples were planned in order to establish statistical validity [23]. Approximately 50 mL TDS samples were withdrawn using a pipette at the exit of the sedimentation basin and at the last flocculation chamber at set times. Rapid mix TDS, temperature throughout the system, salt feed, and raw water feed rates were also monitored regularly. Samples were first taken from the furthest location from the raw water inlet and were then moved forward for subsequent samples.

Figure B18 (Appendix B) shows the raw tracer study data (background TDS subtracted out) for the rapid mix and flocculation chambers (and connecting fittings) and then the rapid mix and flocculation chambers, and the sedimentation basins (and connecting fittings). The steepness in the two curves suggests good mixing throughout and eliminates any concern for flow problems, such as short-circuiting. The full TDS spike concentration was reached in each portion of the plant after approximately 4 and 2.5 times the theoretical detention times of the rapid mix and flocculation chambers (61.5 min.) and the entire system (301.5 min.), respectively. These relatively short times are reasonable and further support the conclusion that short-circuiting, dead zones, and other flow and mixing constraints through the prototype system are not issues of concern. The tracer data was eventually used to determine appropriate sampling times during spiking events (e.g., *Cryptosporidium*) and to calculate contact time (CT) values when considering disinfection practices (Figures B19 and B20, Appendix B).

A step input tracer test was also used to evaluate flow conditions through filter #2 and #3. The test results, plotted in Figures B21 and B22 (Appendix B), showed that salt breakthrough profiles were nearly identical and that steady state salt concentration was reached after approximately two theoretical filter retention times (21 min). The curves were relatively steep suggesting relatively plug-flow conditions.

A pulse input tracer study [23] was conducted on the flocculation unit. The results were compared to curves for a number of theoretical continuous-flow stirred tank reactor (CSTR) scenarios. 30 ml of saturated KCl solution was added at the point where water from the rapid mix chamber entered the first flocculation chamber. Conductivity was measured in water samples taken at the point where water exited the last flocculation chamber in order to evaluate salt flow through the unit.

The pulse input tracer study showed that the water flow pattern through the prototype flocculation unit resembled a 1- to 2-CSTR system (Figure B23, Appendix B). Under ideal plug flow conditions, the unit would behave as a 4-CSTR system. The results suggested that some short-circuiting had occurred in the flocculation system, which could lead to insufficient mixing or incomplete floc formation. The problem was corrected by changing the baffle opening size between chambers from the original design specification of ½-in to 1-in. The mixers were also raised from ½-in to 1 ½-in off the bottom of the tank to avoid sweeping water through the openings. Following the modifications (which are reflected in the design specifications presented in this manual), the tracer study was repeated. The results of the second test (shown in Figure B24, Appendix B) showed that the modifications increased the number of CSTR's by two to three units, which was considered acceptable.

7.4 Bead Studies

Two test runs (83 and 59 hours) were conducted using Ohio River water spiked with 4.5-micrometer (μm) diameter fluorescent polystyrene beads. These runs were performed to further evaluate treatment effectiveness and reliability, as well as the *Cryptosporidium parvum* oocyst feed system. Alum dose was optimized for turbidity reduction based upon jar tests. Average water quality variables at various locations in the pilot plant treatment train are shown in Tables A9 and A10 (Appendix A). The feed system was configured to feed beads into the raw water at a concentration of approximately 1,000 beads/mL.

Log reductions of particles, aerobic bacterial endospores, turbidity, and synthetic beads are summarized in Tables A11 and A12 (Appendix A), and Figures B25 and B26 (Appendix B). Bead values for 59-hour runs were not available at the time of report preparation. One log reduction of particles, turbidity, bacterial endospores, and beads was observed after sedimentation. Filtration generally increased the total reduction of particles, beads, and endospores through Filters 1 and 2 to a log greater than 3.5. During the 83-hour test run, filter 3 was consistently less efficient than Filters 1 and 2 with respect to particle and turbidity reduction. However, filter 3 removed beads and spores more effectively than Filters 1 and 2. Laboratory notes showed that the operators often had trouble maintaining constant flow from the filters, and that Filter 3 was more problematic than the others. The prototype pilot plant used a single-speed gear pump and needle valve system to control flow through the filters. Operators noted that the original set flow could be recovered from a filter after the flow had

dropped by simply tapping the needle valve. The flow problems and inconsistent filter performances were believed to be caused by small particles or air bubbles collecting at the needle valve. The single-speed gear pumps were replaced with digitally controlled variable speed gear pumps (described in earlier report sections) before beginning the 59-hour run. During this run, flow through the filters remained constant and variations in filter performance were greatly reduced.

Thus far, only filtered turbidity levels (Figures B27 and B28, Appendix B) have been used to measure treatment performance for regulatory purposes. Although a turbidity level of 0.3 NTU in at least 95% of the measurements taken each month is currently recognized as a regulatory standard by water utilities, many systems have established filtered turbidity goals as low as 0.1 NTU. The mini pilot plant consistently produced water with a turbidity less than 0.1 NTU, well below the standards set for full-scale systems.

Chapter 8 – System Modifications

8.1 Ease and Flexibility

Since EPA's initial conventional/direct filtration mini pilot plant was constructed to study pathogen removal, three additional plants have been built. Over the years, a number of studies have been undertaken within EPA's Office of Research and Development to address a wide range of drinking water research needs. Some of these studies examined the role of water quality and plant configuration on the removal of iron and arsenic from water, and the effect of ozonation and biological treatment filtration. Minor additions or modifications to the original pilot plant design were made to conduct these studies.

The arsenic removal and ozonation studies are just two examples of the types of studies that can be conducted to examine the role of treatment processes and plant configuration, among other things, on water quality. Only minor additions or modifications to the initial conventional/direct filtration mini pilot plant were made in order to meet these and other alternative research objectives. To illustrate the ease and flexibility of the pilot plant design, brief descriptions of these modifications are discussed in Sections 8.2 and 8.3.

8.2 Arsenic and Iron Removal Studies

Arsenic and iron removal optimization pilot studies are exceptionally useful for predicting the effects of system modifications related to arsenic and iron removal (e.g., adding a strong oxidant, changing the point of oxidant application, adjusting the pH, increasing iron concentration, and replacing filter media with arsenic adsorption media). Before full-scale treatment changes are made and unnecessary costs incurred, pilot-testing some of the above system modifications can help utilities predict how changes to their system and source water treatment will alter the water quality, as well as the capacity of that system to remove iron and arsenic.

Modifications were made to the original pathogen treatment system to run tests that would more accurately simulate the conditions found in a typical iron removal treatment system. As illustrated in Figure 1, ferrous iron, Fe(II), and arsenite, As(III), where added to the water in-line just ahead of the rapid mix chamber. By removing the mixing paddles, the flocculation chamber was modified to resemble a contact vessel typically used in full-scale iron removal systems. The sedimentation step was bypassed because the additional contact time was not necessary and the water was passed through filter

media. Fe(II) and As(III) were added prior to the rapid mix chamber to simulate their respective forms observed in groundwaters. One specific set of experiments was designed to evaluate the point of chlorine addition (necessary to oxidize arsenite). There were two primary experimental processes run: (1) chlorine addition preceding Fe(II) and As(III) addition, enabling the oxidation of iron and arsenic to occur at the same time, and (2) chlorine was added to the treatment process just before entering the filter media; therefore, iron oxidation with oxygen occurred before arsenic oxidation.

Figure 1 illustrates how the pilot plant can be easily modified to address specific research questions, like how changing the point of oxidant addition (specifically a strong oxidant, in this case free chlorine) impacts removal efficiency. Additional experiments were run that also bypassed the contactor for both oxidant application points to test the need for contact time.

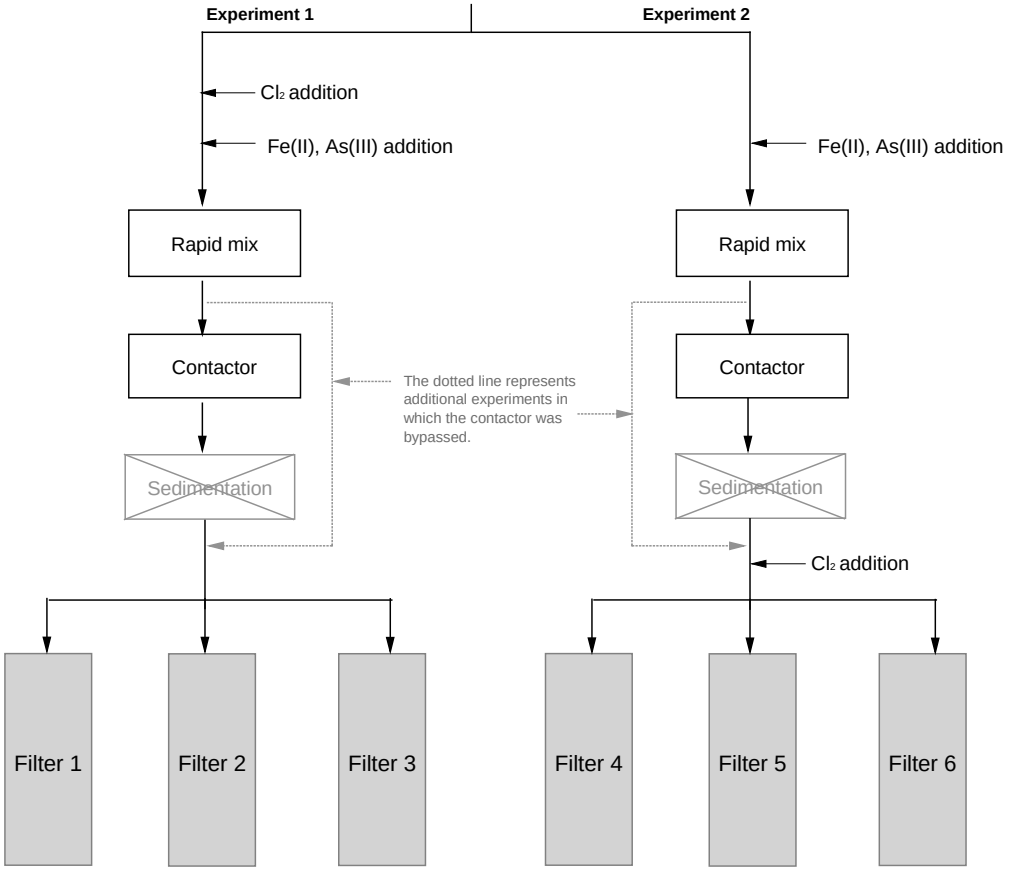

Figure 1. The effect of changing the point of oxidant application on removal efficiency.

8.3 Ozonation Studies

While the original *Cryptosporidium* study evaluated the control of the pathogens using conventional treatment methods (i.e., coagulation, flocculation, sedimentation, and filtration), a second study (referred to below as Phase 2) was conducted at the pilot plant that evaluated the control of these pathogens as a function of filter biological activity and pre-oxidation by ozone. This second study required modifications to the conventional treatment system, as shown in Figure 2. Ozone was produced by passing oxygen gas through a liquid-cooled corona discharge ozone generator (Figure 2). The feed gas ozone concentration was measured with a commercial ozone monitor. Ozone feed gas passed through a sintered stone diffuser at the bottom, while raw water flowed counter-current through the top of the 3.8-centimeter (cm) inside diameter glass contactor. The water in the contactor was maintained at a height of 170-cm. The theoretical detention time was 4.3-min. Tracer study results indicated that the detention times necessary for the effluent tracer concentration to reach 10% and 90% of the influent value were 2.5 and 7.7 min, respectively. During Ohio River Water (ORW) acclimation, the transferred ozone dose, transferred ozone/dissolved organic carbon (DOC) ratio and contactor effluent liquid phase residuals were 2.1 ($\sigma = 0.13$) mg/L, 0.80 ($\sigma = 0.062$) mg/L, and 0.50 ($\sigma = 0.052$) mg/L, respectively. With EFL water, the transferred ozone dose, transferred ozone/DOC ratio and contactor effluent liquid phase residuals were 5.1 ($\sigma = 0.55$) mg/L, 1.0 ($\sigma = 0.13$) mg/L, and 0.90 ($\sigma = 0.27$) mg/L, respectively.

In Trials 1 and 2 during Phase 2, the pilot plants were run for 9.5 and 13.5 hours, respectively. Trial 3 lasted for 36 hours. The extra run time in Trial 3 was necessary to ensure that the sedimentation basin effluent water quality and Cryptosporidium concentrations had stabilized. During Trial 2, Plant 2 influent water was ozonated to achieve a transferred ozone dose of 8.7 mg/L ($\sigma = 1.4$), a transferred ozone/TOC ratio of 3.8 and a contactor effluent liquid phase ozone residual of 0.27 mg/L ($\sigma = 0.085$). .

Pilot-scale trials were carried out in two phases to evaluate the impacts of pre-ozonation, pre-chlorination, and filter biological activity on the filtration removal of seeded *Cryptosporidium* oocysts. The principal goal was to evaluate the impact of variations in filter biological activity. As it turned out, the pre-ozonation and pre-chlorination used to generate differences in filter biological activity had a larger impact on *Cryptosporidium* removals than did the respective filter biological activities. Pre-oxidation with ozone or chlorine was associated with up to 1-log lower *Cryptosporidium* removals. This work generated a wealth of *Cryptosporidium* removal data that may be used for treatment guidance and full-scale plant design specifications.

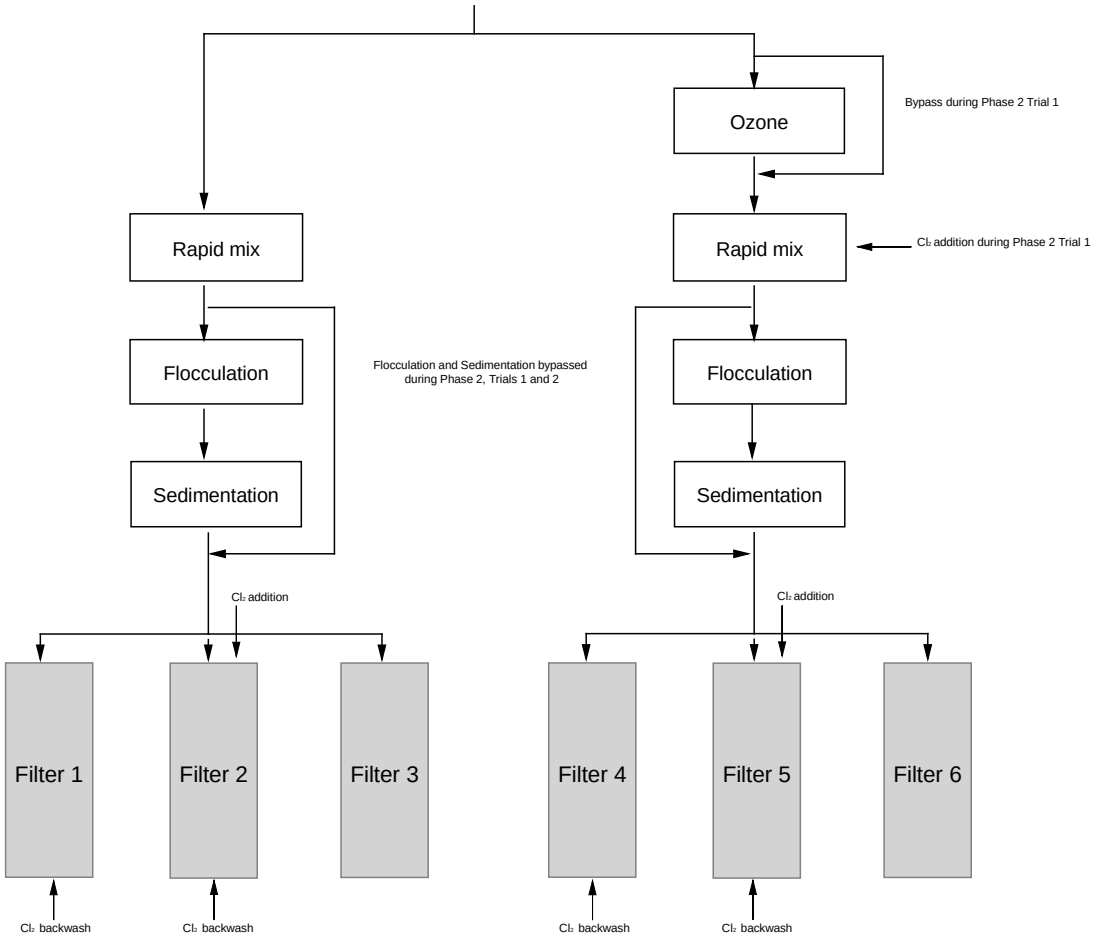

Figure 2. The effect of changing the point of oxidant application on removal efficiency.

Chapter 9 – References

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Appendix A: Tables

Table A6. Pilot plant coagulation design summary and comparisons

Design Parameter	Typical Pilot Plant[a]	Mini Pilot Plant	Full-Scale System
Mixing Chamber Shape	square, rectangular, tube, cylindrical	square	numerous
Mixer Speed [rpm]	118 to 1700	100	varies
Retention Time in Flash Mix [sec]	8 to 180	90	--
G [1/sec]	800 to 1250	195	800 to 5000[b]
Physical Dimensions LxWxH [in]	numerous	3.2 x 3.2 x 7.5	numerous
Volume of Water [L]	6 to 450	0.675	--
Flow [L/min] ([gpm])	3.8 to 450 (1 to 48)	0.45 (0.12)	--

[a] Typical pilot plant specifications were summarized from a critical evaluation of 19 pilot plants primarily located in the United States and Canada: Huck, P. M. & Anderson, W. B. (1991). "State-of-the-Art Report: Drinking Water Treatment Pilot Plants." Project Report ET006 submitted to the Ontario Ministry of the Environment, University of Waterloo (16).

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Table A7. Pilot plant flocculation design summary and comparisons.

Design Parameter	Typical Pilot Plant[a]	Mini Pilot Plant	Full-Scale System
Physical Dimensions LxWxH [in]	numerous	29.25 x 7.5 x 11.5	numerous
Number of Compartments within Tank	1 to 4	4	> 2 to 3[b]
Velocity Gradient [1/sec]	7 to 185	56.2, 30.6, 19.9, 10.8	50 to 10[b]
Mixer Speed [rpm]	10 to 85	30, 20, 15, 10	2 to 15[c]
Volume of Water (total for all units) [L]	92 to 1143	27	numerous
Flow [L/min] ([gpm])	3.8 to 450 (1 to 48)	0.45 (0.12)	numerous
Detention Time (total for all units) [min]	8 to 189	90	> 20

[a] Typical pilot plant specifications were summarized from a critical evaluation of 19 pilot plants primarily located in the United States and Canada: Huck, P. M. & Anderson, W. B. (1991). "State-of-the-Art Report: Drinking Water Treatment Pilot Plants." Project Report ET006 submitted to the Ontario Ministry of the Environment, University of Waterloo (16).

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[c] American Water Works Association (1990). "Water Quality and Treatment." Fourth Edition, McGraw Hill, Inc. (13)

Table A8. Summary of sedimentation basin design.

Parameter	Typical Pilot Plant[a]	Organics Pilot Plant	Modified Organics Pilot Plant	Mini Pilot Plant	Full-Scale System
Q [mL/min]	6,400 to 150,000	6,400	6,400	450	numerous
Detention time [hr]	1.6 to 9	8.6	5.4	3	2 to 4[b]
Volume, gal [ft^3]	7 to 132	872 (117)	548 (73)	21.4(2.86)	numerous
Surface area [ft^2]	--	33.3	20.9	2.85	numerous
Length:width	--	2.08	4.16	2.85	3 to 5[c]
Depth [ft]	--	3.5	3.5	1.0	numerous
Surface loading rate [gpd/ft^2]	--	73	116	60	500 to 1200[c]
Settling velocity (V_s) [cm/sec]	--	0.0035	0.0055	0.0028	0.024 to 0.085, Avg. = 0.045
Overflow velocity (V_o) [ft/min]	--	0.016	0.032	0.016	0.5 to 5.7[b], 0.5 to 3[c]
Re @ 10°C	--	24	29	6.2	< 2000[c]
Inlet velocity (v) [ft/sec]	--	> 0.31	> 0.31		0.5 to 2.0[c]
Weir loading [gpd/ft]	--	304	304	85	< 50,000

[a] Typical pilot plant specifications were summarized from a critical evaluation of 19 pilot plants primarily located in the United States and Canada: Huck, P. M. & Anderson, W. B. (1991). "State-of-the-Art Report: Drinking Water Treatment Pilot Plants." Project Report ET006 submitted to the Ontario Ministry of the Environment, University of Waterloo [(16)].

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Table A9. Pilot plants filter design summary and comparisons.

Design Parameter	Typical Pilot Plant[a]	Mini Pilot Plant	Full-Scale System
Filter Shape	cylinder	cylinder	rectangular
Filter Internal Diameter [in]	4 to 50	1.5	<1100 ft^2 (100 m^2)[b]
Column Height [in]	40 to 165	81	numerous
Filter Material of Construction	glass, acrylic, fiberglass, clear PVC, PMMA[c]	glass	concrete
Bed Support	varies	coarse sand, #3 & #4 gravel	gravel
Filter Media Type	typically anthracite/sand	anthracite/sand	anthracite/sand
Media Uniformity Coefficient [mm]	anthracite: 0.99 to 1.5 sand: 0.4 to 1.5	anthracite: 0.97 sand: 0.46	< 1.65[d]
Media Depth [in]	--	15/15	24 to 35 sand &/or anthracite[d]
Hydraulic Loading Rate [m/hr] ([gpd/ft^2])	5 to 20 (2.0 to 8.2)	4.9 (2 gpd/ft^2)	5 to 25[c]
Water Flowrate (L/min)	0.68 to 11.0	0.097	numerous

[a] Typical pilot plant specifications were summarized from a critical evaluation of 19 pilot plants primarily located in the United States and Canada: Huck, P. M. & Anderson, W. B. (1991). "State-of-the-Art Report: Drinking Water Treatment Pilot Plants." Project Report ET006 submitted to the Ontario Ministry of the Environment, University of Waterloo (16).

[b] James M. Montgomery Consulting Engineers (1985). "Water Treatment Principles and Design." John Wiley and Sons, New York (12).

[c] Polymethyl methacrylate (PMMA) also commonly known by the name brand Plexiglass®

[d] American Water Works Association (1990). "Water Quality and Treatment." Fourth Edition, McGraw Hill, Inc. (13)

Table A10. Jar test and pilot plant operating variables.

	Jar Test			Pilot Plant		
Process	Time (min)	RPM	G (sec -1)	Time (min)	RPM	G (sec -1)
Rapid Mix	1.5	50	192.61	1.5	100	195.1
Floc Chamber One	15	22	56.22	15	30	56.2
Floc Chamber Two	15	15	31.65	15	20	30.6
Floc Chamber Three	15	11	19.88	15	15	19.9
Floc Chamber Four	15	7	10.09	15	10	10.8
Settling Tank	60	0	0	180	0	0

Table A11. Average raw Ohio River water quality during pilot plant evaluation runs.

Run #	Date	Duration (hours)	Turbidity (NTU)	pH	Temperature (°C)	Particles (counts/10 mL)		Bacterial endospores (CFU/100mL)	HPC (CFU/mL)	TOC µg/L
						total	3-6 µm			
1	4/11/1997	5	12.9	7.99	65.1	-	-	-	-	-
2	4/14/1997	11.5	4.5	7.88	67.4	-	-	-	-	-
3	4/23/1997	36	2.4	8.13	21.3	589,000	17,500	-	-	-
3*	-	-	14.8	8.07	21.7	4,900,000	466,000	22000	25450	1.91

* Averages after the activation of the submersible pump

Table A12. Monitoring log and checklist used during Test Run 3.

DATE	TIME	ELAP TIME (hrs)	TURBIDITY-RAW	TURBIDITY-TREATED	pH-RAW	pH-TREATED	TEMP-RAW	TEMP-TREATED	TOTAL PARTICLE COUNT TREATED	PARTICLE COUNT 2-4 TREATED	TOTAL PARTICLE COUNT RAW	PARTICLE COUNT 2-4 RAW	ALUM FLOW RATE mL/min	RAW WATER FLOW RATE mL/min	ALUM VOLUME mL	SAMPLE ID TREATED	SAMPLE ID RAW	METALS	TOC	SPORES	HPC	MIXER SPEEDS	ALUM TUBE POSITION
04/22/97	6:30AM	0											3.9/5.0	480/450	1920								X
04/22/97	7:30AM	1	2.62	1.1	8.05	7.45	21.4	20.8	172779	10835	661884	31488				TR001	R(4)001						
04/22/97	8:30AM	2	2.57	0.89	8.16	7.43	21.4	21	148489	9673	595792	23024	4.9/5.0	450/OK	1440	TR002	R(4)002						X
04/22/97	9:30AM	3	2.56	0.86	8.14	7.41	21.3	20.6	128469	7761	574844	12892				TR003	R(4)003						
04/22/97	10:30AM	4	2.25	0.87	8.15	7.45	21.6	20.7	156592	7922	546192	12748	5.9/5.0	450/OK	1200	TR004	R(4)004						X
04/22/97	11:30AM	5	2.21	1.01	8.14	7.48	21.4	20.6	162139	10132	580492	13668				TR005	R(4)005						
04/22/97	12:30AM	6	2.3	1.04	8.14	7.45	20.9	20.5	148412	8895	576136	10980	5.0/OK	450/OK	680/1680	TR006	R(4)006						X
04/22/97	1:30PM	7	9.54	1.02	8.14	7.35	21.0	20.2	140067	10503	1170360	121070				TR007	R(10)007						
04/22/97	2:30PM	8	14.87	0.83	8.14	7.34	20.9	20.2	132960	10017	1084870	120100	5.0/OK	450/OK	1060	TR008	R(10)008	X	X	X	X	X	X
04/22/97	3:30PM	9	14.83	0.98	8.13	7.36	21.4	20.2	139083	11548	2212960	234640				TR009	R(20)009						
04/22/97	4:30PM	10	16.8	0.96	8.04	7.34	21	20.4	190180	13490	3780280	584940	5	450		TR010	R(20)010						X
04/22/97	5:30PM	11	19.4	1.1	8.18	7.31	21	20.3	160103	17641	3684420	527280				TR011	R(20)011						
04/22/97	6:30PM	12	16.5	1.08	8.09	7.37	21.6	20.8	168704	19262	5305120	618600			920/1920	TR012	R(40)012						X
04/22/97	7:30PM	13	15.9	0.99	7.96	7.16	22	21.5	174792	21556	5155520	555480			1620	TR013	R(40)013						
04/22/97	8:30PM	14	14.4	1	8.16	7.44	22.3		175124	21029	5365600	581200	5		1340	TR014	R(40)014						X
04/22/97	9:30PM	15	16.22	1.06	8.14	7.33	22.3	21.9	171972	19048	5271680	544040		455	1060	TR015	R(40)015						
04/22/97	10:30PM	16	15.1	1.19	8.18	7.26	21.8	21.4	172185	18413	5278960	534720	5	460	740	TR016	R(40)016	X	X	X	X	X	X
04/22/97	11:30PM	17	14.9	1.16	8.07	7.22	21.9	21.5	172546	18306	5422200	540720			460/2000	TR017	R(40)017						
04/23/97	12:30PM	18	14.7	1.08	8.09	7.33	21.9	21.6	168492	17902	5434360	549160	5	455	1740	TR018	R(40)018						
04/23/97	1:30AM	19	15.64	0.96	8.08	7.2	22	21.8	172914	19241	5385920	523320			1460	TR019	R(40)019						
04/23/97	2:30AM	20	16.42	1.12	8.08	7.15	22.1	21.7	176211	20404	5467680	561000	5.1	454	1010	TR020	R(40)020						
04/23/97	3:30AM	21	16.2	0.94	8.08	7.23	22	21.9	174033	19274	5534120	543480			830/2000	TR021	R(40)021						
04/23/97	4:30AM	22	15.85	0.91	8.03	7.23	22.1	22	172157	17636	5423320	510000	5.1	455	1675	TR022	R(40)022						
04/23/97	5:30AM	23	15.33	1	8.04	7.22	22.1	22	173660	17883	5417240	501200			1430	TR023	R(40)023						
04/23/97	6:30AM	24	14.72	1	7.92	7.28	22	22	171991	18171	5446600	493800	5.2/5.0	460	1050	TR024	R(40)024	X					
04/23/97	7:30AM	25	15.15	1.09	8.01	7.24	21.8	21.6	169993	18610	5351360	472400			835/2000	TR025	R(40)025						
04/23/97	8:30AM	26	15	1.05	7.91	7.27	21.8	21.4	172310	19852	5437120	489720	5	460	1720	TR026	R(40)026						
04/23/97	9:30AM	27	13.51	1.06	8.06	7.38	21.3	20.8	171978	18877			5	460		TR027	R(40)027						X
04/23/97	10:30AM	28	13.72	1	8.12	7.45	21.4	20.7	172582	20453	5597960	474240	5.1/5.0	450	1140	TR028	R(40)028						X
04/23/97	11:30AM	29	14.04	1.06	8	7.36	21.3	20.3	172862	20165	5419560	453520			900/2000	TR029	R(40)029						X
04/23/97	12:30AM	30	13.95	1.04	7.91	7.27	21.4	20.4	174156	19305	5795960	415920	5	450	1740	TR030	R(40)030						X
04/23/97	1:30PM	31	14.01	1.04	8.03	7.43	21.6	20.6	182867	21294	5383760	476000			1450	TR031	R(40)031						
04/23/97	2:30PM	32	13.2	0.98	8.14	7.54	21.8	20.5	188447	24533	5596880	467000	5	450	1140/2000	TR032	R(40)032	X	X	X	X	X	X
04/23/97	3:30PM	33	13.95	1.06	8.15	7.51	21.6	20.7	195059	27933	5535800	438480			1760	TR033	R(40)033						
04/23/97	4:30PM	34	13.59	1.08	8.04	7.46	21.6	20.6	194932	27899	5394560	424040	5	450	1480	TR034	R(40)034						
04/23/97	5:30PM	35	13.25	1.33	8.14	7.45	21.4	20.6	211706	32767	5530920	442440			1120	TR035	R(40)035						X
04/23/97	6:30PM	36	13.34	1.21	8.14	7.46	21.4	20.6	231815	42769	5084200	307640	5	450		TR036	R(40)036						
	Avg0-6		2.418	0.962	8.130	7.445	21.333	20.700	152813.333	9203.000	589223.333	17466.667											
	Avg7-36		14.801	1.046	8.073	7.331	21.660	21.041	174862.700	20209.367	4895492.759	465729.310											
	Avg0-36		12.737	1.032	8.083	7.350	21.606	20.983	171187.806	18374.972	4157275.143	388884.286											

Table A13. Average percent and log reductions for Test Run 3.

Parameter	n	% Reduction	Log Reduction
Turbidity	30	92.8	1.15
Total particles	29	95.9	1.42
3-6 µm particles	29	95.2	1.35
Bacterial endospores	4	94.0	1.22
Heterotrophic plate count	4	92.3	1.13
Total organic carbon	4	20	--

Table A14. Water quality parameters for mini pilot plant 83-hour test run.

Parameter	Stage	n	Mean	Std. Deviation	Minimum	Maximum
Turbidity, ntu	Raw	67	15.51	0.65	14.30	17.17
	Settled	67	1.90	0.29	1.20	2.74
	Filter 1	67	0.06	0.02	0.03	0.14
	Filter 2	67	0.06	0.02	0.04	0.12
	Filter 3	67	0.13	0.03	0.08	0.25
pH	Raw	17	8.27	0.09	8.09	8.37
	Settled	17	6.83	0.10	6.70	7.03
	Filter 1	17	6.88	0.20	6.10	7.10
	Filter 2	17	7.00	0.24	6.83	7.94
	Filter 3	17	6.72	1.10	2.05	7.17
Temperature, °F	Raw	41	75.8	0.50	74.9	77.0
	Settled	51	75.0	1.18	72.7	76.8
Total particle counts, counts/10 mL	Raw	35	8415539	689943	6035300	9458700
	Settled	35	784171	173228	443990	1073930
	Filter 1	35	2918	1309	1214	5636
	Filter 2	35	5138	3390	1094	1094
	Filter 3	35	20233	6996	8634	41304
3-6 µm particle counts, counts/10 mL	Raw	35	633079	138357	321830	976800
	Settled	35	91793	34814	38980	159330
	Filter 1	35	136	88	40	497
	Filter 2	35	219	124	57	599
	Filter 3	35	677	220	317	1201
Aerobic bacterial endospores, CFU/100 mL	Raw	6	35000	7668	22000	44000
	Settled	6	2392	531	1650	3000
	Filter 1	6	27	32	8	92
	Filter 2	6	15	9	6	32
	Filter 3	6	8	4	4	12
Synthetic beads, beads/L	Raw	5	732000	178710	42500	979000
	Settled	4	69575	12583	58000	82000
	Filter 1	2	286	297	77	496
	Filter 2	5	259	60	196	436
	Filter 3	5	185	112	58	267

Table A15. Water quality parameters for mini pilot plant 59-hour test run.

Parameter	Stage	n	Mean	Std. Deviatio	Minimum	Maximum
Turbidity, NTU	Raw	45	23.45	0.62	22.30	24.80
	Settled	45	1.59	0.23	1.12	2.00
	Filter 1	44	0.06	0.03	0.01	0.15
	Filter 2	44	0.06	0.03	0.01	0.11
	Filter 3	44	0.06	0.03	0.00	0.11
pH	Raw	13	8.18	0.09	8.01	8.33
	Settled	13	6.88	0.07	6.78	7.03
	Filter 1	13	6.84	0.08	6.74	6.98
	Filter 2	13	6.84	0.08	6.68	6.96
	Filter 3	13	6.84	0.08	6.69	6.98
Temperature, ^{o}F	Raw	23	78.67	2.10	75.50	82.00
	Settled	28	74.69	1.08	73.20	77.00
Total particles, counts/mL	Raw	24	13109312	917017	10666200	14255040
	Settled	24	804969	130786	532570	1056120
	Filter 1	24	2200	780	1044	3865
	Filter 2	24	1336	4991	544	4991
	Filter 3	24	1153	502	531	2320
3-6µm particles, counts/10 mL	Raw	24	1020704	112302	773120	1176350
	Settled	24	64033	14076	32800	84430
	Filter 1	24	130	87	35	355
	Filter 2	24	153	134	19	541
	Filter 3	24	77	74	13	285
Aerobic bacterial endospores, CFU/100 mL	Raw	6	48333	10093	38000	65000
	Settled	6	2008	472	1400	2550
	Filter 1	6	101	68	36	224
	Filter 2	6	3	1	1	4
	Filter 3	6	2	1	1	4
Synthetic beads, beads/L	Raw	5	594100	345015	42500	979000
	Settled	4	348000	62780	290000	410000
	Filter 1	2	286	297	77	496
	Filter 2	5	306	88	196	436
	Filter 3	5	139	101	58	267

Table A16. Average log reductions during 83-hour test run.

Analysis	Stage	n	Avg. Log Reduction	Std. Deviation
Total particles	Settled	35	1.0	0.09
	Filter 1	35	3.5	0.20
	Filter 2	35	3.3	0.34
	Filter 3	35	2.6	0.13
3-6 µm particles	Settled	35	0.9	0.20
	Filter 1	35	3.7	0.23
	Filter 2	35	3.5	0.28
	Filter 3	35	3.0	0.17
Aerobic bacterial endospores	Settled	6	1.2	0.17
	Filter 1	6	3.3	0.42
	Filter 2	6	3.4	0.25
	Filter 3	6	3.7	0.32
Synthetic beads	Settled	4	1.0	0.09
	Filter 1	2	3.5	0.51
	Filter 2	5	3.5	0.11
	Filter 3	5	3.7	0.35
Turbidity	Settled	67	0.9	0.07
	Filter 1	67	2.4	0.15
	Filter 2	67	2.4	0.12
	Filter 3	67	2.1	0.11

Table A17. Average log reductions during 59-hour test run.

Analysis	Stage	n	Avg. Log Reduction	Std. Deviation
Total Particles	Settled	24	1.2	0.06
	Filter 1	24	3.8	0.16
	Filter 2	24	4.1	0.22
	Filter 3	24	4.1	0.18
3-6 µm Particles	Settled	24	1.2	0.08
	Filter 1	24	4.0	0.25
	Filter 2	24	4.0	0.38
	Filter 3	24	4.3	0.39
Aerobic bacterial endospores	Settled	6	1.4	0.12
	Filter 1	6	2.8	0.27
	Filter 2	6	4.3	0.28
	Filter 3	6	4.4	0.28
Turbidity	Settled	45	1.2	0.07
	Filter 1	44	2.6	0.29
	Filter 2	44	2.7	0.31
	Filter 3	44	2.6	0.26

Appendix B: Figures

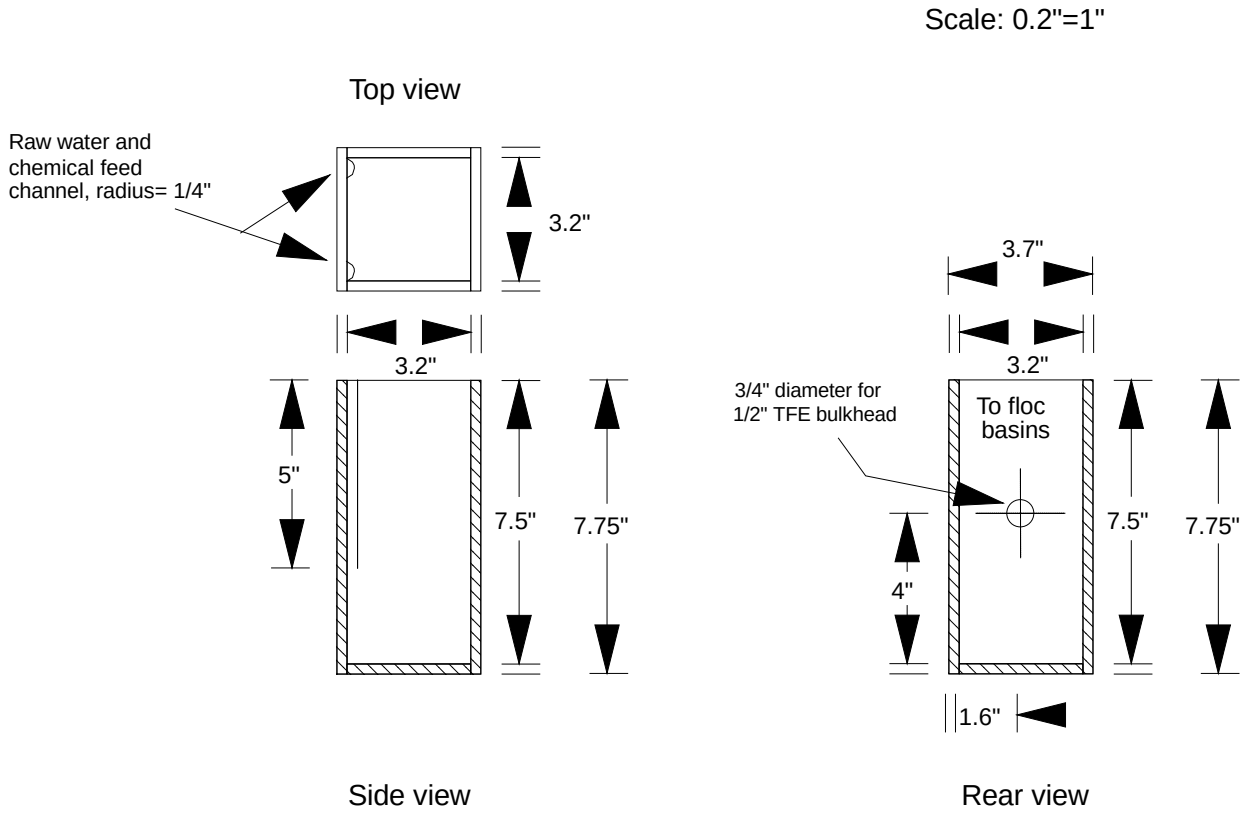

Figure B3. Rapid mix chamber dimensions constructed of ¼-inch polymethyl methacrylate (PMMA).

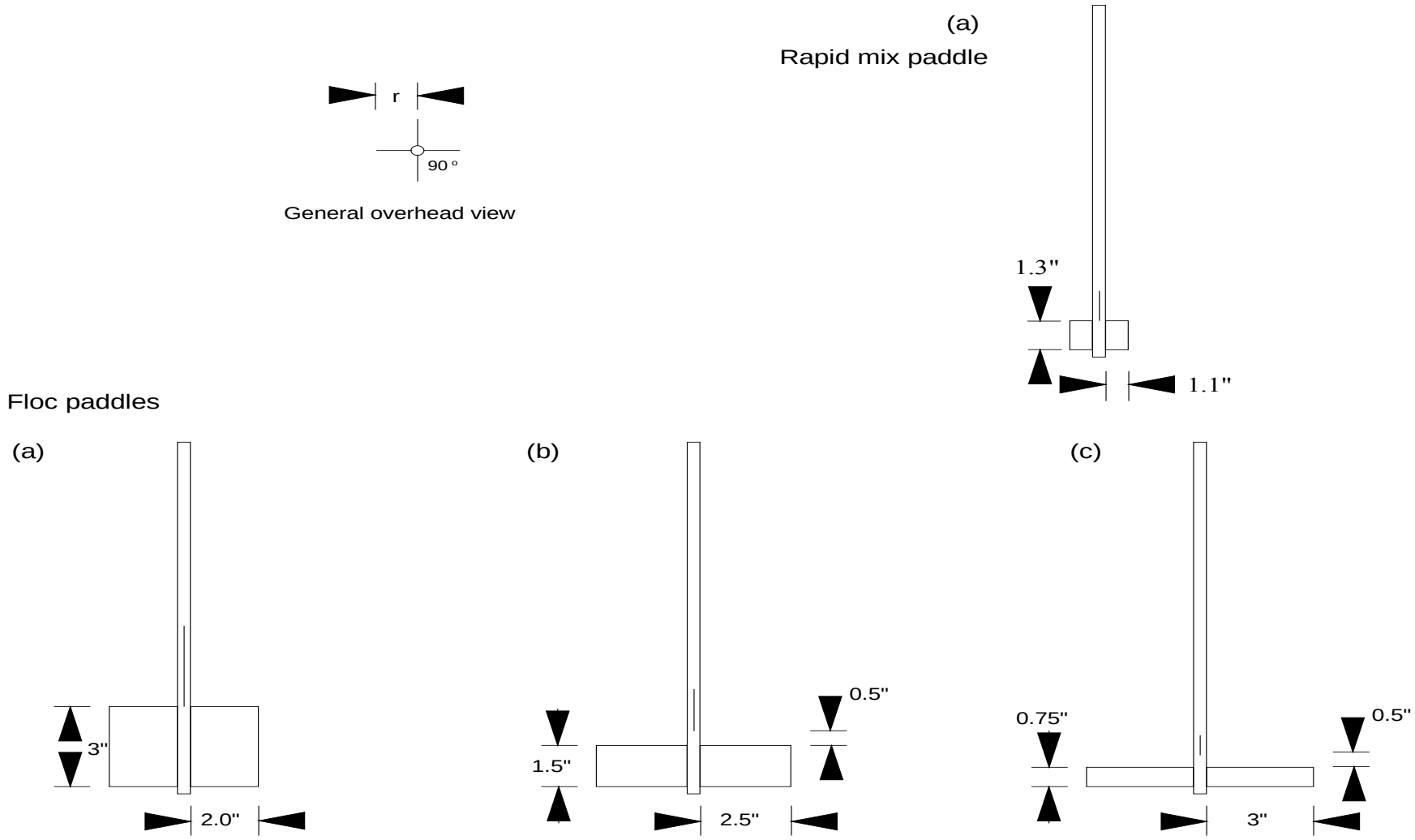

Figure B4. Mixing paddle options/alternatives constructed of stainless steel.

Figure B5. Rapid mixing chamber with influent and alum feed lines.

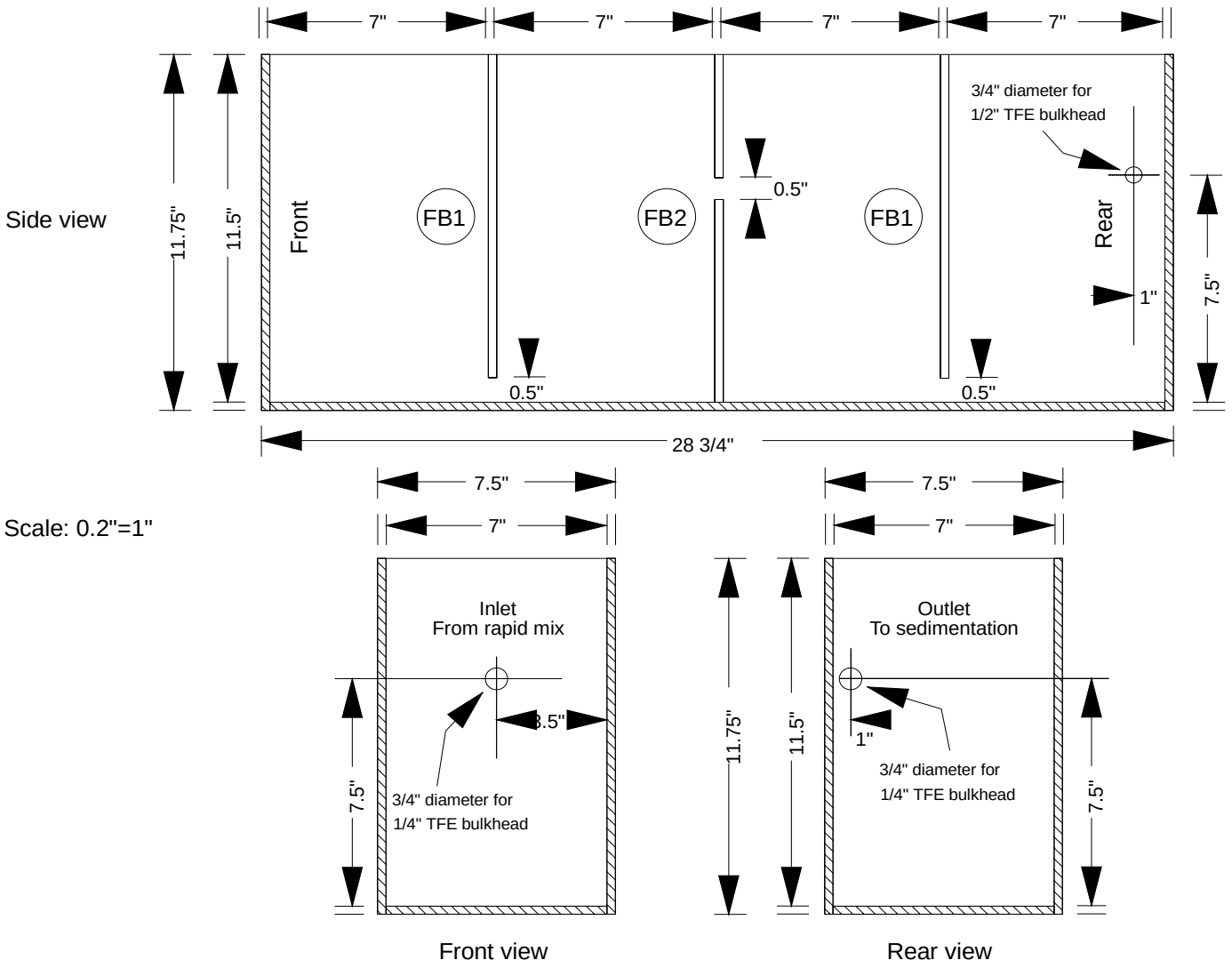

Figure B6a. Flocculation basin dimensions constructed of ¼-inch polymethyl methacrylate (PMMA).

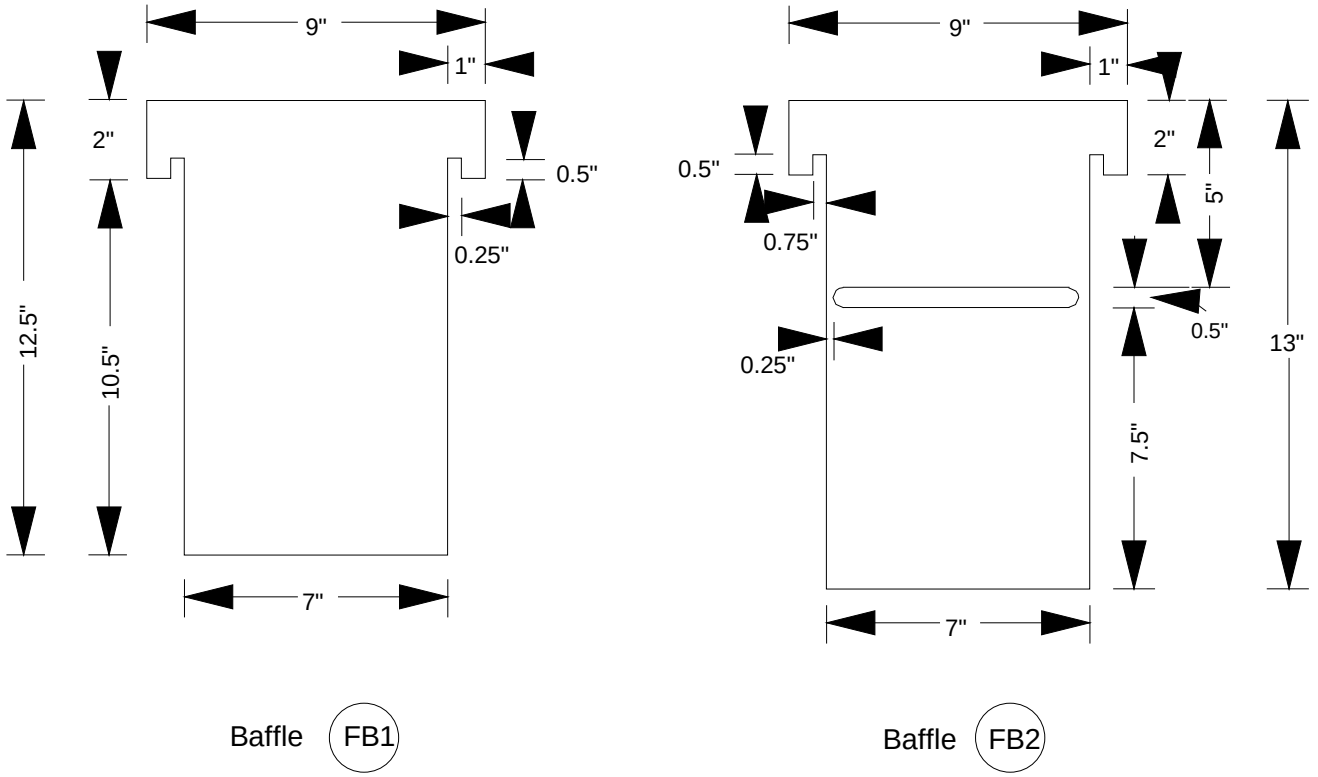

Figure B7b. Flocculation baffle dimensions (constructed of ¼"–in polymethyl methacrylate).

Figure B8c. Flocculation chambers (side view).

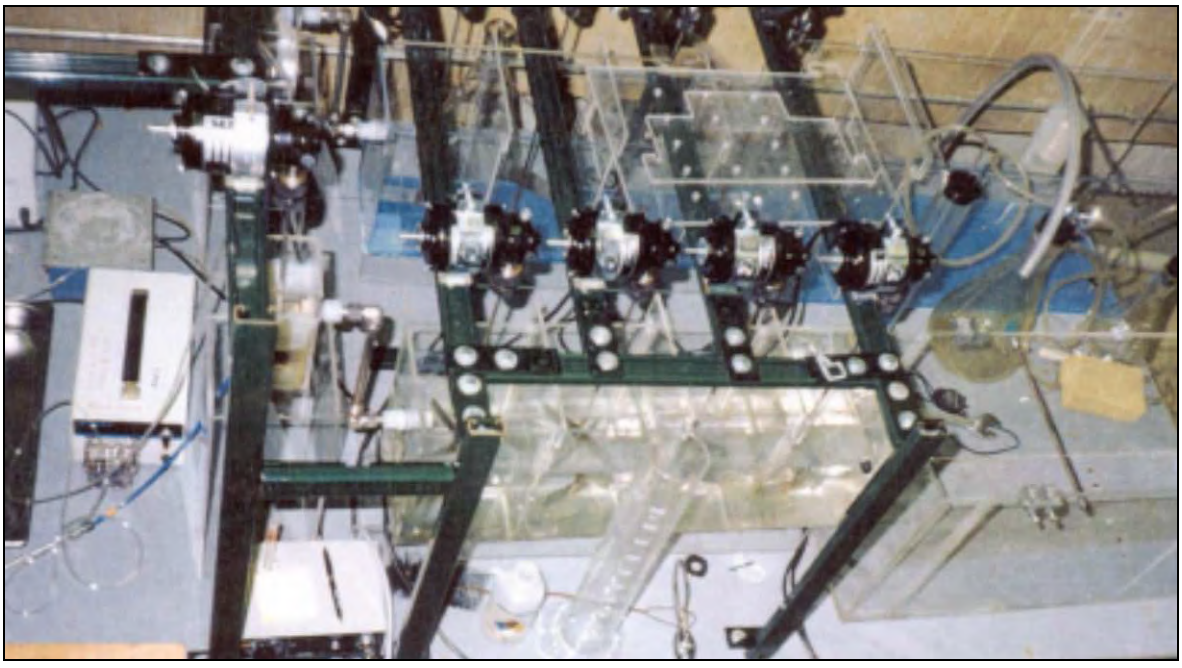

Figure B9d. Flocculation chambers (top view).

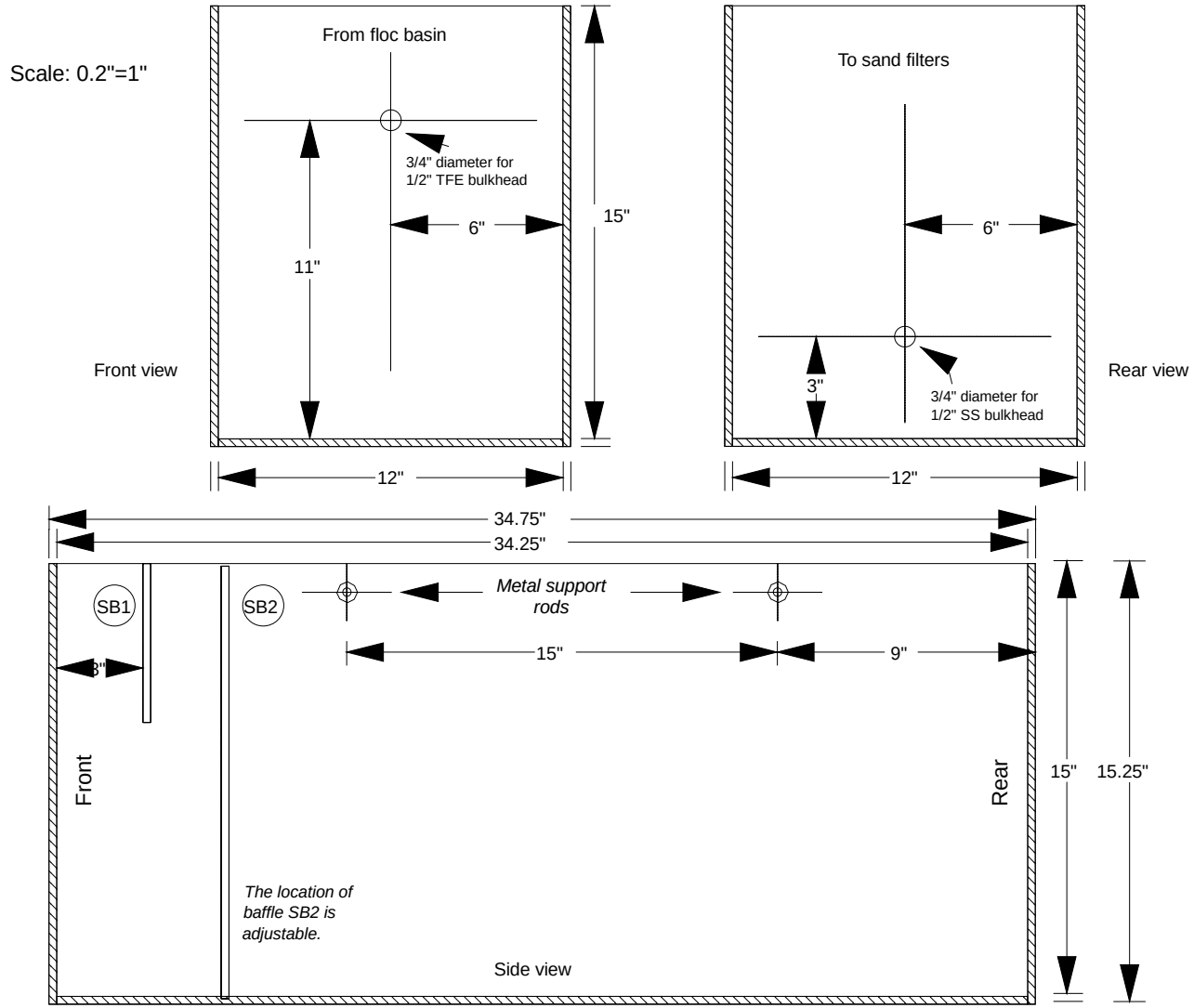

Figure B5a. Settling basin design constructed of ¼-inch polymethyl methacrylate (PMMA).

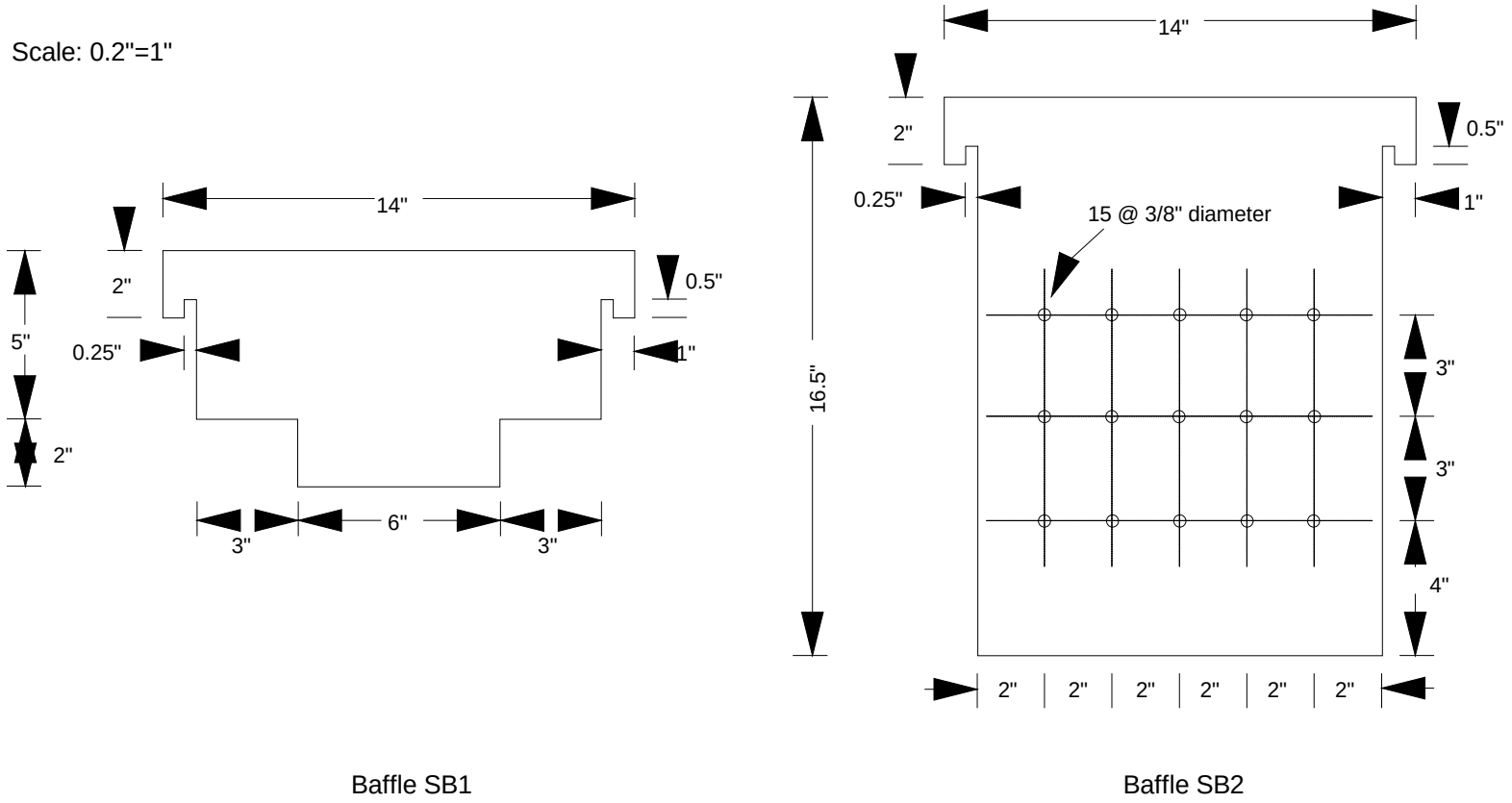

Figure B5b. Settling baffles design constructed of ¼-inch polymethyl methacrylate (PMMA).

Figure B10c. Sedimentation basin showing sludge accumulation after a 72-hr run.

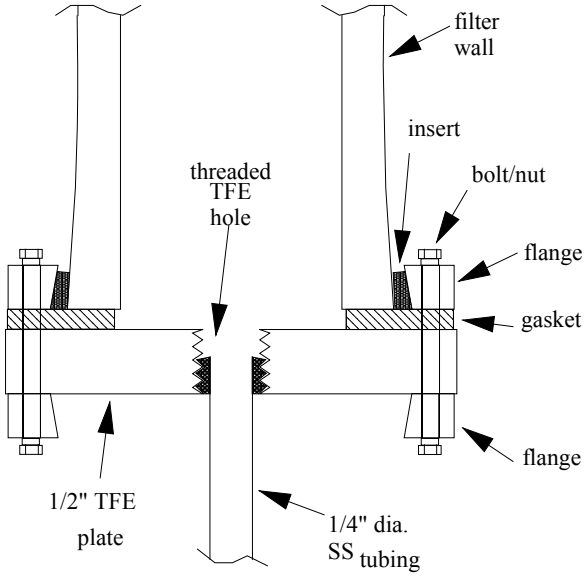

Figure B11a. Filter base design details (not drawn to scale).

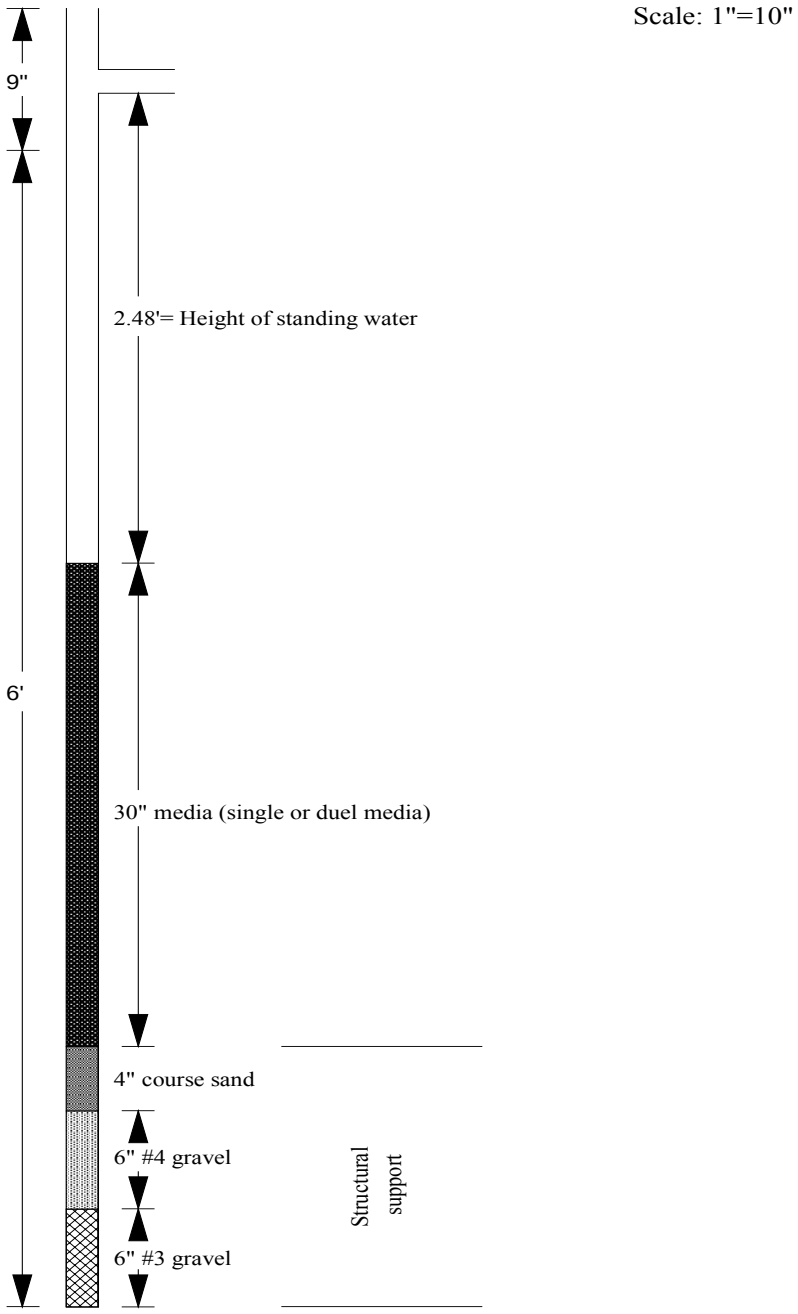

Figure B12b. Filter design and media configuration.

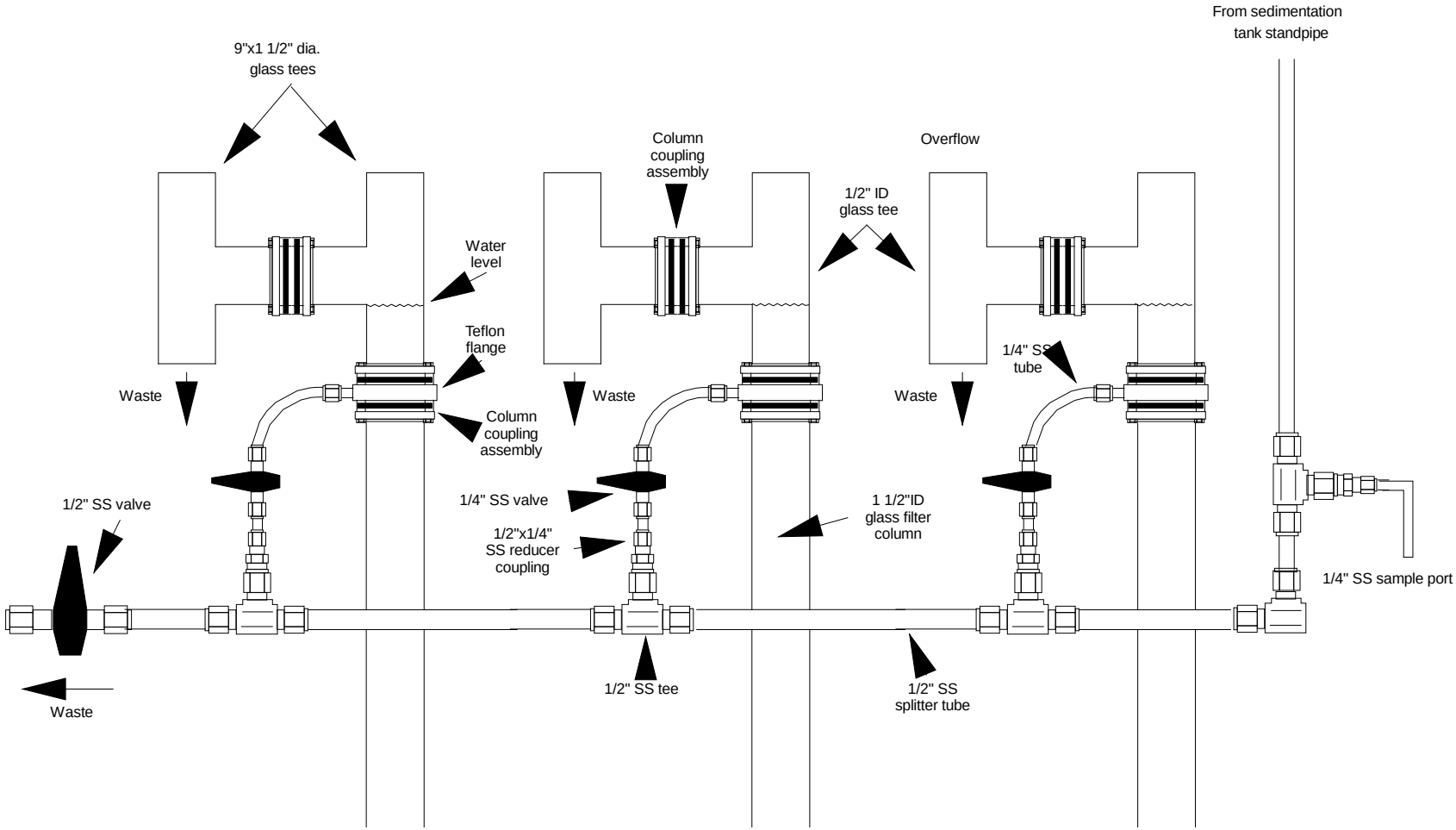

Figure B13c. Detail of filter top including filter splitter tube (not to scale).

Figure B14d. Full view of filter setup.

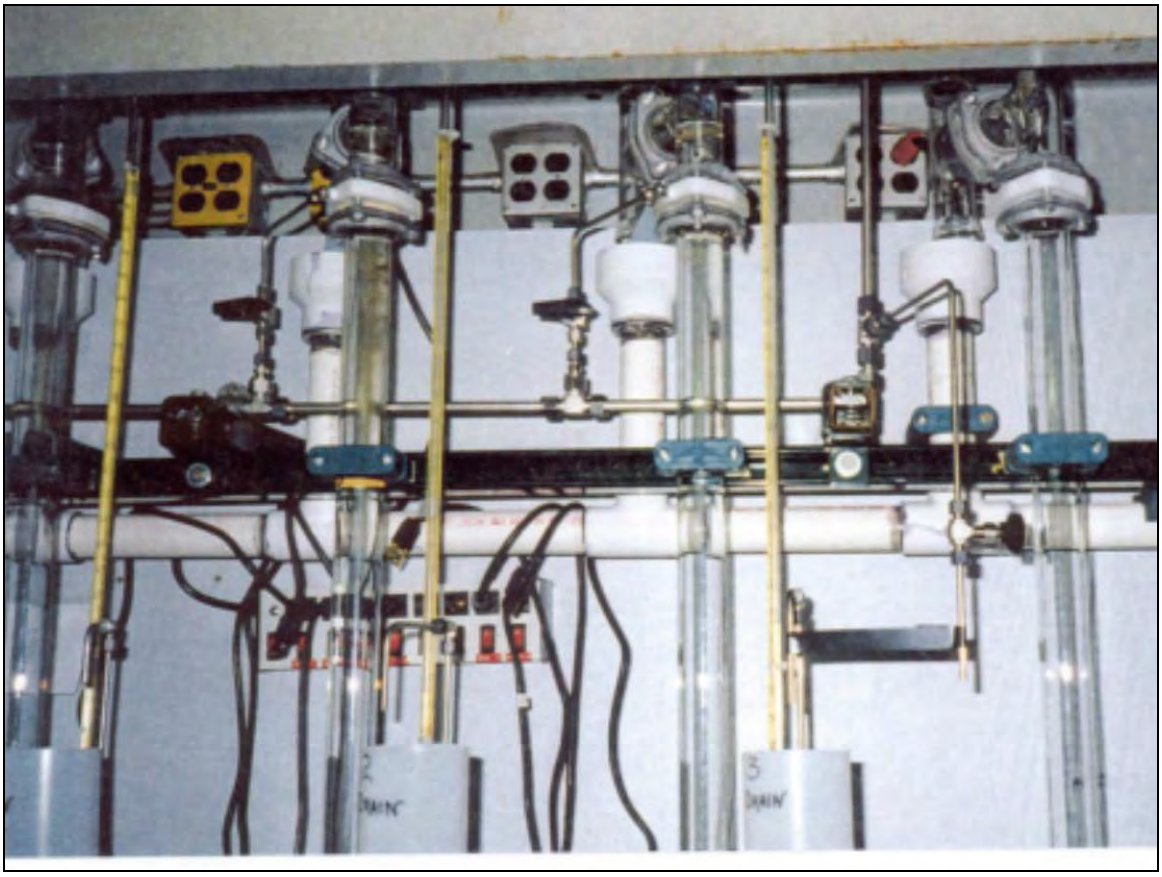

Figure B15e. Filter distribution network showing sample ports for settled water and filtrate.

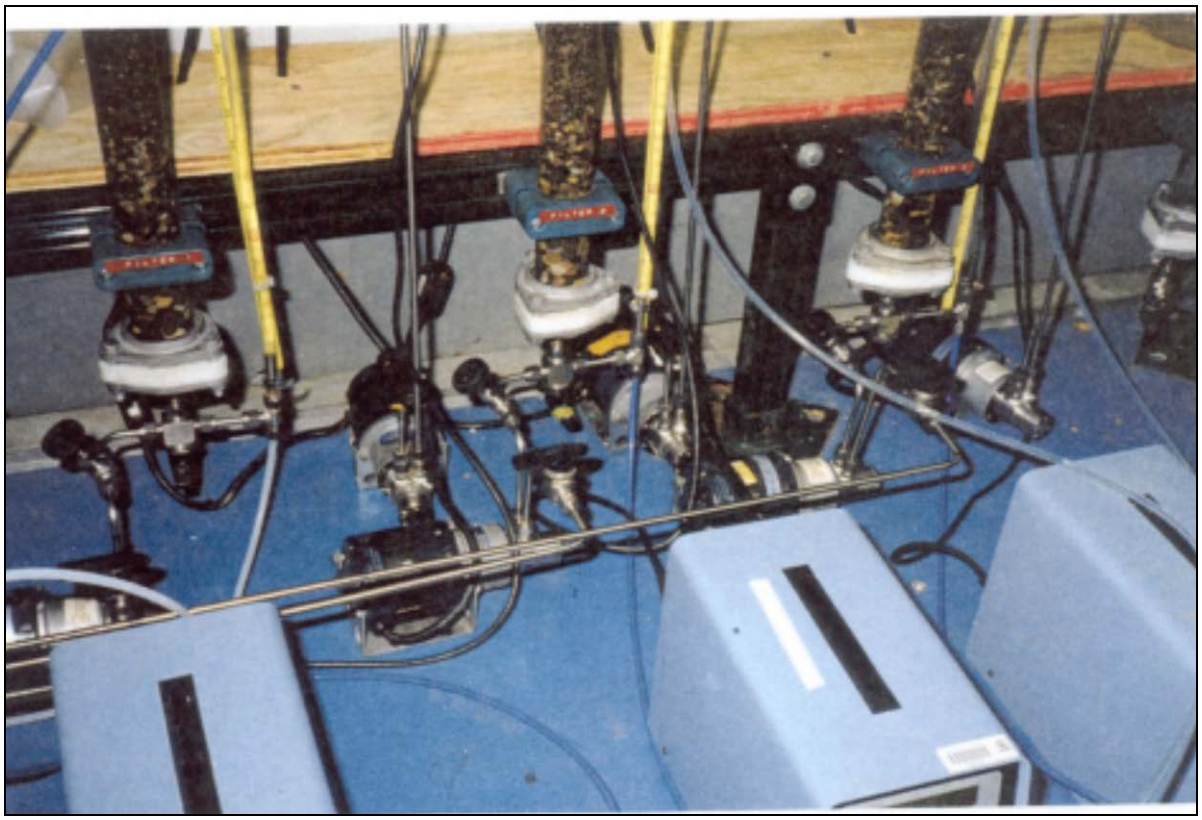

Figure B16f. Filter pump system and backwash pumps.

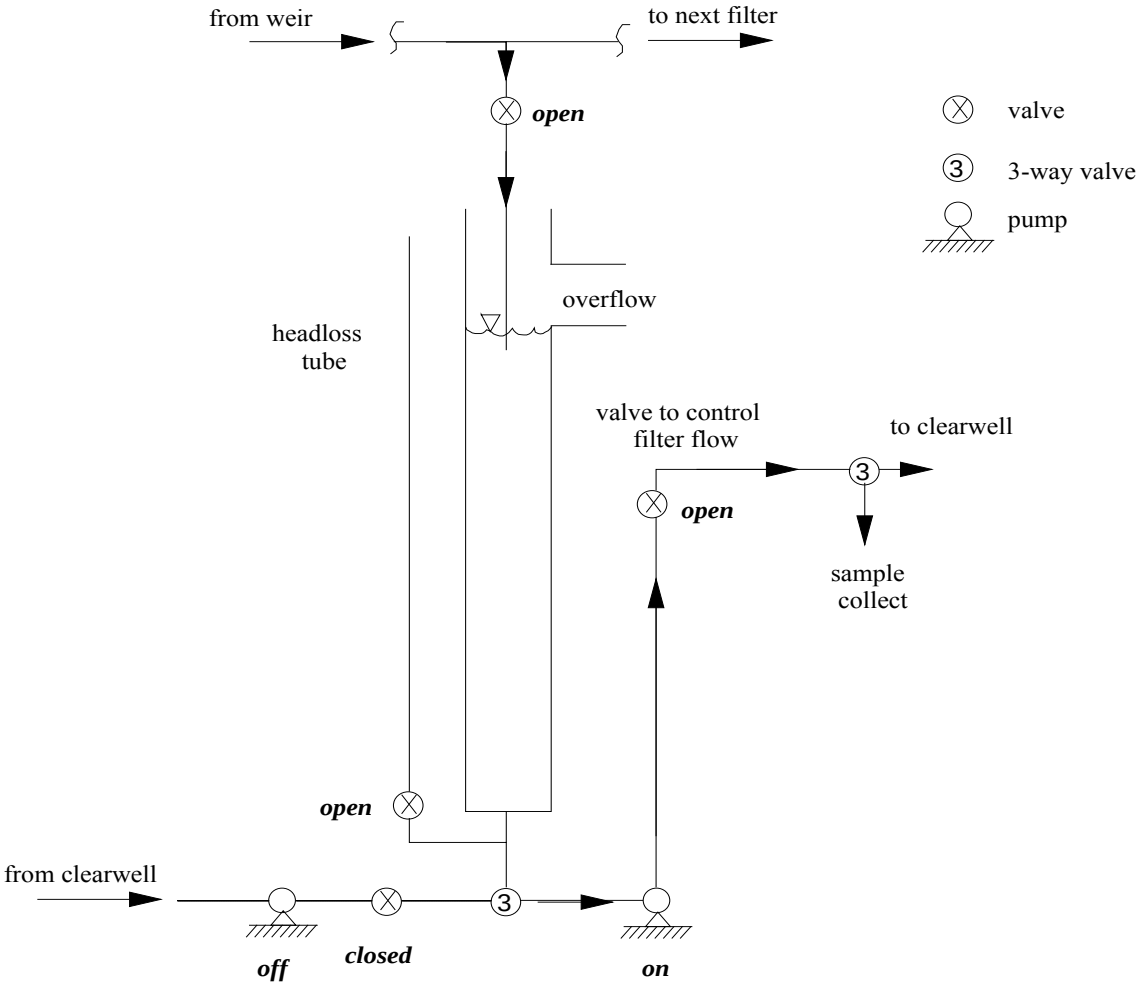

Figure B17a. Water flow direction and filter configuration when in normal operation.

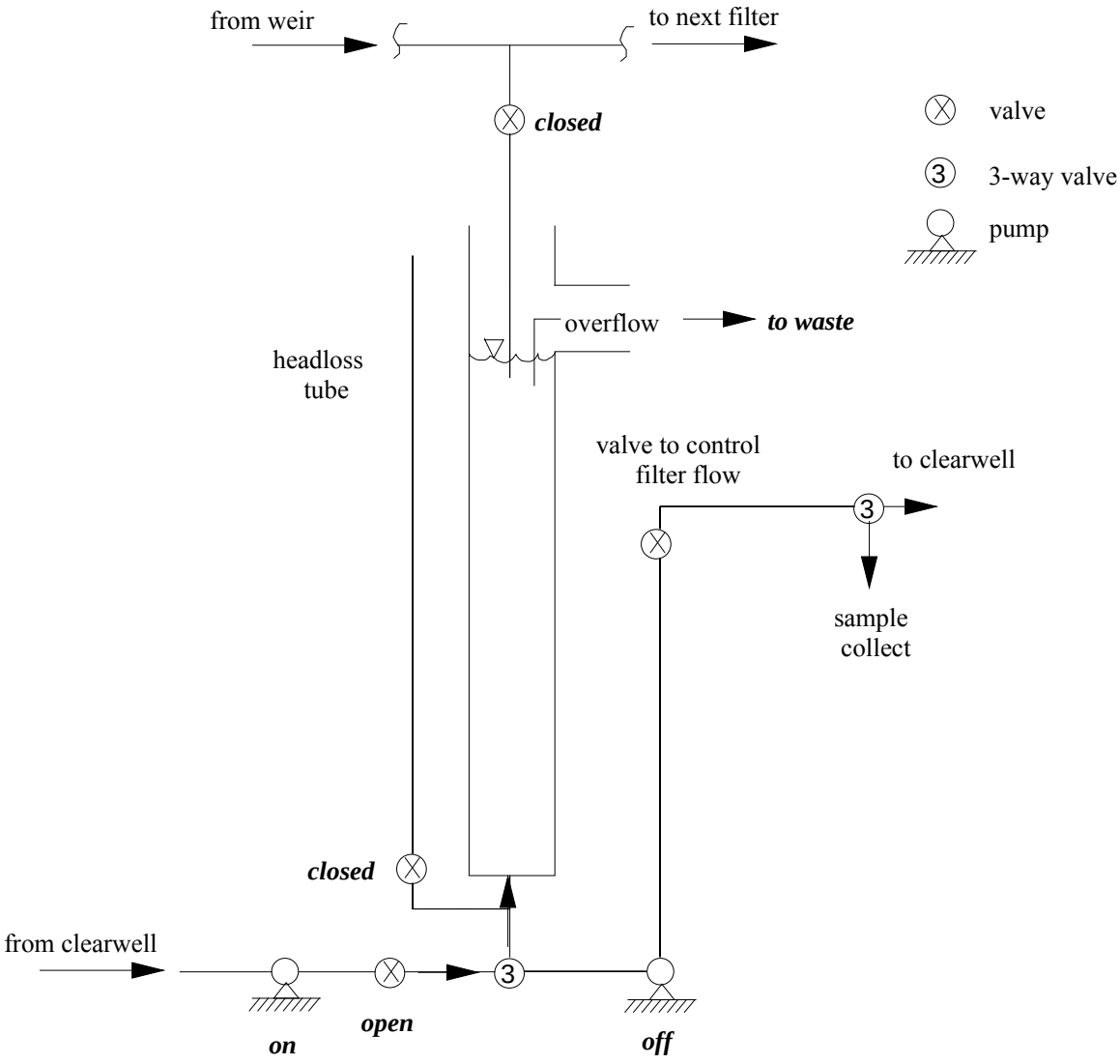

Figure B18b. Water flow direction and filter configuration when in backwash mode.

Figure B19a. Filtrate clearwells showing lines leading to waste and to backwash.

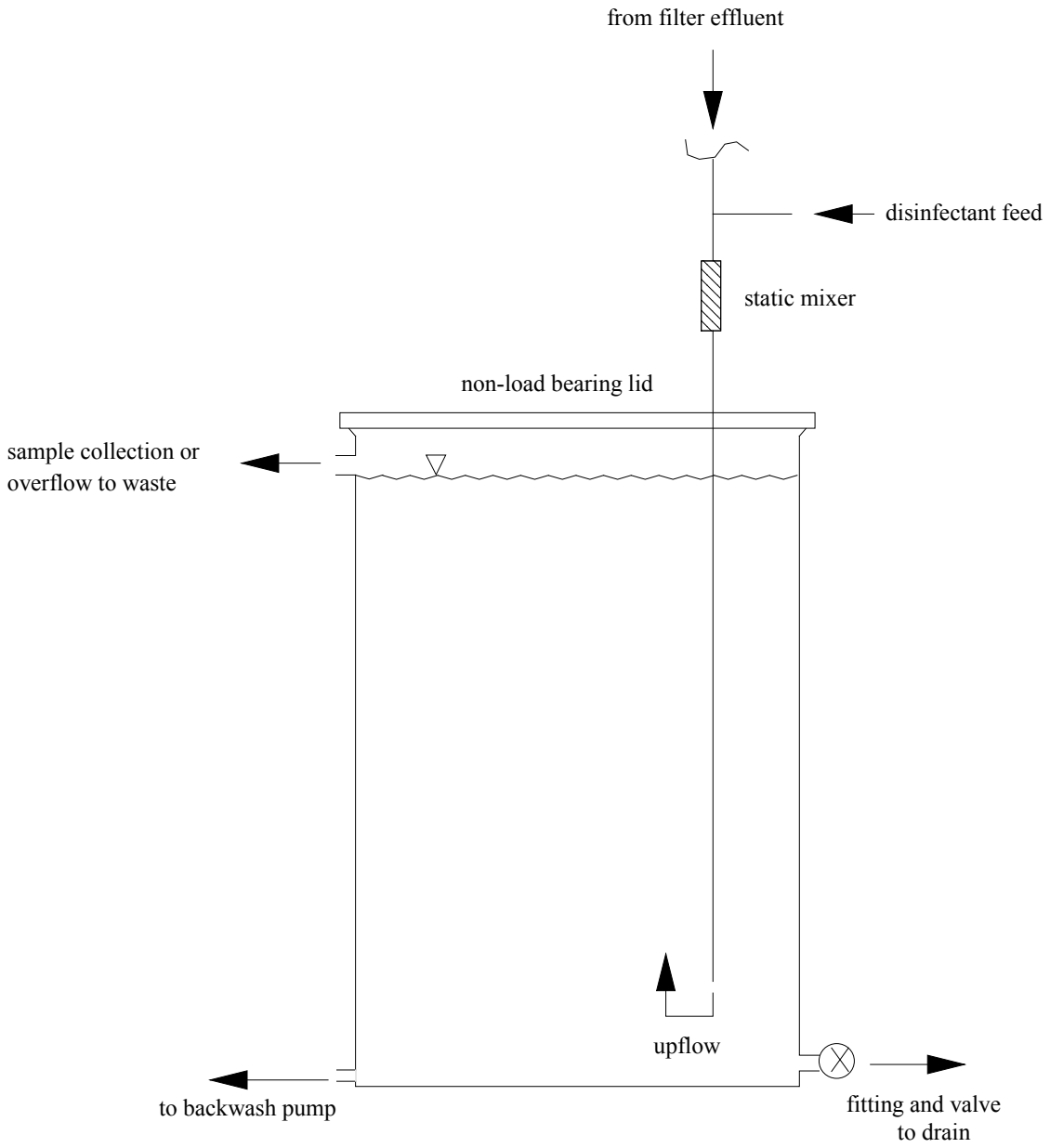

Figure B20b. Schematic of future clearwell (not to scale).

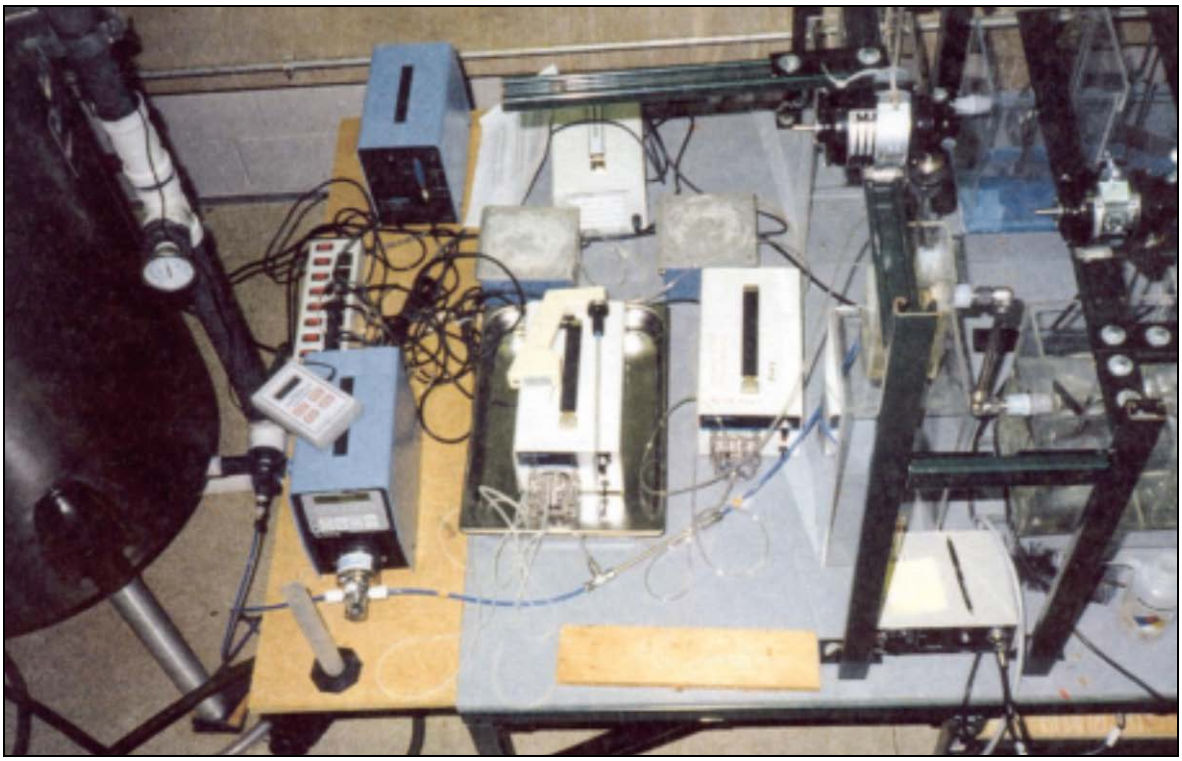

Figure B21. Raw water and alum feed systems for *Cryptosporidium parvum* oocyst.

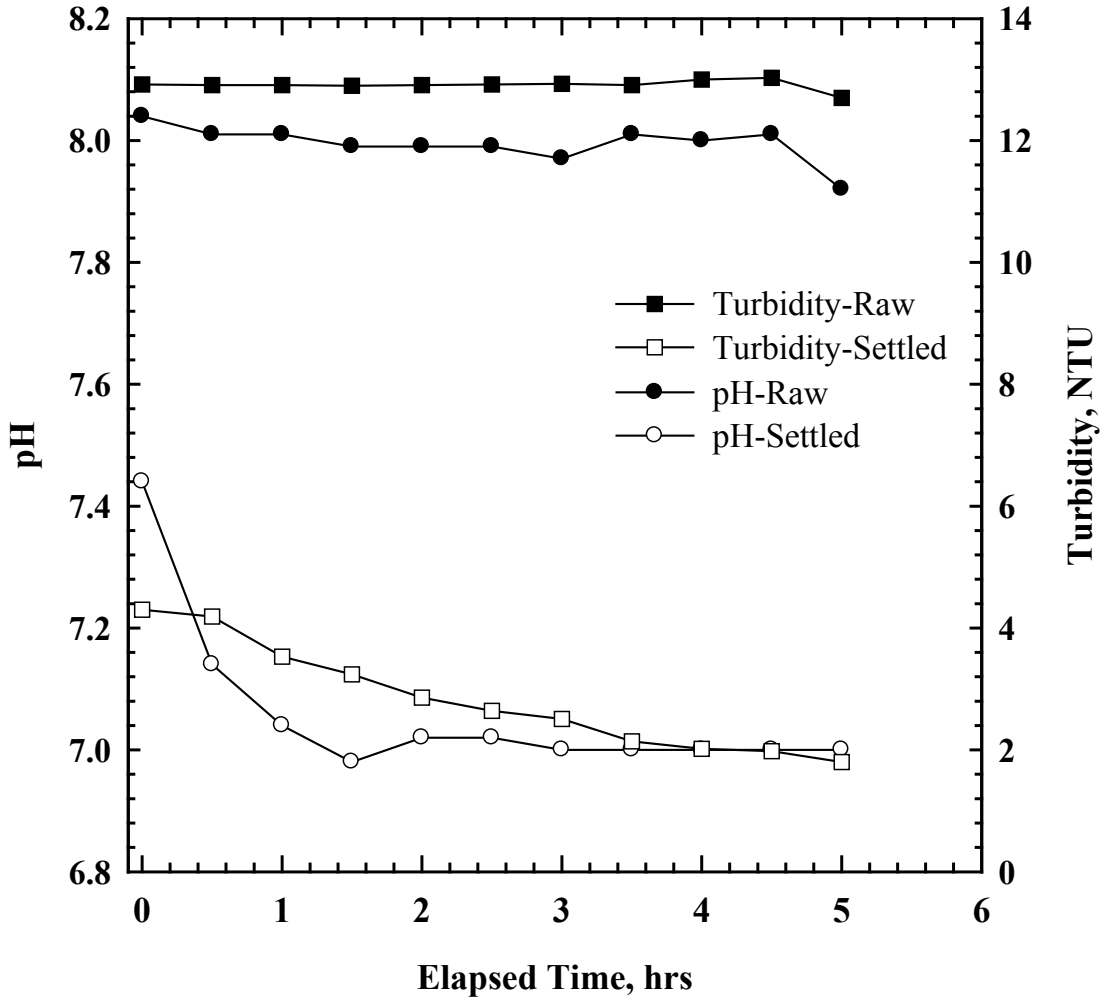

Figure B22. Pilot plant Test Run 1 with Ohio River water treated by alum coagulation. Raw water temperature was 18.1-18.9°C, and settled water temperature was 18.8-19.2°C.

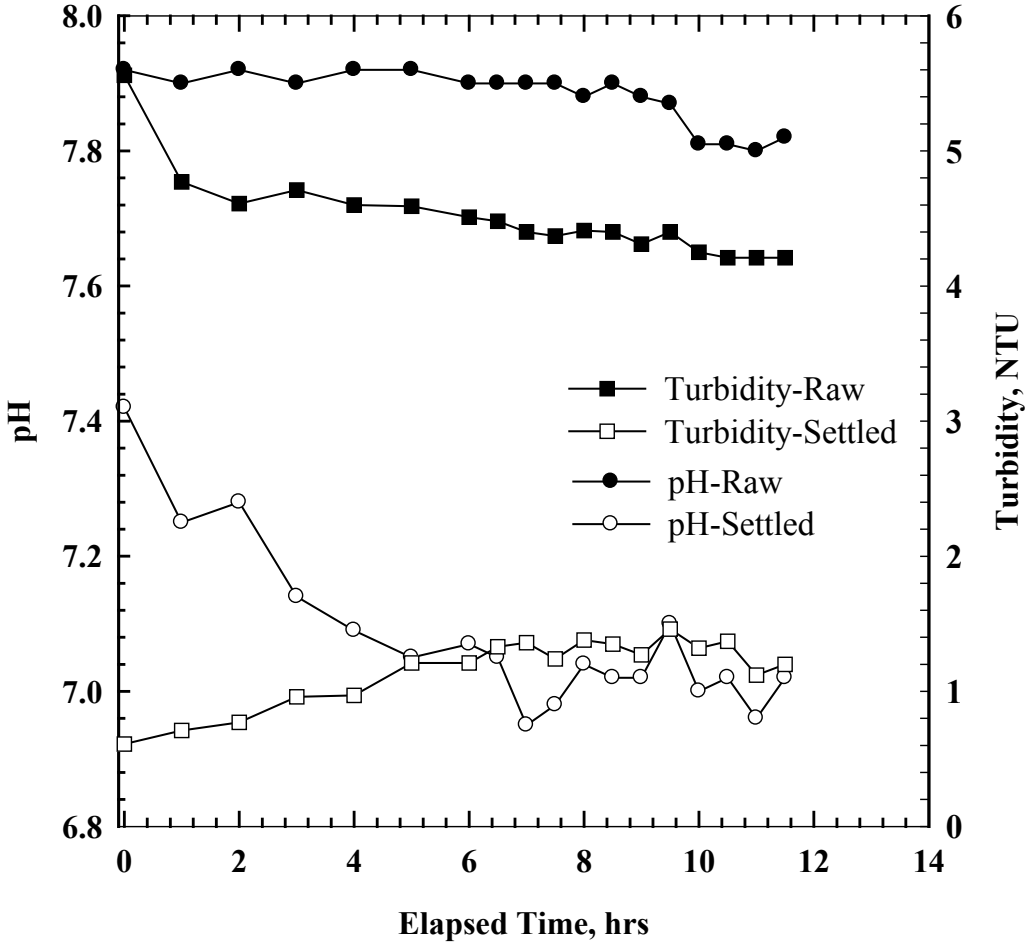

Figure B23. Pilot plant test run 2 with Ohio River water treated by alum coagulation. Raw water temperature was 19.4-20.0°C, and settled water temperature was 18.8-21.3°C.

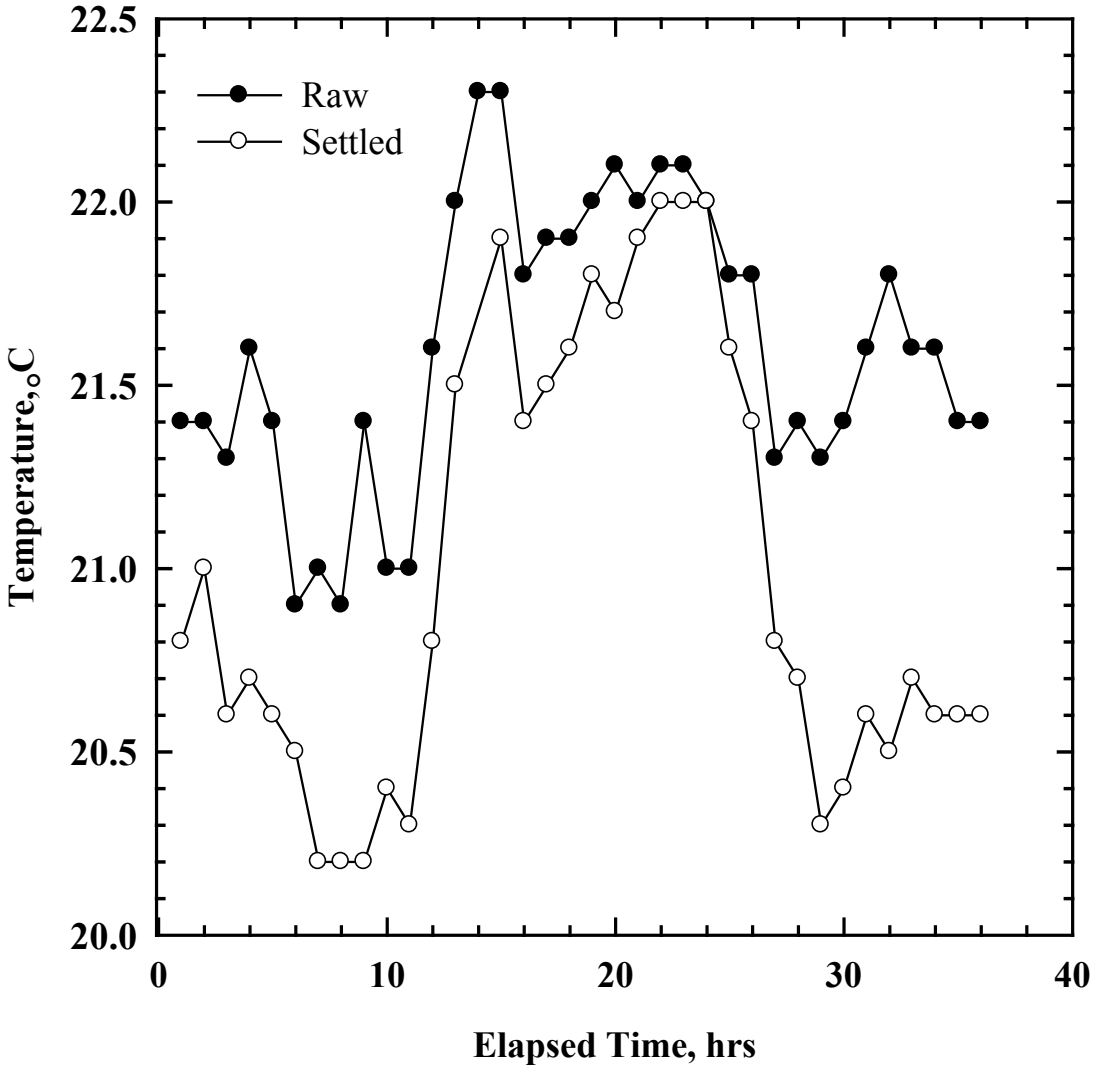

Figure B24. Temperature variation during pilot plant Test Run 3 with Ohio River water treated by alum coagulation.

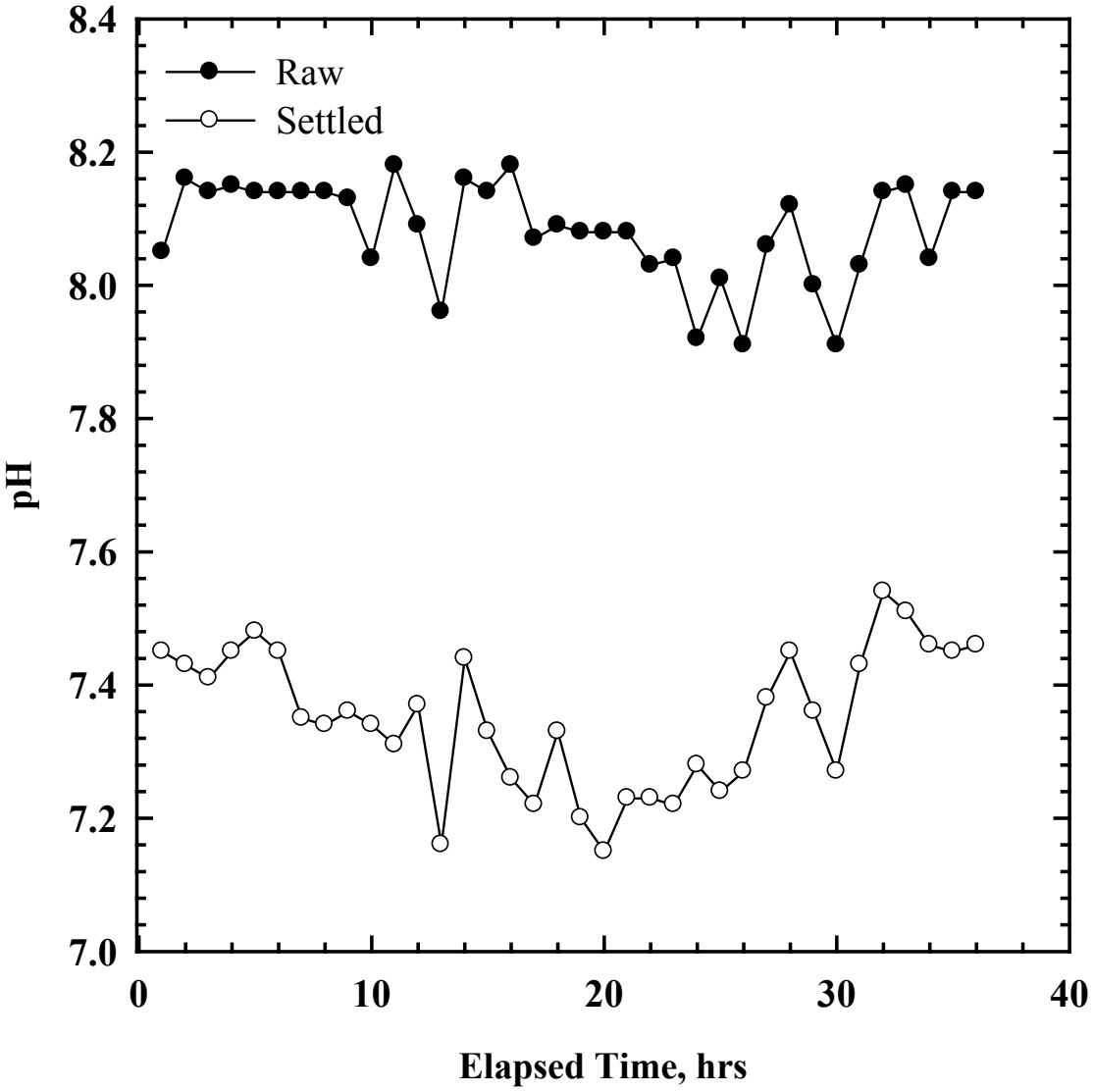

Figure B25. pH variation during pilot plant Test Run 3 with Ohio River water treated by alum coagulation.

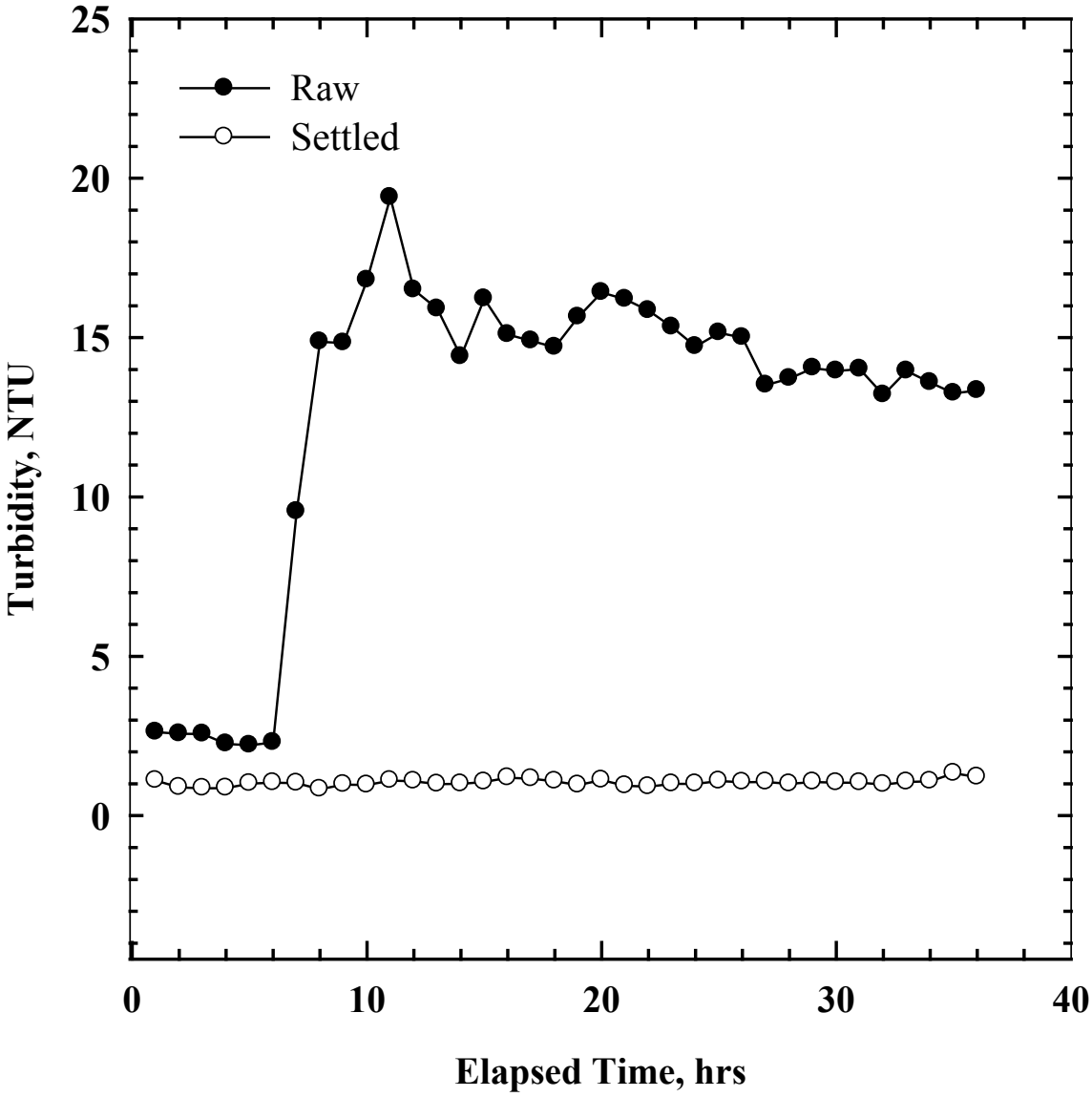

Figure B26. Turbidity variations during pilot plant Test Run 3 with Ohio River water treated by alum coagulation.

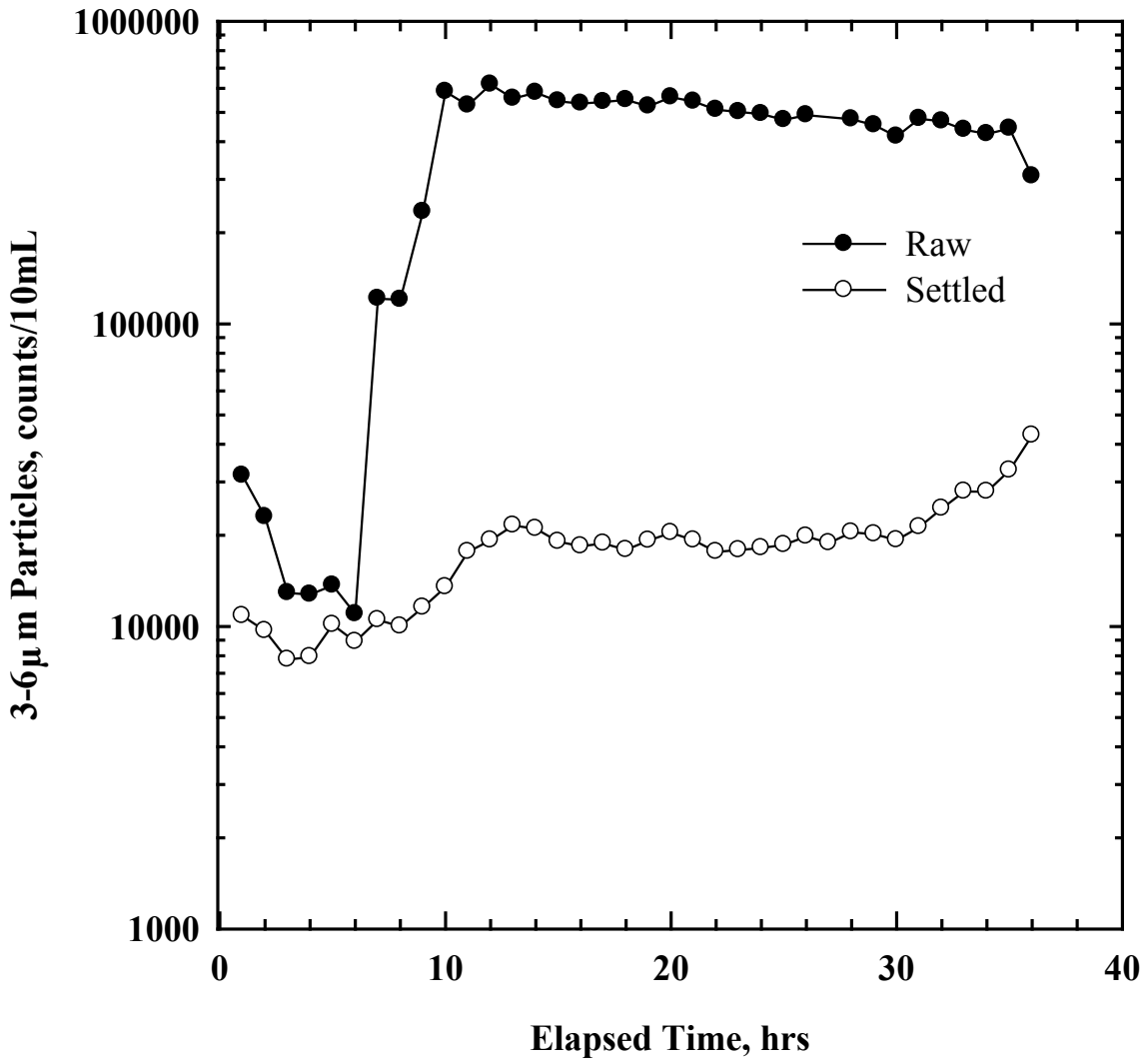

Figure B27. Three to six-micrometer (µm) particle variation during pilot plant Test Run 3 with Ohio River water treated by alum coagulation.

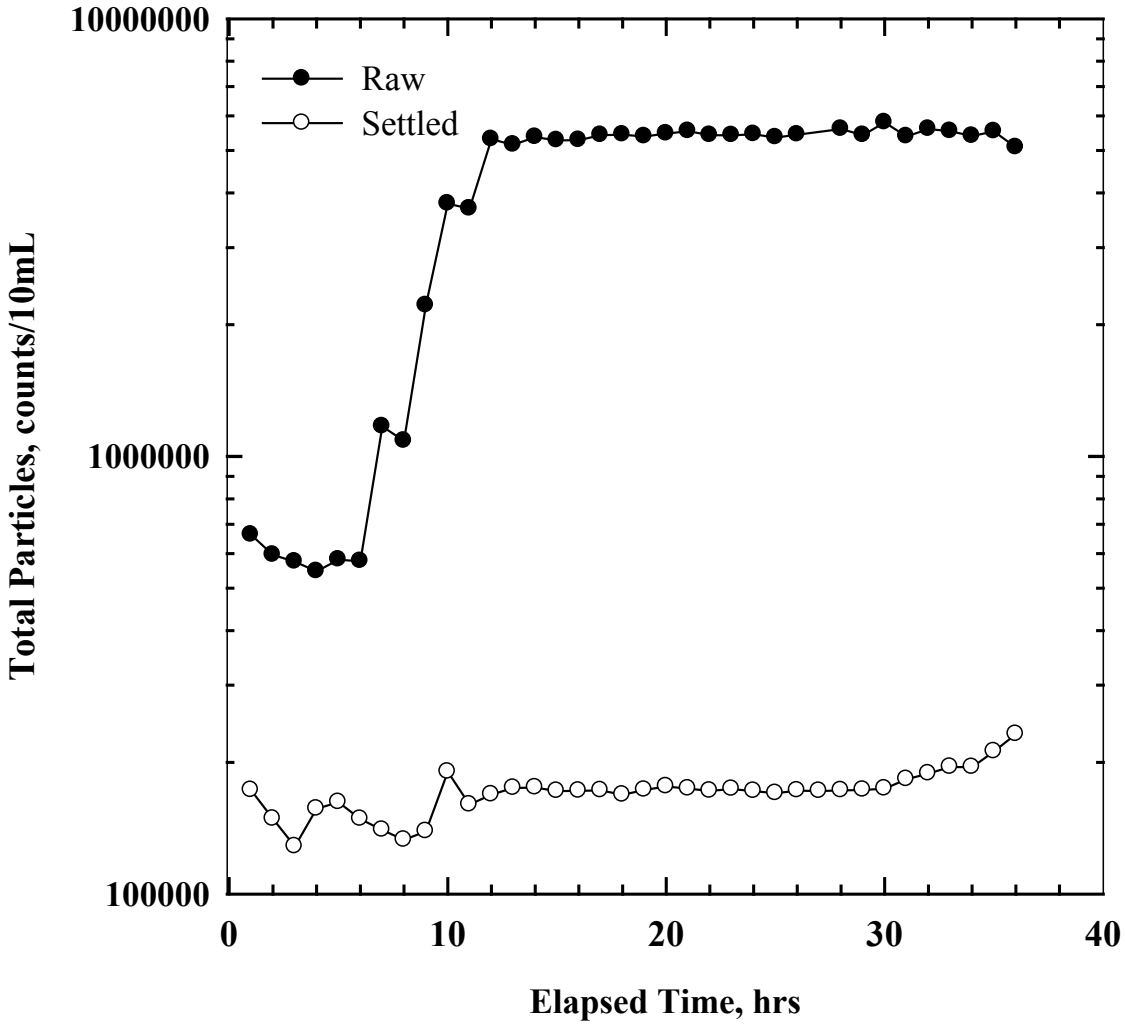

Figure 28. Total particle variation during pilot plant Test Run 3 with Ohio River water treated by alum coagulation.

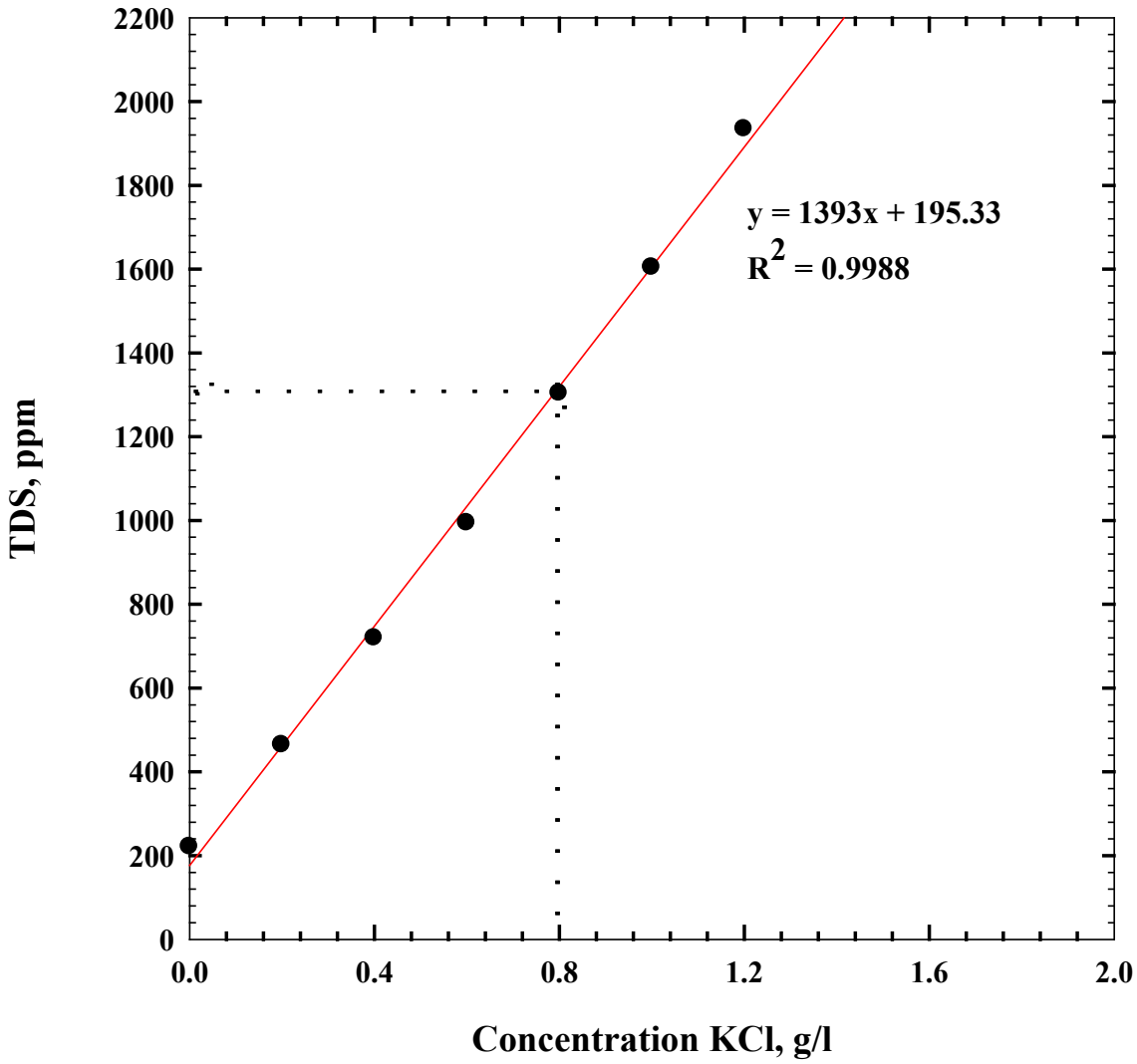

Figure B29. Impact of potassium chloride (KCL) on total dissolved solids (TDS) concentration of Ohio River water.

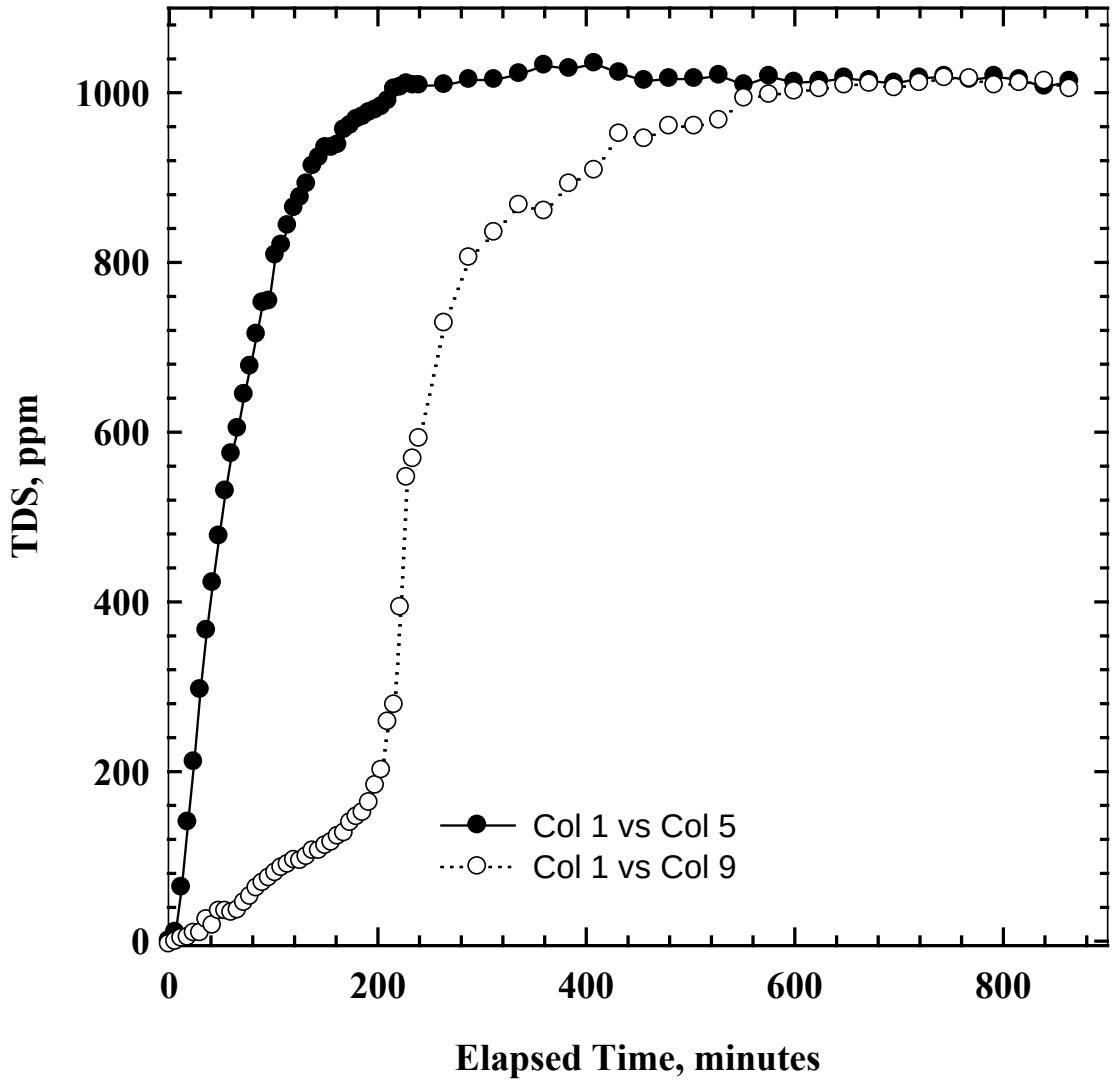

Figure B30. Prototype mini pilot plant rising step tracer test results.

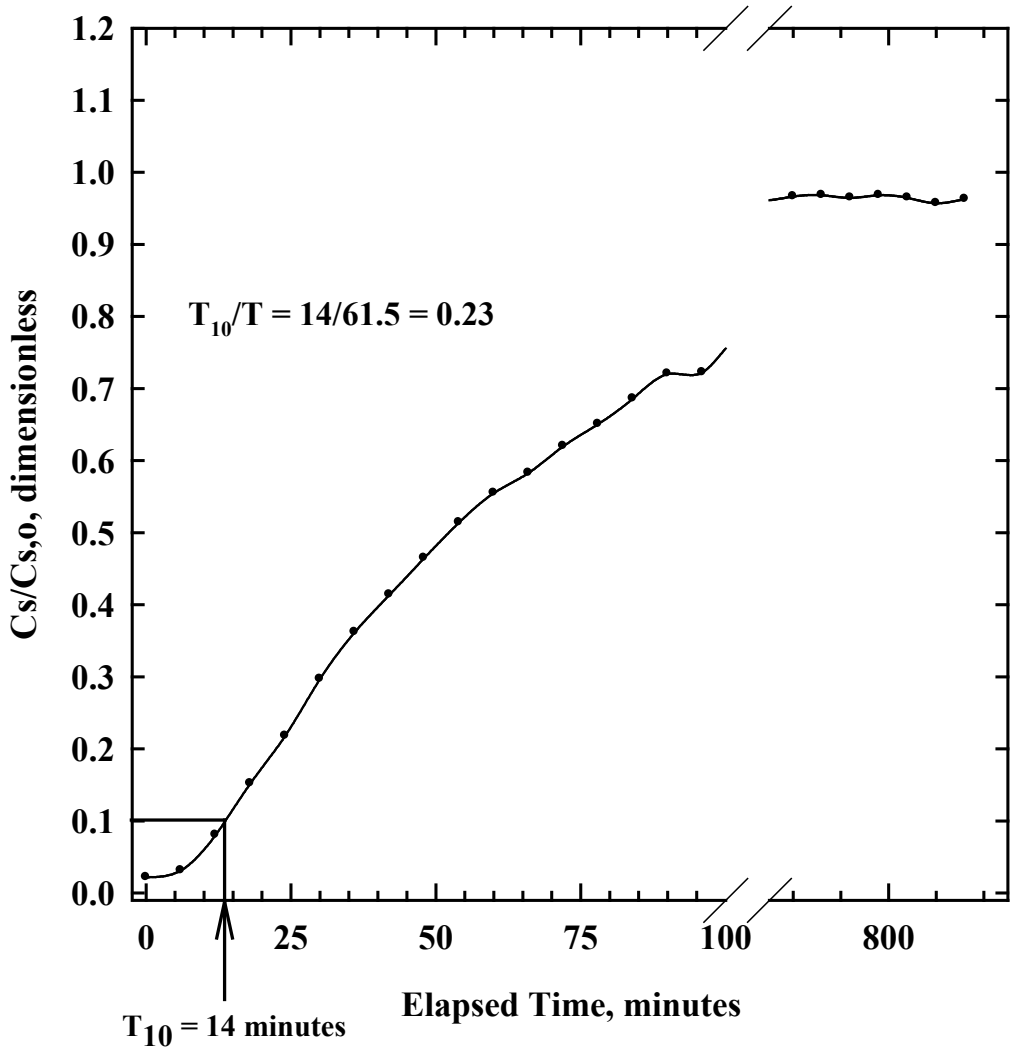

Figure B31. Prototype mini pilot plant rising step tracer results for rapid mix and flocculation processes ($C_s/C_{s,o}$ = normalized tracer concentration).

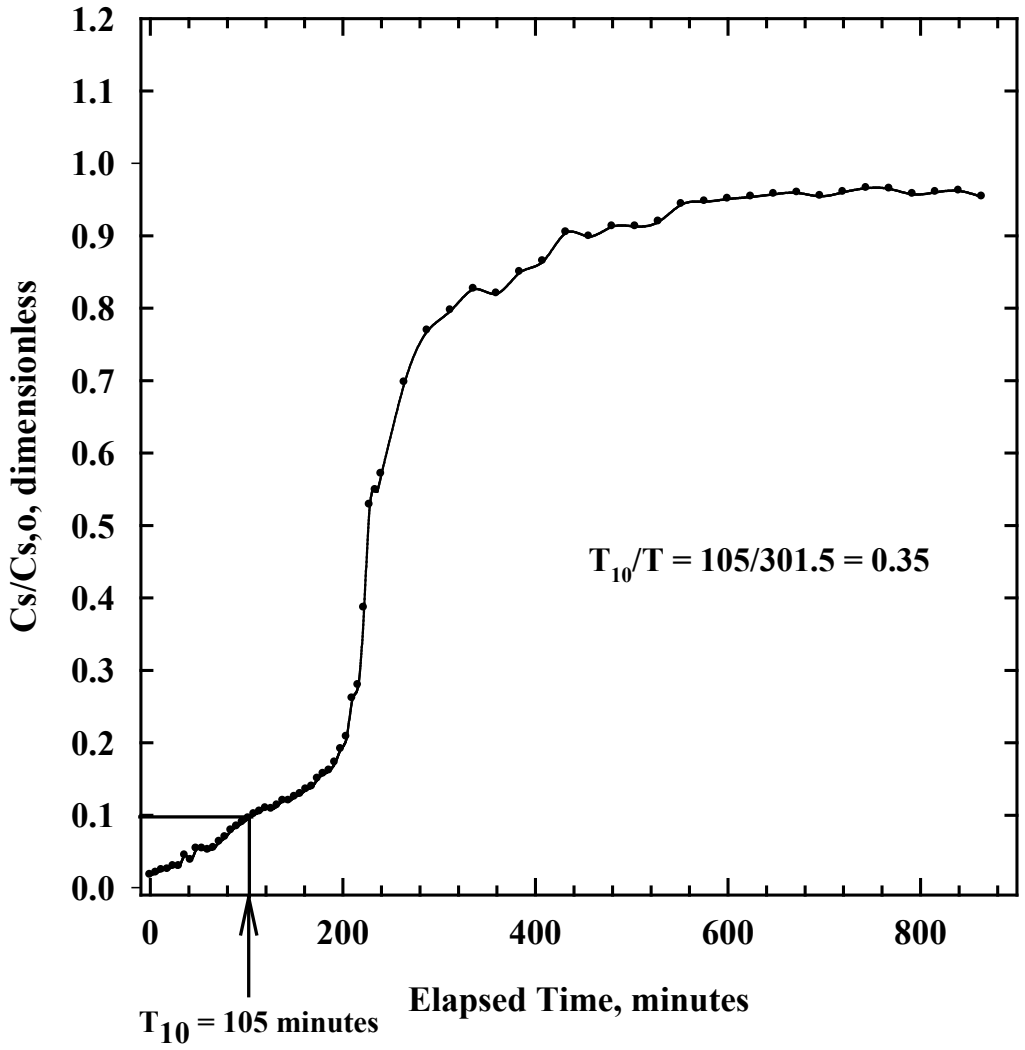

Figure B32. Prototype mini pilot plant rising step tracer results for rapid mix, flocculation, and sedimentation processes ($C_s/C_{s,o}$ = normalized tracer concentration).

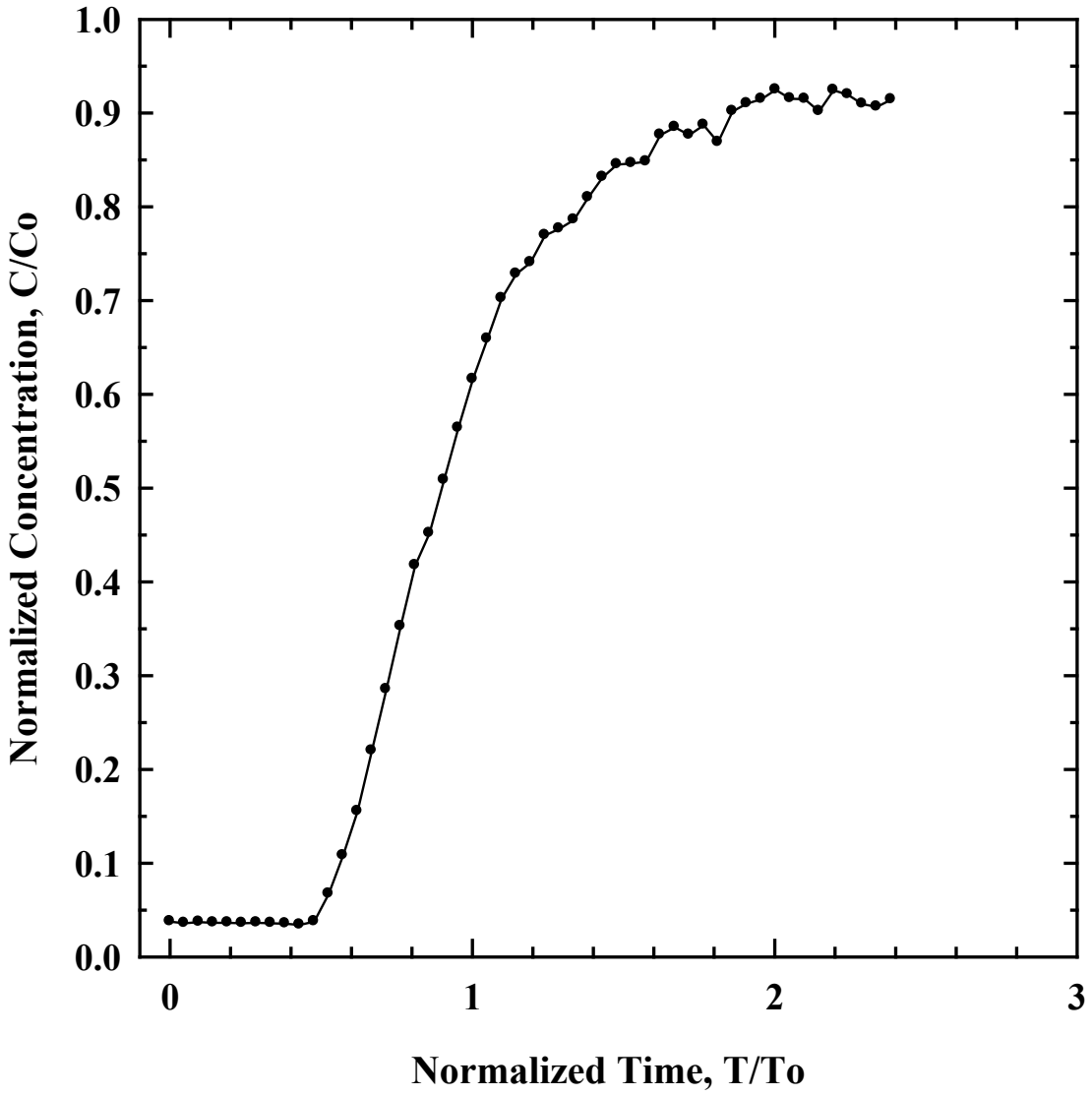

Figure B33. Normalized time vs. normalized concentration of Filter #2.

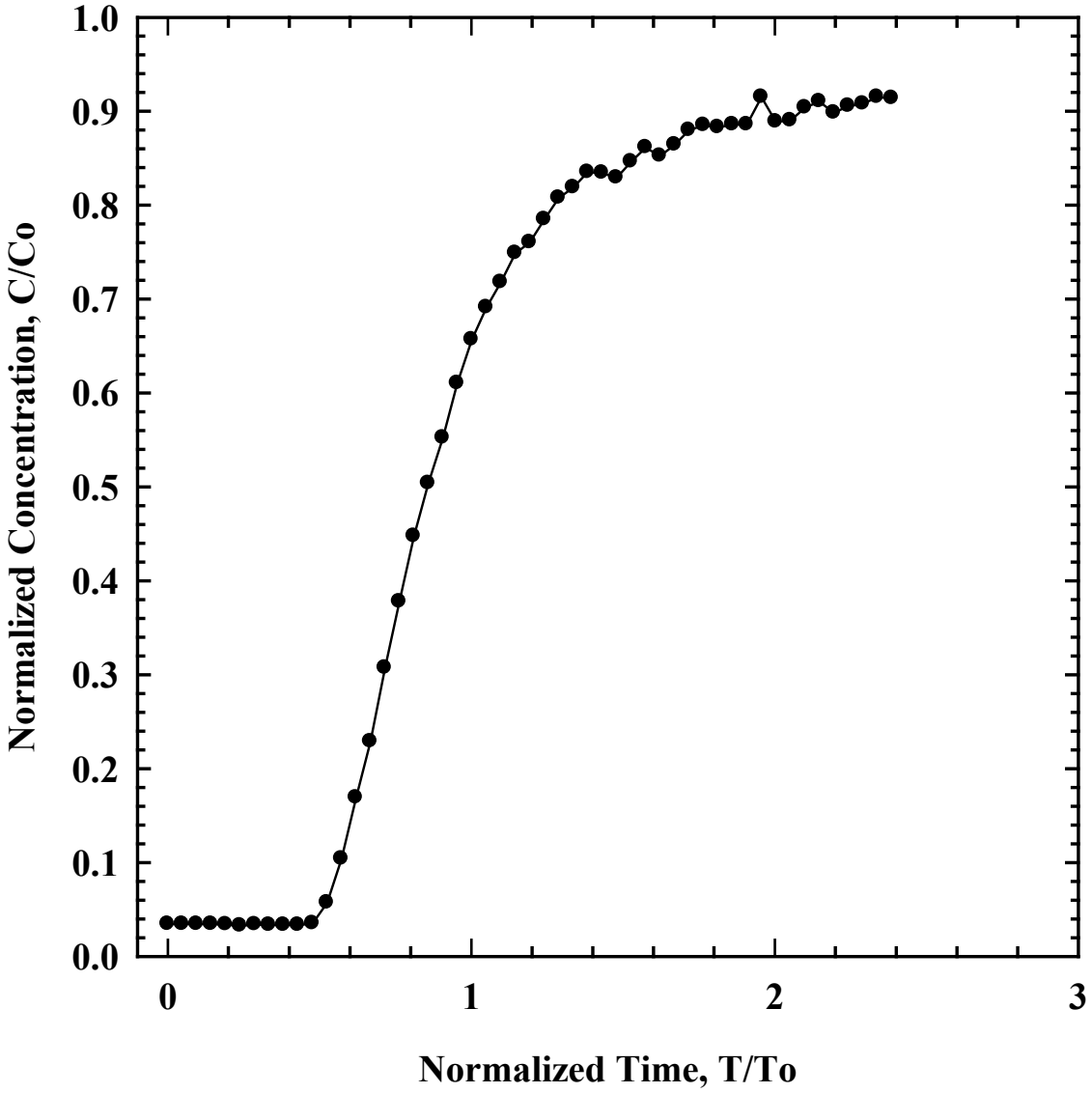

Figure B34. Normalized time vs. normalized concentration of Filter #3.

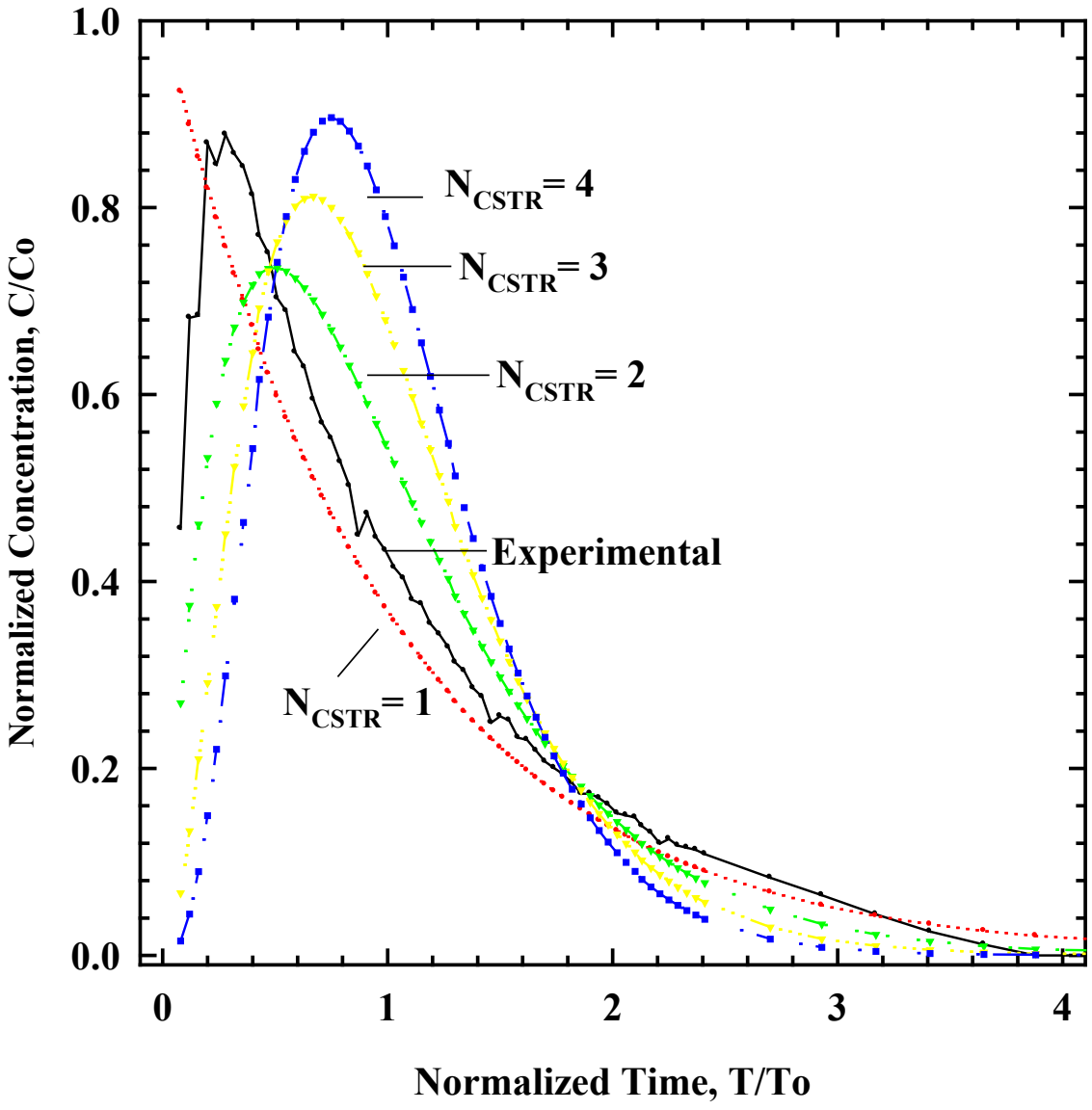

Figure B35. Pulse input tracer study results and theoretical CSTRs.

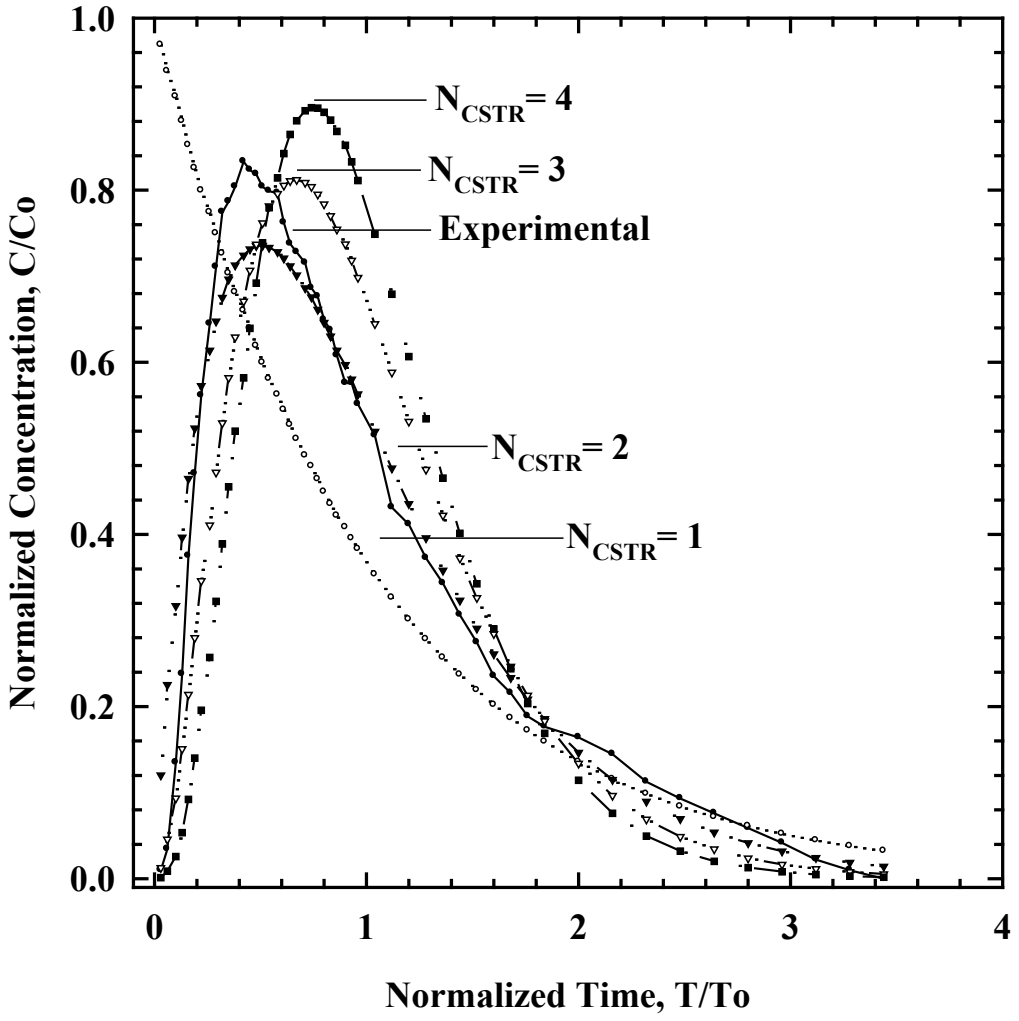

Figure B36. Pulse input tracer study results following flocculation unit modifications.

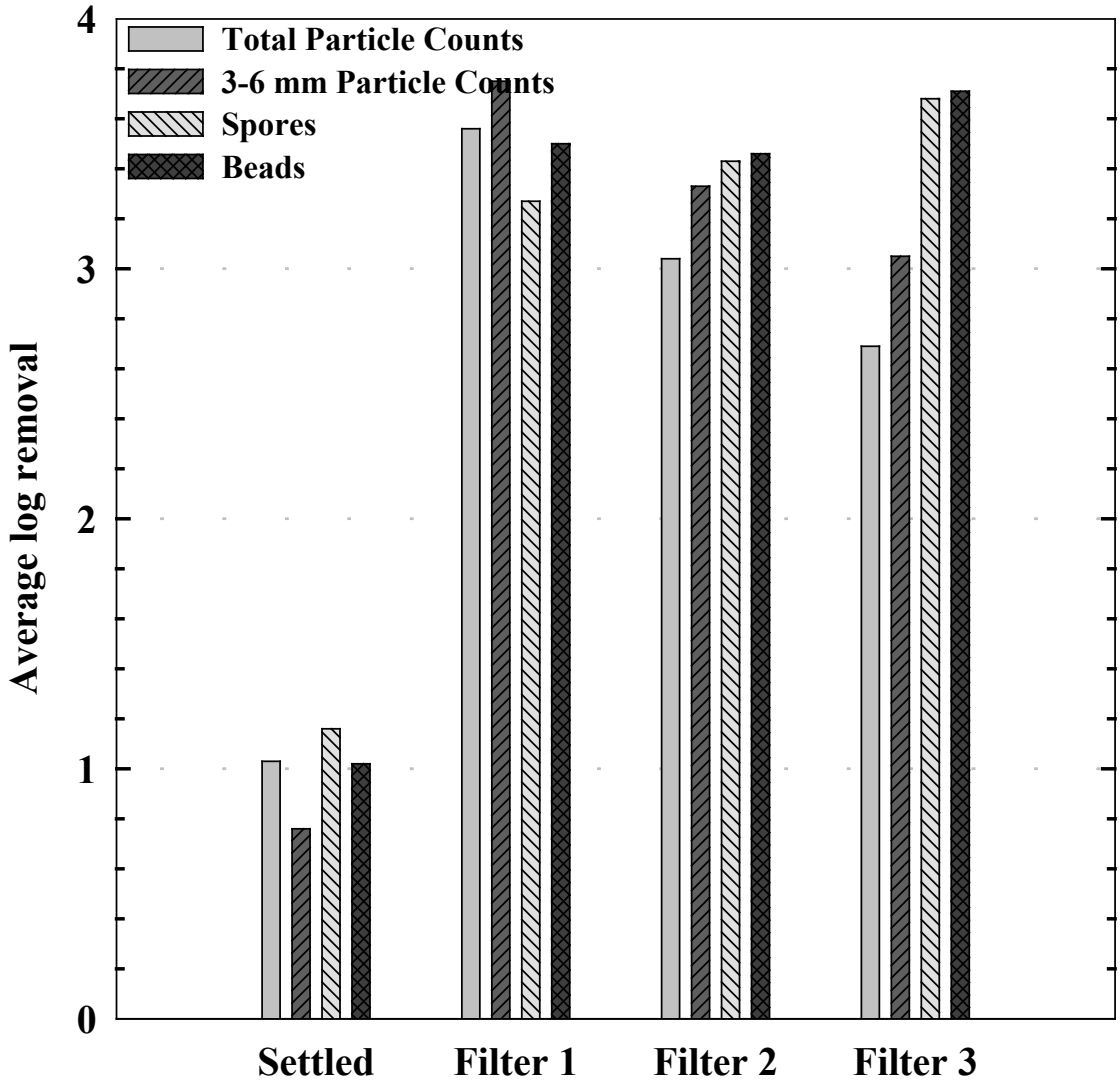

Figure B37. Log removal comparisons (83-hour run).

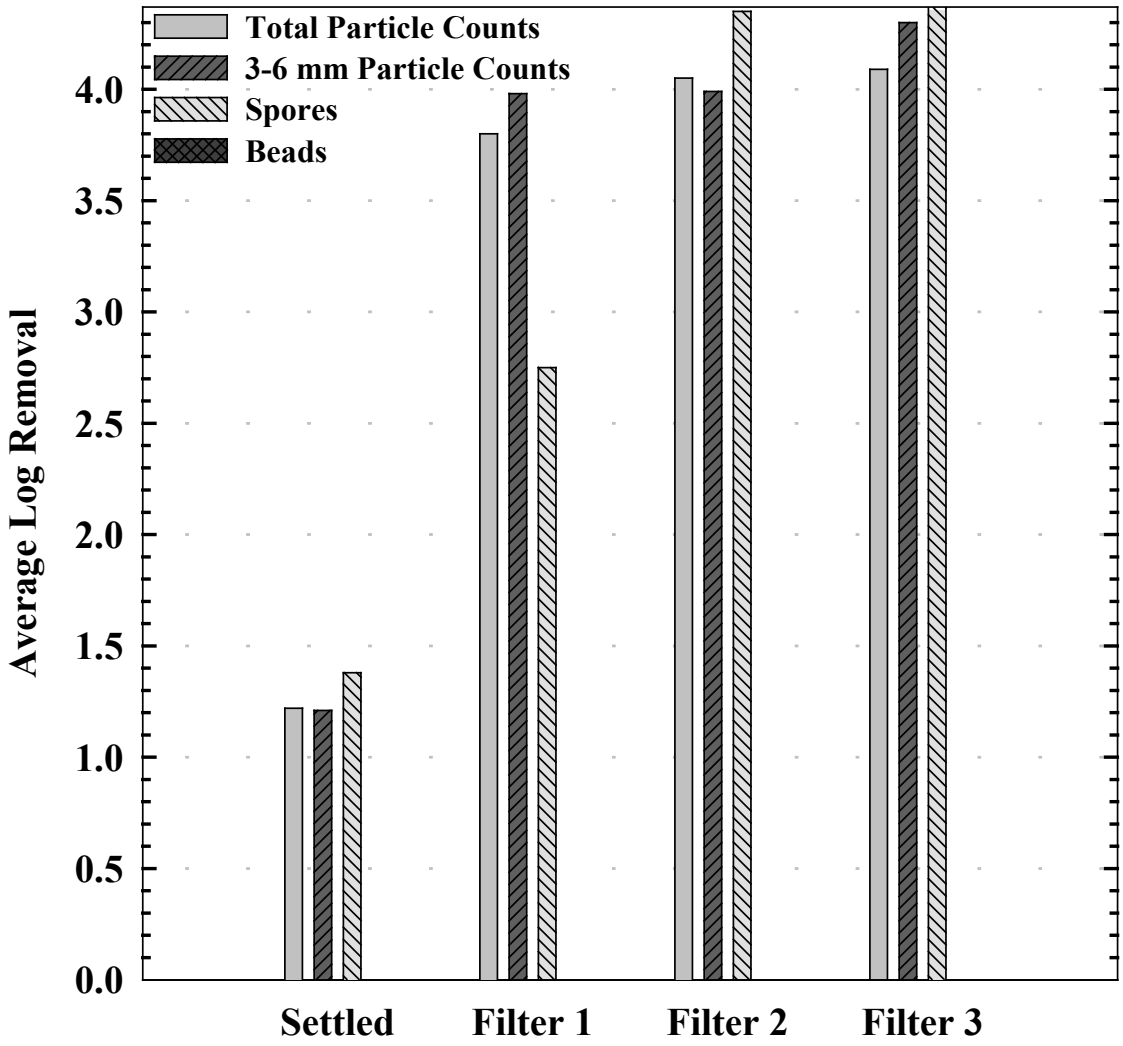

Figure B38. Log removal comparisons (59-hour run).

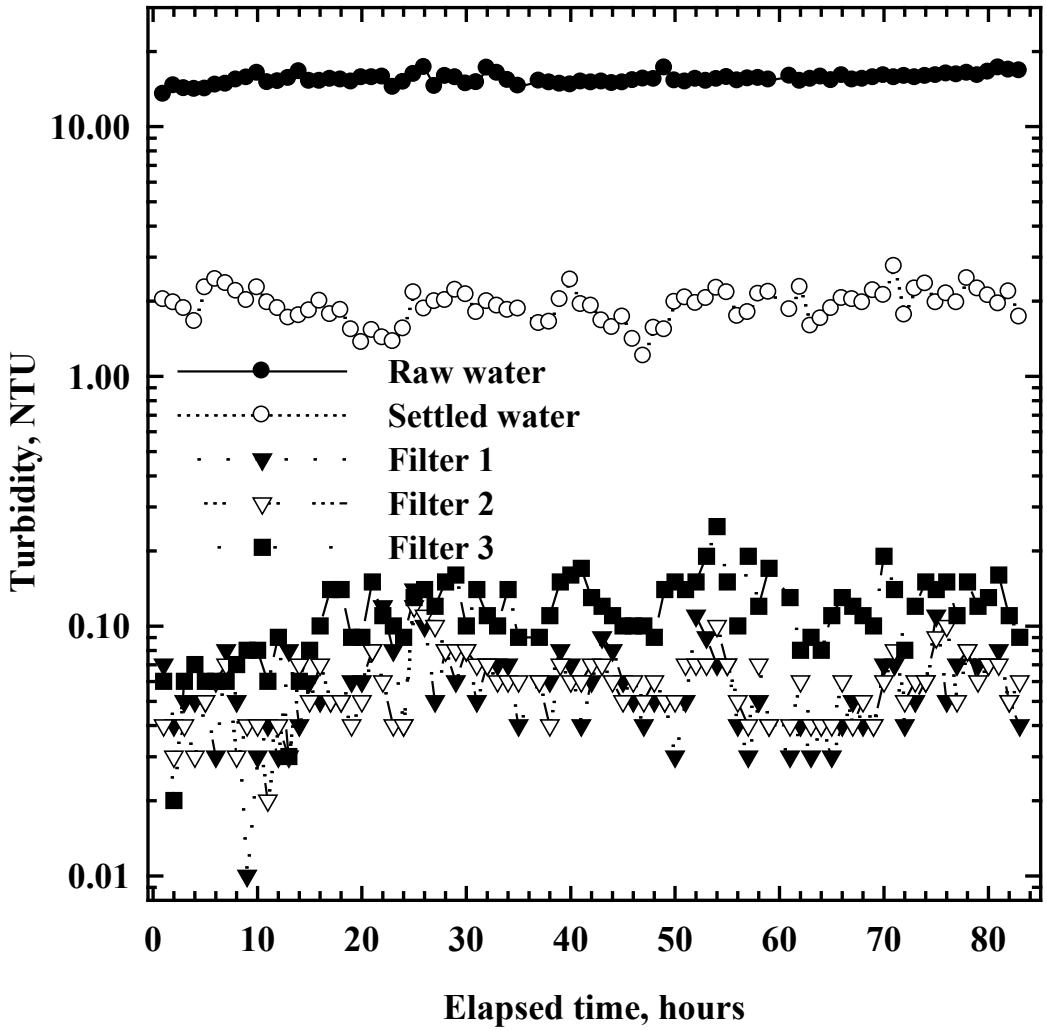

Figure B39. Turbidity values at locations in the pilot plant during 83-hour test run.

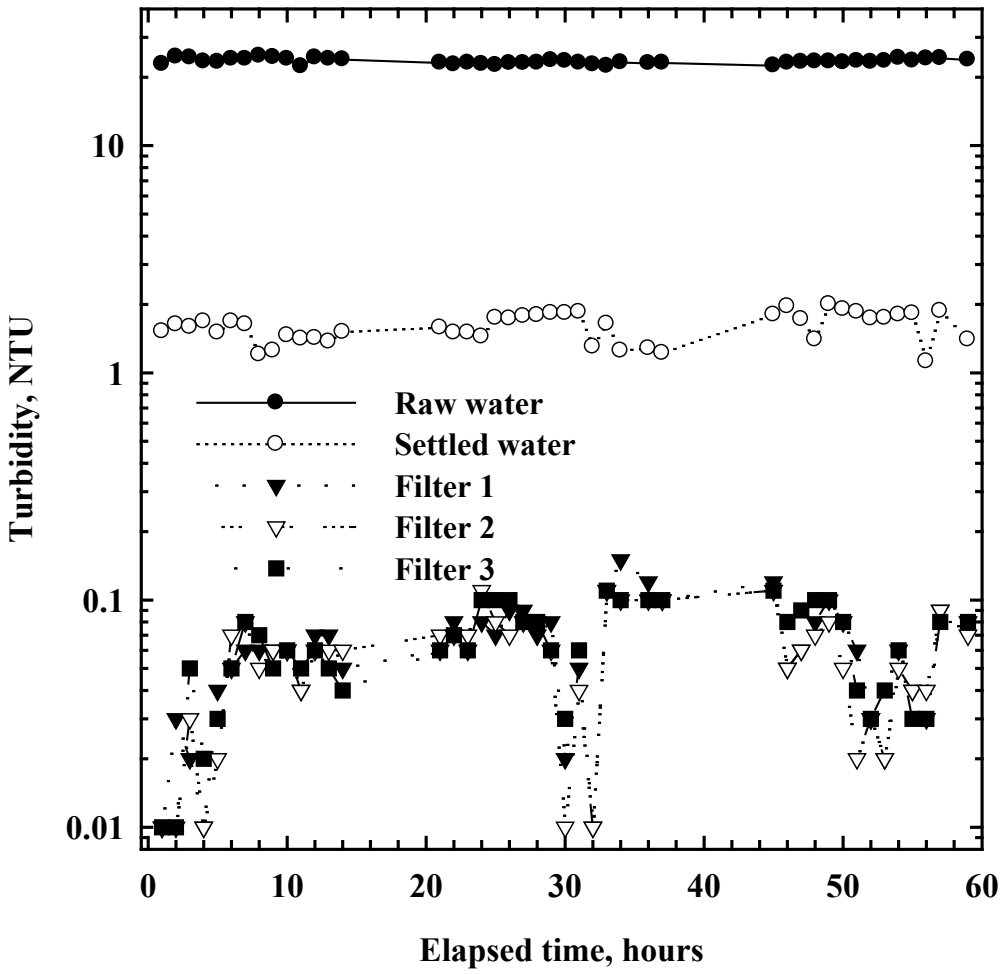

Figure B40. Turbidity values at locations in the pilot plant during 59-hour test run.

Appendix C: Calculations & Worksheets

Table C18. Rapid mix chamber calculations for paddle radius of 1.2-inches (in) and depth of 0.9-in. It is assumed that each base is square with a flow rate of 450 mL/min.

Flow rate (ml/min) =	**450**	**Height**	**Calculated**	**Height**	**Calc. Base**	
Total Residence Time (min) =	**1.5**	**(cm)**	**Base (cm)**	**Inches**	**Inches**	
		1	26.0	0.39	10.23	
Vol. rapid mix basin (L) =	0.675	**2**	18.4	0.79	7.23	
Vol. rapid mix basin (ft^3) =	0.0238	**3**	15.0	1.18	5.91	
		4	13.0	1.57	5.11	
		5	11.6	1.97	4.57	
		6	10.6	2.36	4.18	
		7	9.8	2.76	3.87	
		8	9.2	3.15	3.62	
		9	8.7	3.54	3.41	
		10	8.2	3.94	3.23	
		11	7.8	4.33	3.08	
		12	7.5	4.72	2.95	
		13	7.2	5.12	2.84	
		14	6.9	5.51	2.73	
		15	6.7	5.91	2.64	
		16	6.5	6.30	2.56	
		17	6.3	6.69	2.48	
		18	6.1	7.09	2.41	
		19	6.0	7.48	2.35	
		20	5.8	7.87	2.29	
		21	5.7	8.27	2.23	
		22	5.5	8.66	2.18	
		23	5.4	9.06	2.13	
		24	5.3	9.45	2.09	
		25	5.2	9.84	2.05	

			Paddle Tip H_2O	**Power**	**G**	**G*t**
Inputs		**RPMs**	**Velocity (ft/sec)**	**lbs*ft/sec**	**(1/sec)**	**(unitless)**
# of paddles =	4	**60**	0.432	3.722E-3	90.7	2040
Radius of paddles (in) =	1.10	**65**	0.468	4.733E-3	102.2	2300
Depth of each paddle (in) =	1.3	**70**	0.504	5.911E-3	114.2	2571
Cd =	1.2	**75**	0.540	7.270E-3	126.7	2851
		80	0.576	8.824E-3	139.6	3141
		85	0.612	1.058E-2	152.9	3440
Density (lbm/ft^3) =	62.4	**90**	0.648	1.256E-2	166.6	3748
Dynamic Viscosity ($lb*sec/ft^2$) =	1.90E-05	**95**	0.684	1.478E-2	180.6	4064
		100	0.720	1.723E-2	195.1	4389
		105	0.756	1.995E-2	209.9	4723
Calc.		**110**	0.792	2.294E-2	225.1	5064
Area of all paddles (ft^2) =	0.0397	**115**	0.828	2.621E-2	240.6	5413
		120	0.864	2.978E-2	256.4	5770
		125	0.900	3.366E-2	272.6	6134
		130	0.936	3.786E-2	289.1	6506
		135	0.972	4.240E-2	306.0	6885
		140	1.008	4.729E-2	323.1	7271
		145	1.044	5.254E-2	340.6	7664
		150	1.080	5.816E-2	358.4	8064
		155	1.116	6.418E-2	376.4	8470
Organics Pilot Plant		100	1.31		194	

Table C19. Rapid mix chamber calculations for paddle radius of 1.1-inches (in) and depth of 1.3-in. It is assumed that each base is square with a flow rate of 450 mL/min.

		Height	Calculated	Height	Calc. Base
Flow rate (ml/min) =	**450**	**(cm)**	**Base (cm)**	**Inches**	**Inches**
Total Residence Time (min) =	**1.5**	**1**	26.0	0.39	10.23
		2	18.4	0.79	7.23
Vol. rapid mix basin (L) =	0.675	**3**	15.0	1.18	5.91
Vol. rapid mix basin (ft^3) =	0.0238	**4**	13.0	1.57	5.11
		5	11.6	1.97	4.57
		6	10.6	2.36	4.18
		7	9.8	2.76	3.87
		8	9.2	3.15	3.62
		9	8.7	3.54	3.41
		10	8.2	3.94	3.23
		11	7.8	4.33	3.08
		12	7.5	4.72	2.95
		13	7.2	5.12	2.84
		14	6.9	5.51	2.73
		15	6.7	5.91	2.64
		16	6.5	6.30	2.56
		17	6.3	6.69	2.48
		18	6.1	7.09	2.41
		19	6.0	7.48	2.35
		20	5.8	7.87	2.29
		21	5.7	8.27	2.23
		22	5.5	8.66	2.18
		23	5.4	9.06	2.13
		24	5.3	9.45	2.09
		25	5.2	9.84	2.05

			Paddle Tip H_2O	Power	G	G*t
Inputs		**RPMs**	**Velocity (ft/sec)**	**lbs*ft/sec**	**(1/sec)**	**(unitless)**
# of paddles =	4	**60**	0.432	3.722E-3	90.7	2040
Radius of paddles (in) =	1.10	**65**	0.468	4.733E-3	102.2	2300
Depth of each paddle (in) =	1.3	**70**	0.504	5.911E-3	114.2	2571
Cd =	1.2	**75**	0.540	7.270E-3	126.7	2851
		80	0.576	8.824E-3	139.6	3141
		85	0.612	1.058E-2	152.9	3440
Density (lbm/ft^3) =	62.4	**90**	0.648	1.256E-2	166.6	3748
Dynamic Viscosity ($lb*sec/ft^2$) =	1.90E-05	**95**	0.684	1.478E-2	180.6	4064
		100	0.720	1.723E-2	195.1	4389
		105	0.756	1.995E-2	209.9	4723
Calc.		**110**	0.792	2.294E-2	225.1	5064
Area of all paddles (ft^2) =	0.0397	**115**	0.828	2.621E-2	240.6	5413
		120	0.864	2.978E-2	256.4	5770
		125	0.900	3.366E-2	272.6	6134
		130	0.936	3.786E-2	289.1	6506
		135	0.972	4.240E-2	306.0	6885
		140	1.008	4.729E-2	323.1	7271
		145	1.044	5.254E-2	340.6	7664
		150	1.080	5.816E-2	358.4	8064
		155	1.116	6.418E-2	376.4	8470
Organics Pilot Plant		100	1.31		194	

Table C20. Rapid mix chamber calculations for paddle radius of 1.0–inch (in) and depth of 1.9-in. It is assumed that each base is square with a flow rate of 450 mL/min.

		Height	Calculated	Height	Calc. Base
Flow rate (ml/min) =	**450**	**(cm)**	**Base (cm)**	**Inches**	**Inches**
Total Residence Time (min) =	**1.5**	**1**	26.0	0.39	10.23
		2	18.4	0.79	7.23
Vol. rapid mix basin (L) =	0.675	**3**	15.0	1.18	5.91
Vol. rapid mix basin (ft^3) =	0.0238	**4**	13.0	1.57	5.11
		5	11.6	1.97	4.57
		6	10.6	2.36	4.18
		7	9.8	2.76	3.87
		8	9.2	3.15	3.62
		9	8.7	3.54	3.41
		10	8.2	3.94	3.23
		11	7.8	4.33	3.08
		12	7.5	4.72	2.95
		13	7.2	5.12	2.84
		14	6.9	5.51	2.73
		15	6.7	5.91	2.64
		16	6.5	6.30	2.56
		17	6.3	6.69	2.48
		18	6.1	7.09	2.41
		19	6.0	7.48	2.35
		20	5.8	7.87	2.29
		21	5.7	8.27	2.23
		22	5.5	8.66	2.18
		23	5.4	9.06	2.13
		24	5.3	9.45	2.09
		25	5.2	9.84	2.05

			Paddle Tip H_2O	Power	G	G*t
Inputs		**RPMs**	**Velocity (ft/sec)**	**lbs*ft/sec**	**(1/sec)**	**(unitless)**
# of paddles =	4	**60**	0.393	3.716E-3	90.6	2038
Radius of paddles (in) =	1.00	**65**	0.425	4.725E-3	102.1	2298
Depth of each paddle (in) =	1.9	**70**	0.458	5.901E-3	114.1	2568
Cd =	1.2	**75**	0.491	7.258E-3	126.6	2848
		80	0.524	8.808E-3	139.5	3138
		85	0.556	1.057E-2	152.7	3437
Density (lbm/ft^3) =	62.4	**90**	0.589	1.254E-2	166.4	3744
Dynamic Viscosity ($lb*sec/ft^2$) =	1.90E-05	**95**	0.622	1.475E-2	180.5	4061
		100	0.654	1.720E-2	194.9	4385
		105	0.687	1.992E-2	209.7	4718
Calc.		**110**	0.720	2.290E-2	224.9	5059
Area of all paddles (ft^2) =	0.0528	**115**	0.753	2.616E-2	240.4	5408
		120	0.785	2.973E-2	256.2	5765
		125	0.818	3.360E-2	272.4	6129
		130	0.851	3.780E-2	288.9	6500
		135	0.884	4.233E-2	305.7	6879
		140	0.916	4.721E-2	322.9	7264
		145	0.949	5.245E-2	340.3	7657
		150	0.982	5.806E-2	358.1	8057
		155	1.014	6.406E-2	376.1	8463
Organics Pilot Plant		100	1.31		194	

Table C21. Flocculation calculations for paddle radius of 2-inches (in) and depth of 3-in. Assumptions: (1) four flow basins, (2) each base is square, and (3) the flow rate = 450 mL/min.

Flow rate (ml/min) =	450	Height	Calculated	Height	Calc. Base	
Total Residence Time (min) =	60	(cm)	Base (cm)	Inches	Inches	
		15	21.2	5.9	8.4	
Vol.of each floc basin (L) =	6.75	16	20.5	6.3	8.1	
Vol.of each floc basin (gal) =	1.78	17	19.9	6.7	7.8	
Vol.of each floc basin (ft^3) =	0.238	18	19.4	7.1	7.6	
		19	18.8	7.5	7.4	
		20	18.4	7.9	7.2	
		21	17.9	8.3	7.1	
		22	17.5	8.7	6.9	
		23	17.1	9.1	6.7	
		24	16.8	9.4	6.6	
		25	16.4	9.8	6.5	
		26	16.1	10.2	6.3	
		27	15.8	10.6	6.2	
		28	15.5	11.0	6.1	
		29	15.3	11.4	6.0	
		30	15.0	11.8	5.9	
		31	14.8	12.2	5.8	
		32	14.5	12.6	5.7	
		33	14.3	13.0	5.6	
		34	14.1	13.4	5.5	
		35	13.9	13.8	5.5	
		36	13.7	14.2	5.4	
		37	13.5	14.6	5.3	
		38	13.3	15.0	5.2	
		40	13.0	15.7	5.1	
			Paddle Tip H_2O	Power	G	G*t
Inputs		RPMs	Velocity (ft/sec)	lbs*ft/sec	(1/sec)	(unitless)
# of paddles =	4	5	0.065	5.433E-5	3.5	3117
Radius of paddles (in) =	2	7.5	0.098	1.834E-4	6.4	5727
Depth of each paddle (in) =	3	10	0.131	4.346E-4	9.8	8817
Cd =	1.2	12.5	0.164	8.489E-4	13.7	12322
		15	0.196	1.467E-3	18.0	16198
		17.5	0.229	2.329E-3	22.7	20411
Density (lbm/ft^3) =	62.4	20	0.262	3.477E-3	27.7	24938
Dynamic Viscosity ($lb*sec/ft^2$) =	1.90E-05	22.5	0.295	4.951E-3	33.1	29757
		25	0.327	6.791E-3	38.7	34852
		27.5	0.360	9.039E-3	44.7	40208
Calc.		30	0.393	1.173E-2	50.9	45814
Area of all paddles (ft^2) =	0.167	32.5	0.425	1.492E-2	57.4	51658
		35	0.458	1.863E-2	64.1	57732
		37.5	0.491	2.292E-2	71.1	64027
		40	0.524	2.782E-2	78.4	70535
		42.5	0.556	3.336E-2	85.8	77250
		45	0.589	3.960E-2	93.5	84165
		47.5	0.622	4.658E-2	101.4	91275
		50	0.654	5.433E-2	109.5	98575
		55	0.720	7.231E-2	126.4	113725

Table C22. Flocculation calculations for paddle radius of 2.5-inches (in) and depth of 1.5 in. Assumptions: (1) four flow basins, (2) each base is square, and (3) the flow rate = 450 mL/min.

Flow rate (ml/min) =	450	Height	Calculated	Height	Calc. Base	
Total Residence Time (min) =	60	(cm)	Base (cm)	Inches	Inches	
		15	21.2	5.9	8.4	
Vol.of each floc basin (L) =	6.75	16	20.5	6.3	8.1	
Vol.of each floc basin (gal) =	1.78	17	19.9	6.7	7.8	
Vol.of each floc basin (ft^3) =	0.238	18	19.4	7.1	7.6	
		19	18.8	7.5	7.4	
		20	18.4	7.9	7.2	
		21	17.9	8.3	7.1	
		22	17.5	8.7	6.9	
		23	17.1	9.1	6.7	
		24	16.8	9.4	6.6	
		25	16.4	9.8	6.5	
		26	16.1	10.2	6.3	
		27	15.8	10.6	6.2	
		28	15.5	11.0	6.1	
		29	15.3	11.4	6.0	
		30	15.0	11.8	5.9	
		31	14.8	12.2	5.8	
		32	14.5	12.6	5.7	
		33	14.3	13.0	5.6	
		34	14.1	13.4	5.5	
		35	13.9	13.8	5.5	
		36	13.7	14.2	5.4	
		37	13.5	14.6	5.3	
		38	13.3	15.0	5.2	
		40	13.0	15.7	5.1	
			Paddle Tip H_2O	Power	G	G*t
Inputs		RPMs	Velocity (ft/sec)	lbs*ft/sec	(1/sec)	(unitless)
# of paddles =	4	5	0.082	6.632E-5	3.8	3444
Radius of paddles (in) =	2.5	7.5	0.123	2.238E-4	7.0	6327
Depth of each paddle (in) =	1.5	10	0.164	5.305E-4	10.8	9741
Cd =	1.2	12.5	0.205	1.036E-3	15.1	13614
		15	0.245	1.791E-3	19.9	17896
		17.5	0.286	2.843E-3	25.1	22552
Density (lbm/ft^3) =	62.4	20	0.327	4.244E-3	30.6	27553
Dynamic Viscosity ($lb*sec/ft^2$) =	1.90E-05	22.5	0.368	6.043E-3	36.5	32877
		25	0.409	8.290E-3	42.8	38506
		27.5	0.450	1.103E-2	49.4	44424
Calc.		30	0.491	1.432E-2	56.2	50617
Area of all paddles (ft^2) =	0.104	32.5	0.532	1.821E-2	63.4	57075
		35	0.573	2.275E-2	70.9	63785
		37.5	0.614	2.798E-2	78.6	70740
		40	0.654	3.395E-2	86.6	77931
		42.5	0.695	4.073E-2	94.8	85350
		45	0.736	4.835E-2	103.3	92990
		47.5	0.777	5.686E-2	112.1	100846
		50	0.818	6.632E-2	121.0	108911
		55	0.900	8.827E-2	139.6	125650

Table C23. Flocculation calculations for paddle radius of 3–inches (in) and depth of 0.75-in. Assumptions: (1) four flow basins, (2) each base is square, and (3) the flow rate = 450 mL/min.

Flow rate (ml/min) =	450	Height	Calculated	Height	Calc. Base	
Total Residence Time (min) =	60	(cm)	Base (cm)	Inches	Inches	
		15	21.2	5.9	8.4	
Vol.of each floc basin (L) =	6.75	16	20.5	6.3	8.1	
Vol.of each floc basin (gal) =	1.78	17	19.9	6.7	7.8	
Vol.of each floc basin (ft^3) =	0.238	18	19.4	7.1	7.6	
		19	18.8	7.5	7.4	
		20	18.4	7.9	7.2	
		21	17.9	8.3	7.1	
		22	17.5	8.7	6.9	
		23	17.1	9.1	6.7	
		24	16.8	9.4	6.6	
		25	16.4	9.8	6.5	
		26	16.1	10.2	6.3	
		27	15.8	10.6	6.2	
		28	15.5	11.0	6.1	
		29	15.3	11.4	6.0	
		30	15.0	11.8	5.9	
		31	14.8	12.2	5.8	
		32	14.5	12.6	5.7	
		33	14.3	13.0	5.6	
		34	14.1	13.4	5.5	
		35	13.9	13.8	5.5	
		36	13.7	14.2	5.4	
		37	13.5	14.6	5.3	
		38	13.3	15.0	5.2	
		40	13.0	15.7	5.1	
			Paddle Tip H_2O	Power	G	G*t
Inputs		RPMs	Velocity (ft/sec)	lbs*ft/sec	(1/sec)	(unitless)
# of paddles =	4	5	0.098	6.876E-5	3.9	3507
Radius of paddles [in] =	3	7.5	0.147	2.321E-4	7.2	6443
Depth of each paddle [in] =	0.75	10	0.196	5.501E-4	11.0	9919
Cd =	1.2	12.5	0.245	1.074E-3	15.4	13862
		15	0.295	1.856E-3	20.2	18222
		17.5	0.344	2.948E-3	25.5	22963
Density [lbm/ft^3] =	62.4	20	0.393	4.400E-3	31.2	28055
Dynamic Viscosity [$lb*sec/ft^2$] =	1.90E-05	22.5	0.442	6.266E-3	37.2	33476
		25	0.491	8.595E-3	43.6	39208
		27.5	0.540	1.144E-2	50.3	45234
Calc.		30	0.589	1.485E-2	57.3	51540
Area of all paddles [ft^2] =	0.063	32.5	0.638	1.888E-2	64.6	58115
		35	0.687	2.358E-2	72.2	64948
		37.5	0.736	2.901E-2	80.0	72030
		40	0.785	3.520E-2	88.2	79352
		42.5	0.834	4.223E-2	96.6	86906
		45	0.884	5.012E-2	105.2	94686
		47.5	0.933	5.895E-2	114.1	102685
		50	0.982	6.876E-2	123.2	110897
		55	1.080	9.152E-2	142.2	127941

Table C24. Sedimentation calculation worksheet.

Q (mL/min)	time (hr)	Volume (gal)	Volume (ft^3)	Surface loading rate, SLR (gpd/ft^2)	SLR mL/min (ft^2)	Surface area, As (ft^2)	Depth (ft)	Re
450	4	28.5	3.81	1000	2630	0.17	22.4	
450	3	21.4	2.86	1000	2630	0.17	16.8	
450	2	14.3	1.90	1000	2630	0.17	11.2	
450	6	42.8	5.71	500	1315	0.34	16.8	0.56
450	4	28.5	3.81	500	1315	0.34	11.2	0.84
450	2	14.3	1.90	500	1315	0.34	5.6	1.70
450	6	42.8	5.71	120	316	1.42	4.02	2.20
450	4	28.5	3.81	120	316	1.42	2.86	2.90
450	2	14.3	1.90	120	316	1.42	1.33	5.70
450	6	42.8	5.71	60	158	2.85	2.00	3.70
450	4	28.5	3.81	60	158	2.85	1.33	5.10
450	3	21.4	2.86	60	158	2.85	1.00	6.20
450	2	14.3	1.90	60	158	2.85	0.67	8.10

Table C25. Sedimentation basin design worksheet.

As (ft^2)	Length (ft)	Width (ft)	Depth (ft)	(D x W) A (ft^2)	(W+2D) P (ft)	R (A/P)	(Q/WxD) V_o (ft/min)	Re	L/W
1.42	2.11	0.67	4.02	2.69	8.71	0.31	0.006	2.2	3.14
1.42	2.11	0.67	2.86	1.92	6.39	0.30	0.008	2.9	3.14
1.42	2.11	0.67	1.33	0.89	3.33	0.27	0.018	5.7	3.14
2.85	2.85	1.00	2.00	2.00	5.00	0.40	0.008	3.7	2.85
2.85	2.85	1.00	1.33	1.33	3.66	0.36	0.012	5.1	2.85
2.85	2.85	1.00	1.00	1.00	3.00	0.33	0.016	6.2	2.85
2.85	2.85	1.00	0.67	0.67	2.33	0.29	0.024	8.1	2.85

Table C26. Filter design parameters.

Loading Rate gpm/ft2	**Q ml/min**	**Q m/hr**	**EBCT min.**
2	93	4.9	9.4
4	186	9.8	4.7
6	279	14.7	3.1

Table C27. Combined overflow for various filter configurations.

Number Filters	Q mL/min	LR gpm/ft^2	EBCT min.	Q mL/min	LR gpm/ft^2	EBCT min.	Q mL/min	LR gpm/ft^2	EBCT min.	Combined Overflow mL/min
3	93	2	9.4	93	2	9.4	93	2	9.4	171
2	186	4	4.7	93	2	9.4				171
2	93	2	9.4	93	2	9.4				264
1	279	6	3.1							171
1	186	4	4.7							364
1	93	2	9.4							357

Table C28. Clearwell design worksheet.

Volume (gal)	Length, L (in)	Width, W (in)	Height, H* (in)	Volume (ft^3)	Q (mL/min)	Filter loading rate (gpm/ft^2)	Retention time, (hrs)
9.85	9	9	28	1.31	93	2	6.68
10	12	12	16	1.33	93	2	6.75
10	12	12	16	1.33	186	4	3.38
10	12	12	16	1.33	297	6	2.12
14.6	15	15	15	1.95	93	2	9.87
15	12	12	24	2	93	2	10.14
15	12	12	24	2	186	4	5.07
15	12	12	24	2	297	6	3.18
14.75	9	9	42	1.97	93	2	10
19.54	15	15	20	2.61	93	2	13.2
20	12	12	32	2.67	93	2	13.5
20	12	12	32	2.67	93	4	6.75
20	12	12	32	2.67	93	6	4.14

* Level to overflow

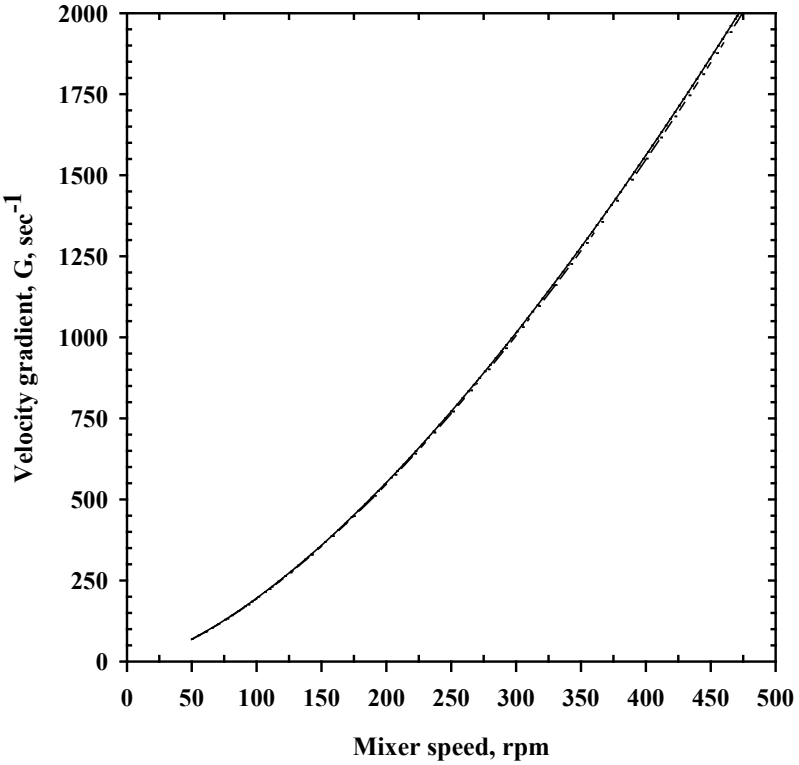

Figure C41. Calculated velocity gradient for four rapid mix paddles having all three radii and depth sizes as identified in Tables C1 through C3.

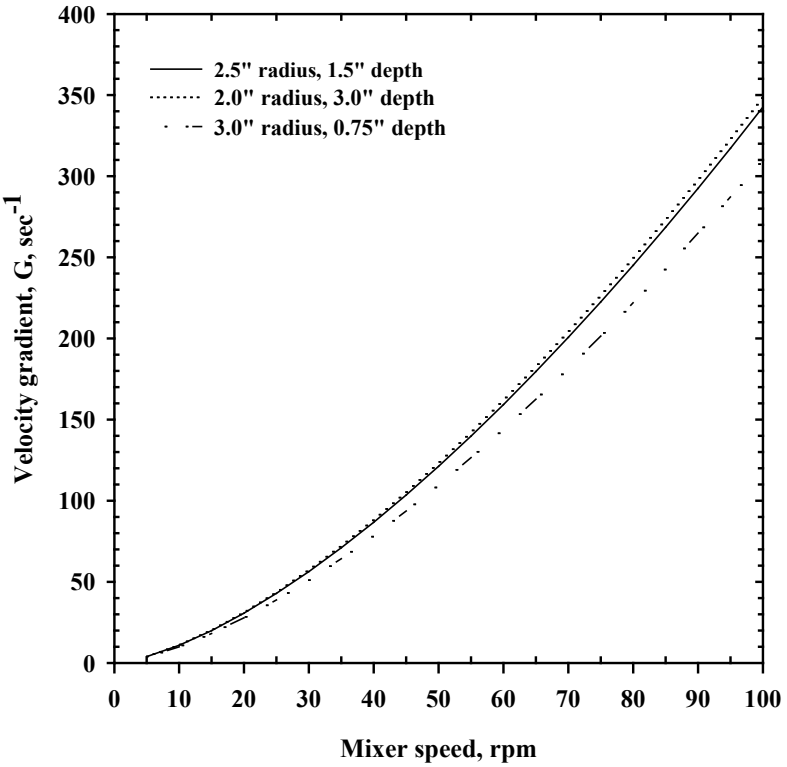

Figure C1. Calculated velocity gradient for four flocculation mix paddles having all three radii and depth sizes identified in Table C4 through C6.

Appendix D: Analysis Results

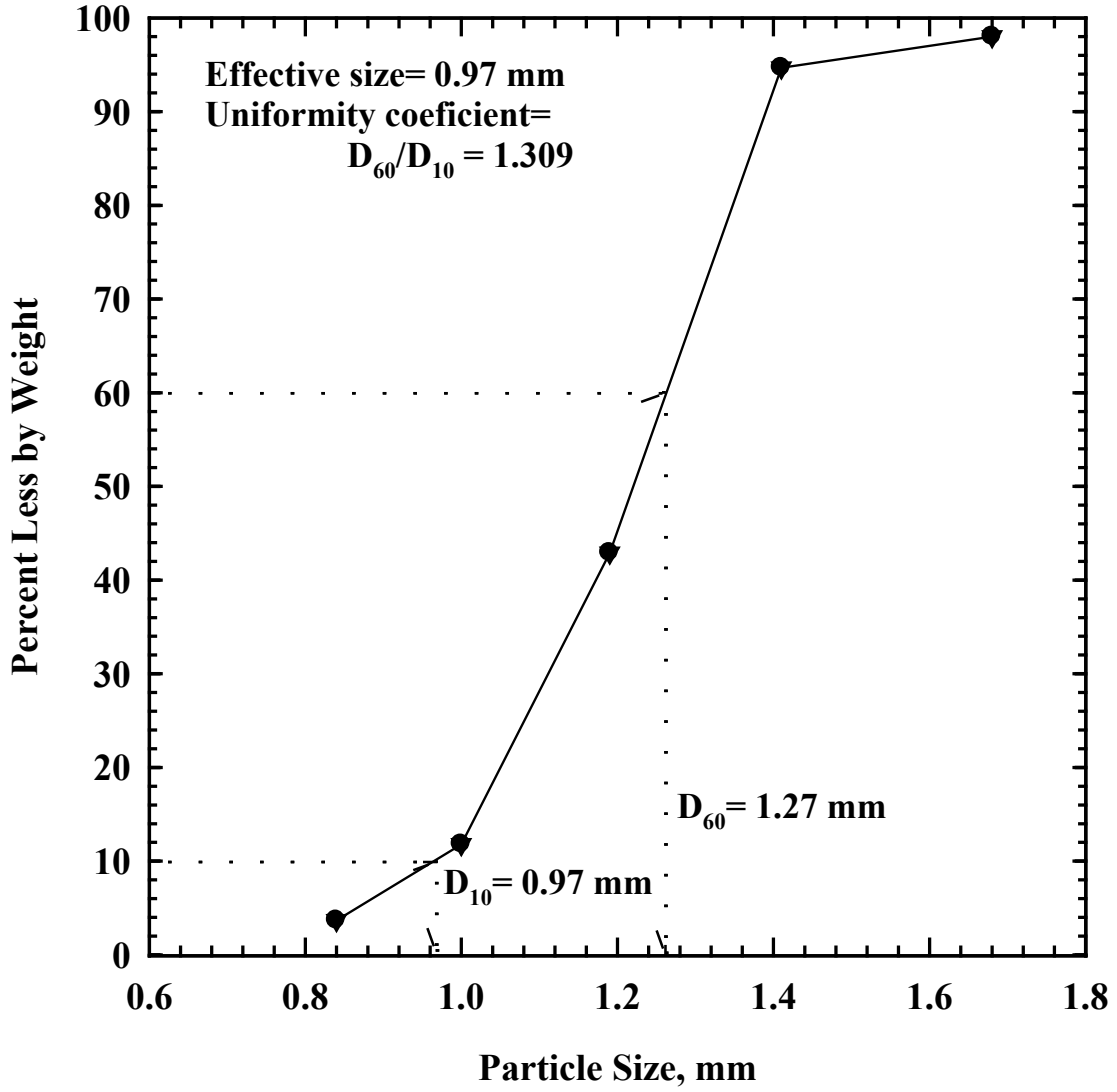

Figure D1. Particle size distribution of anthracite filter media.

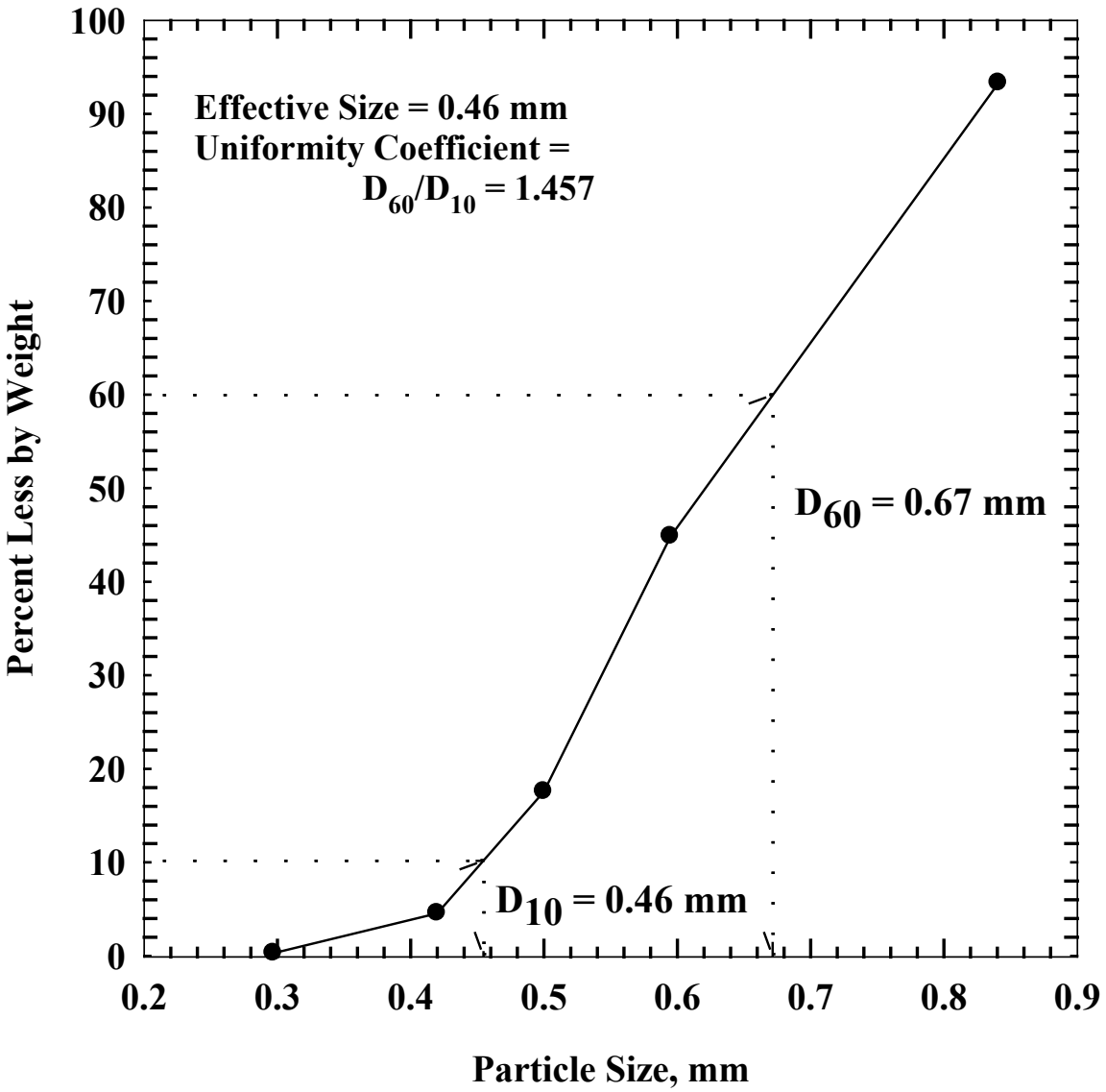

Figure D2. Particle size distribution of fine sand filter media

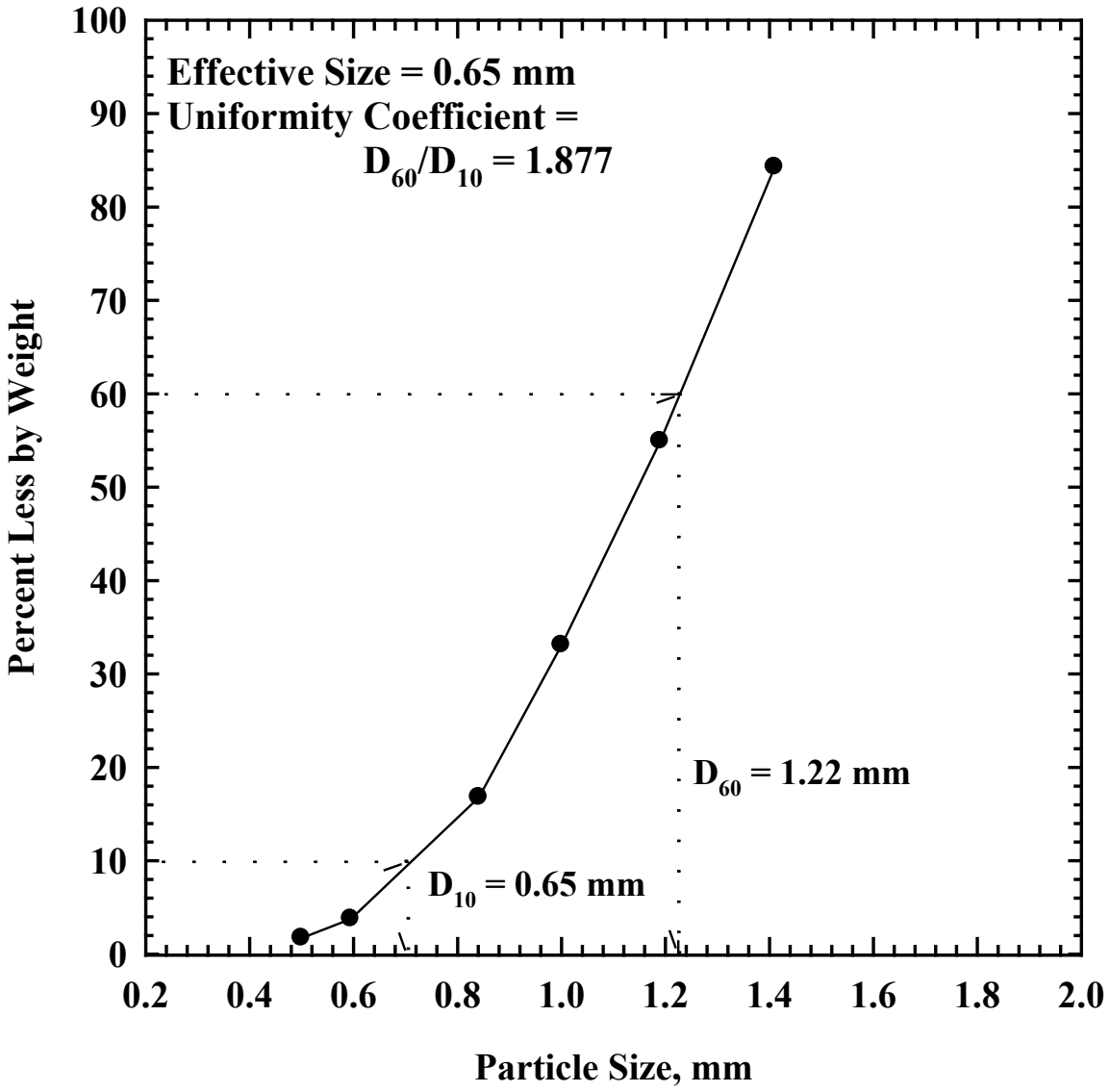

Figure D3. Particle size distribution of coarse sand filter media