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ICR Manual for Bench- and Pilot-Scale Treatment Studies

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Foreword

The Information Collection Rule (ICR) for Public Water Systems (Subpart M of the National Primary Drinking Water Regulations, § 141.141(e)) requires public water systems that meet certain applicability criteria to conduct disinfection byproduct (DBP) precursor removal studies, referred to as treatment studies. These treatment studies are intended to provide cost and performance data on granular activated carbon (GAC) and membrane processes for meeting the DBP regulations. The purpose of the "ICR Manual for Bench- and Pilot-Scale Treatment Studies" is to provide the information necessary to conduct these studies.

This manual is referenced in the final ICR regulation and contains the specific requirements for conducting treatment studies. The document is divided into three parts.

- Part 1 summarizes the ICR regulation, including criteria to determine applicability to the treatment study requirement and includes applications for treatment study options, and provides general guidelines for conducting the treatment studies.
- Part 2 details the requirements of the bench- and pilot-scale GAC studies.
- Part 3 details the requirements of the bench- and pilot-scale membrane studies.

Each of these three Parts is a self contained document, and all references to specific table numbers, figure numbers or section numbers refer to the tables, figures and sections within the Part of the document in which the reference is made unless explicitly stated otherwise. For example, a reference to Table 3-1 in Part 1 refers to Table 3-1 at the end of Part 1, while a reference to Table 3-1 in Part 3 refers to Table 3-1 at the end of Part 3.

DISCLAIMER

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Part 1

General Requirements And Guidelines For Conducting Precursor Removal Studies

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1.0 Introduction

This part of the manual contains information on the ICR requirements for conducting treatment studies, including information on how plants may avoid conducting studies, conduct joint studies, or participate in funding a cooperative research program. General guidelines and requirements for the treatment studies and information common to both GAC and membrane studies will be provided in Section 4.0. Section 5.0 outlines the application process for the various treatment study options and provides the necessary application forms.

This manual has been incorporated by reference in the final ICR regulation, and the detailed requirements for conducting studies are found in this manual rather than in the Federal Register Notice. These detailed requirements are enforceable, and public water systems must comply; however, because of the many site-specific considerations involved in conducting appropriate treatment studies, some flexibility is provided in the protocols.

2.0 Background

The Information Collection Rule (ICR) was a result of the negotiated rule-making process (reg-neg) which was used to reach agreement on a regulatory course of action for control of microbial contaminants and disinfection byproducts (DBPs). The committee which negotiated the rule-making strategy decided that it is necessary to obtain information on the potential impact of future requirements to reduce the level of disinfection byproduct precursors (i.e., natural organic material measured as total organic carbon) on the cost of drinking water treatment in the U.S. In order to accomplish this objective, a requirement to conduct treatment studies is included in the ICR. The committee also felt that the treatment study requirement would accelerate local acquisition of information to assess the feasibility of advanced treatment to reduce the levels of DBP precursors.

3.0 ICR Requirements

3.1 Applicability Monitoring

All public water systems (PWS) which use surface water or ground water under the direct influence of surface water and serve more than 100,000 persons, and PWSs which use only ground water and serve more than 50,000 persons shall conduct treatment study applicability monitoring at the following plants:

- All treatment plants which serve over 100,000 persons (categories A & B in Tables 1 and 2 of § 141.141(b) of the ICR).
- The largest treatment plant owned by a PWS which serves over 100,000 persons if no single plant operated by the PWS serves over 100,000 persons (categories C & D in Tables 1 and 2 of § 141.141(b) of the ICR).
- The largest ground water plant owned by a PWS, with a PWS ground water population served of 50,000 to 99,999 persons (category G in Tables 1 and 2 of § 141.141(b) of the ICR).

The population served includes both wholesale and retail populations. Appendix A to §141.141(a) of the ICR describes the procedure to calculate the populations served by PWSs and treatment plants.

Ground water plants include multiple wells in the same aquifer with no other treatment than chlorination, as described under § 141.141(a)(3) of the ICR, as well as central treatment plants such as softening plants treating water from one or more wells.

Plants that use only purchased finished water that is re-disinfected prior to distribution do not have to conduct treatment study applicability monitoring and are exempt from the treatment study requirement.

Treatment study applicability monitoring is conducted to determine: (1) if the treatment plant precursor levels are low enough to avoid the treatment study requirement, and/or (2) if two or more treatment plants qualify for a common source designation as described in Section 3.6. The treatment study applicability monitoring requirements summarized in Table 3-1 are:

- Twelve (12) consecutive monthly total organic carbon (TOC) samples taken from the plant influent for surface water plants or, twelve (12) consecutive monthly TOC samples taken from the finished water for plants treating only ground water. Treatment plant influent is defined as water that represents the water quality challenge to a particular plant, and finished water is defined as water that does not undergo further treatment by a plant other than maintenance of a disinfectant residual.
- Twelve (12) consecutive monthly total organic halide (TOX) samples evaluated under uniform formation conditions (UFCTOX) may be required for a common source designation. UFCTOX samples are taken from the plant influent for surface water plants and from the finished water for plants treating only ground water.

- If a surface water or ground water plant is using only chlorine as the primary and residual disinfectant, quarterly trihalomethane (THM4) and haloacetic acid (HAA5) distribution system samples can be measured to determine treatment study applicability. Each quarter, samples must be collected from the four following distribution system points: one sample point representative of the maximum residence time for the treatment plant and three sample locations representative of the average residence time in the distribution system for the treatment plant.

All treatment study applicability monitoring shall be conducted using the methods and the mandatory quality control procedures contained in the "DBP/ICR Analytical Methods Manual" (EPA 814-B-96-002). Additionally, the TOC analyses shall be conducted by laboratories that have received approval from EPA to perform TOC analysis for compliance with this rule. Although not a requirement, it is recommended that EPA approved laboratories also analyze the UFCTOX, THM4 and HAA5 samples collected during treatment study applicability monitoring.

This treatment study applicability monitoring must begin no later than three (3) months after the date of publication of the final rule in the Federal Register. Specifically, monthly sampling of TOC, and UFCTOX if required for a common source designation, must begin no later than three (3) months after the date of publication of the ICR. If distribution system DBP samples are to be used to demonstrate treatment study applicability, then quarterly sampling of THM4 and HAA5 distribution system samples must begin between three (3) and six (6) months after the date of publication of the ICR. These results must be submitted to the ICR Treatment Studies Coordinator, at the address listed in Section 5.0, no later than seventeen months after publication of the final rule in the Federal Register.

3.2 Criteria Under Which No Treatment Studies Are Required

TOC: Treatment plants using surface water are excused from conducting treatment studies if they do not exceed an annual average TOC of 4.0 mg/L in the treatment plant influent, based on the twelve monthly TOC samples. Treatment plants using only ground water not under the direct influence of surface water are excused from conducting treatment studies if they do not exceed an annual average TOC of 2.0 mg/L in the finished water, based on the twelve monthly TOC samples.

DBP: Treatment plants that use only chlorine as both the primary and residual disinfectant and have, as an annual average of four quarterly averages, levels of less than 40 μg/L for THM4 and less than 30 μg/L for HAA5 need not conduct treatment studies. Quarterly averages are the arithmetic averages of the four distribution system samples (i.e., one sample point representative of the maximum residence time for the treatment plant and three sample locations representative of the average residence time in the distribution system for the treatment plant).

Full-scale GAC Or Membrane Treatment

For a treatment plant that already uses full-scale GAC or membrane technology capable of achieving precursor removal, a PWS shall conduct the monitoring listed in Table 3-2 and submit full-scale plant data, as per § 141.142 of the ICR, ensuring that the GAC or membrane processes are included in the process train being monitored. GAC capable of removing precursors is defined in the regulation as GAC with an empty bed contact time (EBCT) of 15 minutes or greater with a time between carbon reactivation or replacement not more than nine months. In special cases, GAC plants which operate outside the above specifications of EBCT and reactivation frequency may submit a request to avoid treatment studies, including data demonstrating effective precursor removal. The purpose of this requirement is to not excuse plants from conducting treatment studies which technically have "full-scale GAC treatment", but may have very limited precursor removal. For treatment plants to be considered to have membrane technology to achieve precursor removal, the plant shall use nanofiltration or reverse osmosis membranes. These types of membranes have been demonstrated to be effective for the removal of precursor materials. Membrane plants using technologies other than nanofiltration or reverse osmosis may submit a request to avoid treatment studies, including data demonstrating effective precursor removal.

Grandfathered Studies

A PWS that has conducted precursor removal studies using granular activated carbon or membrane technology (nanofiltration or reverse osmosis) may use the results of those studies in fulfillment of the ICR treatment study requirement if all the following conditions are met:

- The study was conducted using analytical methods described in "DBP/ICR Analytical Methods Manual," EPA 814-B-96-002.
- The study was conducted using a protocol similar to one of those specified in this manual.
- The study data meets the requirements of the ICR and is supplied to EPA.

Request To Avoid Treatment Studies

A PWS that believes it qualifies to avoid the treatment study requirement under any of the conditions listed in Section 3.2 shall submit an application according to the instructions listed in Section 5.2.2 (and Section 5.2.6 for grandfathered studies). The PWS will be notified in writing of EPA's decision regarding these applications.

TOC - An application to avoid treatment studies on the basis of TOC data shall be requested no later than eighteen (18) months after publication of the final rule in the Federal Register, showing the annual average TOC concentration less than the treatment studies trigger levels described in this section.

DBP - If the TOC trigger is exceeded but the distribution system DBPs are less than the levels specified in this section, the PWS shall submit an application on that basis as soon as the final DBP results are available, but no later than eighteen (18) months after publication of the final rule in the Federal Register.

Full-scale GAC or membrane treatment - If the PWS wishes to avoid the treatment studies requirement on the basis of operating full-scale GAC or membrane processes, the PWS shall submit an application, including any full-scale or pilot-scale data showing precursor removal, not later than eighteen (18) months after final rule publication.

Grandfathered Studies - If a PWS believes it qualifies to avoid the requirements for a treatment study under the grandfathered study provisions, it shall submit an application to EPA not later than nine (9) months after publication of the final rule. The application must include a description of the study, the equipment used, the experimental protocol, the analytical methods and any reports resulting from the study. If the grandfathered study is approved then specific information will be requested, including cost information, which must be submitted no later than eighteen (18) months after publication of the final rule in the Federal Register.

3.3 Criteria For Determining Individual Treatment Study Requirements

The reg-neg committee agreed that granular activated carbon and membrane treatment were the technologies most likely to be effective for precursor removal. The committee also had determined that both bench-scale studies and pilot-scale studies should be allowed, recognizing that pilot-scale studies provide more relevant data, but that bench-scale studies should be less expensive to conduct. The treatment objective for all studies should be the achievement of levels of disinfection byproducts less than 40 μg/L and 30 μg/L for THM4 and HAA5, respectively when free chlorine is used as the disinfectant.

Plants required to conduct the monitoring described in Section 3.1 that do not qualify to avoid the treatment studies must conduct individual treatment studies or joint studies, or contribute funds to a cooperative research effort. The scale of the required treatment study (i.e., bench-scale or pilot-scale) is based on both system and plant size as described in Table 2, and footnote 4 to Table 2, of § 141.141(b)(2) of the ICR rule. The required studies for plants that do not meet the avoidance criteria are summarized here.

- All plants that serve 500,000 persons or more shall conduct a pilot-scale study (categories A & B in Tables 1 and 2 of § 141.141(b) of the ICR).

- All plants that serve 100,000 to 499,999 persons shall conduct either a pilot-scale or a bench-scale study (categories A & B in Tables 1 and 2 of § 141.141(b) of the ICR).

- If a PWS serves more than 100,000 persons, but does not own a single plant that serves more than 100,000 persons, then the largest plant owned by that system shall conduct either a pilot-scale or a bench-scale study (categories C & D in Tables 1 and 2 of §141.141(b) of the ICR).

- If a PWS serves 50,000 to 99,999 persons with 50,000 persons or more served by ground water, then the largest plant owned by that system shall conduct either a pilot-scale or a bench-scale study (category G in Tables 1 and 2 of § 141.141(b) of the ICR).

- A PWS with multiple plants operating on a demonstrated common source, as defined in Section 3.6, is not required to conduct more than one treatment study for those plants. A PWS must apply for this option according to the instruction in Section 5.2.3 no later than eighteen (18) months after promulgation of the ICR. If both pilot-scale and bench-scale treatment studies would otherwise be required for treatment plants operating on a common source, the PWS shall conduct a pilot-scale study.

Plants required to conduct individual treatment studies shall submit a study concept form and a study plan to EPA no later than eighteen (18) months after publication of the final rule in the Federal Register. The study concept form and requirements for the study plan are described in Section 5.4. The study plan will be reviewed by EPA, and feedback on the design will be provided if necessary.

3.4 Joint Treatment Studies

Public comment in response to the proposed ICR rule was in favor of allowing systems to cooperate in conducting joint studies. Therefore, the final rule allows plants which treat water from a common water resource, as defined in Section 3.6, and which have similar treatment to join together in conducting studies. Similar treatment means that, for example, softening plants may not conduct joint studies with conventional plants.

The minimum number and types of studies to be conducted during joint studies are described in the final regulation and in Tables 3-3 and 3-4. These minimum requirements were developed in order to maintain some degree of equity in the treatment study requirement while providing some benefit to systems conducting joint studies. Only plants in the same population served category (i.e., $< 500{,}000$ persons or $\geq 500{,}000$ persons) will be allowed to join together to conduct joint studies. The maximum number of plants allowed to join together to conduct joint studies in the $<500{,}000$ size category is six; and for the $\geq 500{,}000$ size category, no more than three plants may join together to conduct a joint study.

An approved grandfathered study may not be used as a joint study unless all the common source requirements, as defined in Section 3.6, and the requirements in Table 3-3 or 3-4 are met, and the PWS which conducted the study submits written concurrence.

Joint studies should be conducted to maximize the benefit to the participating plants. In most cases, when joint studies are conducted, multiple studies are required. The systems should use that opportunity to develop information appropriate for their situations. For example, if it is not obvious whether GAC or membrane technology would be the technology of choice, the joint study could include a comparison of the two. If, on the other hand, membrane technology would have a clear advantage over GAC for a situation where two studies are required, the joint study might include two separate studies of membrane technology, designed to evaluate different membranes, membrane configurations or pretreatments; or conducted at two different locations to provide hands-on experience at each plant.

Request To Conduct Joint Treatment Studies

PWSs that wish to conduct joint treatment studies shall submit a letter of intent to EPA no later than twelve (12) months after publication of the final rule in the Federal Register. All participating PWSs should understand that the letter of intent is not binding. If the results of the full twelve months of monitoring show that a plant may avoid conducting studies because a surface water plant influent TOC is less than 4.0 mg/L or a ground water plant finished water TOC is less than 2.0 mg/L or distribution system THM4 and HAA5 are lower than 40 μg/L and 30 μg/L, respectively, the system may avoid conducting a study under one of those exclusions. Likewise, if the full twelve months of monitoring result in TOC or UFCTOX data which no longer support the common source designation, the systems will not be allowed to conduct joint studies. Also, one or more of the systems may simply change its mind, and decide not to participate in the joint study. The purpose of the letter of intent is to provide early notification to EPA of the interest of the participating PWSs and allow EPA to begin reviewing the supporting information.

Once all of the supporting data has been obtained from the twelve months of applicability monitoring, the cooperative of plants shall submit an application to conduct a joint study, according to the instructions in Section 5.2.4, no later than eighteen (18) months after publication of the final rule in the Federal Register. EPA will review this application and notify the plant cooperative whether the joint study is approved or disapproved.

3.5 Criteria Under Which An Alternative To Conducting A Treatment Study Is Allowed

In lieu of conducting the required treatment study, a PWS may apply to contribute funds to a Disinfection Byproducts/Microbial Research Fund (termed the buyout option). The PWS selecting this option must use a common water resource, as described in Section 3.6, on which a plant or cooperative of plants is conducting a study. A treatment plant serving 500,000 persons or more cannot buy out unless a plant serving 500,000 persons or more is conducting a pilot-scale study on the common source. A treatment plant serving fewer than 500,000 persons can buy out if either a bench-scale or a pilot-scale study is being conducted on the common source. An approved grandfathered study can be used as justification for contributing to the cooperative research effort.

A PWS selecting this alternative for a treatment plant serving a population of 500,000 or more shall contribute $300,000. A PWS choosing this option for a treatment plant serving fewer than 500,000 persons shall contribute $100,000. The funds shall be contributed to the Disinfection Byproducts/Microbial Research Fund, to be administered by the American Water Works Association Research Foundation (AWWARF) under the direction of an independent research council, for use in a dedicated cooperative research program related to disinfectants, disinfection byproducts, and enhanced surface water treatment.

Request To Buy Out Of Treatment Studies

A PWS that believes it qualifies to buy out of the treatment study requirement under the alternative described in the preceding paragraph shall submit a letter of intent no later than

twelve (12) months after the publication of the final rule in the Federal Register expressing its intention to contribute funds to the Disinfection Byproducts/Microbial Research Fund. The letter shall identify the other treatment plant(s) using the common water resource which will be conducting a study.

After all of the supporting data has been obtained from the twelve months of applicability monitoring, the PWS must submit an application to buy out of the treatment study requirement according to the instructions in section 5.2.5. This application must be submitted no later than eighteen (18) months after publication of the final rule in the Federal Register. Approval cannot be final until EPA has confirmed that a treatment study is being conducted by another plant on the common source. EPA will notify the PWS if it can avoid the study by contributing funds to the Disinfection Byproducts/Microbial Research Fund. Information will be provided in the notification of approval on the mechanism for contributing the funds to the research fund. The PWS shall make the contribution no later than 90 days after notification by EPA that the buy out application is approved.

3.6 Criteria For A Common Water Resource

Three treatment study options require that cooperating plants demonstrate that they operate on a common water source: (1) a PWS with multiple plants operating on a common source intending to conduct a single study, (2) a cooperative of treatment plants intending to conduct a joint treatment study, and (3) a plant intending to buy out of the treatment study requirement. A PWS or a cooperative of PWSs applying for one of these treatment study options shall submit an application for a common source designation according to the instructions listed in Section 5.3. This section describes the requirements for a common source designation.

Common River Source

Treatment plants on the same river are considered to have a common source if: (1) each cooperating plant intake is no more than 20 river miles from all other intakes, and the mean influent TOC of each cooperating plant is within 10% of the average of the mean TOCs of all the cooperating plants; or (2) the intake of all cooperating plant are between 20 and 200 river miles apart, and the mean influent UFCTOX of each cooperating plant is within 10% of the average of the mean UFCTOXs of all the cooperating plants. The mean TOC or UFCTOX is calculated from the twelve consecutive months of monitoring to determine treatment studies applicability as described in Section 3.1.

Common Lake, Reservoir Or Ground Water Source Under the Direct Influence

Treatment plants using the same lake, reservoir or ground water resource under the direct influence of surface water are considered to have a common resource if the mean influent TOC of each cooperating plant is within 10% of the average of the mean TOCs of all the cooperating plants. The mean TOC is calculated from the twelve consecutive months of monitoring to determine treatment studies applicability as described in Section 3.1.

Common Ground Water Resource

Treatment plants with intakes from a single aquifer are considered to be using a common source if the mean finished water TOC of each cooperating plant is within 10% of the average of the mean TOCs of all the cooperating plants. The mean TOC is calculated from the twelve consecutive months of monitoring to determine treatment studies applicability as described in Section 3.1.

Table 3-1 Treatment Study Applicability Monitoring Requirements For Plants

Sampling Point	Monthly Analyses	Quarterly Analyses
Plant Influent for Surface Water Plants	TOC and UFCTOX[1]	
Plant Effluent for Ground Water Plants	TOC and UFCTOX[1]	
Four Distribution System Samples for Both Surface and Ground Water Plants		THM4 and HAA5[2]

1 UFCTOX analysis, defined as total organic halides evaluated under uniform formation conditions, is only required for treatment plants using a common river source with intakes between 20 and 200 river miles apart and applying for a common source designation.

2 Treatment plants that use only chlorine as the primary and residual disinfectant may monitor THM4 and HAA5 in the distribution system to determine applicability.

Table 3-2 Monitoring Required Across Full-Scale GAC Or Membrane Processes

Sampling Point	Monthly Analyses[1]
Before GAC or membranes	pH, Alkalinity, Turbidity, Temperature, Calcium and Total Hardness, TOC and UV_{254}
After GAC or membranes	pH, Alkalinity, Turbidity, Temperature, Calcium and Total Hardness, TOC and UV_{254}

Sampling Point	Quarterly Analyses[2]
Before GAC or membranes if disinfectant is applied at any point in the treatment plant prior to these processes	THM4, HAA6, HAN, CP, HK, CH, TOX
After GAC or membranes if disinfectant is applied at any point in the treatment plant prior to these processes	THM4, HAA6, HAN, CP, HK, CH, TOX

1 TOC: total organic carbon. UV_{254}: absorbance of ultraviolet light at 254 nanometers.

2 THM4: trihalomethane (four). HAA6: haloacetic acids (six). HAN: haloacetonitriles. CP: chloropicrin. HK: haloketones. CH: chloral hydrate. TOX total organic halide. For THM4, HAA6, HAN, and HK, analytical results for individual analytes shall be reported.

Table 3-3 Joint Study Requirement For Plants With A Population Served <500,000[1]

No of Plants	Minimum Studies to be Conducted
2	1 pilot (GAC or membrane)
3	1 pilot and 1 bench (GAC or membrane)
4	2 pilots (GAC and/or membrane)
5	2 pilots (GAC and/or membrane),1 bench (GAC or membrane)
6	2 pilots and 2 bench (GAC and/or membrane)

1 Each treatment plant must serve a population less than 500,000.

Table 3-4 Joint Study Requirement For Plants With A Population Served ≥500,000[1]

No. of Plants	Minimum Studies to be Conducted
2	1 pilot (GAC or membrane), 2 bench (GAC and/or membrane)
3	2 pilots (GAC and/or membrane)

1 Each treatment plant must serve a population of 500,000 or more.

4.0 General Guidelines

4.1 Precursor Removal Technology

The reg-neg committee agreed that granular activated carbon and pressure-driven membrane processes held the most promise for widespread application for DBP precursor removal in the U.S., and some of the pros and cons associated with each technology are summarized in Table 4-1. Both technologies have been used to a varying extent and for various purposes for some time, and there were sufficient data available to indicate that each technology has the capability to achieve relatively low levels of precursors under certain circumstances. There was widespread experience in conducting both bench-scale and pilot-scale testing of GAC within the drinking water community but less familiarity with testing membrane technology. The reg-neg committee used a volunteer group of technical experts to craft a tentative strategy for precursor removal testing in the ICR proposal. The outcome was that there should be allowed either bench-scale or pilot-scale testing of either GAC or pressure-driven membrane technology, specifically either reverse osmosis or nanofiltration. The treatment study requirements for both technologies using either bench- or pilot-scale systems are summarized in Table 4-2.

Pilot testing of GAC has been done for decades in the chemical process industry, for wastewater reclamation and drinking water treatment. An effective bench-scale procedure for testing GAC performance, called the rapid small-scale column test (RSSCT), has been used successfully by a number of researchers and has provided results comparable to longer pilot tests. This manual contains procedures for conducting GAC pilot tests and RSSCTs.

There is less experience in the water industry with testing membrane technology, and thus less confidence in specifying a testing technique for the ICR. Therefore, two approaches to bench-scale testing of membrane technology are presented to allow systems opting for membrane bench studies a choice which will provide at least one technique suitable for local circumstances. One approach, termed the rapid bench-scale membrane test (RBSMT), uses a small sheet of membrane material and a small volume of water to allow the PWS the option of conducting membrane testing off-site. The second approach, the single element bench-scale test (SEBST), uses a single membrane element similar to those which would be used in large numbers in a full-scale system. This approach requires testing on-site but may provide better data. Likewise, considerable flexibility is provided for pilot studies. Pilot membrane systems must be designed as a 2-1 array and operated at a recovery of at least 75%. Since membrane pilot studies represent a significant investment, the PWS conducting the test should do so in a way which provides the most appropriate data for its use while, concurrently meeting EPA's need for data from which estimates of national impact of future regulations can be made.

The treatment goals for the ICR treatment studies are effluent levels of disinfection byproducts no greater than those proposed as Stage 2 DBP MCLs in the Federal Register, Vol.59, No.145, Friday, July 29, 1994. Stage 2 proposed MCLs were set at 40 μg/L for THM4 and 30 μg/L for HAA5 as an annual average. These studies will provide information

concerning the feasible level of DBPs that can be achieved, which will be used in a second negotiated rule-making process to determine the final MCLs.

4.2 Influent To The Treatment Studies

The ICR specifies that the precursor removal testing be done on the plant water after it has passed through any full-scale treatment processes currently in place to remove precursors, such as coagulation/sedimentation and filtration. However, one of the guiding principles in considering future regulations for control of DBPs is that removal of DBP precursors should be maximized before contact with disinfectants, especially chlorine. Therefore, the ICR also requires that feed water to the treatment studies be taken from a point in the treatment plant before any application of oxidant or disinfectant that could form chlorinated byproducts. If a chlorine-based oxidant is added prior to full-scale processes which remove precursors, then the full-scale treatment should be simulated on the bench- or pilot-scale prior to introduction to the test system. For example, if a water plant routinely adds chlorine to the rapid mix unit, and a system intends to conduct pilot testing of either membranes or GAC, the system must collect the water for the pilot test ahead of the rapid mix unit and treat the non-chlorinated water with pilot unit processes which simulate the full-scale processes currently in place. For bench-scale testing, it may be possible to alter the point of disinfectant addition for a short enough time to obtain a batch of water from the appropriate point in the treatment process; if not, a small volume of water from a point before disinfectant addition could be obtained and batch-treated to simulate the full-scale processes.

There may be cases where the simulation of some full-scale treatment process may not be appropriate or necessary. For example, since both the RSSCT and the RBSMT use cartridge filtration as a routine test pretreatment step, it would not be necessary to simulate granular media filtration for those procedures. One of the primary concerns in membrane processes is pretreatment to minimize fouling or loss of productivity. Therefore, it may not be appropriate to require that water applied to a membrane system undergo exactly the same processes as the current full-scale system, if there are good reasons to treat the water differently.

Multiple bench-scale tests or long-term pilot studies are generally required to assess seasonal variation or, if seasonal variation is not significant (as is the case for most ground waters), to assess other factors impacting the performance of the precursor removal technology. For example, one of the major factors impacting membrane performance is pretreatment. Therefore, if seasonal variation is not an issue and the water to be treated is not a high-quality ground water, systems may wish to conduct studies under various pretreatment conditions and would be allowed to do so. If seasonal variation does occur, the tests should be conducted to account for it; and for bench-scale tests, the test conditions should be as consistent as possible over all four quarterly tests, with differing results indicating seasonal differences.

Seasonal variability of source waters will not be explicitly defined due to the variety of factors that could lead to significant seasonal variation. One of the most important parameters that can be used to assess the seasonal variability of a water is the TOC concentration, and if

the TOC varies by more than a factor of two over the course of a year, then it is recommended that seasonal variability be evaluated. Another parameter that can be used to assess seasonal variability is the concentration of DBP precursors assessed under simulated distribution system (SDS) conditions. SDS-DBPs are not only affected by the precursor concentrations, but also the conditions of the SDS test including temperature, pH and chlorine residual. Thus, SDS-DBPs may be a better indicator of seasonal variability than TOC for the purposes of the ICR. GAC performance is sensitive to both the concentration and nature of organic precursors in the feed water, and if these parameters vary by more than a factor of two over one year, the effect of seasonal variability on performance should be evaluated. The performance of membrane processes is less sensitive to the concentration of DBP precursors in the feed water; however, seasonal variations in feed water temperature and the concentration of inorganic solutes can have a significant impact on productivity and cost.

The PWS conducting the study must identify the water quality parameters that vary in a given source, and use judgement to decide if these parameters have a significant impact on the ability of the process under investigation to control DBPs. For membrane processes, the effect of seasonal varibility on water production and the rate of membrane fouling must also be considered when assessing the impact of seasonal variability on performance.

4.3 GAC Studies

GAC has limitations for economical precursor removal. If high levels of TOC (greater than 6 to 8 mg/L) are applied to GAC systems with EBCTs in the range of the ICR testing procedure, early breakthrough may occur and the ICR treatment goal of less than 40 μg/L for THM4 and 30 μg/L for HAA5 may not be economical. PWSs with high levels of precursors should be aware that GAC without some additional pretreatment, such as enhanced coagulation or pH control, may not be a good candidate for precursor removal.

Pilot Studies

Details of the pilot study procedure are provided in Part 2 of this manual. Two EBCTs, 10 minutes and 20 minutes, shall be evaluated for the pilot studies. Each EBCT run will be terminated when either 70% breakthrough or steady-state removal of precursors is achieved, as described in Part 2. If either of these criteria is met for the 20-minute contact time prior to 4000 hours run time, a second run at both EBCTs shall be conducted following the same sampling requirements. In all cases, the maximum run length for the pilot-scale study (one or two runs) is 8000 hours. The pilot study should be timed to account for seasonal variations in water quality. If seasonal variation is not a factor and the first 20 minute EBCT terminates before 4000 hours run time, the second run can be used to obtain data on other factors of interest. Factors important in GAC treatment include pretreatment, such as enhanced coagulation or pH adjustment, carbon type and EBCT.

Precursor removal performance is characterized by conducting simulated distribution system (SDS) chlorination experiments on the GAC influent and effluent along with other analyses. The SDS conditions are the average conditions in the distribution system served by the plant conducting the study. The chlorination of samples for SDS analysis is described in

Part 1, Section 4.6, and also in Part 2, Section 6.0, where special requirements for GAC testing are included.

Bench-scale Studies

The bench-scale GAC test is the RSSCT, as described in Part 2. This test shall be run to simulate full-scale EBCTs of 10 minutes and 20 minutes. The RSSCT runs shall be conducted quarterly to account for seasonal variation or in the case of insignificant seasonal variation, to examine other factors as with the pilot studies. If seasonal variation is not significant, the PWS may conduct the four runs at 10- and 20-minute EBCTs at any time. The ICR requires that if the first quarterly RSSCT run is terminated because of early breakthrough, as specified in Part 2, within 20 full-scale-equivalent days for the 10-minute EBCT test or 30 full-scale-equivalent days for the 20-minute EBCT test, the system shall switch to membrane bench tests, conducting the remaining three quarterly tests with only one membrane.

4.4 Membrane Studies

Membrane processes such as nanofiltration and reverse osmosis have been shown to achieve very high removals of DBP precursors that would enable utilities treating feed waters with TOC concentrations greater than 10 mg/L to meet the ICR treatment goal of 40 μg/L for THM4 and 30 μg/L for HAA5 when free chlorine is used as both the primary and residual disinfectant. Membranes treating ground waters have demonstrated excellent control of DBPs while maintaining acceptable productivity. However, a limited number of studies on surface waters indicate that severe membrane fouling can occur when treating these waters. This may require that surface waters undergo extensive pretreatment, such as enhanced coagulation or microfiltration, prior to membrane treatment.

Pilot Studies

Part 3 of this manual describes the requirements of the membrane pilot studies. The evaluation of only one membrane type under one set of operating conditions is required during a pilot study. The pilot study shall be run continuously over a period of one year, with allowances for down-time due to membrane cleaning, maintenance or other reasons. The pilot-scale run time shall be no less than 6600 hours, which represents approximately 75% of one calendar year. A pilot system must use standard elements at least 2.5 inches in diameter by 40 inches in length. This size requirement is for membranes in spiral-wound configurations, but standard hollow-fiber elements can also be used, although hollow-fiber technology is not recommended for surface waters. The system must consist of at least two stages, with a minimum of two pressure vessels in the first stage and one pressure vessel in the second stage (i.e., a 2-1 array), and each pressure vessel must contain at least three membrane elements.

Membrane performance is to be assessed in terms of productivity and permeate water quality including precursor removal. Precursor removal is measured by conducting SDS chlorination experiments on the membrane feed and permeate along with other analyses. The SDS conditions are the average conditions of the distribution system served by the plant conducting the study.

Bench-scale Studies

Two approaches for bench-scale membrane testing are described in Part 3, the RBSMT and the SEBST. Additionally, there are two options provided for conducting SEBSTs: (1) quarterly studies and (2) a yearlong study. The RBSMT and quarterly SEBST studies require that two membranes be evaluated four times over the course of one year to account for seasonal variation, or in the case of insignificant seasonal variation, to examine other factors. If seasonal variation is not significant, the PWS may conduct the four runs on two membranes at any time. Some variables that a PWS may wish to investigate include pretreatment, additional membrane types and operating parameters such as flux and recovery. The yearlong SEBST study requires that one membrane be evaluated for a run time of at least 6600 hours over a one year period.

Three options for bench-scale membrane testing are provided to allow some flexibility in meeting the ICR requirements. The RBSMT can be run off-site and offers a great deal of operational flexibility, while a single element test may provide better data but must be conducted on-site and would require long-term operator attention and a continuous supply of treated, unchlorinated feed water. The long-term SEBST study provides the most flux data, but only for one membrane type. Regardless of the approach selected, the membranes investigated must be evaluated with respect to productivity and permeate quality including precursor removal as assessed under SDS conditions.

4.5 Analytical Methods

A list of approved analytical methods for the treatment studies is provided in Table 7 of the ICR rule. These methods and mandatory quality control procedures are contained in the "DBP/ICR Analytical Methods Manual" (EPA 814-B-96-002). One method not described in this manual is the measurement of conductivity or total dissolved solids (TDS) with either a conductivity probe or a TDS meter. TDS or conductivity measurements are commonly used to assess the rejection characteristics of a membrane. Method 2510 B (Standard Methods, 18th ed., 1992) describes the procedure for measuring conductivity with a probe. Measurement of TDS is similar to the measurement of conductivity; the main difference is that a TDS meter is calibrated to read conductivity as TDS in mg/L using a specific conversion factor.

Some of the data sheets in Parts 2 and 3 contain spaces for all nine of the HAA species; however, only the following six HAAs are required: monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid, dibromoacetic acid and bromochloroacetic acid. These six HAAs make up HAA6, and the first five HAAs in this list make up HAA5. If additional HAAs are measured, then they should be reported.

4.6 Chlorination Procedures

SDS Test Procedure

As described in § 141.144(b)(3) of the ICR rule, samples collected during the treatment studies must be chlorinated under site-specific SDS conditions to evaluate the formation of THM4, HAA6 and TOX.

The SDS conditions that must be selected are incubation time, free chlorine residual at the end of the incubation period, pH during incubation, and the temperature during incubation. These conditions should be representative of the average distribution system conditions at the time of the test, and the same set of conditions must be used for the influent sample and the corresponding effluent sample for each experiment. For the bench-scale studies, it is required that the same pH, incubation time, free chlorine residual and temperature be used for all SDS samples during a quarter; however, different SDS conditions can be used during different quarters to simulate the current distribution system conditions. If chlorine is not used as the final disinfectant in practice, then the target free chlorine residual should be set at 1.0 to 0.5 mg/L under the SDS pH, incubation time and temperature.

The chlorine dose required to achieve the target chlorine residual can be determined by first conducting a demand study with the water sample. The SDS incubation time, temperature and pH should be used during the demand study, but the chlorine dose should be varied. The chlorine residual can be plotted as a function of chlorine dose, and this relationship can be used to determine the chlorine dose required to achieve the target chlorine residual. Since the TOC of a water can vary over the course of a run (e.g., the GAC effluent), the chlorine demand will also vary. To achieve the same free chlorine residual in these samples, the chlorine dose must be varied according to the demand.

The target pH can be difficult to achieve for poorly buffered samples, and it may be necessary to buffer these waters to achieve the desired pH at the end of the incubation period.

UFC Test Procedure

The uniform formation conditions (UFC) procedure is a standardized set of representative chlorination conditions:

Incubation time:	24 ± 1 hours
Incubation temperature:	20.0 ± 1.0°C
Buffered pH:	8.0 ± 0.2
24-hour chlorine residual:	1.0 ± 0.4 mg Cl_2/L

Some ICR monitoring requirements include the evaluation of TOX under UFC conditions (i.e., UFCTOX) to demonstrate a common source for some types of surface water resources. The standard operating procedure for the UFC test is included in Appendix 2-B located at the end of Part 2 of this manual.

Table 4-1 Factors For Consideration In Selecting Treatment Study Technology

Technology	Pros	Cons
Membranes (Nanofiltration and Reverse Osmosis)	-Can remove pathogens and DBP precursors to very low levels. -Can remove inorganic contaminants.	-Fouling can limit the application of membrane technology for surface waters. -The concentrate waste stream requires disposal and/or treatment.
GAC	-Typically less expensive than membrane technology. -A variety of finished water qualities are available through blending.	-Generally not feasible with GAC influent TOC > 6 to 8 mg/L without additional pretreatment. -Does not remove pathogens.

Table 4-2 Summary Of Treatment Study Requirements For GAC And Membrane, Pilot-Scale And Bench-Scale Systems

Technology	Bench-Scale	Pilot-Scale
Membranes (Nanofiltration and Reverse Osmosis)	*The three options are:* 1.) RBSMT studies evaluating two membranes at four recoveries over four quarters. 2.) Single element studies evaluating two membranes at 75% recovery over four quarters. 3.) Long-term single element studies evaluating one membrane at 75% recovery over at least 6600 hours.	-A minimum configuration of: two pressure vessels in the first stage and one pressure vessel in the second stage. -At least three elements per pressure vessel. -A minimum 2.5" x 40" element size. -A minimum recovery of 75%. -Minimum 6600 hour runtime.
GAC	-RSSCT studies evaluating two EBCTs (10 and 20 minutes) conducted quarterly. -Operated until 70% breakthrough.	-At least two inch diameter columns evaluating 10 and 20 minute EBCTs run until 70% breakthrough. -If the 70% breakthrough occurs prior to 4000 hours runtime for the 20 minute EBCT, a second pilot run must be conducted.

5.0 Applications And Reports

A PWS must submit the following for each plant required to conduct treatment study applicability monitoring according to the schedule listed in Table 5-4: (1) the treatment study applicability data and (2) an application for one of the treatment study options. This section includes application materials for the various treatment study options, which include:

1. Individual treatment studies
2. Treatment study avoidance
3. Single study by multiple plants operating on a common source and owned by the same PWS (abr., single study for multiple plants)
4. Joint treatment studies
5. Treatment study buyout
6. Grandfathering previous studies

All data, applications and reports relevant to the treatment studies shall be submitted to the following address:

U.S. EPA
Technical Support Division
ICR Treatment Studies Coordinator
26 West Martin Luther King Drive
Cincinnati, OH 45268

5.1 Application Materials And Deadlines

This section includes nine forms (Tables 5-1, 5-2, and 5-5 thru 5-11) that are to be used in the application process for various treatment study options. Every correspondence between the plant or PWS and EPA must include the general information sheet shown in Table 5-1. All plants required to conduct treatment study applicability monitoring shall submit their treatment study applicability data on the form shown in Table 5-2, no later than seventeen (17) months after promulgation of the ICR. This applicability data is required to review most applications.

Table 5-3 summarizes the tables and additional information required with each application. All applications shall consist of a cover letter, a general information form (Table 5-1) and at least one additional table. The cover letter must be signed by the official contact person of the applying PWS (or each PWS involved in a joint study). This letter should include any special circumstances or information to be considered during the review of the application. Only one application can be submitted at a time, and multiple applications will be returned to the sender without consideration.

Table 5-4 summarizes the deadlines for the applicability data, treatment study option applications, start of studies, quarterly progress reports, and the final treatment study report. The deadlines are listed relative to the date of rule publication since the ICR was not

promulgated at the time this manual was finalized. However, a blank column is provided in Table 5-4 so that the actual dates can be entered into the table when available.

EPA will provide technical assistance through the Safe Drinking Water Hotline at 1-800-426-4791. If the Hotline is unable to answer a question, it will be forwarded to a technical assistance group that will provide an answer.

5.2 Treatment Study Option Review Criteria

The general criteria by which applications for each treatment study option will be reviewed is presented here. These criteria may not be inclusive of all situations, but are intended to provide an indication of the necessary requirements to qualify for each of the treatment study options.

5.2.1 Individual Studies

The individual study requirements are based on plant size and are summarized as follows:

- Plants serving 500,000 persons or more must conduct a pilot-scale treatment study.
- Plants serving fewer than 500,000 persons must conduct either a bench-scale or a pilot-scale treatment study.
- A study concept form, Table 5-11, and study plan shall be submitted for each study and will be reviewed according to the criteria described in Section 5.4.

5.2.2 Treatment Study Avoidance

A plant intending to avoid the treatment study requirement on the basis of TOC, DBPs or full-scale membrane or GAC technology shall submit the application in Table 5-5 along with the general information form, Table 5-1. This section describes the criteria that must be met to avoid the requirement of conducting a treatment study.

Plants can avoid treatment studies on the basis of TOC.

- Treatment plants using surface waters or ground waters under the direct influence of surface water with a yearly average influent TOC concentration less than 4.0 mg/L, based on monthly applicability monitoring, do not have a treatment study requirement.
- Treatment plants using only ground waters with a yearly average finished water TOC concentration less than 2.0 mg/L, based on monthly applicability monitoring, do not have a treatment study requirement.

Or

Plants can avoid treatment studies on the basis of THM4 and HAA5.

- Plants must be using only free chlorine as the primary and residual disinfectant AND the mean of four quarterly average THM4 concentrations must be less than 40 µg/L AND the mean of four quarterly average HAA5 concentrations must be less than 30 µg/L.

- The quarterly average THM4 and HAA5 are determined from four distribution system samples as described in Sections 3.1 and 3.2

Or

Plants can avoid treatment studies if they use full-scale membrane or GAC.

- Full-scale GAC technology is defined as GAC with an empty bed contact time of at least 15 minutes and a reactivation or replacement frequency of no less than 9 months.
- Full-scale membrane technology is defined as nanofiltration or reverse osmosis capable of removing DBP precursors.
- Plants using full-scale GAC or membranes that do not meet the above criteria may apply for treatment study avoidance if data demonstrating effective precursor removal is included with the application.
- A plant using full-scale membrane or GAC technology must conduct the monitoring and submit full-scale plant data as described in Section 3.2 ensuring that GAC or membranes technology is included in the treatment train being monitored.

5.2.3 Single Study For Multiple Plants Owned By A Single PWS

A PWS operating multiple plants on a demonstrated common source may apply to conduct a single treatment study for all plants using that common source. The PWS shall submit the application in Table 5-6 along with a common source designation application, Table 5-10. Additionally a general information form, Table 5-1, must be submitted for each plant involved in the single study for multiple plants, and all information shall be included in a single application packet. The criteria that must be met for approval of this treatment study option are:

- All cooperating plants must demonstrate that they are owned by a single PWS.
- All cooperating plants must demonstrate that they operate on a common source according to the criteria described in Section 5.3.
- If the largest plant owned by the system and operating on a common source serves 500,000 persons or more, then a single pilot-scale study must be conducted by the PWS at that source.
- If the largest plant owned by the system and operating on a common source serves under 500,000 persons, then a single bench-scale or pilot-scale study must be conducted by the PWS at that source.
- A study concept form, Table 5-11, and study plan must be submitted for each study and will be reviewed according to the criteria described in Section 5.4.

5.2.4 Joint Treatment Studies

Multiple plants owned by different PWSs operating on a demonstrated common source may apply to conduct joint treatment studies. The cooperative of plants shall submit the application in Table 5-7 along with a common source designation application, Table 5-10. Additionally, a general information form, Table 5-1, must be submitted for each plant involved in the joint study. Only a single joint study application, containing all of the necessary information, shall

be submitted by the cooperative of plants. In order for a joint treatment study to be approved, the following criteria must be met:

- All cooperating plants must demonstrate that they are in the same size category (i.e., all plants serve either≥ 500,000 persons or < 500,000 persons).
- All cooperating plants must demonstrate that they operate on a common source according to the criteria described in Section 5.3.
- All cooperating plants must demonstrate that they use similar treatment.
- The number and type of studies to be conducted must be consistent with the rules outlined in Section 3.4.
- A study concept form, Table 5-11, and study plan must be submitted for each study and will be reviewed according to the criteria described in Section 5.4.
- An approved grandfathered study cannot be used as a joint treatment study unless all of the joint study criteria are met, and the PWS submits written concurrence of the PWS which conducted the study.

PWSs intending to conduct a joint study should notify EPA of this intent no later than twelve (12) months after ICR promulgation. The joint study letter of intent should include the same information required in the actual application, including all available applicability data and common source data. However, it should be understood that this letter is not binding, and the PWS can pursue other options prior to the deadline for treatment study option applications (i.e., eighteen months after publication of the ICR). The purpose of this letter is to allow EPA to start reviewing the available information; however, EPA cannot make a final decision until all supporting data has been submitted.

5.2.5 Treatment Study Buyout

Plants may apply to contribute to a DBP/Microbial Research Fund in lieu of conducting a treatment study if the criteria described in this section are met. A PWS seeking to buy out of the treatment study requirement for a plant(s) shall submit the application in Table 5-8 along with a common source designation application, Table 5-10. Additionally, a general information form, Table 5-1, must be submitted by the plant applying for the buyout and for the plant operating on the common source which is conducting a treatment study. This section describes the criteria that must be met for a buyout to be approved.

- Plants must demonstrate that they operate on a common source according to the criteria described in Section 5.3.
- At least one plant operating on the common source must conduct a treatment study.
- Plants serving 500,000 persons or more must contribute $300,000 to the cooperative research fund.
- Plants serving fewer than 500,000 persons must contribute $100,000 to the cooperative research fund.
- A plant serving 500,000 persons or more will only be permitted to buy out if another common source plant serving 500,000 persons or more is conducting a pilot-scale study.
- A plant serving fewer than 500,000 persons will be permitted to buy out if another common source plant is conducting a bench-scale or a pilot-scale study.

- An approved grandfathered study can be used by other common source systems to buy out of a treatment study.

PWSs intending to buy out of the treatment study requirement should notify EPA of this intent no later than twelve (12) months after ICR promulgation. The buyout letter of intent should include the same information required in the actual application, including all available applicability data and common source data. However, it should be understood that this letter is not binding, and the PWS can pursue other options prior to the deadline for treatment study option applications (i.e., eighteen months after publication of the ICR). The purpose of this letter is to allow EPA to start reviewing the available information; however, EPA cannot make a final decision until all supporting data has been submitted.

5.2.6 Grandfathering Previous Treatment Studies

A plant intending to grandfather a previous study to meet the treatment study requirement shall submit the application in Table 5-9 along with the general information form, Table 5-1. Additionally, the PWS must provide documentation to demonstrate the grandfathered study meets the following requirements:

- The study was conducted using the analytical methods described in "DBP/ICR Analytical Methods Manual," EPA 814-B-96-002.
- Both HAA6 and THM4 were evaluated using free chlorine and under SDS conditions representative of the distribution system conditions experienced in the full-scale plant during the study, as described in Section 4.6.
- The study was conducted using a protocol similar to one of the methods described in Part 2 or 3 of this manual.
- A bench-scale study cannot be grandfathered to meet a pilot-scale study requirement.

Additionally, a plant must be able to provide the following information eighteen (18) months after publication of the ICR rule:

- The process performance data specified in Part 2 or Part 3 of this manual in a format specified by EPA.
- The cost information requested in Part 2 or Part 3 of this manual.

5.3 Review Criteria For A Common Source Designation

In order to conduct a single study for multiple plants (Section 5.2.3), conduct a joint treatment study (Section 5.2.4) or buy out of a treatment study (Section 5.2.5), the cooperating plants must demonstrate that they operate on a common source. Table 5-10 is an application for a common source designation. Only one common source application shall be submitted for the group of cooperating plants; however, a general information form, Table 5-1, for each of the cooperating plants must be included with the common source application. This section describes the criteria for determining a common source designation for various water sources.

5.3.1 Rivers And Streams

Treatment plants on the same river are considered to have a common source if:

- Each cooperating plant intake is no more than 20 river miles from all other intakes, and the mean treatment plant influent TOC of each of the cooperating plants is within 10% of the average of the mean TOC of all cooperating plants. (The mean is calculated from twelve consecutive months of monitoring).

Or

- The intakes of all cooperating plants are between 20 and 200 river miles apart and the mean treatment plant influent UFCTOX of each of the cooperating plants is within 10% of the average of the mean UFCTOX of all cooperating plants. (The mean is calculated from twelve consecutive months of monitoring).

5.3.2 Lakes, Reservoirs And Ground Waters Under The Direct Influence

Treatment plants using the same lake, reservoir or ground water under the direct influence are considered to have a common source if:

- The mean treatment plant influent TOC of each of the cooperating plants is within 10% of the average of the mean TOC of all cooperating plants. (The mean is calculated from twelve consecutive months of monitoring).

5.3.3 Ground Water Aquifers

Treatment plants using ground water are considered to have a common resource if:

- The wells supplying water to the plants are developed in the same aquifer AND the mean treatment plant finished water TOC of each of the cooperating plants is within 10% of the average of the mean TOC of all cooperating plants. (The mean is calculated from twelve consecutive months of monitoring).

5.4 Review Criteria For Study Concept Forms

All plants conducting individual treatment studies (Section 5.2.1), single studies for multiple plants (Section 5.2.3) or joint treatment studies (Section 5.2.4), shall submit a study concept form for each study to be conducted. Table 5-11 must be filled out for each study, and a brief study plan (usually not more than two pages of text and two pages of figures) shall accompany each study concept form. Each plant involved in the study must also submit Table 5-1. These forms and study plans will be reviewed by EPA primarily to insure that the study is consistent with the requirements of the rule, and the study plans will also be reviewed for technical soundness. This section describes the information that should be included in the study concept form and study plan:

- The technology to be investigated during the study, GAC or membrane technology.
- The scale of the study, pilot or bench.

- First point at which a chlorine-based disinfectant is added in the plant.
- Point at which water to be used in the treatment study will be sampled.
- A brief description of all pretreatment processes to be used in the treatment study (e.g., full-scale alum coagulation at a range of doses from 20 to 40 mg/L, full-scale sedimentation, full-scale sand filtration at a 2.5 gpm/ft^2 filtration rate, bench-scale acid addition to pH $\approx$ 5.0 and bench-scale cartridge filtration).
- An estimate of the TOC concentration of the treatment study feed water after all pretreatment processes.
- The seasonal variability of the source water, and an estimate of how many tests over a one year period would be required to evaluate the impact of these seasonal variations on GAC or membrane.
- If membrane studies are to be conducted, the study description should include the procedure to be used (i.e., RBSMT, SEBST or a pilot system), and the model number, manufacturer and molecular weight cutoff of all membranes being investigated.
- If GAC studies are to be conducted, the study description should include the carbon type(s) being investigated, the carbon particle diameter to be investigated and the column diameter.
- If quarterly bench-scale studies are to be conducted, the study description should include the number of runs that will be used to assess seasonal variation. If this is less than four runs, the planned experiments for the remaining quarterly runs should be described.

5.5 Treatment Study Progress Reports

In order to insure that the treatment studies are progressing a timely manner and to identify the potential for delays, quarterly correspondence will occur between plants conducting studies and EPA. The PWS, or cooperative of PWSs, should submit a progress report for each treatment study being conducted. The one page progress report in Table 5-12 should be submitted quarterly at the following times: one month, four months, seven months and ten months after the start of the treatment studies. This report requests information such as the number of bench-scale studies completed, the cumulative run time for pilot-scale studies, any unplanned down-time, the number of primary and duplicate DBP samples collected to date and other information to help EPA track the progress of the treatment studies.

5.6 Final Treatment Study Report

One complete data report shall be submitted no later than thirty-eight (38) months after publication of the final rule in the Federal Register. Specific data reporting requirements for the treatment studies are described in Parts 2 and 3 of this manual for GAC and membrane studies, respectively. Data sheets are included in each part to demonstrate the required data elements. Prior to the deadline to commence treatment studies, a computer diskette containing data collection software will be provided to the Official ICR Contact at all PWSs conducting treatment studies. This software shall be used to record and report most of the treatment study data and shall be submitted to EPA along with the final treatment study report.

In addition to the computer file, the plant must submit a summary report describing the experimental design, analytical and experimental methods, significant results, process performance and/or cost analyses (if conducted), a QA/QC summary, problems encountered during the study, and any other information relevant to the treatment studies that is not included in the computer data file. A plant required to conduct a treatment study must also report design information on any full-, pilot- or bench-scale processes that precede the advanced treatment process under investigation. This design information should include process schematics, chemical doses and concentrations, hydraulic detention times, overflow rates, loading rates, flow rates and any other critical design parameters.

Table 5-1 General Public Water System And Plant Information (page 1 of 2)

Public Water System Information

Utility name	
PWSID#	WIDB# (optional)
PWS combined population served	
PWS ground water population served	

Official Contact Person

Name	
Mailing address	
Phone #	
FAX #	
E-mail address	

ICR Contact Person

Name	
Mailing address	
Phone #	
FAX #	
E-mail address	

Treatment Plant Information

Plant name	
Plant ICR #	
Plant combined population served	
Plant ground water population served	
Plant surface water population served	

Plant Contact Person

Name	
Mailing address	
Phone #	
FAX #	
E-mail address	

Table 5-1 General Public Water System And Plant Information (page 2 of 2))

Treatment Plant Type (Select Appropriate Box)

Plant Type ID	Plant Type Code	Plant Type	Box
1	CONV	Conventional Filtration	
2	DF	Direct Filtration	
3	ILF	In-Line Filtration	
4	SSF	Slow Sand Filtration	
5	SOFT	Softening	
6	TS/SOFT	Two Stage Softening	
7	CS/SOFT	Coagulation/Sedimentation/Softening	
8	STS	Split Treatment/Softening	
9	CPTS	Complex Parallel Train/Softening	
10	DIS/GW	Disinfection Only/Ground Water	
11	OTHER/GW	Other Groundwater (describe below)	
12	UNFILT/SW	Unfiltered Surface Water	
13	MEMBRANE	Membrane Treatment	
14	DIS/WHSALE	Disinfection of Wholesale Supply	
15	OTH	Other (describe below)	
17	PURCHASED	Purchased Finished Water Without Re-Disinfection	

Describe other:

Table 5-2 Treatment Study Applicability Data Reporting Form (page 1 of 2)

Utility name		PWSID #	
Plant name		Plant ICR #	
Plant surface water population served		Plant ground water population served	

Monthly TOC (mg/L) Applicability Monitoring [1]

Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	Average

1 TOC monitoring is to be conducted on the treatment plant influent for surface waters and on the finished water for ground waters.

Monthly UFCTOX (μg/L) Applicability Monitoring [2,3]

Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12	Average

2 UFCTOX monitoring may be required if a treatment plant is trying to qualify for a common source designation.

3 UFCTOX monitoring is to be conducted on the treatment plant influent for surface waters and on the finished water for ground waters.

Quarterly DBP (μg/L) Applicability Monitoring [4]

	Date of sample collection	Max[5] DSS THM4	1st Avg[6] DSS THM4	2nd Avg[6] DSS THM4	3rd Avg[6] DSS THM4	Max[5] DSS HAA5	1st Avg[6] DSS HAA5	2nd Avg[6] DSS HAA5	3rd Avg[6] DSS HAA5	Quarterly average THM4	Quarterly average HAA5
1st quarter											
2nd quarter											
3rd quarter											
4th quarter											
yearly avg.											

4 Treatment plants that use only chlorine as the primary and residual disinfectant may monitor THM4 and HAA5 to determine applicability.

5 The Max DSS (distribution system sample) point must be representative of the maximum residence time for the treatment plant.

6 The three Avg DSS sample locations must be representative of the average residence time for the treatment plant.

Table 5-2 Treatment Study Applicability Data Reporting Form (page 2 of 2)

Information for Approved ICR Laboratory Conducting TOC Analysis

Laboratory name	
ICR Laboratory ID Code	

Official Laboratory Contact Person

Name	
Mailing address	
Phone #	
FAX #	
E-mail address	

Table 5-3 Information Required With ICR Treatment Study Option Applications

Application	Required tables	Additional information
Applicability data[1]	Table 5-1, Table 5-2	None.
Individual study	Table 5-1, Table 5-11 and study plan	A cover letter.
Treatment study avoidance	Table 5-1, Table 5-5	A cover letter and data demonstrating the use of full-scale GAC, NF or RO if applicable.
Single study for multiple plants[2]	Tables 5-1, Table 5-6, Table 5-10, Table 5-11 and study plan	A cover letter.
Joint treatment study[2]	Tables 5-1, Table 5-7, Table 5-10, Tables 5-11 and study plans	A cover letter and data demonstrating that the plants operate similar treatment trains.
Buyout[2]	Tables 5-1, Table 5-8, Table 5-10	A cover letter.
Grandfathered treatment study	Table 5-1, Table 5-9	A cover letter and data demonstrating that the study meets the requirements of the ICR.
Treatment study progress reports	Table 5-1, Table 5-12	None.

1 Note the deadline for the treatment study applicability data, Table 5-2, is one month prior to all treatment study option applications except for the grandfathered study application.

2 Note that Table 5-1 must be submitted for each plant involved these treatment study options.

Table 5-4 Important Deadlines Related To The ICR Treatment Studies

Action	Deadline (no later than)	Date
Start treatment study applicability monitoring	3 mos. after pub.	
Submit grandfathered study application	9 mos. after pub.	
Submit joint study letter of intent	12 mos. after pub.	
Submit buyout letter of intent	12 mos. after pub.	
Submit treatment study applicability data form	17 mos. after pub.	
Submit treatment study avoidance application	18 mos. after pub.	
Submit treatment study concept form	18 mos. after pub.	
Submit single study/multiple plants application	18 mos. after pub.	
Submit joint treatment study application	18 mos. after pub.	
Submit buyout application	18 mos. after pub.	
Submit grandfathered study data	18 mos. after pub.	
Deadline for buyout payment	90 days after approval	
Start collecting data from the treatment studies	23 mos. after pub.	
Submit first treatment study progress report	24 mos. after pub.	
Submit second treatment study progress report	27 mos. after pub.	
Submit third treatment study progress report	30 mos. after pub.	
Submit fourth treatment study progress report	33 mos. after pub.	
Submit final treatment study report	38 mos. after pub.	

Table 5-5 Treatment Study Avoidance Application

Utility name		PWSID #	
Plant name		Plant ICR #	

Application for avoidance is based on (check one of the following boxes):

(1) Average influent TOC is below 4.0 mg/L for a surface water plant[1] ☐

(2) Average finished water TOC is below 2.0 mg/L for a ground water plant[1] ☐

(3) Average distribution system THM4 < 40 ug/L and HAA5 < 30 ug/L[2] ☐

(4) The treatment plant is using full-scale GAC as described in the ICR[3] ☐

(5) The treatment plant is using full-scale membrane treatment (NF or RO)[3] ☐

1 The average TOC concentrations are calculated from the 12 months of applicability monitoring

2 The average DBP concentrations are calculated from the 12 months of applicability monitoring, and the plant must be using only chlorine as the primary and residual disinfectant.

3 Include the full-scale plant data required under Section 141.142(a) of the ICR rule, demonstrating the use of full-scale GAC or membrane technology.

Table 5-6 Application For Multiple Plants Owned By A Single PWS And Operating On A Common Source To Conduct A Single Treatment Study[1]

Plants Applying to Conduct a Single Common Source Study[2]

Plant name	Plant ICR #	PWSID #	Plant population served

Proposed Studies to be Conducted[3,4]

Technology to be investigated (GAC or membranes)	Scale of study (pilot or bench)

1 Only one application accompanied by one common source application, Table 5-10, should be submitted.

2 Each cooperating plant must submit Table 5-1 with this application.

3 A study concept form, Table 5-11, must be submitted for each proposed study to be conducted during the common source study.

4 Only one treatment study is required for multiple plants owned by a single PWS and operating on a common source. If the largest plant serves at least 500,000 persons, then the single study for multiple plants must be a pilot-scale study.

Table 5-7 Joint Treatment Study Application[1]

Plants Applying to Conduct the Joint Study[2]

Plant name	Plant ICR #	PWSID #	Plant population served

Proposed Studies to be Conducted[3,4]

Technology to be investigated (GAC or membranes)	Scale of study (pilot or bench)

1 Only one application accompanied by one common source application, Table 5-10, should be submitted.

2 Each cooperating plant must submit Table 5-1 with this application.

3 A study concept form, Table 5-11, must be submitted for each proposed study to be conducted during the joint treatment study.

4 The number and type of studies required for a joint study is determined from the size and number of cooperating plants as described in Section 141.141 (e) of the ICR rule and Tables 3-2 and 3-3 of this manual.

Table 5-8 Treatment Study Buyout Application[1]

Utility name		PWSID #	
Plant name		Plant ICR #	

Plant combined population served	
Proposed buyout fee[2]	

Information for the Common Source Treatment Plant Conducting a Study[3,4]

Plant name			
Plant ICR #		PWSID#	
Plant combined population served			
Plant ground water population served			
Plant surface water population served			

Official contact person

Name	
Mailing address	
Phone #	
FAX #	
E-mail address	

ICR contact person

Name	
Mailing address	
Phone #	
FAX #	
E-mail address	

1 One common source application, Table 5-10, should be submitted with this application.

2 The amount of funds to be contributed to the research fund is based on the total plant population served and is described in Section 141.141(e) of the ICR rule.

3 At least one plant operating on a demonstrated common source must conduct a treatment study for a buyout to be approved.

4 A plant serving fewer than 500,000 persons can buy out if a pilot-scale study is being conducted on the common source; however, a plant serving greater than 500,000 persons can not buy out if a smaller plant is conducting a bench-scale study on the common source.

Table 5-9 Grandfathered Treatment Study Application

Utility name		PWSID #	
Plant name		Plant ICR #	

Plant combined population served

What technology was investigated?	
What was the scale of the study according to ICR?	
What chlorination conditions were used for DBP samples?	
At what point in the full-scale plant was water collected for the study?	
Where is the first point that chlorine is added in the full-scale plant?	
Was the treatment study influent collected prior to the addition of chlorine-based oxidants?	
What was the duration of the study?	

Study Description and Supporting Information

Attach a brief (no more than five page) description of the study which should include: (1) the experimental procedure used, (2) the analytical methods used, (3) all processes used prior to membranes or GAC, and (4) the operating and design parameters used in the study.

Also attach any reports resulting from the study that would help to demonstrate that the study was consistent with the requirements of the ICR.

Table 5-10 Common Source Designation Application

Source water name	
Source water type	

List of Plants Applying for a Common Source Designation[1]

Plant name	Plant ICR #	PWSID #	Average TOC[2] (mg/L)	Average UFCTOX[3] (ug/L)	River miles to the intake of the most distant plant[4]

Mean of all average plant TOC values (mg/L)		Mean of all average plant UFCTOX values (ug/L)	
90% of the mean TOC (mg/L)		90% of the mean UFCTOX (ug/L)	
110% of the mean TOC (mg/L)		110% of the mean UFCTOX (ug/L)	

1 All plants applying for a common source designation must also submit Table 5-1.

2 The TOC requirement is for plants using (1) river sources with intakes less than 20 river miles apart, (2) lakes and reservoirs, and (3) ground water resources.

3 The UFCTOX requirement is for plants using river sources with intakes between 20 and 200 river miles apart.

4 Plants operating on a common river source must report the distance, in river miles, from the intake of each cooperating plant to the most distant intake of a cooperating plant.

Table 5-11 Study Concept Form[1]

General Study Information

Is this an individual or a joint study?	
Will GAC or membranes be investigated?	
Is this a pilot- or a bench-scale study?	
At what point in the full-scale plant will water be collected for the study?	
Where is the first point that chlorine is added in the full-scale plant?	
Will the treatment study influent be collected prior to the addition of chlorine based oxidants?	
What is the average TOC concentration of the treatment study influent?	
How many tests will be required to evaluate seasonal variability?	

GAC Study Information

Carbon type and manufacturer to be investigated	
Carbon particle diameter	
Carbon column diameter	

Membrane Study Information

Procedure to be used (RBSMT, SEBST, pilot)	
Element size to be investigated	
Model number and manufacturer of membrane #1	
Molecular weight cutoff of membrane #1	
Model number and manufacturer of membrane #2	
Molecular weight cutoff of membrane #2	

Study Plan

Attach a brief study plan (usually not more than two pages of text and two pages of figures) which should include the equipment to be used, pretreatment to be used prior to GAC or membranes, design parameters, operating parameters, whether or not seasonal variability need to be evaluated and if seasonal variability can be evaluated in fewer than four quarters, the parameters that will be investigated in lieu of seasonal variability.

1 One study concept form must be submitted for each study to be conducted.

Table 5-12 Treatment Study Progress Report

Date: _____

General Information

Plant ICR #	
Type of study (e.g., individual, joint, multiple plant)	
Scale of study (i.e., pilot or bench)	
Technology (i.e., membranes or GAC)	
What was the study start date?	
What is the anticipated finish date?	
What is the anticipated date for the final report?	

Pilot Study Information

What is the cumulative runtime?	
What is the cumulative downtime?	
Is the system currently operating?	

Bench Study Information

How many quarterly runs have been completed?	
Is seasonal variability being investigated?	

GAC Study Information

Has headloss been a problem?	
What is the runtime to Stage 2 DBP breakthrough?	
What is the anticipated runtime to 70% breakthrough?	

Membrane Study Information

Has membrane fouling been a problem?	
What is the nature of the foulant?	
What cleaning procedure has been effective?	
What is the cleaning frequency for the system?	
Have the proposed Stage 2 MCLs been obtainable?	

Sampling Information

Number of primary DBP samples collected to date?	
Number of duplicate DBP samples collected to date?	

Part 2

Granular Activated Carbon Precursor Removal Studies

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Notice

This Section was prepared for the EPA's Office of Ground Water and Drinking Water under the guidance of the Drinking Water Technology Branch, Drinking Water Standards Division (small purchase order #4W-1951-MASA). Members of the Technologies Working Group who convened to provide technical support to the Regulatory Negotiating Committee for the D/DBP Rule played a significant role in the development of the treatment study approach, and in some instances in the preparation of the text for this Section.

Contents

Figures

Tables

1.0 Introduction

The Information Collection Requirements (ICR) for Public Water Systems (Subpart M of the National Primary Drinking Water Regulations), § 141.141(e) requires certain water systems to conduct disinfection byproduct (DBP) precursor removal studies, termed herein as treatment studies. The public water systems affected by this requirement are defined in the ICR rule, § 141.141(b) and the treatment studies are defined in § 141.144 and Part 1 of this document.

The objectives of the treatment studies are to generate representative process performance data to be used for the development of treatment cost estimates at different levels of organic DBP control. The two appropriate candidate technologies to be investigated by treatment studies are granular activated carbon (GAC) adsorption and membrane separation processes. Both processes have been shown to be effective for the removal of DBP precursors. The treatment studies can be conducted with bench-scale and/or pilot-scale systems using effluent from the full-scale treatment processes already in place that remove DBP precursors.

The purpose of this part of the ICR Manual for Bench- and Pilot-Scale Treatment Studies is to provide guidance in conducting pilot- and bench-scale GAC treatment studies to meet the requirements of the ICR rule. The target audience of this document are the parties that will conduct or oversee these treatment studies, including water treatment plant operators, scientists, and engineers, utility managers, and consulting engineers.

Based on the information presented in Sections 2.0 (Figure 2-3), 4.0 and 5.0 it is anticipated that waters having TOC values above 6 to 8 mg/L in the GAC influent, will have very early breakthrough and yield very short GAC run times to achieve DBP control at the Stage 1 and 2 levels of the proposed Disinfectants/Disinfection Byproducts Rule. These short run times will increase the operational costs of GAC treatment. Thus, it is suggested that utilities with treated water TOC values above 6 to 8 mg/L: (a) evaluate DBP precursor removal options such as enhanced/optimized coagulation or biological filtration prior to GAC treatment, (b) pH control during GAC operation, or (c) run treatment studies with membranes, as described in § 141.144 of the ICR and Part 3 of this document, instead of GAC.

This treatment studies manual is referenced in the ICR rule and contains specific requirements of the rule. The ICR requirements listed in this manual include analytical and reporting requirements for each type of study. This manual also provides guidance to assist in setting-up and conducting these studies, and this guidance should not be interpreted as specific requirements. In preparing this manual, an effort has been made to distinguish between specific ICR requirements and guidance.

2.0 Background

2.1 Adsorption Of Natural Organic Matter And Disinfection Byproduct Precursors

Granular activated carbon can be used for adsorbing natural organic matter (NOM) and and therefore, limiting the formation of disinfection byproducts. The effectiveness of the GAC adsorption process is impacted by NOM characteristics which may be a function of the origin and pretreatment of the source water. Specifically, NOM characteristics such as initial concentration, molecular size and hydrophobicity affect the adsorbability, as does pH, and pretreatment processes such as coagulation and ozonation.

For drinking water purposes, NOM is typically quantified by total organic carbon (TOC) or dissolved organic carbon (DOC). After sedimentation and filtration there is usually very little difference between TOC and DOC and they are often used interchangeably. UV absorbance, commonly measured at a wavelength of 254 nm, can also be used to assess a fraction of the NOM. The component of NOM that reacts to form DBPs, termed DBP precursors, can be assessed indirectly by measuring the amount of DBPs formed under specific disinfection conditions of dose, time, temperature and pH. Formation potential (FP) conditions are used to approximate the maximum DBP formation, while simulated distribution system (SDS) and uniform formation conditions (UFC) are used to represent the level of DBPs formed under conditions encountered in practice.

A breakthrough curve that represents the adsorption behavior of NOM is shown in Figure 2-1. To facilitate comparisons of breakthrough behavior of waters with different influent (initial) concentrations, the effluent concentration, c, is normalized by the influent concentration, c_0. The amount of water treated is expressed as operation time, or as throughput in number of bed volumes (**BV**) treated at a given empty bed contact time (**EBCT**):

$$\mathbf{BV = t/EBCT} \qquad \mathbf{(2.1)}$$

where **t** is the operation time or

$$\mathbf{BV = \text{treated water volume}/V_b} \qquad \mathbf{(2.2)}$$

where $\mathbf{V_b}$ is the GAC bed volume. Expressing the operation time or amount of water treated as throughput in bed volumes treated, facilitates comparisons of results from GAC adsorbers with different EBCTs.

For most natural waters the influent concentration varies during a short GAC run, typically by 10 to 20% as shown in Figure 2-1, where the instantaneous influent concentration is normalized by the average influent concentration. However, for surface waters the influent concentration can vary by as much as a factor of two to three when the GAC run is long enough to cover seasonal trends. The immediate breakthrough is the effluent fraction that is present in the first sample. If this level remains constant for any

length of time, as shown in Figure 2-1, then the immediate breakthrough represents the nonadsorbable NOM fraction. Typically, the nonabsorbable fraction is 5 to 20% of the influent NOM as measured by DOC, and 0 to 10% as measured by UV absorbance. Initial breakthrough is the point at which the effluent concentration increases beyond the nonabsorbable fraction. It characterizes the first portion of the breakthrough of the adsorbable fraction. Pseudo steady-state represents a section in the breakthrough curve in which little if any changes occur in the effluent concentration at a constant influent concentration. NOM removal in this region is due to biodegradation and/or slow adsorption.

The DOC breakthrough of three treated waters with different influent concentrations and by GAC columns with different EBCTs is shown in Figure 2-2. All three waters display an immediate breakthrough of about 5 to 10%, but the breakthrough behavior thereafter is very different: earlier exhaustion of the GAC occurs with increasing influent DOC concentration. The mid-point, or 50%, breakthrough occurs after 2000, 4000 and 12,000 bed volumes for Palm Beach ground water, Mississippi River water and Ohio River water, respectively. For Mississippi River water, a plateau is reached after 12,000 bed volumes. Sampling was not continued long enough to establish a plateau for the other two waters. This range of adsorption behavior represents that found in practice.

To ascertain whether differences in influent TOC concentrations impact breakthrough behavior, the number of bed volumes to 50% breakthrough (BV_{50}) was correlated to the influent concentration for data from 23 TOC breakthrough curves. The correlation is shown in Figure 2-3 (Summers et al., 1994b) and a best-fit curve yields the following equation:

$$BV_{50} = 21{,}700 \cdot TOC^{-1.3} \qquad (2.3)$$

These data are for bituminous coal based GACs and are from 16 different water sources from around the world, including river waters, lake/pond waters, and ground waters. As can be seen, breakthrough behavior is highly correlated, $r^2 = 0.88$, to influent concentration. While the differences in the NOM adsorbability of the sources waters should not be ignored, the influent concentration gives a good estimate of the effectiveness of GAC.

Many drinking water utilities will be optimizing their coagulation processes to meet the enhanced coagulation requirements of the proposed Disinfectants/Disinfection Byproduct Rule. To achieve better removal of DOC by coagulation lower pH values are often used. If the GAC system is used after coagulation then the lower pH values will also enhance the removal of TOC by GAC as shown in Figure 2-4 (Hooper et al., 1995). The increased effectiveness of GAC after enhanced coagulation is due to both lower pH and lower influent TOC values, as well as changes in the molecular size and hydrophobicity of the NOM. Semmens et al. (1986a; 1986b) have also shown the positive impact of lower pH and increased coagulant dose on GAC performance for Mississippi River water. The breakthrough data from GAC columns treating enhanced coagulated waters at low pH, below 7.0, were not utilized in the development of the correlation shown in Figure 2-3.

Of particular importance is the use of GAC to remove NOM for the control of DBP formation. The breakthrough behavior of TOC and total trihalomethane formation potential (TTHMFP) for three different waters is shown in Figures 2-5, 2-6, and 2-7. The breakthrough behavior of TOC seems to be a good, but somewhat conservative indicator for that of TTHMFP. The rapid small-scale column test (RSSCT) was utilized in these studies. The scaling factor (SF) is the ratio of the GAC particle size used in the full-scale column to that in the RSSCT and establishes the relationship between the EBCT of the full-scale system ($EBCT_{LC}$) and the RSSCT. These relationships are defined in Section 5.0.

The formation of the four different trihalomethane (THM) species after GAC adsorption is shown in Figure 2-8 for ozonated Ohio River water. In the influent water the formation potential is highest for chloroform. However, after GAC treatment chloroform and dichlorobromomethane are formed at the same level and dibromochloromethane and bromoform are formed at proportionally higher levels compared to chloroform. This shift in the relative THM speciation to the more brominated species is thought to be due to shifts in the bromide to TOC ratios (Summers et al. 1993). Since bromide is not removed by GAC, the bromide to TOC ratios in the effluent at the beginning of the GAC run are high, and this leads to the formation of proportionally more brominated THM species after chlorination. As the TOC breaks through the bromide to TOC ratio approaches that of the influent and chloroform formation will again dominate.

2.2 Prediction Of Field-Scale GAC Performance

A variety of methodologies have been applied for the prediction or simulation of the breakthrough behavior of full-scale GAC columns. These include pilot-plant columns, numerical modeling using data from equilibrium and kinetic lab tests, non-scaled mini-column tests and the RSSCT. Of these pilot-plant columns and the RSSCT are the most commonly used. The two dominant factors that control the breakthrough in GAC columns are the adsorption capacity (extent of adsorption) and the rate of adsorption (adsorption kinetics). These two parameters must be accurately assessed by any method that successfully emulates full-scale GAC behavior. Characterizing the different GAC performance methodologies in terms of operation time and numerical modeling requirements is useful. Under most circumstances, minimizing the operation time of the evaluation system and reducing the modeling component will lead to lower costs, but reliability and accuracy must not be sacrificed. For evaluation methodologies utilizing column contactors, the GAC particle size and the column length or EBCT are indicators of the operation time. Consideration of the above listed criteria has led to the use of pilot columns and RSSCTs as the most commonly chosen methods of GAC performance evaluation.

Pilot columns which utilize the same GAC and influent water as the full-scale system have been shown to be accurate and reliable predictors of the breakthrough behavior in full-scale columns both in terms of the capacity and rate of adsorption (Wood and DeMarco 1980, DeMarco et al. 1983, DeMarco and Brodtman 1984, Chrobak, Kelleher, and Suffet 1985, and Speth et al. 1989). They also have the advantage of not requiring the use of numerical models for data interpretation. Because they must utilize column lengths and GAC particle

sizes that are the same as full-scale columns, pilot columns have the same operation time as the full-scale system. This equivalent operation time, coupled with the capital investment required for the pilot system, can lead to costs higher than other methods of evaluation. Pilot columns have the distinct advantage over other methods in that the biodegradability of the compound of interest can be assessed, as can the impact of seasonal variability, if the columns are operated on a long-term basis.

Another predictive approach to breakthrough behavior is to assess the equilibrium adsorption capacity by the bottle-point method, commonly referred to as the isotherm test, and to estimate the adsorption kinetics with completely mixed batch reactors or differential column batch reactors. Data from these tests are used as input to a fixed-bed numerical model for predicting the breakthrough. Limited success has been achieved using this approach to emulate full-scale systems due to inaccuracies in the assessment of both the adsorption capacity and kinetics in complex mixtures, such as those in natural waters (Sontheimer, Crittenden and Summers, 1988). This approach is attractive due to the use of small GAC particle sizes, which leads to short operation times. However, its utility is limited due to the constraints of requiring a numerical model for the evaluation of both kinetic parameters and adsorption capacity. More importantly, this approach does not adequately assess any long-term changes in the adsorption capacity or kinetics due to the presence of a background matrix nor does it assess the impact of biological activity on NOM removal.

Mini-columns utilize small particle and column sizes to shorten the operation time to a small fraction of that in the full-scale or pilot-scale column. When they are not scaled to the dimensions of a full-scale adsorber, mini-columns are limited to the assessment of GAC adsorption capacity. These columns are usually operated with particle sizes of 0.05 to 0.1 mm, column lengths of 2 to 5 cm, and flow rates which yield operation times of a few hours. While only the capacity data can be directly compared to full-scale data, this approach is very useful for the relative comparison of different GACs. Thus, they are a good tool for selectively screening GACs to determine the most efficient GAC prior to any additional studies, such as pilot columns. An advantage this approach holds over batch isotherm tests is that the competitive interactions between adsorbing compounds are assessed under dynamic conditions similar to the full-scale system (Summers and Crittenden, 1989).

To compare mini-column results to those from the full-scale system, kinetic parameters which characterize the external and internal mass transfer and a numerical model are required. In this approach mini-columns are used to assess the adsorption capacity and short fixed-bed test results are used to yield the external and internal mass transfer coefficients. These parameter values are then used in diffusion-adsorption models to predict the breakthrough behavior.

Small-scale columns are mini-columns in which similitude to full-scale GAC adsorbers has been maintained. The relationship between the particle size, column length or EBCT, hydraulic loading and operation time of the small- and large-scale columns (pilot or full) is determined through the use of dimensional analysis. Successful application of the small-scale columns produces breakthrough curves which are equivalent to those of a full- or pilot-scale

adsorber. The method was pioneered by Frick (1982) and further developed and extensively applied by Crittenden and co-workers (Crittenden, Berrigan, and Hand 1986; Crittenden et al. 1987, 1989 and 1991: Hineline, Crittenden, and Hand 1987) leading to the rapid small-scale column test.

The RSSCT has a number of advantages over the other methods used to predict or simulate full-scale GAC performance. Depending on the conditions, this method can be conducted in less than one percent to 15 percent of the time that is required for a pilot- or full-scale column study. Because of the short operation time of the RSSCT, several column runs can be conducted in the time required to complete one pilot column run. This allows for the optimization of design and pretreatment options. The volume of influent water required is normally small enough that an adequate volume of water can be transported to a laboratory, thus eliminating the need for a field study and the associated costs. As compared to the predictive model approach, separate experimental efforts to evaluate the adsorption capacity and kinetics are not required nor is the use of numerical or analytical models.

A potential drawback of the RSSCT is the possible difficulty in obtaining a representative batch of influent water. Since there is often natural variability in the influent water quality, the use of a batch influent may yield misleading results as compared to the long term operation of full- or pilot-scale systems, which embody influent water variations. Thus, the selection of a representative sample to serve as the influent to the RSSCT is paramount. The effect of seasonal water quality variations can be assessed by conducting these tests several times a year. Furthermore, organic matter removal in a GAC column due to long-term biodegradation is not simulated by the RSSCT, since the microorganisms may not have enough time to acclimate.

Another consideration in using the RSSCT is the dependence of intraparticle diffusivity on GAC particle size. The design equations were originally developed with the assumption of constant diffusivity (CD). However, a number of small column tests and batch kinetic tests have shown that the diffusion coefficient decreases proportionally with decreasing particle size and a proportional diffusivity (PD) design approach has been developed. Both approaches and a review of the method are described in Summers and Crittenden (1989) and Crittenden et al. (1991).

A summary of the application of RSSCTs to predict the field-scale control of NOM and DBP formation is shown in Table 2-1. About thirty comparisons of RSSCT results to those of pilot- or full- scale columns have been made for the adsorption of organic matter as measured by TOC, DOC or UV absorbance.

Summers et al. (1989) investigated both the PD- and CD-designed small-scale columns with four parallel columns of different particle sizes. In this study, NOM that had been extracted from a ground water (Fuhrberg, Germany) was added to tap water, which had been previously treated by GAC to remove adsorbable compounds. In addition to characterization by DOC, UV-absorbance at 254 nm was also measured and reported in this part of this manual as the spectral absorption coefficient (SAC). As shown in Figure 2-9, the CD-

designed columns yielded earlier breakthrough as particle size decreased. The results from the PD-designed columns well-predicted the breakthrough from the pilot column, d_p =1.58 mm, as shown in Figure 2-10.

The results from three parallel RSSCTs with the same batch influent source (Ohio River water) are shown in Figure 2-11 (Namuduri, 1990). As can be seen, the reproducibility of this test is very good. The use of UV absorbance to characterize the adsorption of the extracted ground water NOM also proved successful, as indicated by the SAC results in Figure 2-12.

In the study by Wallace et al. (1988) and McGuire et al. (1989) five different raw water sources were used: Colorado River, California State Project, Ohio River, Mississippi River, and Delaware River. For these waters, the PD design yielded good comparisons between the DOC results of the small-scale and the pilot columns. Good predictability of DOC results was also found for Lake Gaillard water at two EBCTs (Malcolm Pirnie, 1990).

Summers et al. (1992) investigated the use of RSSCTs with three different GAC types and three water sources: Delaware River, Palm Beach Florida groundwater and Ohio River. The PD design was used in all cases. The RSSCT adequately predicted pilot- or full- scale results in all nine cases for the breakthrough of TOC and UV absorbing substances. In all of the above cases biodegradation of organic matter did not preclude the use of the RSSCT. The application of the RSSCT to predict the TOC breakthrough behavior of a filter adsorber that was regularly backwashed is shown in Figure 2-13 (Summers et al., 1994a). The pilot-scale breakthrough was well-predicted by the non-backwashed RSSCT, except in the initial breakthrough section. Although the RSSCT data shown is from a column that was not backwashed, a parallel study with backwashed RSSCTs showed little impact of backwashing (Hong et al., 1994).

Only a few studies, Summers et al. (1992, 1994a, 1995), Cummings and Summers (1994) and Metz, Summers and DeMarco (1993), have also investigated the use of RSSCTs for the prediction of DBP control. These are summarized in Table 2-1 (Studies 5 thru 8). Cummings and Summers (1994) found the RSSCT to well predict the pilot-scale breakthrough behavior of THM and TOX precursors in a Florida groundwater for three different GACs. An example for SDS-TOX is shown in Figure 2-14. Some problems were encountered for THM species that were formed at concentrations below 5 ug/L. TTHM formation potential results from a filter adsorber are shown in Figure 2-15. Like that found for TOC for this water source (see Figure 2-13), the RSSCT did not well-predict the initial breakthrough results, but the immediate breakthrough and mid-point breakthrough were well-predicted. Metz, Summers and DeMarco (1993) used RSSCTs to predict the full-scale control of non-THM DBPs, as well as THM and TOX in Ohio River water with reactivated GAC. The RSSCT predicted slightly earlier breakthrough in the initial breakthrough portion of the breakthrough curve for formed HAA5 and chloral hydrate, as shown in Figure 2-16 for HAA5. The RSSCT results from individual formed DBP species can also be compared to those from field-scale GAC columns. Examples are shown in Figure 2-17 for dibromochloromethane and in Figure 2-18 for bromochloroacetic acid (BCAA). The results

from Figure 2-18 are from a current study in which the applicability of RSSCTs to predict field-scale behavior is being evaluated for four waters and six parameters as listed in Table 2-1 (Summers et al., 1995). One important conclusion of that study is that obtaining a representative sample for the RSSCT is critical to the success of the RSSCT for predicting field-scale breakthrough behavior.

While limited to nine raw water sources and 30 direct comparisons to field adsorbers, the RSSCT using the PD design approach has been shown to be an effective method for predicting NOM breakthrough in pilot- or full-scale GAC columns. Unlike other predictive tools, the RSSCT does not require numerical modeling nor additional capacity or kinetic tests, yet can be completed in a small fraction of the time and costs of a pilot-scale study. Therefore, the RSSCT may be very useful in gathering representative information that will allow for the development of treatment cost estimates for different levels of organic DBP control by GAC.

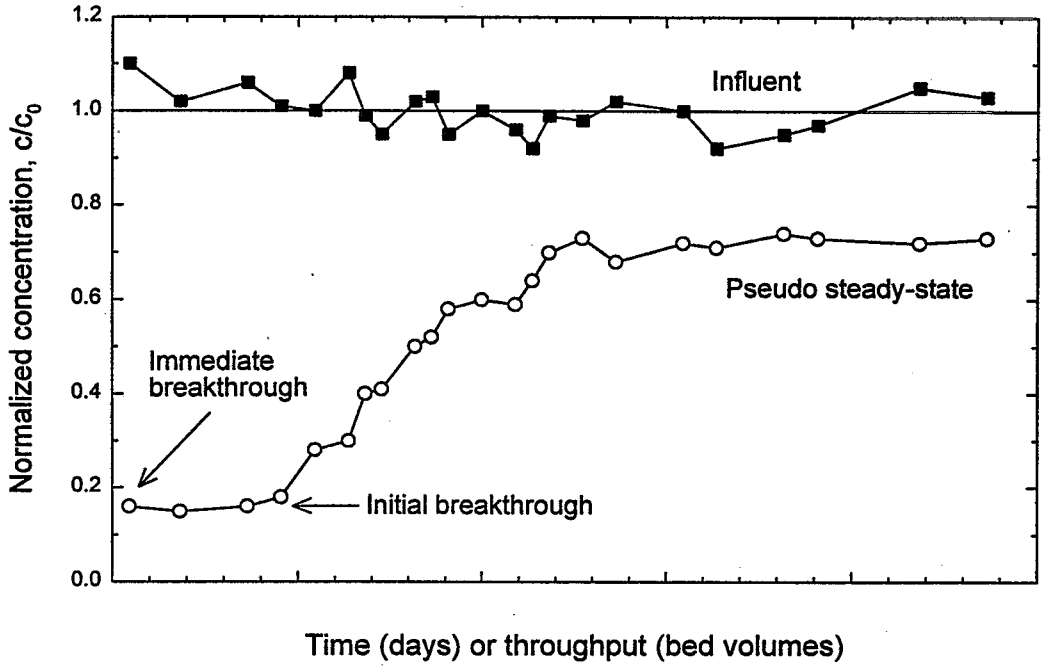

Figure 2-1 Description of NOM breakthrough terminology

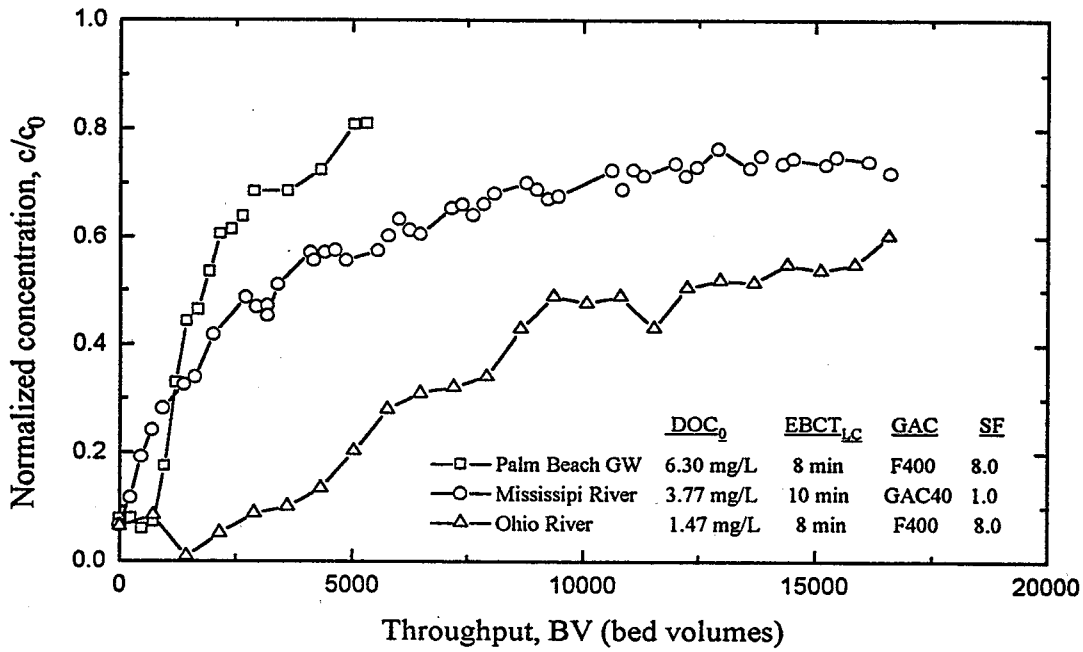

Figure 2-2 DOC breakthrough for three treated waters

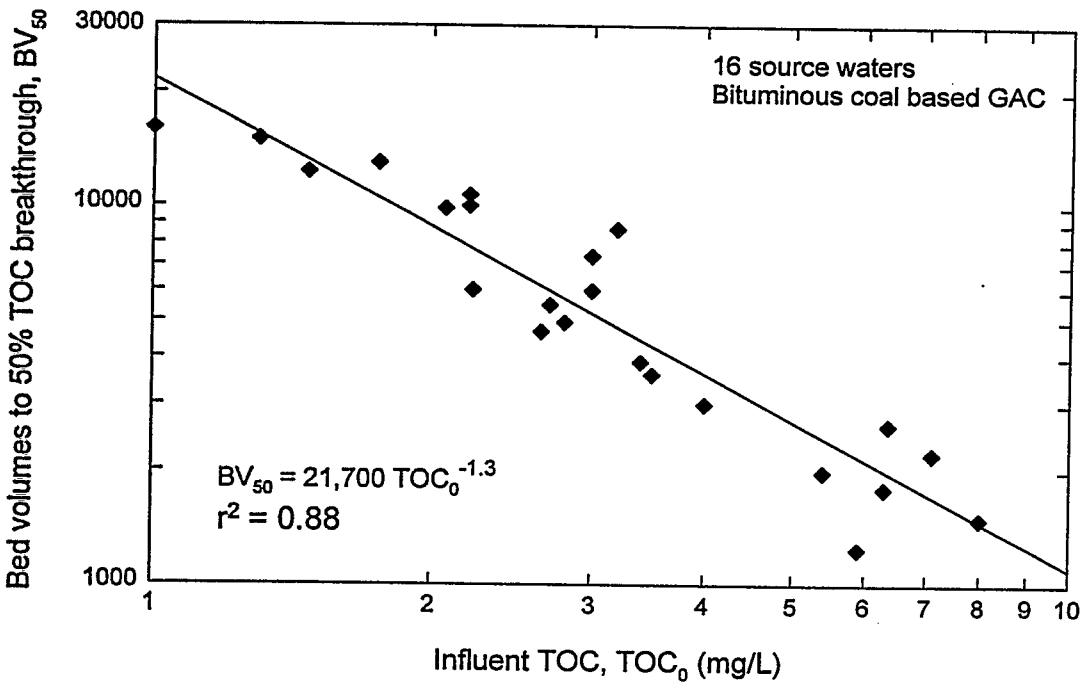

Figure 2-3 Correlation between influent TOC and bed volumes to 50% TOC breakthrough

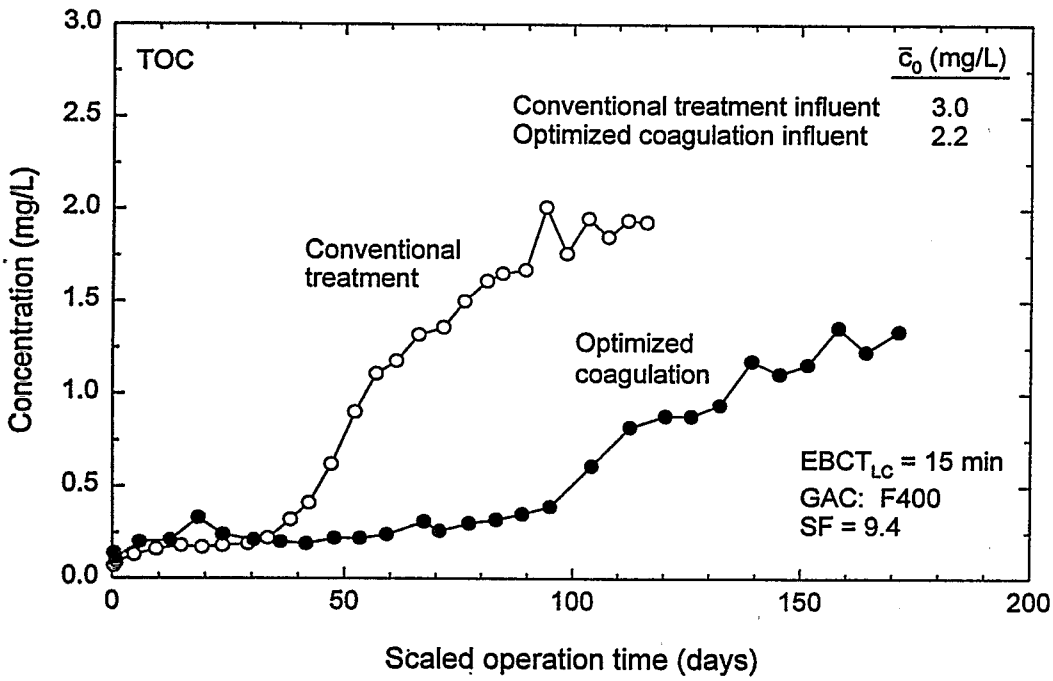

Figure 2-4 Effect of optimized coagulation on TOC breakthrough for Harsha Lake water

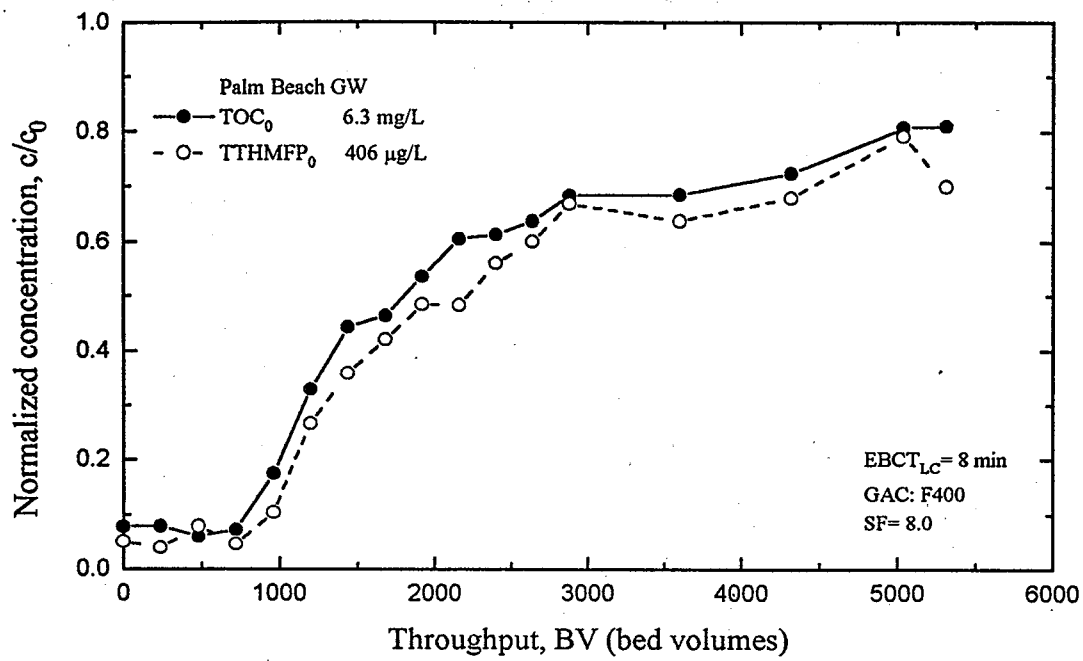

Figure 2-5 TOC and TTHMFP breakthrough for Palm Beach groundwater

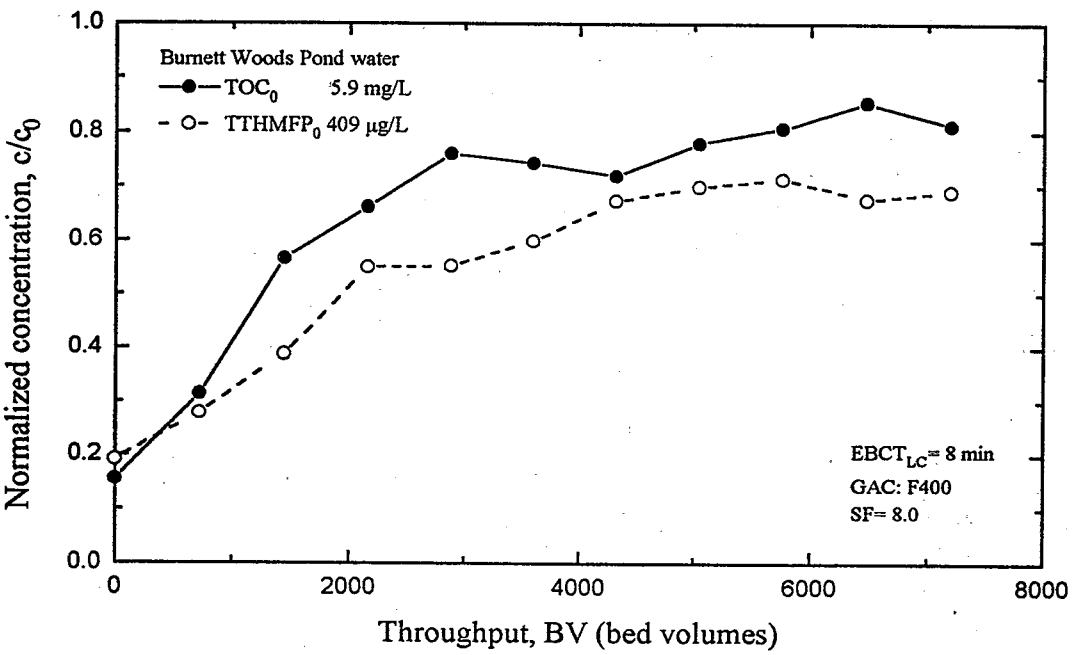

Figure 2-6 TOC and TTHMFP breakthrough for Burnett Woods Pond water

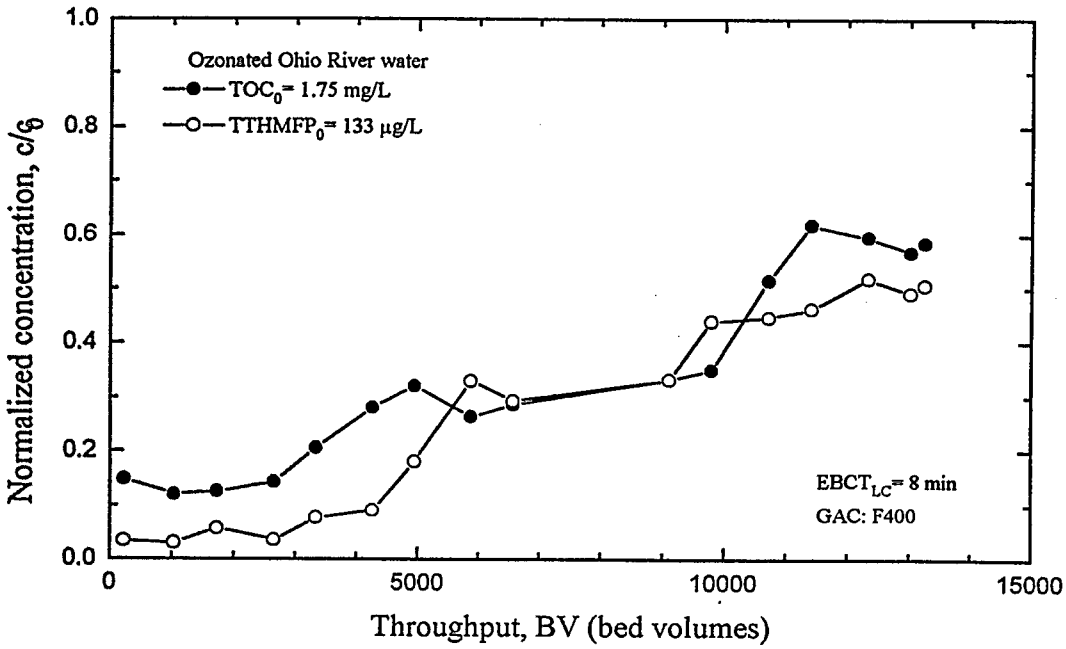

Figure 2-7 TOC and TTHMFP breakthrough for ozonated Ohio River water

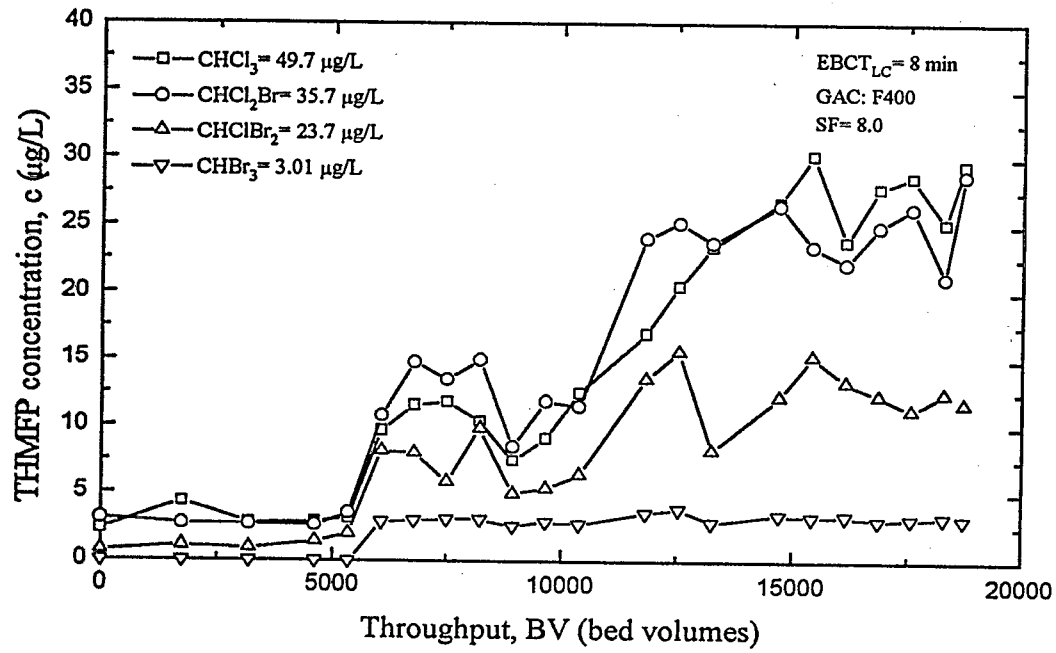

Figure 2-8 THM species breakthrough behavior for ozonated Ohio River water

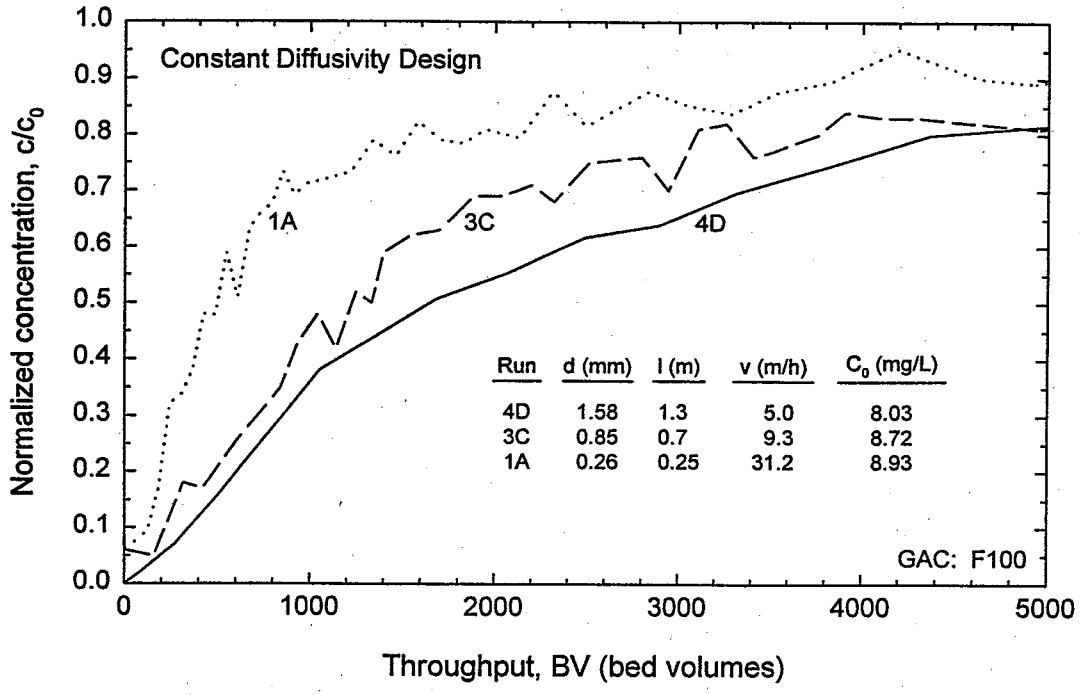

Figure 2-9 Application of constant diffusivity design (X = 0) to DOC breakthrough of Fuhrberg NOM (Summers et al., 1989)

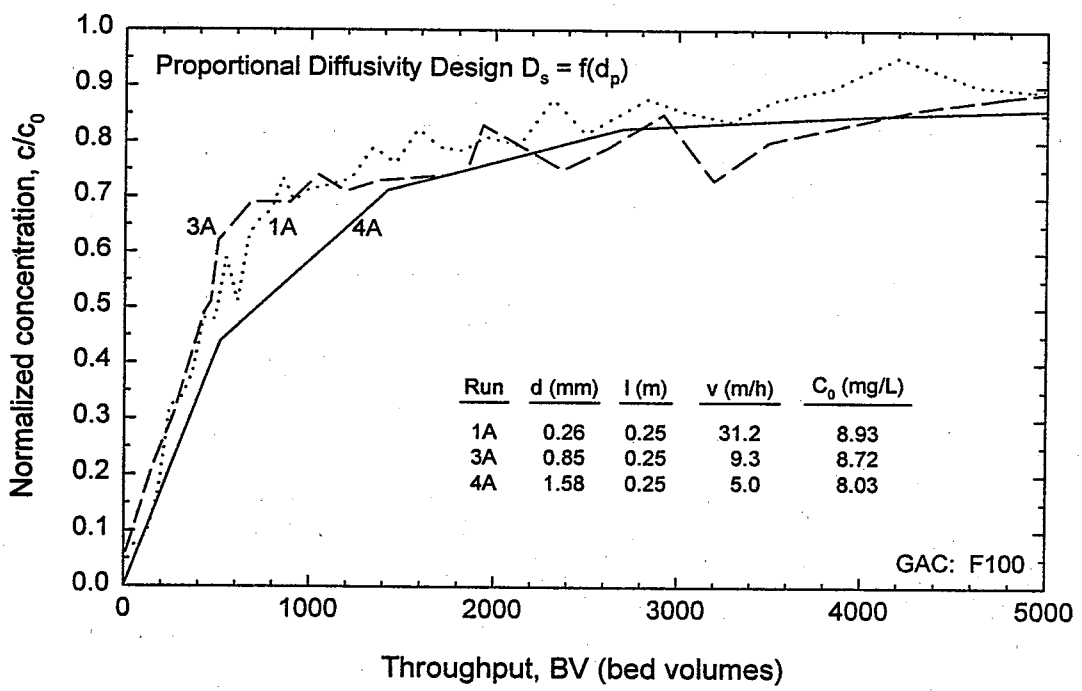

Figure 2-10 Application of proportional diffusivity design (X = 1) to DOC breakthrough of Fuhrberg NOM (Summers et al., 1989)

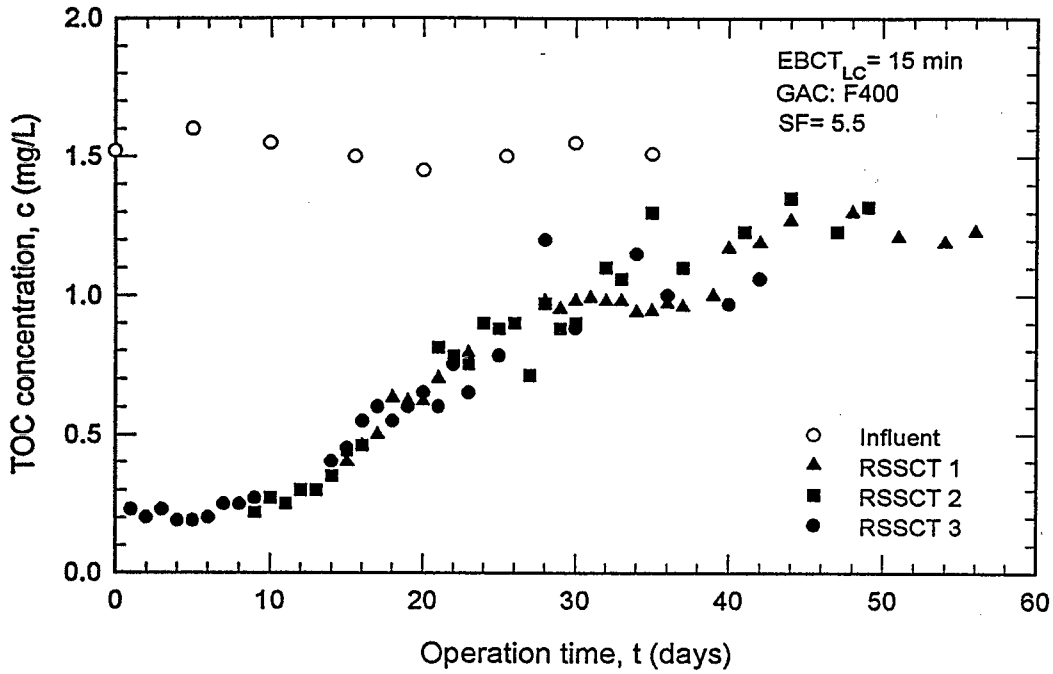

Figure 2-11 RSSCT reproducibility with Ohio River water (Namuduri, 1990)

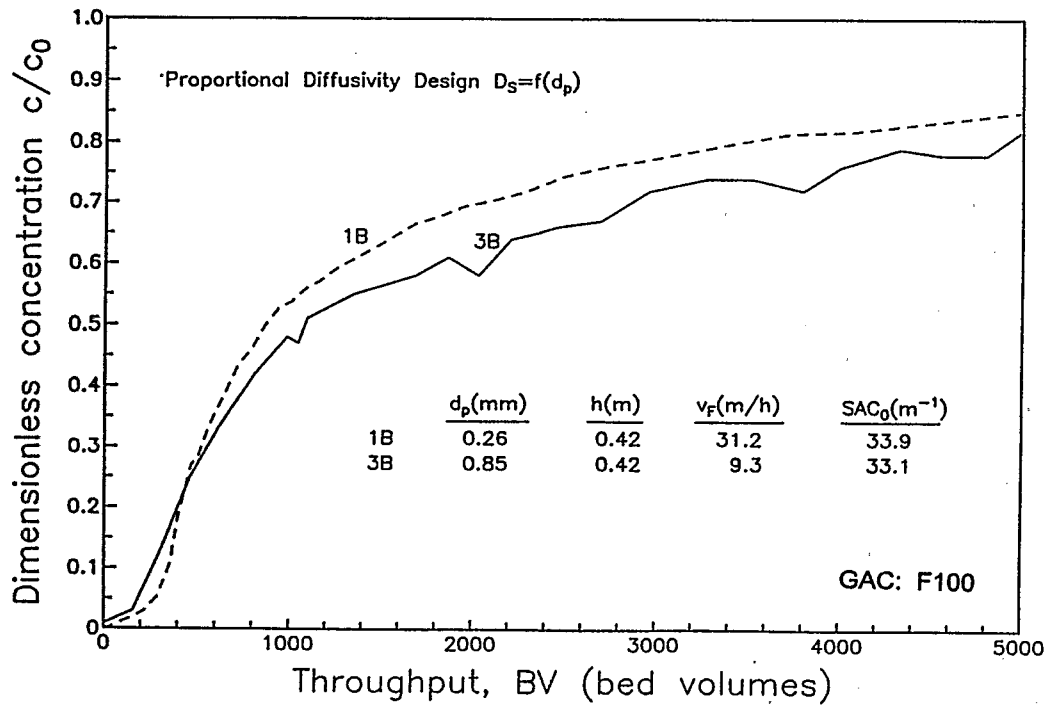

Figure 2-12 UV absorbance (SAC) breakthrough comparison for Fuhrberg NOM (Summers et al., 1989)

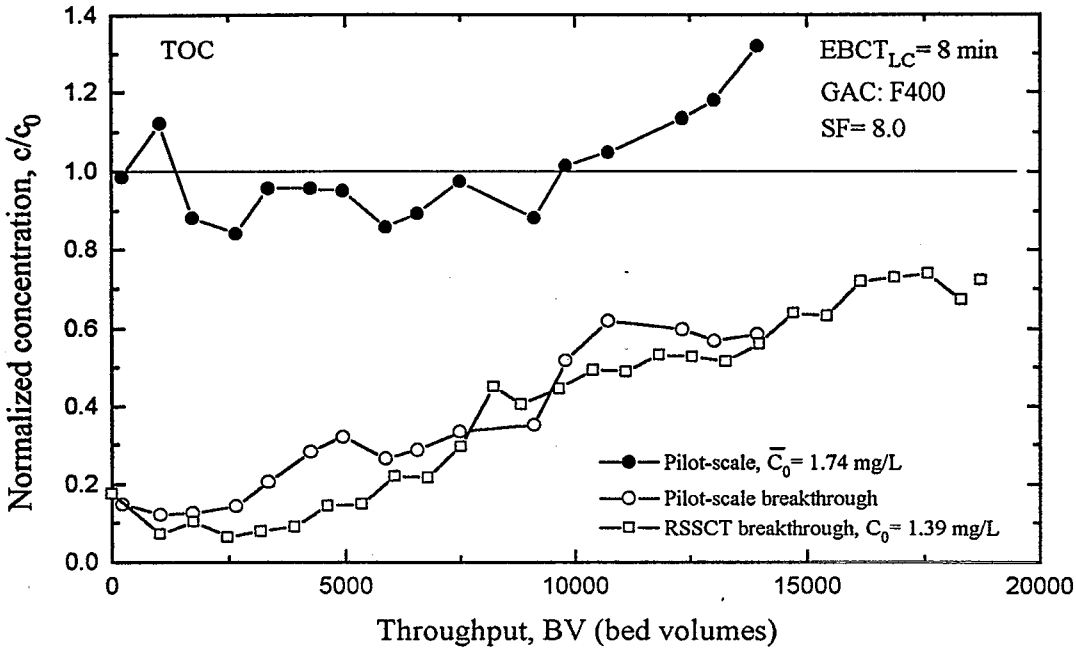

Figure 2-13 TOC breakthrough comparison for Ohio River water and a backwashed filter adsorber (Summers et al., 1994a)

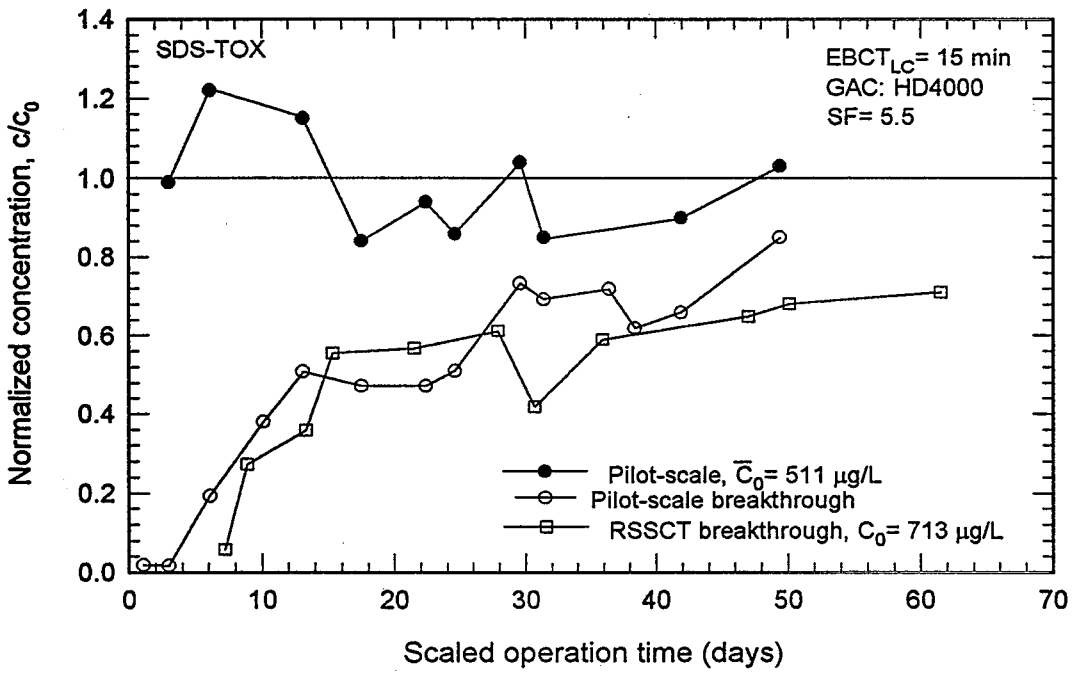

Figure 2-14 SDS-TOX breakthrough comparison for Palm Beach GW (Cummings and Summers, 1994)

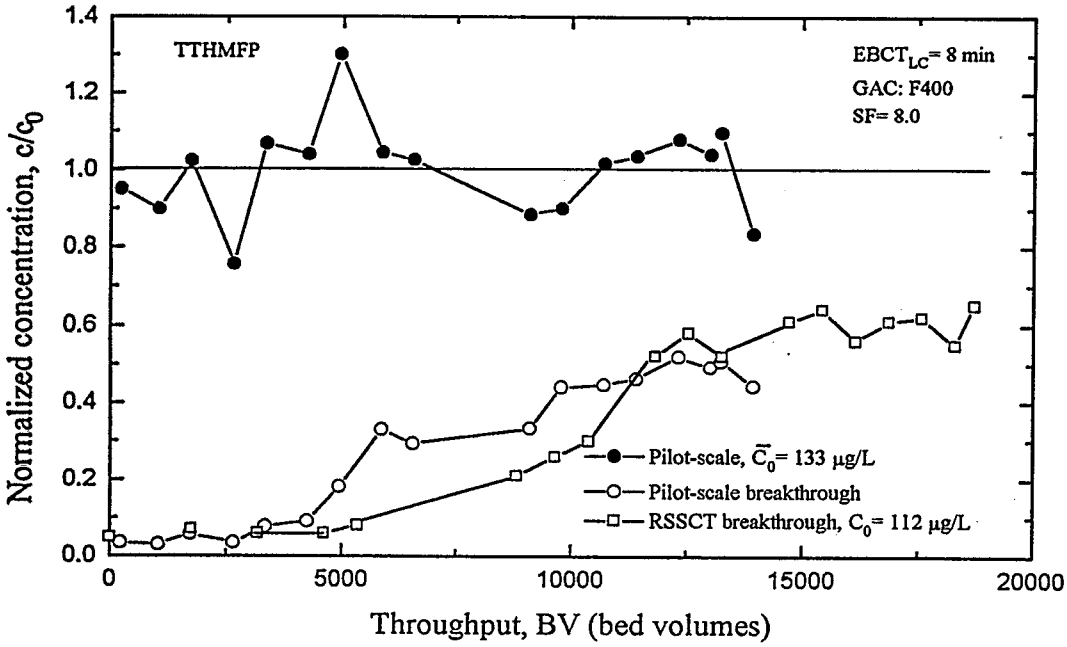

Figure 2-15 TTHMFP breakthrough comparison for Ohio River water and a backwashed filter adsorber (Summers et al., 1994)

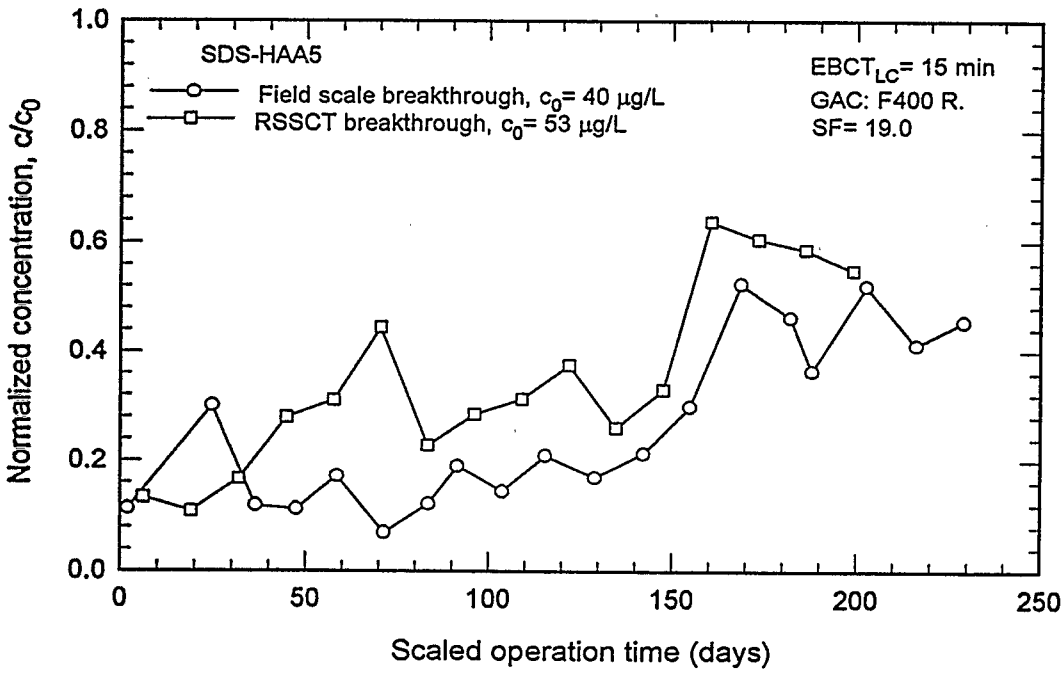

Figure 2-16 SDS-HAA5 breakthrough comparison for Ohio River Water (Metz, Summers, and DeMarco, 1993)

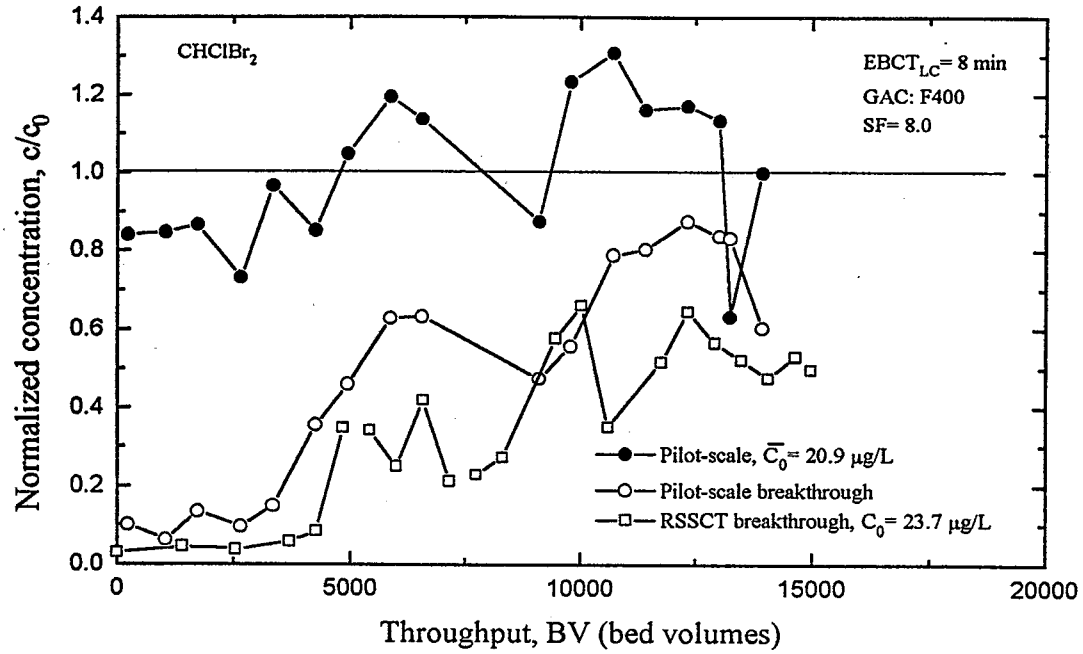

Figure 2-17 $CHClBr_2$FP breakthrough comparison for Ohio River water and a backwashed filter adsorber

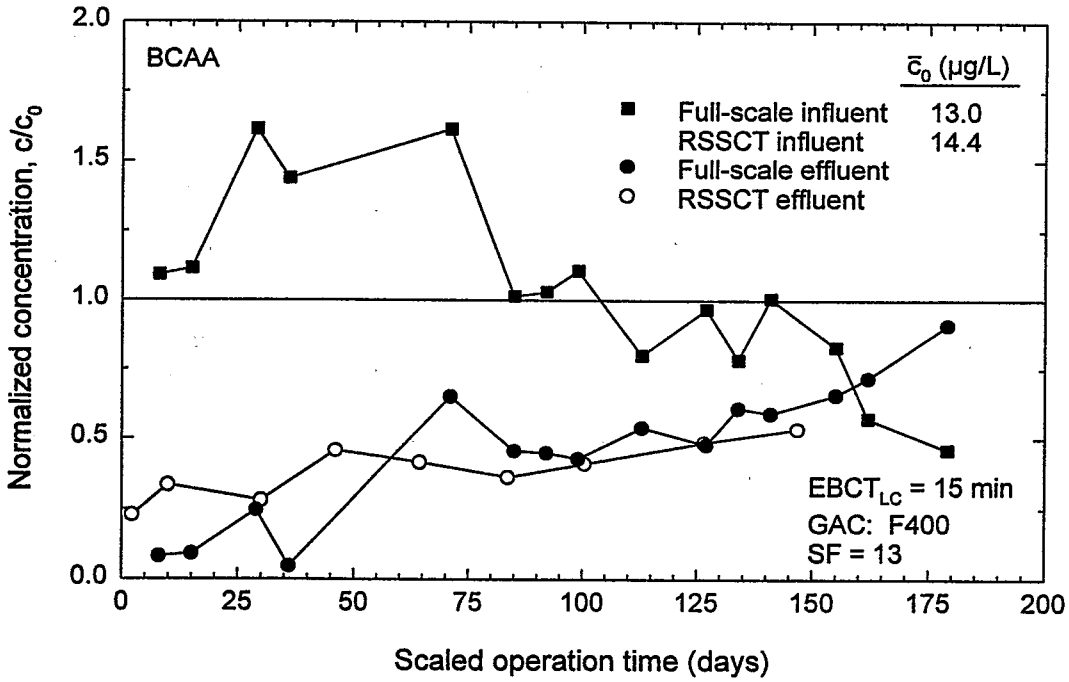

Figure 2-18 SDS-BCAA breakthrough comparison for Ohio River water

Table 2-1 Summary of RSSCT application to NOM and DBP formation control.

Study	Water Source	Treatment	TOC (mg/L)	$EBCT_{LC}$ (min)	d_{SC} (mm)	Parameters
1	Fuhrberg NOM	extracted	8.0 - 8.9	1.6, 3.0, 16	0.26, 0.85	TOC, UVA
2	Colorado River	conv	2.1	15, 30, 60	0.21	TOC
2	State Project, CA	conv	2.2	15	0.21	TOC
2	Ohio River	conv	2.2	15	0.21	TOC
2	Mississippi River	conv	2.7	20	0.21	TOC
2	Delaware River	conv	2.7	15	0.21	TOC
3	Lake Gaillard, CT	direct fil	1.8	5.4, 15	0.21	TOC
4	Delaware River	O_3/conv	2.5	15 (3)*	0.20	TOC
5	Palm Beach GW	softened/ O_3/biofil	6.6	15 (3)*	0.20	TOC, UVA, TOX, THM
6	Ohio River	conv	1.8	15 (3)*	0.05	TOC, UVA, TOX, THM, HAA, CH
7	Ohio River	O_3/conv	1.4	8	0.20	TOC, UVA, THM
8	Mississippi River	conv/O_3	2.8	6.2	0.11	TOC, UVA, TOX, THM, HAA, CH
8	Ohio River	conv	2.1	15	0.08	TOC, UVA, TOX, THM, HAA, CH
8	Passaic River, NJ	conv	3.2	20	0.11	TOC, UVA, TOX, THM, HAA, CH
8	Lake Gaillard, CT	direct fil/ O_3	1.5	15	0.20	TOC, UVA, TOX, THM, HAA, CH

1) Summers et al., 1989
2) Wallace et al., 1988
3) MP/SCCRWA, 1990
4) Summers et al., 1992
5) Cummings and Summers, 1994
6) Metz, Summers, and DeMarco, 1993
7) Summers et al., 1994a
8) Summers et al., 1995

*three GAC types

3.0 Treatment Study Influent

The ICR Rule, § 141.144(b), states that "The treatment study shall be conducted with the effluent from treatment processes already in place that remove disinfection byproduct precursors and TOC." The intent of the treatment study is to assess the additional removal of DBP precursors by GAC. However, the influent to the GAC must be taken prior to the first point of use of oxidants or disinfectants that would form chlorinated DBPs, § 141.144(b). This is to insure that the DBP precursors are not reacted prior to the GAC treatment and that oxidant residuals are not present in the GAC influent, which would lead to oxidation of the GAC. If the use of these oxidants or disinfectants precedes any full-scale treatment process that removes DBP precursors, then bench- or pilot-scale treatment processes that represent these full-scale treatment processes are required to generate treated water that has not been exposed to oxidants or disinfectants that form chlorinated DBPs for use in the GAC treatment study.

This presumes that the most appropriate location in the treatment train for the advanced precursor removal process under study is after the in-place treatment processes. However, there may be cases where the simulation of some full-scale treatment process may not be appropriate or necessary. For example, since the RSSCT uses cartridge filtration as a routine test pretreatment step, it would not be necessary to simulate granular media filtration for those procedures. Also, utilities may investigate the optimization of existing treatment processes, like enhanced/optimized coagulation, or the addition of new DBP precursor removal processes, like biological filtration prior to the GAC treatment studies.

A schematic diagram of three possible scenarios is shown in Figure 3-1 and explained in Table 3-1 for a full-scale conventional treatment system. The sample points for the bench- or pilot-scale systems must precede the addition point of the chlorine based oxidant or disinfectant. For example, if pilot-plant studies are to be conducted and the oxidant/disinfectant is added at Point A, then water for the treatment study must be taken at Point I and a continuous flow pilot plant with coagulation, sedimentation and filtration processes must be used prior to the GAC columns. These pilot plant processes must produce a water quality that represents that from the full-scale system. It is critical that the pilot plant system be cleaned or in use long enough that no leaching from or adsorption to the materials of construction occur, since this would affect the TOC or DBP formation. If the oxidant/disinfectant is added at Point B, then pilot-scale continuous-flow filtration must be provided prior to the GAC columns.

If the bench-scale RSSCT is used for the GAC treatment study, then batch bench-scale coagulation/flocculation, sedimentation and filtration can be used if treatment study water is taken at Point I. Like that for the pilot-scale system, these bench-scale batch processes must produce a water quality that represents that from the full-scale system. As will be shown in Section 5.0, the RSSCT requires 200 to 400 liters (50 to 100 gallons) per run for most situations. This volume of water can be batch coagulated, flocculated and settled in a laboratory using clean 55-gallon drums or other appropriately sized clean vessels. It is critical that the vessels be clean and no leaching from or adsorption to the vessel walls

occurs, that would affect the TOC or the DBP formation. Because of stability problems associated with storing ozonated waters, and acclimation times for biotreatment, plants that want to investigate ozonation directly before GAC application should do so at the pilot scale. If a bench-scale GAC treatment study is to be used for a plant with post-ozonation and no biotreatment, then a batch of water should be taken prior to ozonation and ozonated and biotreated at the bench-scale, prior to the bench-scale GAC run.

RSSCT columns are often prone to the development of rapid pressure (headloss) buildup as small particle sizes of GAC are used. Membrane or cartridge filtration of the RSSCT influent diminishes the rapid pressure buildup to an acceptable level. Membranes, such as glass fiber filters and cartridge filters with 1.0 μm nominal pore openings, have been shown to be effective in reducing headloss. In all cases the filtration system must be extensively cleaned to insure that no organic matter is released into the treatment study water. This should be checked using distilled water with a low organic matter content. This membrane or cartridge filtration can also serve as the bench-scale filtration treatment process that emulates the full-scale filtration process, if the treatment study water was taken at Points I or II.

Figure 3-1 illustrates the location of the treatment study influent water for a conventional treatment system, i.e., coagulation, flocculation, sedimentation and filtration. If other treatment processes that remove the DBP precursors or affect the formation of DBPs are used in the full-scale plant and the oxidant/disinfectant addition precedes them, then bench- or pilot-scale treatment processes that represent these full-scale treatment processes are required prior to the GAC treatment study. These processes include, but are not limited to, softening, recarbonation, aeration, ozonation, powdered activated carbon addition and pH adjustment.

As discussed in Section 5.0, it is critical that the batch of water taken from the full-scale plant for use as the RSSCT influent be representative of the water quality of the season of interest. The batch influent water should be immediately evaluated, on-site if possible, for TOC, UV_{254}, pH, alkalinity, hardness (total and calcium), ammonia and bromide, prior to use as the RSSCT influent. The dissolved oxygen levels should also be checked prior to running the RSSCT as extremely high or low deviations from the field-scale value may affect TOC adsorption.

Part 1, Section 4.7 requires that design information for all full-, pilot- or bench-scale pretreatment processes that precede the bench/pilot systems be reported. Any costs incurred due to the addition of pretreatment processes to an existing plant should be estimated and reported. In addition the point in the full-scale treatment train in which water for the pilot- or bench-scale treatment systems should be noted. The flow rate for all pilot-scale processes preceding the pilot-scale GAC adsorber should be reported. The flow rate for continuous systems or the volume for batch systems for all bench-scale processes preceding the bench-scale GAC adsorber should be reported.

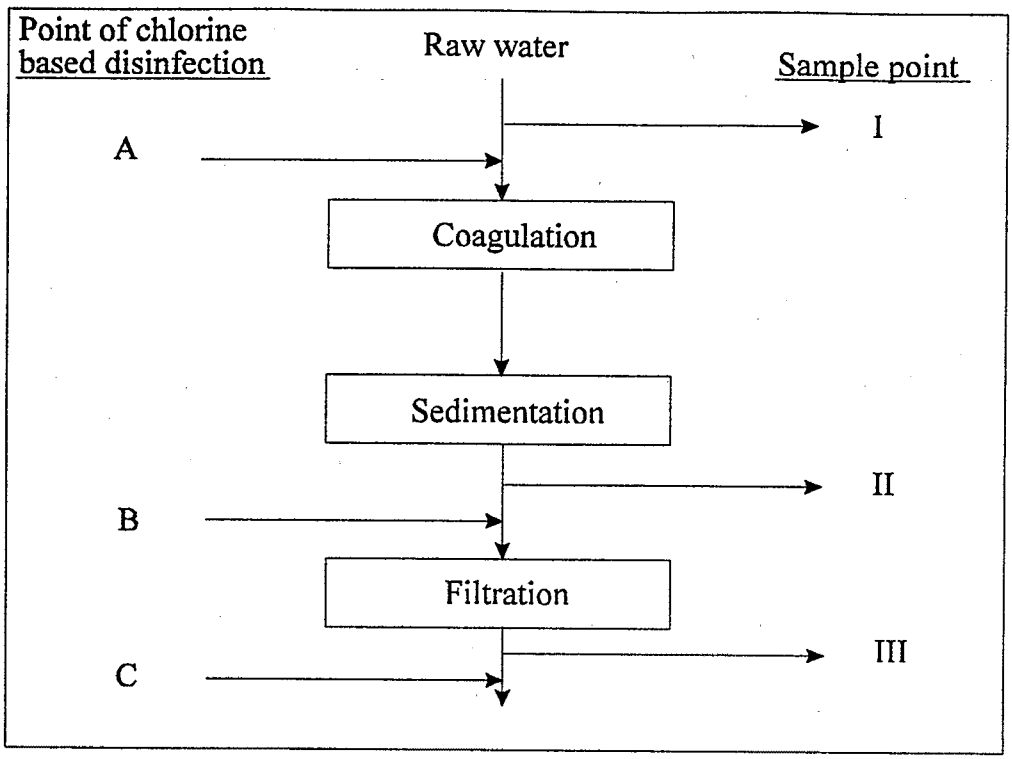

Figure 3-1 Full-scale plant sample points for bench/pilot scale GAC tests

Table 3-1. Sample point and required pretreatment for GAC tests (See Figure 3-1)

Addition point of chlorine based chemical	Required sample point[1]	Required pilot plant continuous flow pretreatment[2]	Required bench scale batch pretreatment
A- before coagulation sedimentation	I	coagulation sedimentation media filtration	coagulation[2] sedimentation[2] 1.0 μm membrane filtration[3]
B- after sedimentation	II	media filtration	1.0 μm membrane filtration[3]
C- after filtration	III	none	1.0 μm membrane filtration[3]

1) In all cases samples for GAC testing must be taken before the addition point of chlorine-based chemicals
2) Pilot and bench-scale pretreatment should be designed to simulate the full-scale treatment processes. All full-scale processes that impact the adsorbability of organic matter should be simulated by pilot and bench-scale processes, e.g., pH adjustment, aeration, softening, recarbonation, and ozonation.
3) Filtration with membranes or cartridges with 1.0 μm nominal pore openings is to be used prior to all RSSCTs. This use simulates full-scale media filtration for purposes of RSSCT pretreatment and minimizes pressure build-up in the RSSCT column.

4.0 Pilot-Scale GAC Test Protocol

4.1 Design

As discussed in Section 2.0, well designed and operated pilot-scale GAC columns have been found to yield results that are comparable to those of full-scale GAC systems. The GAC used in the pilot columns should be representative of that to be used in the full-scale columns with respect to particle size and activity. The GAC selected for use in the pilot column must meet the AWWA Standard for Granular Activated Carbon ANSI/AWWA B604-90 (Appendix 2-C). This standard describes the sampling and characterization of the GAC. A representative batch of GAC shall be obtained from the manufacturer and care should be taken in choosing a sample from this batch for the pilot column, as it will contain a range of particle sizes. The smaller particles in a batch will tend to yield better removal performance because the mass transfer kinetics are faster and the capacity may be higher. However, smaller particles will lead to faster buildup of headloss. A sample tube, riffle splitter, sample reducer or coning and quartering technique can be used to obtain a representative sample (Randtke and Snoeyink, 1983). The coning and quartering technique is described in Appendix 2-A.

Typically, 8x30 or 12x40 mesh (US Std.) sized GAC is used in water treatment, although custom sized GAC can be obtained. These GACs have average particle diameters (APDs) of about 1.6 and 1.1 mm, respectively. To minimize the chances of channeling in a GAC column, the inner column diameter should be at least 25 times greater than the APD of the GAC. The ICR Rule specifies the use of columns with a minimum inner diameter of 2.0 inches (51 mm). The ICR Rule requires that GAC columns with EBCTs of 10 and 20 minutes be tested. The pilot testing shall include the water quality parameters listed in Table 4-0.

An example of a typical pilot plant set-up that can be used to gather the required information is shown in Figure 4.1. A filter with inert media, e.g., sand, anthracite or garnet, is also shown in Figure 4-1, although if the treatment study water is taken at Point III (Figure 3-1) pilot-scale filtration is not required. If the GAC column inner diameter is 6 inches or less, then all GAC column values and piping material in contact with the water shall be limited to glass, Teflon or stainless steel. Glass columns are recommended so that the height of the GAC or filter media can be easily monitored during operation and backwashing. A plastic safety shield should be used for glass GAC columns. If the GAC column inner diameter is greater than 6 inches or the cross sectional surface area is greater than 0.2 square feet, then other material of construction can be used. However, the column's piping and valves must be cleaned or in use long enough that no leaching from or adsorption to the materials of construction occur, since this would affect the TOC or DBP formation. This lack of impact must be demonstrated by a blank run with no GAC in the column. Provisions should be made for backwashing the filter and the GAC columns. Appropriate valving and a non-chlorinated backwash water supply are needed. The columns should be at least 60% longer than the media or GAC bed depth to allow for the expansion of the bed during backwashing without loss of media. Pressure gauges should be provided on the lines at the

top of each column to allow pressure buildup monitoring. Pressure relief valves should be added to the top of each column. Screens with openings slightly smaller than the smallest media size should be placed at the bottom of each column or in the tubing/pipe connectors at the bottom of the columns. The screen should retain 70 mesh (US Std.) particles. This prevents carry-over of the particles to the next column or into the effluent.

A flow control valve should be placed after the last column. By controlling the flow at this point, the columns will always remain under positive pressure during the run. This prevents the buildup of air pockets in the column. The tubing/pipe connecting the columns should be sized to carry the appropriate flow. For two inch diameter columns, 1/4 or 3/8 inch tubing is sufficient. The effluent line should break to the atmosphere at a level higher than the top of the GAC bed. This will prevent the water level from falling below the top of the GAC bed if flow to the columns stops and siphoning occurs.

Figure 4-1 shows two 10 min EBCT columns in series. Configured in this manner data from both the 10 and 20 min EBCT columns can be gathered at once by sampling at the designated points. Sampling of columns in series should always begin at the last sample point and proceed upstream to minimize flow variations. The two columns could also be arranged in parallel with one containing enough GAC for a 10 min EBCT and the other enough for a 20 min EBCT. There are advantages and disadvantages of both series and parallel operation. Series operation requires less equipment, but is less flexible with respect to operation compared to parallel operation.

It is also possible to utilize sequential operation in which a study is first conducted with one of the two EBCTs columns prior to testing with the second EBCT column. Compared to series or parallel operation, sequential operation requires the least amount of equipment, but takes the longest time to complete and requires the influent to be monitored for both runs, thus doubling the analytical costs of influent monitoring.

A representative hydraulic loading rate, also termed superficial velocity, **v**, should be used:

$$\mathbf{v = Q/A} \qquad \mathbf{(4.1)}$$

where **Q** is the volumetric flow rate and **A** is the column cross sectional area. A value for v in the range of 2 to 6 (gallons/min)/ft^2 (5 to 15 m/hr) shall be used. Higher values of v yield longer bed lengths, **l**, as

$$\mathbf{l = v \cdot EBCT} \qquad \mathbf{(4.2)}$$

The EBCT can also be defined as

$$\mathbf{EBCT = V_b/Q} \qquad \mathbf{(4.3)}$$

where V_b is the GAC bed volume. Values of v in this range will yield bed depths of 2.8 to 8.2 ft (0.83 to 2.5 m) and 5.6 to 16.4 ft (1.7 to 5.0 m) for EBCTs of 10 and 20 min, respectively.

4.2 Operation

When loading the GAC into the columns care should be taken to reach the desired design bed depth and avoid entrapping air in the GAC beds. Based on the required bed volume of GAC

$$V_b = l \cdot A \qquad (4.4)$$

for the 10 or 20 min EBCT columns and the manufacturers supplied dry bed (apparent) density (mass of GAC/ V_b), the mass or weight of GAC required to yield a 10 or 20 min EBCT can be calculated: mass = V_b x bed density. An amount of representative GAC that is 20% more than this mass should be carefully weighed and noted. From this amount of GAC the GAC columns will be filled. The amount of GAC in the column will be calculated by the difference between the original amount and that remaining after filling.

The empty GAC column should be valved off and filled with non-chlorinated filtered water to a level of about 50% of the design GAC bed depth. The dry GAC should be slowly and carefully added to the column to a depth of about 5 to 10% greater than the design bed depth. Allow the GAC to remain in the bed to become 'wet' with unchlorinated filtered water. This can take up to 12 hours for most GACs, but low density GACs may take longer than 24 hours. The GAC bed should then be carefully backwashed with unchlorinated filtered water to remove only the fines. The bed should be initially expanded by 10%, and held at this level until most of the very fine particles are washed out. The bed can then be slowly (over a 5 minute period) expanded to a 40% level. It is important to ensure that only the fines are being backwashed out of the column. Backwash the GAC at this level for about 20 min. Slowly (over a 30 sec period) turn the backwash supply water off and allow the GAC to settle. The settled bed depth should be about 5% longer than the design bed depth. If it is not, add more GAC to the column to achieve this bed depth. A longer initial bed depth is needed as the GAC will compact during operation. Allow the GAC to sit submerged in the unchlorinated filtered water overnight before start-up, to allow the air in the pores to dissolve.

Prior to start-up, backwash the GAC at 40% bed expansion for 5 min. Again check the settled bed depth. Weigh the amount of GAC remaining and subtract this amount from the initial amount to determine the weight of GAC added to the columns. Report the mass of GAC added to the columns in Table 4-1. This approach does not directly account for the mass of fines backwashed out of the column, however, they are typically a small amount compared to the total mass of GAC in the column.

Open the appropriate valves to send the water stream to the GAC columns. A pump to feed the water to the GAC or filter/GAC system may be needed if the influent water is not

under enough pressure to overcome the headloss in the GAC or filter/GAC system. The flow rate should be set to yield EBCTs of 10 and 20 min using the flow control valve at the end of the system.

$$Q = V_b/EBCT = (l \cdot A)/EBCT \qquad (4.5)$$

Use the valves at the top of the column (backwash water waste valves), see Figure 4-1, to release any air trapped in the system.

After 12 to 18 hours of operation check the GAC bed depth levels, as the bed should reach most of its compaction during this period. Readjust the flow rate to yield the 10 and 20 min EBCT based on this measured bed depth, with a margin of error of +/- 5%. If series operation is used and only one column needs adjustment, add more GAC or remove excess GAC and adjust the flow. Weigh the amount of GAC added or taken from the columns and appropriately adjust the reported mass of GAC used in each column. If more is added, the bed must be backwashed and run for at least 4 hours before sampling. If GAC is removed from the column, it must be dried at 100°C for at least 24 hours prior to weighing. Take the first samples after about 24 hours of operation.

The flow rate should be maintained to within 5% of that needed to produce the 10 and 20 min EBCT. Flow rates should be checked daily and adjusted to within this tolerance. Unusually long periods of no flow to the columns (longer than 1 to 2 hours per day with a maximum of 7 hours per week) should be accounted for by not including it in the cumulative operation time. Therefore, operation time may be shorter than clock time.

If proper filtration at the full- or pilot-scale is maintained, then the GAC columns should not need to be backwashed during operation. A clean-bed pressure drop of 0.05 to 0.15 psi per ft of bed depth can be expected. High values of v and low values of the GAC particle size will yield higher headloss. If the buildup of headloss becomes excessive, greater than 10 psi (or some other site determined value) above the clean bed value, then the GAC columns should be backwashed. Expansion of the bed volume by 25% for 20 min should be adequate. Often the GAC at the top of the bed will bind together causing the GAC to rise as an intact segment. This problem can be overcome by opening the top of the column and rodding the bed, i.e., disturbing the top 2 to 4 inches (5 to 10 cm) of the bed with a rod. This problem occurs less often with columns with diameters greater than 4 inches. Slowly turn the backwash supply water off (30 sec period) and allow the GAC to settle. The water used for backwashing should be GAC effluent that has been collected prior to backwashing and stored off-line.

4.3 Sampling

A wide range in breakthrough behavior like that shown in Figure 4-2 is expected for GAC columns with EBCTs in the 10 to 20 min range. This range in adsorption behavior makes sampling the GAC column effluent difficult, as the goal is to characterize the breakthrough behavior. Figure 4-3 depicts a sampling scenario which will meet the sample frequency

requirements listed in Table 4-0 and yield a well characterized breakthrough curve. A minimum of 15 influent samples and 15 effluent samples at both 10 and 20 min EBCTs are required. If the 10 and 20 min EBCT runs are being operated at the same time, either in series as shown in Figure 4-1, or in parallel, then the 15 influent samples should be taken at the same time as 20 min EBCT effluent samples. If the runs for the 10 and 20 min EBCT are being made at different times, then at least 15 influent samples need to be taken over the course of both runs. These influent samples need to be taken at the same time as the effluent samples.

Three duplicate influent samples need to be taken over the course of the run. They should be taken at approximately equally spaced intervals through the run. The first duplicate influent sample should be taken with the third or fourth influent sample, the second duplicate influent sample should be taken with the seventh or eighth influent sample and the third duplicate influent sample should be taken with the eleventh, twelfth or thirteenth influent sample.

As stated in Table 4-0 and illustrated in Figure 4-3, effluent samples should be taken after the first day and then at 3% to 7% increments of the average influent TOC. The average influent TOC is defined as the running average of the influent TOC at the time of sampling. This approach requires a relatively quick turn around time for TOC analysis. The intent is to yield a good assessment of the breakthrough with a minimum number of samples. More frequent effluent monitoring for TOC may be necessary in order to sample for the other analytes at the 3% to 7% increments of the average influent TOC.

Three duplicate effluent samples need to be taken over the course of the run for each EBCT tested. They should be taken at approximately equally spaced intervals through the run. The first duplicate effluent sample should be taken with the third or fourth effluent sample, the second duplicate effluent sample should be taken with the seventh or eighth effluent sample and the third duplicate effluent sample should be taken with the eleventh, twelfth or thirteenth effluent sample.

The breakthrough of UV absorbance at a wavelength of 254 nm, UV_{254}, often parallels that of TOC and may be used to estimate the sampling times. However, UV-absorbing substances are normally better removed by GAC and UV_{254} breakthrough lags behind that of TOC. Thus, the relationship between UV_{254} and TOC in the GAC effluent needs to be first established. This requires that both TOC and UV_{254} data were collected for a previous GAC run. Thus, if this monitoring approach is to be used, prior experience with GAC treatment of the site-specific water is needed.

If on-site TOC or fast turn-around of TOC measurement, or previous GAC experience are not available, a sampling plan may be estimated from the influent TOC by the following procedure. In Figure 2-3 a correlation was presented that related the number of bed volumes to 50 percent TOC breakthrough, $\mathbf{BV_{50}}$, to the influent TOC concentration, $\mathbf{TOC_0}$, for bituminous coal based GACs. This relationship can be expressed by the following equation (Equation 2.3):

$$BV_{50} = 21{,}700 \cdot TOC_0^{-1.3} \quad (4.6)$$

The time in days to 50 percent TOC breakthrough, t_{50}, can be estimated by the following equation for an EBCT in minutes:

$$t_{50} = BV_{50} \cdot EBCT/1440 \quad (4.7)$$

Based on the shape of previous TOC breakthrough curves, a 1-9-4-1 sample plan is recommended for the 15 effluent samples. The first sample is taken after one day, nine additional samples are taken at regular time intervals up to the 50 percent breakthrough, four samples are taken at regular time intervals after 50 percent breakthrough, and one sample is taken at the end of the run. The sample time interval in days, t_{int}, for the first half of the TOC breakthrough can be estimated from the following:

$$t_{int} = (t_{50} - 1)/9 \quad (4.8)$$

Since TOC breakthrough curves are not symmetrical and tend to have a lower slope after 50 percent breakthrough, the sample time interval after 50 percent breakthrough should be estimated as 50 percent longer than t_{50}.

Table 4-2 presents a general sample plan and a sample plan for ten examples with TOC_0 values of 2.0, 2.5, 3.0, 4.0, and 6.0 mg/L and EBCTs of 10 and 20 minutes. Figure 2-3 and Equations 4.6, 4.7 and 4.8 are utilized for this method of estimating a sample plan. This approach is based on a data set limited to 16 water sources and one general GAC type, and may not be valid in all cases. If the pH value of the water to be treated is 7.0 or below then the BV_{50} value may be 10 to 40 percent higher than the value given by Equation 4.6, based on the work of Hooper et al. (1995).

It is strongly suggested that on-site TOC or fast turn-around TOC measurements be used whenever possible to characterize the breakthrough and accurately determine the sample times.

Both the 10 and 20 minute EBCTs of the pilot study shall be run until: a) the effluent TOC concentration is 70% of the average influent TOC concentration on two consecutive TOC sample dates that are at least two weeks apart, or b) 50% TOC breakthrough occurs and a plateau is reached in which the effluent TOC concentration does not increase over 1440 hours by more than 10% of the average influent TOC concentration. The 10 minute EBCT run will take about half of the time required for the 20 minute EBCT. If the 10 and 20 minute EBCT contactors are operated in series, then operation of the 10 minute EBCT contactor must continue until the 20 minute EBCT run is terminated. However, the 10 minute EBCT contactor does not need to be sampled after 70% breakthrough or a plateau is achieved.

It is strongly recommended that the pilot-scale columns be run continuously. Down time that cannot be avoided should not be included in the cumulative run time.

If either the 70% breakthrough or the plateau criteria is met for the 20 minute EBCT prior to 4000 hours run time, a second run shall be conducted following the same sampling requirements. In all cases, the maximum run length for the pilot-scale study (one or two runs) is 8000 hours. The pilot-scale testing should be of sufficient duration and appropriate timing to capture seasonal variations in water quality. If seasonal variation is not significant (e.g. as is the case for most ground waters), other factors, such as pretreatment, carbon type, etc. can be evaluated.

The pilot-plant design parameters, sampling times and results should be reported in accordance with Tables 4-1, 4-3 and 4-4 of part 2. Samples should be taken according to the procedures described in the "ICR Sampling Manual" (EPA 814-B-96-001). The approved analytical methods for the analytes listed in Table 4-0 are listed in Table 7 § 141.142 of the ICR Rule, described in "DBP/ICR Analytical Methods Manual" (EPA 814-B-96-002) and must be used by all systems conducting treatment studies. Laboratory QA/QC plans listed in this manual must also be followed. Guidance for the simulated distribution system (SDS) test and the chlorine demand test are given in Section 6.0 of this document.

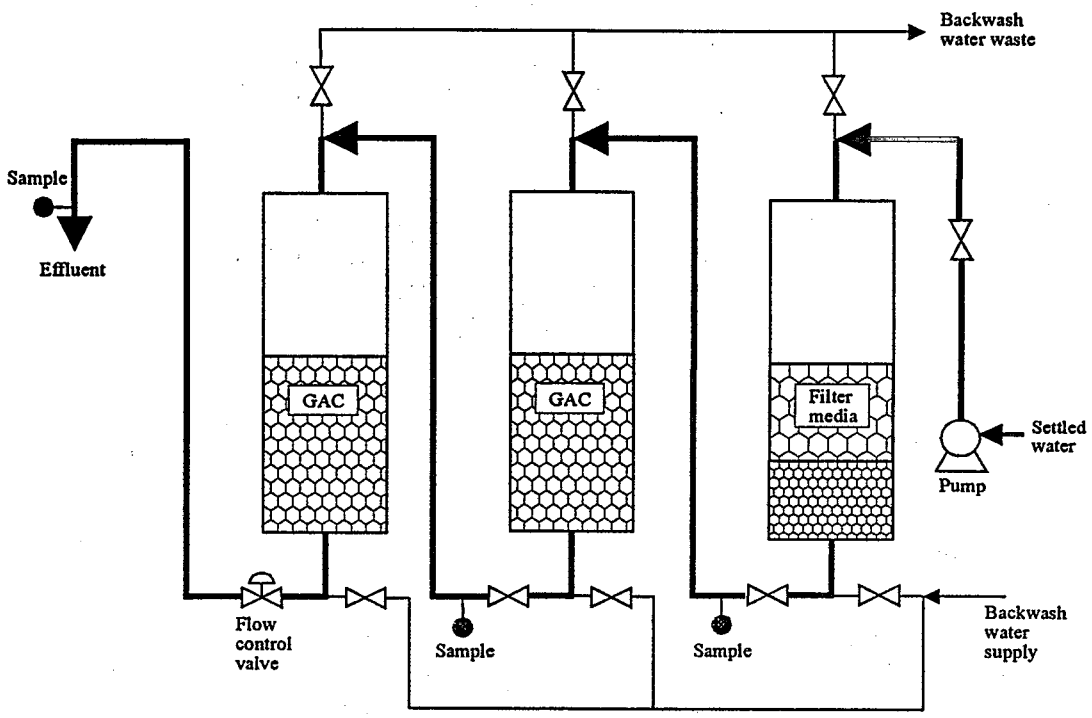

Figure 4-1. Pilot plant set-up

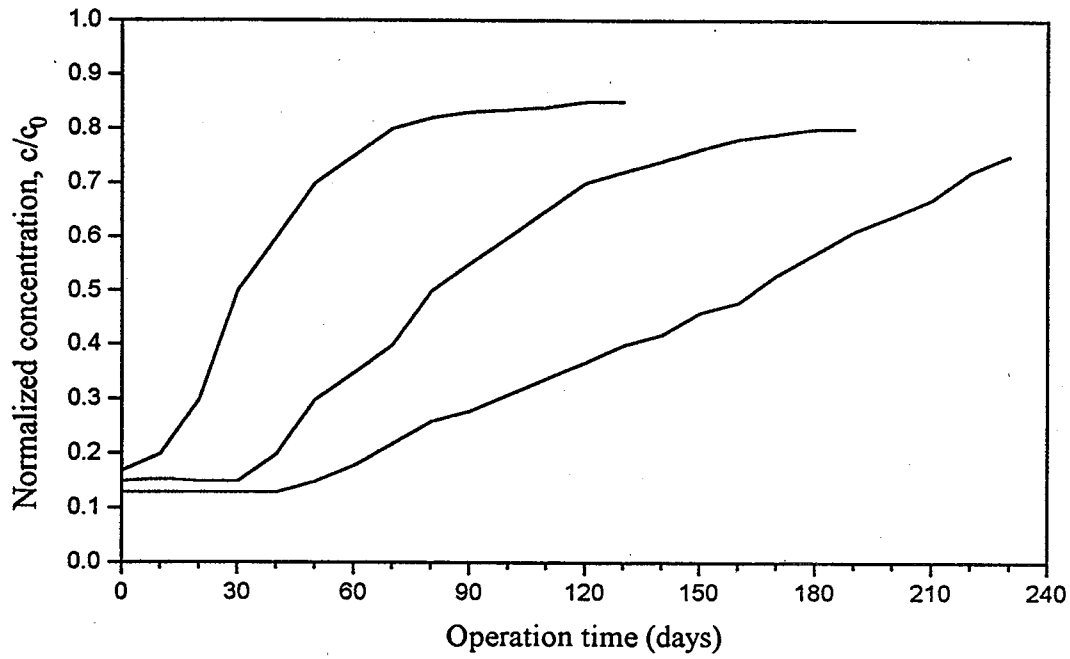

Figure 4-2 Typical GAC breakthrough behavior for natural organic matter

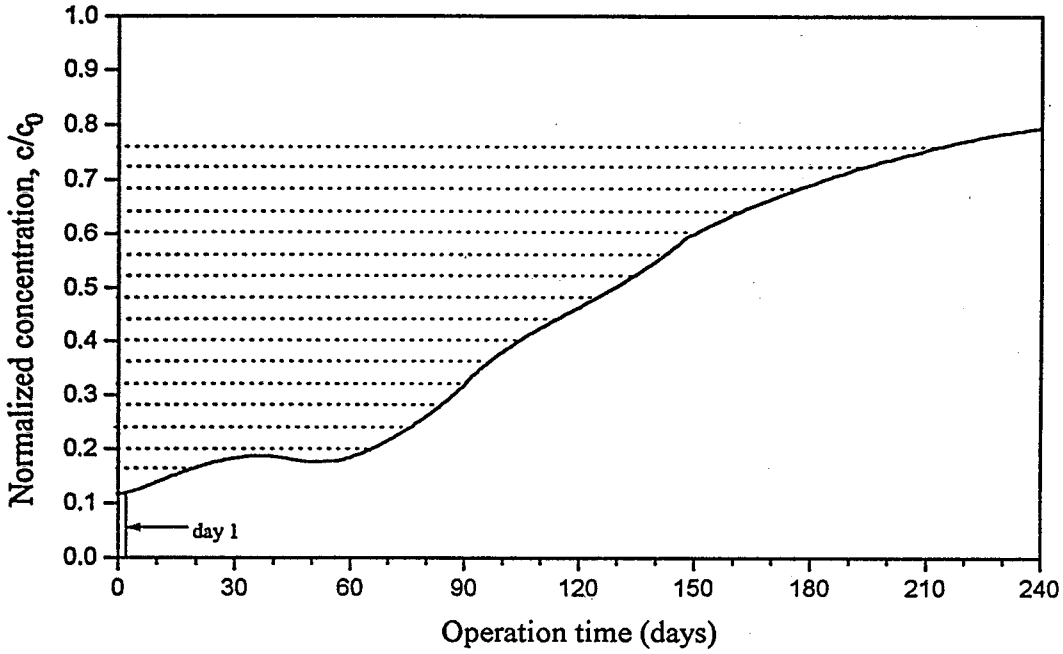

Figure 4-3 Pilot plant breakthrough and sampling

Table 4-0. Sampling of GAC Pilot-scale Systems

Sampling Point	Analyses	Sample Frequency[3,4]
GAC Influent	pH, alkalinity, turbidity, temperature, total & calcium hardness, ammonia, bromide, TOC and UV_{254}. SDS[1] for THM4, HAA6, TOX, and chlorine demand.	A minimum of 15 samples taken at the same time as the samples for GAC effluent[5].
GAC Effluent @ EBCT=10 min	pH, turbidity, temperature, ammonia[2], TOC and UV_{254}. SDS[1] for THM4, HAA6, TOX, and chlorine demand.	A minimum of 15 samples. One after one day, and thereafter at 3% to 7% increments of the average influent TOC.
GAC Effluent @ EBCT=20 min	pH, turbidity, temperature, ammonia[2], TOC and UV_{254}. SDS[1] for THM4, HAA6, TOX, and chlorine demand.	A minimum of 15 samples. One after one day, and thereafter at 3% to 7% increments of the average influent TOC.

1 - SDS conditions are defined in Part 1, Section 4.6 of this document. Additional guidance is found in Section 6.0 of this Part.

2 - If present in the influent.

3 - More frequent effluent monitoring may be necessary in order to predict the 3% to 7% increments of average influent TOC.

4 - Three duplicate samples are required for the influent and the effluent at each EBCT.

5 - If columns for EBCT=10 min and EBCT=20 min are run simultaneously, then influent samples should be taken at the same sample frequency as that for GAC effluent at EBCT=20 min.

Table 4-1. PILOT PLANT DESIGN PARAMETERS

Utility name and address _____

_____

Utility ID number _____

Contact person _____

Contact phone number _____

Contact FAX number _____

GAC type and manufacturer _____

GAC mesh size _____ US std mesh

EBCT= 10 min

Bed depth, l _____mm or _____inches

Volumetric flowrate, Q _____ml/min or _____ gal/hr

Superficial velocity, v _____m/hr or_____gpm/ft^2

Mass (dry) of GAC _____ grams

EBCT= 20 min

Bed depth, l _____mm or _____inches

Volumetric flowrate, Q _____ml/min or _____ gal/hr

Superficial velocity, v _____m/hr or_____gpm/ft^2

Mass (dry) of GAC _____ grams

Design and operation comments _____

_____

_____

_____

Table 4-2 Estimated Sample Times for Pilot-plant GAC Column Operation

Sample number	Sample time	SAMPLE TIME (DAYS)									
		TOC = 2.0 mg/L		TOC = 2.5 mg/L		TOC = 3.0 mg/L		TOC = 4.0 mg/L		TOC = 6.0 mg/L	
		EBCT = 10 min	EBCT = 20 min	EBCT = 10 min	EBCT = 20 min	EBCT = 10 min	EBCT = 20 min	EBCT = 10 min	EBCT = 20 min	EBCT = 10 min	EBCT = 20 min
1	1 day	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	1 day + t_{int}	7.7	15	6.0	11.2	4.9	9.0	3.7	6.5	2.5	4.2
3	1 day + $2t_{int}$	14	28	11.0	21.3	8.9	17	6.4	12	4.1	7.4
4	1 day + $3t_{int}$	21	42	16.1	31.5	13	25	9.1	17	5.6	11
5	1 day + $4t_{int}$	28	55	21.1	42	17	33	12	23	7.2	14
6	1 day + $5t_{int}$	35	69	26	52	21	41	14	28	8.7	17
7	1 day + $6t_{int}$	41	83	31	62	25	49	17	34	10	20
8	1 day + $7t_{int}$	48	96	36	72	29	57	20	39	12	23
9	1 day + $8t_{int}$	55	110	41	82	33	65	23	45	13	27
10	t_{50}	62	120	46	92	37	73	25	50	15	30
11	$t_{50} + 1.5t_{int}$	72	140	54	108	42	85	29	59	17	35
12	$t_{50} + 3.0t_{int}$	82	160	61	123	48	97	33	67	20	40
13	$t_{50} + 4.5t_{int}$	92	180	69	138	54	109	37	75	22	44
14	$t_{50} + 6.0t_{int}$	100	200	76	153	60	120	41	83	24	49
15	End of run	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR
	BV_{50}	8870	8870	6650	6650	5260	5260	3630	3630	2150	2150
	t_{50} (days)	61.6	123	46.2	92.4	36.5	73.1	25.2	50.4	14.9	29.9
	t_{int} (days)	6.7	13.6	5.0	10.2	3.9	8.0	2.7	5.5	1.5	3.2

EOR = End of run

Table 4-3. GAC PILOT PLANT SAMPLING

Utility name and address _____

_____

Utility ID number _____

Contact person _____

Contact phone number _____

Contact FAX number _____

	Date (M/D/Y)	Time	Operation time (day)
GAC Influent[1] (A group) pH, alk, turb, temp, TH, CaH, NH_4-N, Br, TOC, UV and SDS			
Sample A1			1.0
Sample A2			
Sample A3			
Sample A4			
Sample A5			
Sample A6			
Sample A7			
Sample A8			
Sample A9			
Sample A10			
Sample A11			
Sample A12			
Sample A13			
Sample A14			
Sample A15			
Sample D1-I			
Sample D2-I			
Sample D3-I			

1) Sample influent at the same time as EBCT= 20 min effluent if EBCT= 10 min and EBCT= 20 min are being run at the same time. If EBCT= 10 min and EBCT= 20 min are being run at different times then the GAC influent of both runs need to be monitored

Sampling comments _____

_____

_____

GAC PILOT PLANT SAMPLING (page 2) Utility ID # _____

	Date (M/D/Y)	Time	Operation time (day)
GAC Effluent EBCT= 10 min (B group) pH, turb, temp, NH_4-N[2], TOC, UV, & SDS			
Sample B1			1.0
Sample B2			
Sample B3			
Sample B4			
Sample B5			
Sample B6			
Sample B7			
Sample B8			
Sample B9			
Sample B10			
Sample B11			
Sample B12			
Sample B13			
Sample B14			
Sample B15			
Sample D1-10			
Sample D2-10			
Sample D3-10			
GAC Effluent EBCT= 20 min (C group) pH, turb, temp, NH_4-N[2], TOC, UV, & SDS			
Sample C1			1.0
Sample C2			
Sample C3			
Sample C4			
Sample C5			
Sample C6			
Sample C7			
Sample C8			
Sample C9			
Sample C10			
Sample C11			
Sample C12			
Sample C13			
Sample C14			
Sample C15			
Sample D1-20			
Sample D2-20			
Sample D3-20			

2) Sample for NH_4-N only if present in influent

Table 4-4. PILOT PLANT RESULTS

Utility name and address _____

_____

Utility ID number _____

Contact person _____

Contact phone number _____

Contact FAX number _____

GAC INFLUENT

Group A	alk	TH	CaH	NH_4-N	turb
Sample A1					
Sample A2					
Sample A3					
Sample A4					
Sample A5					
Sample A6					
Sample A7					
Sample A8					
Sample A9					
Sample A10					
Sample A11					
Sample A12					
Sample A13					
Sample A14					
Sample A15					
Sample D1-I					
Sample D2-I					
Sample D3-I					

Units: alk, TH, CaH- mg/L as $CaCO_3$; NH_4-N- mg/L; turb- ntu

GAC influent results comments _____

_____

_____

_____

PILOT PLANT RESULTS (page 2) Utility ID # _____

GAC INFLUENT

Group A	pH	temp.	Br	TOC	UV
Sample A1					
Sample A2					
Sample A3					
Sample A4					
Sample A5					
Sample A6					
Sample A7					
Sample A8					
Sample A9					
Sample A10					
Sample A11					
Sample A12					
Sample A13					
Sample A14					
Sample A15					
Sample D1-I					
Sample D2-I					
Sample D3-I					

Group A-SDS	Cl dose	Cl res.	CD	temp.	pH	H. time
Sample A1						
Sample A2						
Sample A3						
Sample A4						
Sample A5						
Sample A6						
Sample A7						
Sample A8						
Sample A9						
Sample A10						
Sample A11						
Sample A12						
Sample A13						
Sample A14						
Sample A15						
Sample D1-I						
Sample D2-I						
Sample D3-I						

Units: TOC, Cl dose, Cl res., CD- mg/L; UV- cm^{-1}; temp- °C; Br- µg/L; H. time- hrs

PILOT PLANT RESULTS (page 3) Utility ID # _____

GAC INFLUENT

Group A-SDS	TOX	THM4	$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$
Sample A1						
Sample A2						
Sample A3						
Sample A4						
Sample A5						
Sample A6						
Sample A7						
Sample A8						
Sample A9						
Sample A10						
Sample A11						
Sample A12						
Sample A13						
Sample A14						
Sample A15						
Sample D1-I						
Sample D2-I						
Sample D3-I						

Group A-SDS	HAA6	MCAA	DCAA	TCAA	MBAA	DBAA	BCAA	TBAA	CDBAA	DCBAA
Sample A1										
Sample A2										
Sample A3										
Sample A4										
Sample A5										
Sample A6										
Sample A7										
Sample A8										
Sample A9										
Sample A10										
Sample A11										
Sample A12										
Sample A13										
Sample A14										
Sample A15										
Sample D1-I										
Sample D2-I										
Sample D3-I										

Units: SDS- µg/L

PILOT PLANT RESULTS (page 4) Utility ID # _____

GAC EFFLUENT - EBCT= 10 min

Group B	NH_4-N^2	pH	turb.	temp.	TOC	UV
Sample B1						
Sample B2						
Sample B3						
Sample B4						
Sample B5						
Sample B6						
Sample B7						
Sample B8						
Sample B9						
Sample B10						
Sample B11						
Sample B12						
Sample B13						
Sample B14						
Sample B15						
Sample D1-10						
Sample D2-10						
Sample D3-10						
Group B-SDS	Cl dose	Cl res.	CD	temp.	pH	H. time
Sample B1						
Sample B2						
Sample B3						
Sample B4						
Sample B5						
Sample B6						
Sample B7						
Sample B8						
Sample B9						
Sample B10						
Sample B11						
Sample B12						
Sample B13						
Sample B14						
Sample B15						
Sample D1-10						
Sample D2-10						
Sample D3-10						

Units: NH_4-N, TOC, Cl dose, Cl res., CD- mg/L; turb- ntu; UV- cm^{-1};temp- °C;
H. time-hrs 2) Sample for NH_4-N only if present in influent

PILOT PLANT RESULTS (page 5) Utility ID # _____

GAC EFFLUENT - EBCT= 10 min

Group B-SDS	TOX	THM4	$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$
Sample B1						
Sample B2						
Sample B3						
Sample B4						
Sample B5						
Sample B6						
Sample B7						
Sample B8						
Sample B9						
Sample B10						
Sample B11						
Sample B12						
Sample B13						
Sample B14						
Sample B15						
Sample D1-10						
Sample D2-10						
Sample D3-10						

Group B-SDS	HAA6	MCAA	DCAA	TCAA	MBAA	DBAA	BCAA	TBAA	CDBAA	DCBAA
Sample B1										
Sample B2										
Sample B3										
Sample B4										
Sample B5										
Sample B6										
Sample B7										
Sample B8										
Sample B9										
Sample B10										
Sample B11										
Sample B12										
Sample B13										
Sample B14										
Sample B15										
Sample D1-10										
Sample D2-10										
Sample D3-10										

Units: SDS- µg/L

PILOT PLANT RESULTS (page 6) Utility ID # _____

GAC EFFLUENT - EBCT= 20 min

Group C	NH_4-N[2]	pH	turb.	temp.	TOC	UV
Sample C1						
Sample C2						
Sample C3						
Sample C4						
Sample C5						
Sample C6						
Sample C7						
Sample C8						
Sample C9						
Sample C10						
Sample C11						
Sample C12						
Sample C13						
Sample C14						
Sample C15						
Sample D1-20						
Sample D2-20						
Sample D3-20						
Group C-SDS	Cl dose	Cl res.	CD	temp.	pH	H. time
Sample C1						
Sample C2						
Sample C3						
Sample C4						
Sample C5						
Sample C6						
Sample C7						
Sample C8						
Sample C9						
Sample C10						
Sample C11						
Sample C12						
Sample C13						
Sample C14						
Sample C15						
Sample D1-20						
Sample D2-20						
Sample D3-20						

Units: NH_4-N, TOC, Cl dose, Cl res., CD- mg/L; turb- ntu; UV- cm^{-1};temp- °C;
H. time-hrs 2) Sample for NH_4-N only if present in influent

PILOT PLANT RESULTS (page 7) Utility ID # _____

GAC EFFLUENT - EBCT= 20 min

Group C-SDS	TOX	THM4	$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$
Sample C1						
Sample C2						
Sample C3						
Sample C4						
Sample C5						
Sample C6						
Sample C7						
Sample C8						
Sample C9						
Sample C10						
Sample C11						
Sample C12						
Sample C13						
Sample C14						
Sample C15						
Sample D1-20						
Sample D2-20						
Sample D3-20						

Group C-SDS	HAA6	MCAA	DCAA	TCAA	MBAA	DBAA	BCAA	TBAA	CDBAA	DCBAA
Sample C1										
Sample C2										
Sample C3										
Sample C4										
Sample C5										
Sample C6										
Sample C7										
Sample C8										
Sample C9										
Sample C10										
Sample C11										
Sample C12										
Sample C13										
Sample C14										
Sample C15										
Sample D1-20										
Sample D2-20										
Sample D3-20										

Units: SDS- µg/L

5.0 Bench-Scale GAC Test Protocol

5.1 Design

Scaling equations, which are used to design the RSSCT, have been developed based on dimensional analysis to maintain similitude to the full-scale GAC column (Frick, 1982; Crittenden, Berrigan, and Hand 1986; Crittenden et al. 1987, 1989 and 1991; Hineline, Crittenden, and Hand 1987). The critical RSSCT design parameters are the EBCT and the hydraulic loading rate or superficial velocity (v). Also of interest is the operation time (t). The scaling relationship is a function of the carbon particle size used in the small-(RSSCT) and large-(pilot or full) scale columns. The scaling factor (**SF**) can be defined as the ratio of particle diameters (**d**) of the large particle column (**LC**) to that of small particle column (**SC**)

$$\mathbf{SF = d_{LC}/d_{SC}} \qquad \mathbf{(5.1)}$$

The dependency of intraparticle diffusivity, as expressed by the diffusion coefficient (**D**), on particle size can be written as

$$\mathbf{D_{SC} = (d_{SC}/d_{LC})^{X} \cdot D_{LC} = SF^{-X} \cdot D_{LC}} \qquad \mathbf{(5.2)}$$

where **X** is the diffusivity factor. The RSSCT was originally developed with the assumption that intraparticle diffusivity did not change with particle size. Thus, the design equations were initially based on an assumption of constant diffusivity (CD), with X=0 in Equation 5.2.

A number of small column tests and batch kinetic tests have shown that the diffusion coefficient decreases proportionally with decreasing particle size and a proportional diffusivity (PD) design approach has been developed. In fact, several studies have shown a linear relationship between D and d, especially for NOM as measured by TOC and UV_{254}, (Benz, 1989; Summers and Crittenden, 1989; Crittenden et al., 1991; Summers et al., 1994a; 1995). This linear dependency is characterized by setting X=1 in Equation 5.2 and leads to the proportional diffusivity design approach. The EBCT and operation time of the RSSCT are both directly related to that of the large-scale column by the ratio of the small to large particle diameters, or the inverse of SF.

$$\mathbf{EBCT_{SC} = (d_{SC}/d_{LC}) \cdot EBCT_{LC} = EBCT_{LC}/SF} \qquad \mathbf{(5.3)}$$

$$\mathbf{t_{SC} = (d_{SC}/d_{LC}) \cdot t_{LC} = t_{LC}/SF} \qquad \mathbf{(5.4)}$$

The similitude velocity in the RSSCT, $\mathbf{v^*_{SC}}$, is also directly related to the velocity in the large-scale column by the scaling factor or the ratio of the large to small particle diameters.

$$\mathbf{v^*_{SC} = (d_{LC}/d_{SC}) \cdot v_{LC} = v_{LC} \cdot SF} \qquad \mathbf{(5.5)}$$

The design of a RSSCT based on Equations 5.3 and 5.5 will yield a RSSCT column with the same length as the large-scale column.

$$l_{SC} = v^*_{SC} \cdot EBCT_{SC} = (v_{LC} \cdot SF) \cdot (EBCT_{LC}/SF) \quad (5.6)$$

$$l_{SC} = v_{LC} \cdot EBCT_{LC} = l_{LC} \quad (5.7)$$

However, RSSCTs designed with such long lengths will likely produce excessive headloss and are difficult to operate at the bench-scale level.

To shorten the RSSCT length, the dominance of internal mass transfer over external mass transfer is utilized. The design velocity of the RSSCT, v_{SC}, can be reduced to a value below that of the similitude velocity as long as it is above the minimum velocity at which the RSSCT can be operated such that internal mass transfer still dominates. This minimum velocity is defined using the minimum Reynolds number, $Re_{SC,min}$, which ranges from 0.02 to 0.13, depending on the molecular weight of the compound (Crittenden et al. 1987). The lack of impact of Re_{SC} on the breakthrough curve is shown in Figure 5-1 (Summers et al. 1994a). The removal of natural organic matter, as measured by TOC, by a GAC column with full-scale GAC particles (12x40 mesh), a length of 1.2 m (3.9 ft), an EBCT of 10 minutes and Re_{LC} of 5 was modeled. Reducing the Reynolds number from 5 in the large-scale column to 0.05 in the RSSCT with a d_{SC} of 0.11 mm had very little impact on the modeled breakthrough curve.

Using a Re_{SC} in the RSSCT that is lower than that in the full-scale system allows for the use of a lower v_{SC} in the RSSCT. As shown in Equation 5.6, lower v_{SC} values will result in shorter columns and lower flow rates, both of which are desirable for bench-scale operation. The design equation for the RSSCT hydraulic loading thus becomes

$$v_{SC} = SF \cdot v_{LC} \cdot (Re_{SC,min}/Re_{LC}) \quad (5.8)$$

Values of $Re_{SC,min}$ ranging from 1.0 to 0.5 have been successfully used and are recommended. For the example modeled in Figure 5-1, the scaling factor yields a $EBCT_{SC}$ of 1.0 min. Using a $Re_{SC,min}$ of 0.5 in the RSSCT yields a v_{SC} of 7.2 m/hr, the same as that in the pilot column. A v_{SC} of 7.2 m/hr and an $EBCT_{SC}$ of 1.0 min produces a column depth of 12 cm (4.7 in.), as compared to 120 cm (47 in.) in the large-scale column or in the RSSCT if the similitude velocity, v^*_S, were used.

Based on the above discussion, it is recommended that the equations summarized in Table 5-1 be used for the RSSCT design when NOM is the target component. These equations are based on proportional diffusivity and have been found to yield results that are comparable to those of pilot- and full-scale systems (Table 2-1).

The two most commonly used sizes of GAC for drinking water treatment are the 8x30 and 12x40 US Std. mesh with apparent particle diameter (APD), d_{LC}, of 1.6 and 1.1 mm, respectively. The 8x30 mesh GAC is often used in filter adsorbers, while the 12x40 mesh

GAC is commonly used in post-filter adsorbers. The design of several RSSCTs based on these two large particle size GACs are shown in Tables 5-2 and 5-3. These tables show the $EBCT_{SC}$ and l_{SC} values needed in the RSSCT to yield designs that are the equivalent of 10 and 20 min full-scale EBCTS. Also shown in Tables 5-2 and 5-3 are the volumetric flow rate (Q_{SC}) and minimum volume of influent water required for the RSSCT (V_{SC}) for two RSSCT columns with inner column diameters (DC_{SC}) of 8.0 and 11.0 mm. These two column sizes with lengths that accommodate the RSSCT-GAC bed depths are commercially available.

The RSSCT designs shown in Tables 5-2 and 5-3 were generated using a proportional diffusivity design based on the equations in Table 5-1 with a $Re_{SC,min}$ of 0.5. A temperature of 20°C, which yields a kinematic viscosity of 1.0×10^{-6} m^2/s, and a porosity in the large-scale column of 0.45 were assumed. Since the performance of the RSSCT is not sensitive to the $Re_{SC,min}$, as shown in Figure 5-1, precise values for the viscosity and porosity are not needed for the calculation of v_{SC}.

For both the 8x30 and 12x40 mesh full-scale particles, RSSCTs have been designed with four different particle sizes, d_{SC}: 60x100 (200 μm), 100x200 (112 μm), 170x230 (76 μm) and 230x325 (54 μm) mesh size. Other particle sizes can be used in the RSSCTs, but previous runs have been made with d_{SC} values in this range. Smaller d_{SC} values will yield shorter run times, but may yield excessive headloss buildup, while larger d_{SC} values will yield longer run times. The operation (run) time of the RSSCT, t_{SC}, is dependent on the scaling factor and the run time in the large scale system, t_{LC}. For purposes of these designs a total operation time, t_{LC}^T, value of 180 days was assumed. A conservative t_{LC}^T value, longer than needed, should be chosen, as it sets the volume of water needed to run the RSSCT, V_{SC}, which is sampled prior to the start of the RSSCT. RSSCT operation times range from 6 to 23 days for the RSSCTs representing the 8x30 GAC and 9 to 33 days for that representing the 12x40 GAC.

Without any prior GAC adsorption experience with the water to be treated, it is difficult to estimate the length of a full-scale adsorber run, t_{LC}^T. One method to estimate t_{LC}^T and the required influent volume for the RSSCT, V_{SC}, is to use the correlation presented in Figure 2-3 (Equation 2.3). It relates the number of bed volumes to 50 percent TOC breakthrough, $\mathbf{BV_{50}}$, to the influent TOC concentration, $\mathbf{TOC_0}$, for bituminous coal based GACs. This relationship can be expressed by the following equation:

$$\mathbf{BV_{50} = 21{,}700 \cdot TOC_0^{-1.3}} \qquad \mathbf{(5.9)}$$

The time in days to 50 percent TOC breakthrough, $\mathbf{t_{50}}$, for the large-scale column can be estimated by the following equation for an EBCT in minutes :

$$\mathbf{t_{50} = BV_{50} \cdot EBCT_{LC}/1440} \qquad \mathbf{(5.10)}$$

where BV_{50} is calculated by Equation 5.9. If the total operation time is defined as the time to achieve greater than 75% breakthrough or reach a pseudo-steady-state plateau, then it can be estimated as twice that of t_{50}.

$$t_{LC}^{T} = 2 \cdot t_{50} \qquad (5.11)$$

The required influent volume for the RSSCT can be estimated from BV_{50} assuming that the total volume required is twice the volume to 50% breakthrough:

$$V_{SC} = 2 \cdot BV_{50} \cdot EBCT_{LC} \cdot Q_{SC}/SF = Q_{SC} \cdot t_{LC}^{T}/SF = Q_{SC} \cdot t_{SC}^{T} \qquad (5.12)$$

The volume actually taken for the RSSCT influent should be at least 30 percent larger than this value to allow for influent sampling and as precautionary measure due to the heterogeneous nature of the adsorption of NOM. If a nonbituminious coal based GAC is to be used, then use Equations 5.9 through 5.12 and multiple V_{SC} by a factor of 2 to yield the volume of water taken for the RSSCT influent. This will very likely be a very conservative, more volume than needed, value.

As shown by Equation 5.9 and Figure 2-3, higher influent TOC values lead to earlier breakthrough. Very early breakthrough can lead to a situation where the total effluent volume treated is less than the volume of water needed for the analyses required to monitor the RSSCT breakthrough. To insure that an adequate sample volume is present in the effluent, it is recommended that a RSSCT column with a DC_{SC} of 11 mm or greater be used for waters with a GAC influent TOC value greater than 4 mg/L or for waters with a high level of poorly adsorbing NOM.

The RSSCT designs outlined in Tables 5-2 and 5-3 are not inclusive of all acceptable designs, but are intended to represent the experience gathered to-date with RSSCTs and natural organic matter removal (Table 2-1). However, the proportional diffusivity design equations shown in Table 5-1 should be used.

A schematic of the equipment configuration for the RSSCT is shown in Figure 5-2. All components of the bench-scale system shall be of glass, Teflon or stainless steel construction. One-quarter inch Teflon tubing, rated for appropriate system pressures, should be used throughout the system. A positive displacement feed pump with controls for stroke frequency and stroke volume should be used. It is very important that the pump for the system be selected based on the appropriate system pressures and flow rates. It is recommended that one pump be used for each RSSCT (10 and 20 min EBCT) when operated in parallel. To dampen the pulse created during pumping with a positive displacement feed pump, a 0.5 L stainless steel air-tight container (pulse dampener) is placed at the top of the system. A gas sample cylinder is well-suited for this purpose. During start-up of the RSSCT this container is not filled with water and the compressibility of the air in the container serves to dampen the pulsing action of the pump.

The batch of RSSCT influent water should be prefiltered with membrane or cartridge filters with nominal pore openings of about 1.0 μm. This will reduce the buildup of excessive headloss during the RSSCT run. The membrane or cartridge filters should be thoroughly flushed with low organic content water and the TOC of the filter effluent should be measured to ensure that no TOC is being leached from the membrane or filter. As a

precautionary step, an optional column containing a filter media, e.g. glass beads, can be used as a pre-filter, as shown in Figure 5-2, to eliminate excessive headloss build-up in the carbon columns.

Typically, glass columns with inner diameters (ID) of 4 to 15 mm are used. Standard chromatography columns with IDs of 8 to 15 mm are available. One-quarter inch outer diameter glass tubes with 4 mm ID have also been used, but are not recommended due to excessive pressure build-up. The ratio of column inner diameter to carbon diameter should be 25 or greater. Multiple columns used in parallel (not shown) should each be equipped with a flow control valve to accommodate flow rate adjustments for the individual columns. In addition, the influent line to each column should have a shut-off valve, to prevent flow interruptions to the other columns in case a column needs to be taken off-line during operation.

Series operation of RSSCTs cannot be used as the sample volume requirements of the intermediate sample point, EBCT = 10 min, are so large that they significantly affect the breakthrough and the volume of water treated by the second column.

Before the column is packed with the GAC, a series of three stainless steel screens, coarse, fine and coarse, should be placed at the bottom of the inside of the column as shown in Figure 5-2. The screens serve to contain the carbon in the column. The fine screen should have openings that are smaller than the smallest carbon particles. The coarse screens have openings that are only slightly larger. For example, for 60x100 GAC, 60 mesh screens are used for the coarse screens and a 200-mesh screen is used for the fine screen. A depth of 1 to 2 cm of glass beads, which have a larger mesh size than the fine screen but a smaller mesh size than the carbon, can be used to replace the top coarse screen. Glass wool has also been used in place of the glass beads, although its use may cause a faster headloss buildup. The glass beads, or glass wool, serve as an additional support for the carbon bed. An additional screen, with a mesh size smaller than the carbon, should be placed on top of the glass beads or glass wool. Care should be taken in handling the screens, glass beads and especially the glass wool if used. They should all be thoroughly cleaned prior to use, so that no detectable organic carbon leaches from them..

A flow control valve should be placed after the RSSCT column, except when a positive displacement pump is used, in which case a flow restricter should be used at this point. In either case, by controlling or restricting the flow at this point, the columns will always remain under positive pressure during the run. This prevents the buildup of air pockets in the column. The effluent line should break to the atmosphere at a level higher than the top of the GAC bed, as shown in Figure 5-2. This will prevent the water level from falling below the top of the GAC bed if flow to the columns stops and siphoning occurs. In addition, the influent line should be airtight and securely attached to the reservoir to prevent pumping air into the columns.

The granular activated carbon selected for use in the RSSCT must meet the AWWA Standard for Granular Activated Carbon ANSI/AWWA B604-90 (Appendix 2-C). This standard covers the sampling and characterization of the GAC.

A representative sample of the carbon is taken from the carbon stock, as discussed in Section 4.0 and Appendix 2-A. This sample is ground to an appropriate mesh size for the RSSCT. It is very important that all of the carbon sample be ground such that the entire amount passes the upper sieve of the desired mesh size range. Not grinding the entire amount of GAC sample so that it to passes the upper screen size may lead to a ground GAC sample which has a higher adsorption capacity than the unground full-scale GAC. The use of very small sized carbon, 400 mesh (< 0.038 μm), leads to excessive headloss in the column. Typical mesh sizes used in RSSCTs are 60 x 100 (200 μm APD), 100 x 200 (112 μm APD) and 170 x 230 (76 μm APD). Smaller particles sizes, such as 200 x 325 (60 μm APD), 230 x 325 (54 μm APD) or 200 x 400 (57 μm APD) mesh sizes, can be used if the system is designed for high pressures ($>$ 50 psi).

After sieving, the ground carbon should be washed with purified water. Deaerated, low organic concentration, distilled water, termed laboratory clean water (LCW), should be used. Step-wise decantation in a beaker can be used to wash the carbon. Pour the wash water over the ground GAC, stir the slurry until the GAC is wet, allow the GAC to settle for 1 to 2 minutes and then decant. The amount of washing depends on the carbon-to-wash vessel volume ratio. For ratios of 0.1 or less, 50 to 100 decantations may be necessary. Care should be taken to *thoroughly* wash the carbon to avoid headloss buildup in the column caused by fines. An ultrasonic bath may be cautiously used to better remove the carbon fines. The carbon can be placed in a beaker filled with low organic content water and sonicated for 10 seconds at a low setting followed by decantation. This process can be repeated once followed by step-wise decantation until all fines are removed. Excessive sonication of the carbon will result in the formation of additional fines and must be avoided. After washing, the ground carbon is dried overnight to a constant weight at a temperature of 80°C. The temperature should be increased to 100°C for 4 hours. The carbon is then weighed again and if the weight is more than 5% different than the previous weight, then drying at 100°C should be continued to a constant weight. High temperature drying leads to the formation of additional fines. The dried carbon is then transferred to a clean bottle, capped and stored in a desiccator until ready for use.

5.2 Operation

The bed density of the ground GAC should be assessed by measuring the dry weight of ground GAC per unit bed volume. This can be done by precisely weighing about 2 grams of ground GAC and adding it to a 5 ml or 10 ml calibrated graduated cylinder and determining the bed volume of GAC. The calibration of the graduated cylinder should be verified using a precise volume from a suitable pipet. If the volume measurements differ by 5% or greater, the graduated cylinder should be recalibrated. The cylinder should be vibrated or tapped by hand to allow the ground GAC to compact. The bed density, ρ_{SC}, is the GAC (dry) weight divided by the GAC bed volume.

An appropriate mass of dried carbon, m_{SC}, is calculated based on the RSSCT column diameter, DC_{SC}, required bed depth, l_{SC}, and on the ground GAC bed density.

$$m_{SC} = l_{SC} \cdot \rho_{SC} \cdot [\pi (DC_{SC})^2/4] \qquad (5.13)$$

After weighing this carbon mass, the carbon is 'prewetted' by placing it into an Erlenmeyer flask and adding LCW to a level of about one inch over the carbon surface. The ground GAC is then deaerated by applying a vacuum for at least 15 minutes. The vacuum will help speed up the removal of air which may be trapped inside the pores of the carbon particles. Removing the trapped air prior to the column operation will prevent diffusion hindrance of the inward diffusing organic adsorbate. The carbon is easier to deaerate if it is allowed to sit overnight, 16 to 24 hr, in LCW, prior to deaeration.

After deaeration remove the excess LCW, so that a ground GAC slurry exists that can be transferred into the column with a laboratory spatula. The prewetted and deaerated carbon is then packed into the column as a slurry. The column should be first filled with LCW to a level of 25% of the GAC bed depth. The column should be tapped, very gently, during the addition of the GAC slurry to pack the carbon particles as the column is filled. The carbon bed should be completely submerged during and after the packing process. LCW should be used during the packing and testing of the columns. The integrity of the RSSCT system should be tested for leaks, air pockets or immediate headloss buildup with LCW by opening the appropriate valves and feed the LCW to the system for about 10 minutes. Resolve any problems that are identified. A plastic safety shield should be used around all glass GAC columns.

The reservoir is then filled with the water to be evaluated. The columns are disconnected from the feed system and the feed system from the reservoir to the carbon columns is purged of air and the LCW with the feed solution. The column(s) are placed into position and the flow rate adjusted to the desired level. The flow rate should be maintained to within 5% of that needed to produce the equivalent of the 10- and 20- min full-scale EBCT. Flow rates should be checked at least twice a day and adjusted to within this tolerance. Unusually long periods of no flow to the columns (longer than 0.5 hour per day) should be accounted for by not including it in the cumulative operation time. Therefore, operation time may be shorter than clock time.

The first 20 minutes of flow should be wasted, and the first sample should be taken after 1.0 hour. Samples are taken as specified in the next section, and flow and pressure measurements are recorded at regular intervals. During operation, the pressure should be closely monitored. Significant increases suggest a need to change to a clean filter and/or drain the dampener which becomes less effective as it accumulates a large amount of water. In severe cases of pressure build-up, the RSSCT column may be taken off-line and the top 0.5 cm of the GAC bed stirred to break apart large lumps that form and are responsible for excessive headloss.

5.3 Sampling

A wide range of breakthrough behavior like that shown in Figure 4-2 is expected for GAC columns with EBCTs in the 10 to 20 min range. This range of adsorption behavior coupled with the short RSSCT run times makes sampling the RSSCT column effluent even more difficult than that for the pilot column. Figure 5-3 depicts a sampling scenario which will meet the sample frequency requirements listed in Table 5-0.

The first step is to sample a batch of water that is to be used as the influent to the RSSCT. Section 3.0 discusses sample point location and pretreatment. It is imperative that an adequate volume and a representative sample of the water to be GAC treated be taken. Minimum required volumes for the RSSCT are listed in Tables 5-2 and 5-3 for an anticipated full-scale run time of 180 days. Longer run times may occur, especially for low TOC (< 3 mg/L) or low pH (< 7.3) influent waters at a 20 min EBCT. Thus, larger volumes of water should be gathered for conditions which will lead to long run times.

For bituminous coal based-GAC and pH values above 7.3, Equation 5.12 can be used to estimate V_{SC}. The volume actually taken for the RSSCT influent should be at least 30 percent larger than this value to allow for influent sampling and as precautionary measure due to the heterogeneous nature of the adsorption of NOM. Only one batch of influent water per run is gathered so its representativeness is critical to the success of the RSSCT in evaluating field-scale performance.

The two approaches for operation of the required two RSSCTs, 10 and 20 minute equivalent EBCTs, are parallel and sequential operation. In parallel operation both columns are run at the same time and the influent batch of water must be of sufficient volume to satisfy both columns. In sequential operation one RSSCT is run and sampled first, followed by the other RSSCT. This requires two batches of influent water, each of which needs to be checked for representativeness and to be sampled during operation according to Table 5-0. As stated earlier, series operation of two columns with EBCTs of 10 min cannot be used due to sampling limitations.

Prior to the operation of the RSSCT, the water quality of the batch influent water should be immediately evaluated on-site for TOC, UV_{254}, pH, alkalinity, hardness (total and calcium), ammonia and bromide. The intent of this preliminary water quality evaluation is to quickly ascertain the representativeness of this water without waiting for off-site laboratory analysis. The representativeness of this water should be confirmed by comparison with previous water quality data. In many cases, UV_{254} and bromide analyses cannot be conducted on-site, in which case they should not be used as a check of representativeness. Once the representativeness of this water has been confirmed, the water should be prefiltered with a membrane or cartridge filter, as described in Section 5.2. If possible this batch of GAC influent water should be stored at 4°C. If this is not possible then the water should be stored at the lowest possible temperature. In all cases an aliquot of the stored water should be brought to laboratory room temperature prior to use for the RSSCT. The aliquot should be of sufficient volume to last for one or two days as the RSSCT influent. Depending on the

temperature of storage and aliquot volulme, it can take several hours to bring the water to room temperature. Furthermore, as the pH of the batch influent water may change during storage, the influent pH of each aliquot should be measured and adjusted if necessary. For some waters, it may be necessary to readjust the pH of the aliquot as it is used.

Sampling is described in Table 5-0 and in the following paragraphs. A minimum of two samples for alkalinity, total and calcium hardness, ammonia and bromide should be taken from the batch influent to the RSSCT; one at the startup and one midway through the run. A minimum of three samples for pH, temperature, TOC, UV_{254} and SDS for THMs, HAA6, TOX, and chlorine demand should be taken from the batch influent to the RSSCT: one at the start-up, one midway through the run and one at the end. A minimum of 12 effluent samples and three duplicate effluent samples at both 10 and 20 min full-scale equivalent EBCTs are required.

Effluent samples should be taken after the first hour and then at 5% to 8% increments of the average influent TOC. The average influent TOC is defined as the running average of the influent TOC at the time of sampling. This approach requires a very quick turn around time for TOC analysis. The intent is to yield a good assessment of the breakthrough with a minimum number of samples. More frequent effluent monitoring for TOC may be necessary in order to sample for the other analytes at the 5% to 8% increment of the average influent TOC.

Three duplicate samples of the RSSCT effluent should be taken at different times on the breakthrough curve. One should be taken with the third or fourth sample, one with the seventh or eighth sample and one with the tenth or eleventh sample. Because of the unsteady state nature of GAC adsorption, i.e., the effluent concentration increases with operation time, the duplicate sample, if taken after the normal sample, may yield different results, as the time to collect a sample can be quite long. To overcome this problem, a sample volume sufficiently large to satisfy both the normal and duplicate sample should be collected in one container and then split in two samples.

The breakthrough of UV_{254} often parallels that of TOC and may be used to estimate the sampling times. However, UV-absorbing substances are normally better removed by GAC and their breakthrough lags behind that of TOC. Thus, the relationship between UV_{254} and TOC in the GAC effluent needs to be established. This requires the use of TOC and UV_{254} data from a previous GAC run. Thus, if this monitoring approach is to be used, prior experience with GAC treatment of the site-specific water is needed.

If on-site TOC analysis or if a fast turn-around of TOC measurement results is not available, a sampling plan may be estimated by the following procedure. The time in days to 50 percent TOC breakthrough, t_{50}, for the large-scale column can be estimated by Equation 5.10 for an EBCT in minutes. Based on the shape of previous TOC breakthrough curves a 1-7-3-1 sample plan is recommended for the 12 effluent samples. The <u>first</u> sample is taken after one hour of RSSCT operation, <u>seven</u> additional samples are taken at regular time intervals through the 50 percent breakthrough, <u>three</u> samples are taken at regular time

intervals after 50 percent breakthrough and one sample is taken at the end of the run. The sample time interval in large scale operation days, t_{int}, for the first half of the TOC breakthrough can be estimated from the following:

$$t_{int} = t_{50}/7 \qquad (5.14)$$

Since TOC breakthrough curves are not symmetrical and tend to have a lower slope after 50 percent breakthrough, the sample time interval after 50 percent breakthrough should be estimated as 50 percent longer than t_{int} $(1.5 \cdot t_{int})$.

Table 5-4 presents a general sample plan and sample plans for ten examples with TOC_0 values of 2, 2.5, 3, 4 and 6 mg/L and $EBCT_{LC}$s of 10 and 20 minutes. To calculate the actual sample times for the RSSCT the sample time values (scaled days) in Table 5-4 are divided by the scaling factor for the specific RSSCT. The exception is the first sample, which is sampled after one hour of RSSCT operation for all cases. Figure 2-3 and Equations 5.9, 5.10 and 5.14 are utilized in this method of estimating a sample plan. This approach is based on a data set limited to 17 water sources and one general GAC type, and may not be valid in all cases. Based on the work of Hooper et al. (1995), for a given TOC if the pH value of the water to be treated is 7.0 or below, then the BV_{50} value may be 10 to 40 percent higher than that calculated by Equation 5.9.

It is strongly suggested that on-site TOC or fast turn-around TOC measurement be used whenever possible to characterize the breakthrough and accurately determine the sample times.

§ 141.144(b)(1)(i) of the ICR Rule states that both the 10 and 20 minute EBCT RSSCTs shall be run until (a) the effluent TOC concentration is 70% of the average influent TOC concentration on two consecutive sample dates that are at least two full-scale equivalent weeks apart, or (b) after 50% breakthrough a plateau is reached in which the effluent concentration does not increase over a two full-scale equivalent month period by more than 10% of the average influent. In all cases, the maximum run length is one full-scale equivalent year.

RSSCTs at both EBCTs shall be conducted quarterly over one year in order to capture the seasonal variation in water quality and adsorption behavior. Thus, a total of four RSSCTs at each EBCT are required. If after completion of the first quarter RSSCTs it is found that the effluent TOC reaches 70% of the average influent TOC within 20 full-scale equivalent days on the EBCT = 10 min test or within 30 full-scale equivalent days on the EBCT = 20 min test, then the last three quarterly tests shall be conducted using bench-scale testing with only one membrane, as described in Part 3 of this manual.

Based on the information used to generate Figure 2-3 it is anticipated that waters that have both TOC values above 6 mg/L and pH values above 7 in the GAC influent will have very early breakthrough and yield times to 70% breakthrough below those limiting values discussed above. Thus, it is recommended that utilities with treated water TOC values above 6 mg/L evaluate optimized pretreatment processes prior to GAC as described in Section 1.0

or run treatment studies with membranes, as described in Part 3.0, instead of GAC. Waters with low pH, less than 7, may yield longer 70% breakthrough times and thus, low pH waters with TOC values in the 6 to 8 mg/L range may yield acceptable breakthrough times.

The RSSCT design parameters, sampling times and results should be reported in accordance with Tables 5-5 through 5-9. Samples should be taken according to the procedures described in the "ICR Sampling Manual" (EPA 814-B-96-001). The approved analytical methods for the analytes listed in Table 5-0 are listed in Table 7 § 141.142 of the ICR Rule. These methods and laboratory QA/QC plans are described in "DBP/ICR Analytical Methods Manual" and must be used by all systems conducting treatment studies. Guidance for the simulated distribution system (SDS) test and the chlorine demand test are given in Section 6.0 of this document.

5.4 Design Example

To illustrate the design of an RSSCT the following example is provided. The design equations are provided in Table 5-1 and in Sections 5.1 and 5.2.

Example Problem: Design a RSSCT with a 20 minute EBCT for a water with a GAC influent TOC concentration of 3.0 mg/L.

1) Assume that the GAC column will be placed after a conventional filter; termed post-filter GAC contactor. Therefore, a 12x40 mesh GAC (d_{LC} = 1.1 mm) will likely be utilized.

2) A 100x200 mesh GAC (d_{SC} = 0.112 mm) is selected for use in the RSSCT. This particle size has been widely used and is large enough not to cause problems with excessive pressure build-up and small enough to yield short RSSCT run times. Using Equation 5.1, this combination of particle sizes yields the following SF

$$SF = d_{LC}/d_{SC} = 1.1 \text{ mm} / 0.112 \text{ mm} = 9.82$$

3) The EBCT of the RSSCT can be calculated using Equation 5.3

$$EBCT_{SC} = EBCT_{LC}/SF = 20 \text{ min}/9.82 = 2.04 \text{ min}$$

4) Assuming a $Re_{SC,min}$ of 0.5, a bed porosity of 0.45 and a temperature of 20°C, which yields a kinematic viscosity of $1.0 \cdot 10^{-6}$ m^2/s, Equation 5.8 in the form presented in Table 5-1, yields the following v_{SC},

$$\begin{aligned} v_{SC} &= SF \cdot v_{LC} \cdot (Re_{SC,min}/Re_{LC}) = Re_{SC,min} \cdot \nu_{LC} \cdot \epsilon_{LC}/d_{SC} \\ &= 0.5 \cdot 1 \cdot 10^{-6} (m^2/s) \cdot 0.45 / 0.112 \text{ (mm)} \cdot 1 \cdot 10^3 \text{ (mm/m)} \\ &= 0.00201 \text{ m/s} = 0.120 \text{ m/min} = 12.0 \text{ cm/min} \\ &= 7.23 \text{ m/h} \end{aligned}$$

5) The length of the RSSCT bed can be calculated from

$$l_{SC} = v_{SC} \cdot EBCT_{SC} = 0.120 \text{ m/min} \cdot 2.04 \text{ min} = 0.245 \text{ m}$$
$$= 24.5 \text{ cm}$$

6) Assuming a RSSCT column with an inner diameter of 8.0 mm (0.8 cm), yields the following flow rate, Q_{SC},

$$Q_{SC} = v_{SC} \cdot \pi \cdot (DC_{SC})^2/4 = 12.0 \text{ cm/min} \cdot \pi \cdot (0.8 \text{ cm})^2/4$$
$$= 6.06 \text{ cm}^3\text{/min}$$
$$= 6.06 \text{ ml/min}$$

7) The mass of GAC needed for the RSSCT can be calculated with Equation 5.13 once the density of the 100x200 mesh GAC has been calculated, as described in Section 5.2. A typical value of ρ_{SC} is 0.5 g/cm^3,

$$m_{SC} = l_{SC} \cdot \rho_{SC} \cdot [\pi(DC_{SC})^2/4]$$
$$= 24.5 \text{ cm} \cdot 0.5 \text{ g/cm}^3 \cdot [\pi(0.8 \text{ cm})^2/4]$$
$$= 6.16 \text{ g}$$

8) To calculate the total run time of the RSSCT, use Equations 5.9 (valid for bituminous coal based GACs) and 5.10 and the influent TOC to yield the bed volumes and time to 50% breakthrough,

$$BV_{50} = 21{,}700 \cdot TOC_0^{-1.3} = 21{,}700 \cdot 3.0^{-1.3}$$
$$= 5200 \text{ bed volumes}$$

$$t_{50} = BV_{50} \cdot EBCT_{LC}/1440 = 5200 \cdot 20 \text{ min } /1440$$
$$= 72.2 \text{ days}$$

Assuming that the total run time is twice that to 50% breakthrough (Equation 5.11) yields

$$t_{LC}^T = 2 \cdot t_{50} = 2 \cdot 72.2 \text{ days}$$
$$= 144 \text{ days}$$

and using Equation 5.4 the RSSCT run time is

$$t_{SC}^T = t_{LC}^T/SF = 144 \text{ days} / 9.82$$
$$= 14.7 \text{ days}$$

9) The minimum volume of influent water needed for the RSSCT can be calculated from Equation 5.12

$$V_{SC} = Q_{SC} \cdot t_{SC}^T = 6.06 \text{ ml/min} \cdot 14.7 \text{ days} \cdot 1440 \text{ min/day}$$
$$= 128{,}000 \text{ ml}$$
$$= 128 \text{ L}$$

The volume actually sampled should be at least 30% larger than V_{SC},

$$\text{Total GAC influent volume} = 1.3 \cdot V_{SC} = 1.3 \cdot 128 \text{ L} = 166 \text{ L}$$

A summary of the design for this example is provided below, as are the design values for a RSSCT with a 10 min EBCT (same influent TOC, 3 mg/L; particle size, d_{SC} = 0.112 mm; and column diameter, DC_{SC} = 0.8 cm, as the 20 minute EBCT system).

Parameter	EBCT=20 min	EBCT=10 min
SF	9.82	9.82
$EBCT_{SC}$, min	2.04	1.02
v_{SC}, m/h	7.23	7.23
l_{SC}, cm	24.5	12.3
Q_{SC}, ml/min	6.06	6.06
m_{SC}, g	6.16	3.08
BV_{50}, bed volumes	5200	5200
t_{50}, days	72.2	36.1
t_{LC}^{T}, days	144	72.2
t_{SC}^{T}, days	14.7	7.4
V_{SC}, L	128	64
Total influent volume, L	166	84

The sampling times can be estimated from Table 5-4 for a bituminous coal based GAC.

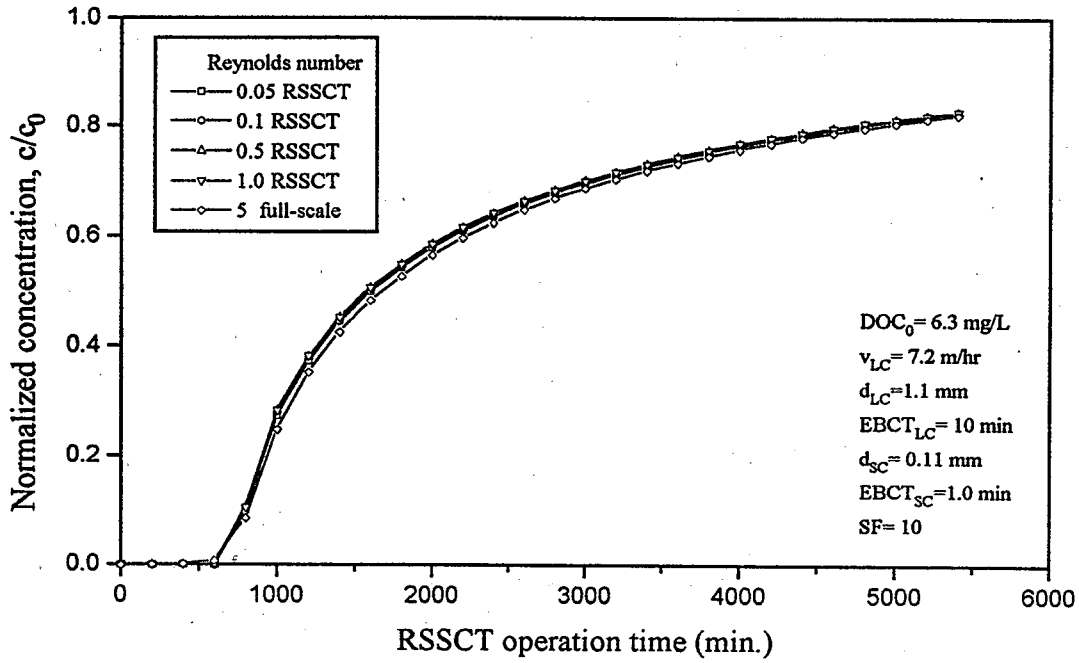

Figure 5-1. Impact of Reynolds number on breakthrough

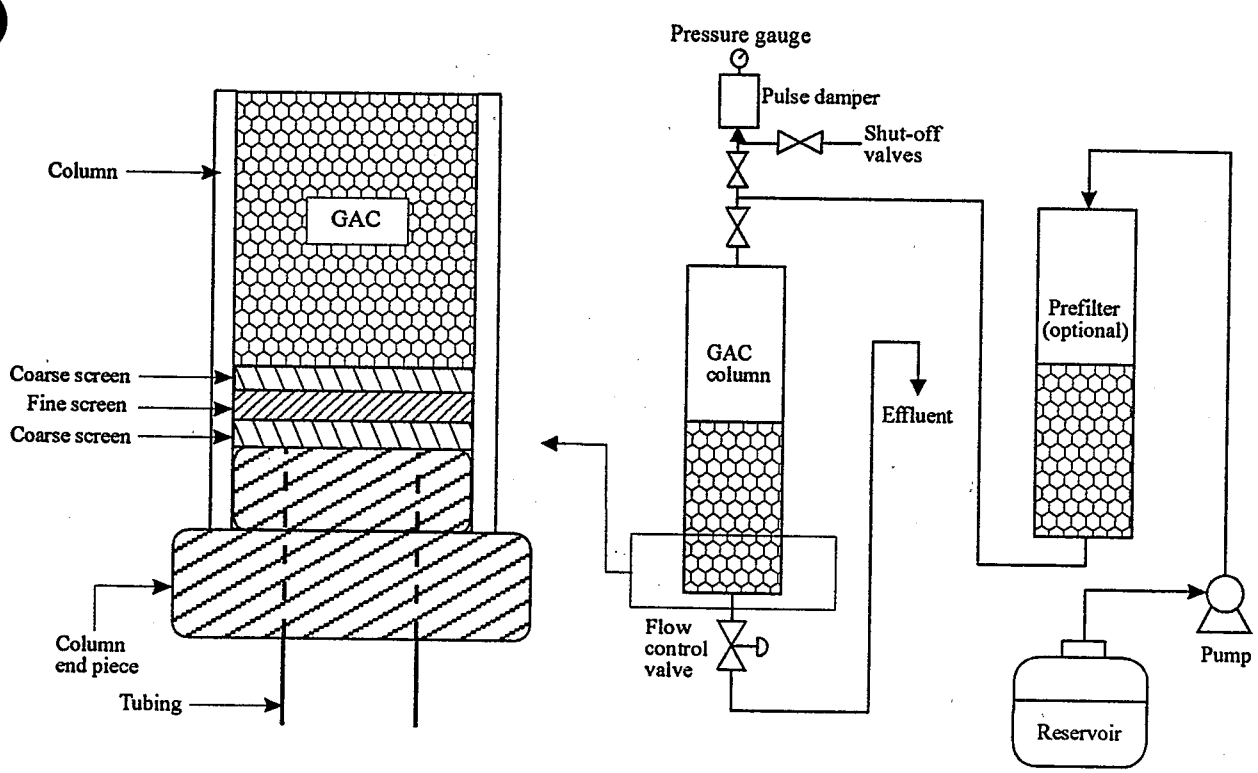

Figure 5-2 RSSCT set-up

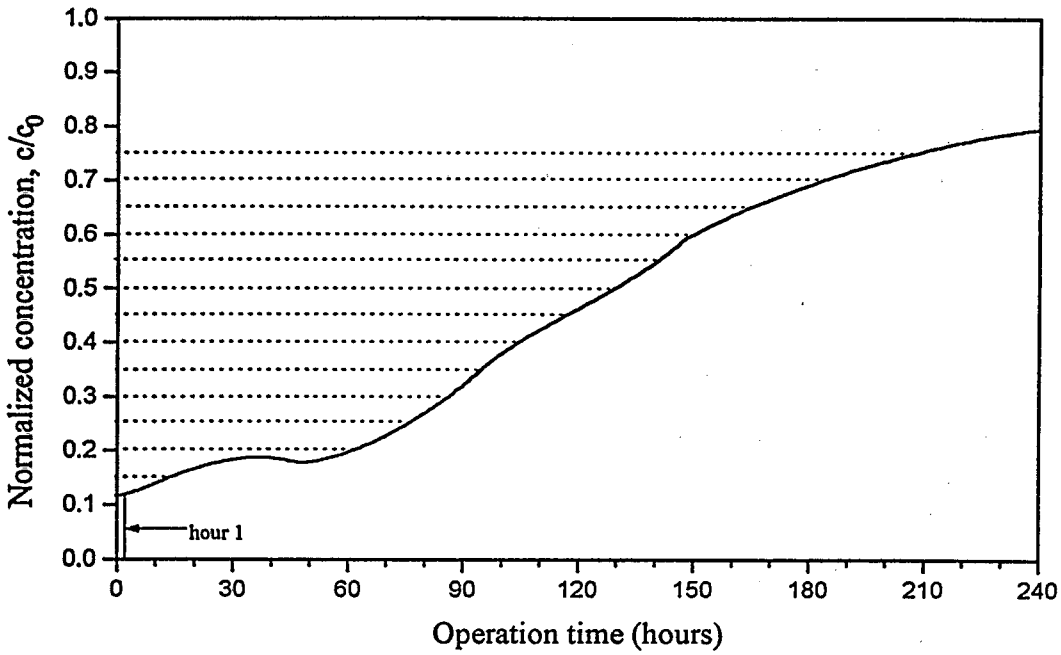

Figure 5-3 RSSCT breakthrough and sampling

Table 5-0. Sampling of GAC Bench-scale Systems

Sampling Point	Analyses	Sample Frequency[2]
GAC Influent	Alkalinity, total & calcium hardness, ammonia and bromide.	Two samples per batch of influent evenly spaced over the RSSCT run.
GAC Influent	pH, turbidity, temperature, TOC and UV_{254}. SDS[1] for THM4, HAA6, TOX, and chlorine demand.	Three samples per batch of influent evenly spaced over the RSSCT run.
GAC Effluent @ EBCT=10 min (scaled)	pH, temperature, TOC and UV_{254}. SDS[1] for THM4, HAA6, TOX, and chlorine demand.	A minimum of 12 samples. One after one hour, and thereafter at 5% to 8% increments of the average influent TOC.
GAC Effluent @ EBCT=20 min (scaled)	pH, temperature, TOC and UV_{254}. SDS[1] for THM4, HAA6, TOX, and chlorine demand.	A minimum of 12 samples. One after one hour, and thereafter at 5% to 8% increments of the average influent TOC.

1 - SDS conditions are defined in Part 1, Section 4.6 of this document. Additional guidance is found in Section 6.0 of this Part.

2 - Three duplicate effluent samples are required at each EBCT.

Table 5-1. RSSCT proportional diffusivity (X=1) design equations

$$SF = \frac{d_{LC}}{d_{SC}}$$

$$D_{SC} = \left(\frac{d_{SC}}{d_{LC}}\right) D_{LC} = \frac{D_{LC}}{SF}$$

$$EBCT = \frac{\text{bed volume}}{\text{flowrate}} = \frac{\text{bed depth}}{\text{velocity}} = \frac{1}{v}$$

$$v = \frac{\text{flowrate}}{\text{cross sectional area}} = \frac{Q}{\pi DC^2 / 4}$$

$$EBCT_{SC} = \left(\frac{d_{SC}}{d_{LC}}\right) EBCT_{LC} = \frac{EBCT_{LC}}{SF}$$

$$t_{SC} = \left(\frac{d_{SC}}{d_{LC}}\right) t_{LC} = \frac{t_{LC}}{SF}$$

$$v_{SC} = \left(\frac{d_{LC}}{d_{SC}}\right) v_{LC} \left(\frac{Re_{SC,min}}{Re_{LC}}\right) = \frac{Re_{SC,min}\, \upsilon_{LC} \varepsilon_{LC}}{d_{SC}}$$

$$Re = \frac{dv}{\upsilon \varepsilon}$$

$$\upsilon = \frac{\mu}{\rho_w}$$

$$l_{SC} = v_{SC} EBCT_{SC}$$

$$Q_{SC} = v_{SC} \frac{\pi (DC_{SC})^2}{4}$$

$$V_{SC} = Q_{SC} t_{SC}^{T}$$

Notation:

d= particle diameter (L)
D= intrapaticle diffusion coefficient (L^2/T)
DC= column diameter (L)
EBCT= empty bed contact time (T)
l= bed depth (L)
Q= volumetric flowrate (L^3/T)
Re= Reynolds number (-)
SF= scaling factor (-)
t= run time (T)
v= hydraulic loading or superficial velocity (L/T)
V= minimum required water volume (L^3)
ε= bed porosity (-)
μ= dynamic viscosity (M/L·T)
ρ_w= density of water (M/L^3)
υ= kinematic viscosity (L^2/T)

Subscripts:

LC= large particle column
SC= small particle column

Superscript:

T: total

Table 5-2. RSSCT design for full-scale 8x30 mesh GAC (d_{LC}= 1.6 mm)

mesh size (US std.)	60x100	100x200	170x230	230x325
d_{SC} (mm)	0.200	0.112	0.076	0.054
SF(-)	8.00	14.3	21.0	29.6
v_{SC} (m/h)	4.05	7.23	10.7	15.0
t_{SC} (days)[1]	22.5	12.6	8.55	6.08
$EBCT_{LC}$= 10 min				
$EBCT_{SC}$(min)	1.25	0.70	0.48	0.34
l_{SC} (mm)	84.4	84.4	84.4	84.4
$EBCT_{LC}$= 20 min				
$EBCT_{SC}$ (min)	2.50	1.40	0.95	0.68
l_{SC} (mm)	169	169	169	169
DC_{SC}= 8.0 mm				
Q_{SC} (ml/min)	3.39	6.06	8.93	12.6
V_{SC} (liters)[1]	110	110	110	110
DC_{SC}= 11.0 mm				
Q_{SC} (ml/min)	6.41	11.5	16.9	23.8
V_{SC} (liters)[1]	208	208	208	208

Assumptions: $Re_{SC,\,min}$= 0.5, υ_{LC}= 1.0x10^{-6} m^2/s (T= 20°C), ε_{LC}= 0.45
1) t_{LC}= 180 days

Table 5-3. RSSCT design for full-scale 12x40 mesh GAC (d_{LC}= 1.1 mm)

mesh size (US std.)	60x100	100x200	170x230	230x325
d_{SC} (mm)	0.200	0.112	0.076	0.054
SF (-)	5.50	9.82	14.5	20.4
v_{SC} (m/h)	4.05	7.23	10.7	15.0
t_{SC} (days)[1]	32.7	18.3	12.4	8.84
$EBCT_{LC}$= 10 min				
$EBCT_{SC}$ (min)	1.82	1.02	0.69	0.49
l_{SC} (mm)	123	123	123	123
$EBCT_{LC}$= 20 min				
$EBCT_{SC}$ (min)	3.64	2.04	1.38	0.98
l_{SC} (mm)	245	245	245	245
DC_{SC}= 8.0 mm				
Q_{SC} (ml/min)	3.39	6.06	8.93	12.6
V_{SC} (liters)[1]	160	160	160	160
DC_{SC}= 11.0 mm				
Q_{SC} (ml/min)	6.41	11.5	16.9	23.8
V_{SC} (liters)[1]	302	302	302	302

Assumptions: $Re_{SC,min}$= 0.5, υ_{LC}= 1.0x10^{-6} m^2/s (T= 20°C), ε_{LC}= 0.45
1) t_{LC}= 180 days

Table 5-4 Estimated sample times for RSSCT operation

Sample number†	Sample time	SAMPLE TIME (SCALED DAYS)*									
		TOC = 2.0 mg/L		TOC = 2.5 mg/L		TOC = 3.0 mg/L		TOC = 4.0 mg/L		TOC = 6.0 mg/L	
		EBCT = 10 min	EBCT = 20 min	EBCT = 10 min	EBCT = 20 min	EBCT = 10 min	EBCT = 20 min	EBCT = 10 min	EBCT = 20 min	EBCT = 10 min	EBCT = 20 min
1‡	1 hour	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	t_{int}	8.8	18	6.6	13	5.2	10	3.6	7.2	2.1	4.3
3	$2t_{int}$	18	35	13	26	10	21	7.2	14	4.3	8.5
4	$3t_{int}$	26	53	20	40	16	31	11	22	6.4	13
5	$4t_{int}$	35	70	26	53	21	42	14	29	8.5	17
6	$5t_{int}$	44	88	33	66	26	52	18	36	11	21
7	$6t_{int}$	53	106	40	79	31	63	22	43	13	26
8	t_{50}	62	123	46	92	37	73	25	50	15	30
9	$t_{50} + 1.5t_{int}$	75	150	56	112	44	89	31	61	18	36
10	$t_{50} + 3.0t_{int}$	88	176	66	132	52	104	36	72	21	43
11	$t_{50} + 4.5t_{int}$	101	202	76	152	60	120	41	83	25	49
12	End of run	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR	EOR
	BV_{50}	8870	8870	6650	6650	5260	5260	3630	3630	2150	2150
	t_{50} (days)	61.6	123	46.2	92.4	36.5	73.1	25.2	50.4	14.9	29.9
	t_{int} (days)	8.8	17.6	6.6	13.2	5.2	10.4	3.6	7.2	2.1	4.3

EOR = End of run

*Actual RSSCT sample times for samples 2 through 12 are calculated by dividing scaled days by scaling factor (SF).

†Three duplicate samples are needed: they should be sample numbers 3 or 4, 7 or 8, and 10 or 11.

‡In all cases sample number 1 must be taken after 1 hour of RSSCT operation.

Table 5-5. RSSCT DESIGN PARAMETERS Run No. _____

Utility name and address _____

_____

Utility ID number _____

Contact person _____

Phone number _____

FAX number _____

GAC type and manufacturer _____

Original GAC mesh size _____ US std mesh

Diameter of full-scale GAC, d_{LC} _____ mm

$EBCT_{LC}$= 10 min

Diameter of GAC used in RSSCT, d_{SC} _____ mm

Scaling factor, SF _____ (-)

$EBCT_{SC}$ _____ min

Minimum Reynolds number, $Re_{SC,min}$ _____ (-)

Kinematic viscosity, υ _____ m^2/s

Bed porosity, ε_{LC} _____ (-)

Superficial velocity, v_{SC} _____ m/hr

Bed depth, l_{SC} _____ mm

RSSCT column inner diameter, DC_{SC} _____ mm

Bed (apparent) density (dry) of GAC, ρ_{SC} _____ g/ml

Mass (dry) of GAC, m_{SC} _____ grams

Volumetric flow rate, Q_{SC} _____ ml/min

$EBCT_{LC}$= 20 min

Diameter of GAC used in RSSCT, d_{SC} _____ mm

Scaling factor, SF _____ (-)

$EBCT_{SC}$ _____ min

Minimum Reynolds number, $Re_{SC,min}$ _____ (-)

Kinematic viscosity, υ _____ m^2/s

Bed porosity, ε_{LC} _____ (-)

Superficial velocity, v_{SC} _____ m/hr

Bed depth, l_{SC} _____ mm

RSSCT column inner diameter, DC_{SC} _____ mm

Bed (apparent) density (dry) of GAC, ρ_{SC} _____ g/ml

Mass (dry) of GAC, m_{SC} _____ grams

Volumetric flow rate, Q_{SC} _____ ml/min

Table 5-6. RSSCT SAMPLING - $EBCT_{LC}$= 10 min Run No._____

Utility name and address _____

_____

Utility ID number _____

Contact person _____
Contact phone number _____
Contact FAX number _____

	Date (M/D/Y)	Time	Operation time (hr)
GAC Influent (A group) alk, TH, CaH, NH_4-N, Br			
Sample A1-10			0
Sample A2-10			
GAC Influent (B group) pH, turb, temp, TOC, UV, and SDS			
Sample B1-10			0
Sample B2-10			
Sample B3-10			
GAC Effluent (C group) pH, temp, TOC, UV, and SDS			
Sample C1-10			1
Sample C2-10			
Sample C3-10			
Sample C4-10			
Sample C5-10			
Sample C6-10			
Sample C7-10			
Sample C8-10			
Sample C9-10			
Sample C10-10			
Sample C11-10			
Sample C12-10			
Sample D1-10			
Sample D2-10			
Sample D3-10			

Table 5-7. RSSCT SAMPLING - $EBCT_{LC}$= 20 min Run No._____

Utility name and address _____

_____

Utility ID number _____

Contact person _____
Contact phone number _____
Contact FAX number _____

	Date (M/D/Y)	Time	Operation time (hr)
GAC Influent (A group) alk, TH, CaH, NH_4-N, Br			
Sample A1-20			0
Sample A2-20			
GAC Influent (B group) pH, turb, temp, TOC, UV, and SDS			
Sample B1-20			0
Sample B2-20			
Sample B3-20			
GAC Effluent (C group) pH, temp, TOC, UV, and SDS			
Sample C1-20			1
Sample C2-20			
Sample C3-20			
Sample C4-20			
Sample C5-20			
Sample C6-20			
Sample C7-20			
Sample C8-20			
Sample C9-20			
Sample C10-20			
Sample C11-20			
Sample C12-20			
Sample D1-20			
Sample D2-20			
Sample D3-20			

Table 5-8. RSSCT RESULTS - $EBCT_{LC}$= 10 min Run No._____

Utility name and address _____

_____

Utility ID number _____
Contact person _____
Contact phone number _____
Contact FAX number _____

GAC Influent (Batch)

Group A	alk	TH	CaH	NH_4-N	Br
Sample A1-10					
Sample A2-10					

Group B	pH	temp.	turb.	TOC	UV
Sample B1-10					
Sample B2-10					
Sample B3-10					

Group B-SDS	Cl dose	Cl res.	CD	temp.	pH	H. time
Sample B1-10						
Sample B2-10						
Sample B3-10						

Group B-SDS	TOX	THM4	$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$
Sample B1-10						
Sample B2-10						
Sample B3-10						

Group B-SDS	HAA6	MCAA	DCAA	TCAA	MBAA	DBAA	BCAA	TBAA	CDBAA	DCBAA
Sample B1-10										
Sample B2-10										
Sample B3-10										

Units: alk, TH, CaH- mg/L as $CaCO_3$; NH_4-N, TOC, Cl dose, Cl res., CD- mg/L; turb- ntu; UV- cm^{-1}; temp- °C; Br and SDS- µg/L; H. time- hrs

RSSCT RESULTS - $EBCT_{LC}$= 10 min (page 2) Run No._____

Utility ID # _____

GAC EFFLUENT

Group C	pH	temp.	TOC	UV
Sample C1-10				
Sample C2-10				
Sample C3-10				
Sample C4-10				
Sample C5-10				
Sample C6-10				
Sample C7-10				
Sample C8-10				
Sample C9-10				
Sample C10-10				
Sample C11-10				
Sample C12-10				
Sample D1-10				
Sample D2-10				
Sample D3-10				

Group C-SDS	Cl dose	Cl res.	CD	temp.	pH	H. time
Sample C1-10						
Sample C2-10						
Sample C3-10						
Sample C4-10						
Sample C5-10						
Sample C6-10						
Sample C7-10						
Sample C8-10						
Sample C9-10						
Sample C10-10						
Sample C11-10						
Sample C12-10						
Sample D1-10						
Sample D2-10						
Sample D3-10						

Units: TOC, Cl dose, Cl res., CD- mg/L; turb- ntu; UV- cm^{-1};
temp- °C; H. time- hrs

RSSCT RESULTS - $EBCT_{LC}$= 10 min (page 3) Run No._____

Utility ID # _____

GAC Effluent

Group C-SDS	TOX	THM4	$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$
Sample C1-10						
Sample C2-10						
Sample C3-10						
Sample C4-10						
Sample C5-10						
Sample C6-10						
Sample C7-10						
Sample C8-10						
Sample C9-10						
Sample C10-10						
Sample C11-10						
Sample C12-10						
Sample D1-10						
Sample D2-10						
Sample D3-10						

Group C-SDS	HAA6	MCAA	DCAA	TCAA	MBAA	DBAA	BCAA	TBAA	CDBAA	DCBAA
Sample C1-10										
Sample C2-10										
Sample C3-10										
Sample C4-10										
Sample C5-10										
Sample C6-10										
Sample C7-10										
Sample C8-10										
Sample C9-10										
Sample C10-10										
Sample C11-10										
Sample C12-10										
Sample D1-10										
Sample D2-10										
Sample D3-10										

Units: SDS- µg/L

Table 5-9. RSSCT RESULTS - $EBCT_{LC}$= 20 min Run No._____

Utility name and address _____

_____

Utility ID number _____
Contact person _____
Contact phone number _____
Contact FAX number _____

GAC Influent (Batch)

Group A	alk	TH	CaH	NH_4-N	Br
Sample A1-20					
Sample A2-20					
Group B	pH	temp.	turb.	TOC	UV
Sample B1-20					
Sample B2-20					
Sample B3-20					

Group B-SDS	Cl dose	Cl res.	CD	temp.	pH	H. time
Sample B1-20						
Sample B2-20						
Sample B3-20						

Group B-SDS	TOX	THM4	$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$
Sample B1-20						
Sample B2-20						
Sample B3-20						

Group B-SDS	HAA6	MCAA	DCAA	TCAA	MBAA	DBAA	BCAA	TBAA	CDBAA	DCBAA
Sample B1-20										
Sample B2-20										
Sample B3-20										

Units: alk, TH, CaH- mg/L as $CaCO_3$; NH_4-N, TOC, Cl dose, Cl res., CD- mg/L; turb- ntu; UV- cm^{-1}; temp- °C; Br and SDS- µg/L; H. time- hrs

RSSCT RESULTS - $EBCT_{LC}$= 20 min (page 2) Run No._____

Utility ID # _____

GAC EFFLUENT

Group C	pH	temp.	TOC	UV
Sample C1-20				
Sample C2-20				
Sample C3-20				
Sample C4-20				
Sample C5-20				
Sample C6-20				
Sample C7-20				
Sample C8-20				
Sample C9-20				
Sample C10-20				
Sample C11-20				
Sample C12-20				
Sample D1-20				
Sample D2-20				
Sample D3-20				

Group C-SDS	Cl dose	Cl res.	CD	temp.	pH	H. time
Sample C1-20						
Sample C2-20						
Sample C3-20						
Sample C4-20						
Sample C5-20						
Sample C6-20						
Sample C7-20						
Sample C8-20						
Sample C9-20						
Sample C10-20						
Sample C11-20						
Sample C12-20						
Sample D1-20						
Sample D2-20						
Sample D3-20						

Units: TOC, Cl dose, Cl res., CD- mg/L; turb- ntu; UV- cm^{-1};
temp- °C; H. time- hrs

RSSCT RESULTS - $EBCT_{LC}$= 20 min (page 3) Run No._____

Utility ID # _____

GAC Effluent

Group C-SDS	TOX	THM4	$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$
Sample C1-20						
Sample C2-20						
Sample C3-20						
Sample C4-20						
Sample C5-20						
Sample C6-20						
Sample C7-20						
Sample C8-20						
Sample C9-20						
Sample C10-20						
Sample C11-20						
Sample C12-20						
Sample D1-20						
Sample D2-20						
Sample D3-20						

Group C-SDS	HAA6	MCAA	DCAA	TCAA	MBAA	DBAA	BCAA	TBAA	CDBAA	DCBAA
Sample C1-20										
Sample C2-20										
Sample C3-20										
Sample C4-20										
Sample C5-20										
Sample C6-20										
Sample C7-20										
Sample C8-20										
Sample C9-20										
Sample C10-20										
Sample C11-20										
Sample C12-20										
Sample D1-20										
Sample D2-20										
Sample D3-20										

Units: SDS- µg/L

6.0 Simulated Distribution System Chlorination Conditions

According to ICR Rule § 141.144(b)(3), samples taken to monitor the pilot- and bench-scale GAC breakthrough that will be analyzed for the formation of THM4, HAA6, and TOX, and for chlorine demand should be chlorinated under site-specific simulated distribution system (SDS) conditions. The SDS conditions of incubation time, temperature, pH, and chlorine residual should be representative of actual plant and distribution system conditions at the time of the GAC study. However, the selection and control of these conditions can be complex, especially for samples from the GAC effluent.

6.1 Selection Of SDS Chlorination Conditions

The chlorine demand (chlorine dose subtracted from chlorine residual, based on Standard Method 2350: Oxidant Demand/ Requirement) in the GAC effluent increases throughout the breakthrough curve because the amount of organic matter exiting the GAC column increases with time. A constant chlorine dose for all samples would yield decreasing chlorine residual concentrations as samples in the beginning of the breakthrough curve will have much lower chlorine demands than later samples. This chlorination approach would not be representative of full-scale GAC operation, where the chlorine dose would be varied to yield a CT or set distribution system residual. Therefore, a constant chlorine residual approach is recommended, whereby the chlorine dose is adjusted according to the demand of each sample, with the goal of obtaining a target chlorine residual concentration after the specified incubation period. The target residual should be that which represents the residual concentration in the distribution system at a representative residence time. As will be discussed later, a chlorine demand study can be used to determine the chlorine dose required to yield the target chlorine residual.

The SDS incubation time should be set to match a residence time in the distribution system that represents average conditions for the specific distribution system at the time of the GAC study. The SDS incubation temperature should be chosen in the same manner.

Depending on the alkalinity and chlorine dose, the pH of the sample can decrease after chlorination. Significant changes in pH have been shown to affect DBP formation (Summers et al. 1994c; Hooper et al. 1994). For many utilities the pH of the water will be adjusted prior to distribution, often for corrosion control. The SDS pH should reflect this final distribution system pH. As will be discussed later, SDS samples may be buffered prior to chlorination to maintain the SDS pH.

For the RSSCTs it is recommended that the SDS conditions of incubation time, temperature, pH and chlorine residual chosen remain constant through the duration of any given RSSCT run, although changes can be made in the conditions chosen for each quarterly RSSCT run to reflect seasonal variability. For pilot-scale studies the SDS conditions of incubation time, pH and chlorine residual should remain constant throughout the run. While it is recognized that these conditions can change in a distribution system over the course of a GAC run, complications in interpreting and utilizing the SDS-DBP data dictate that constant

SDS conditions be used for these parameters. Temperature variations in the distribution system, however, can be incorporated into the SDS conditions of a pilot-scale run. The chlorination conditions used for each sample should be recorded in Table 4-4 for pilot-scale studies or Tables 5-8 and 5-9 for bench-scale studies.

Some difficulty may be encountered when attempting to achieve target SDS chlorine residuals for GAC effluent samples, as the unsteady-state behavior of GAC is reflected in chlorine demand. This difficulty is heightened by the presence of inorganic compounds which may exert a significant chlorine demand, and are not removed by GAC. If inorganic demand is significant, then it may account for a large fraction of the total chlorine demand present at the beginning of the breakthrough curve, when organic chlorine demand is well removed by the GAC. With breakthrough, organic demand increases, while inorganic chlorine demand remains constant, thus diminishing the effect of inorganic demand on total demand.

For GAC effluent samples, chlorine demand usually correlates well with TOC concentration, and this relationship can be utilized to aid in predicting chlorine demand, without directly accounting for inorganic demand. Figure 6-1 is a plot of chlorine demand against TOC for Mississippi River (New Orleans, LA) water and Harsha Lake (sw Ohio) water. For Mississippi River water, a linear curve fit has a positive y-axis intercept of 0.3, indicating an inorganic chlorine demand of approximately 0.3 mg Cl_2/L. Harsha Lake water does not show an appreciable inorganic chlorine demand, as the linear curve fit passes through the origin.

If prior experience with GAC relating chlorine demand to TOC is not available, a method has been developed that simulates breakthrough conditions to obtain a relationship between chlorine demand and TOC, without requiring the operation of a separate GAC column. The method is termed a dilution study, and is based on diluting the GAC influent water to several intermediate TOC concentrations and investigating the chlorine demand of these dilution samples. However, while TOC is diluted, the inorganic background should not be affected by the procedure. This is accomplished by diluting the GAC influent with water taken from the GAC effluent very early in GAC operation, so that natural organic matter removal is maximized and inorganic constituents are conserved.

The following outlines the dilution study procedure. Two aliquots of water are needed: one from the GAC influent, and one from the GAC effluent (20 minute EBCT, if possible) taken as early as possible in the study, so that natural organic matter removal is maximized. The aliquot from the GAC effluent is termed the dilution aliquot. The two aliquots are systematically mixed to form seven dilution samples with varying composition, as outlined in Table 6-1. The volume of each dilution sample should be sufficient for TOC and UV_{254} analysis and to chlorinate at three doses for chlorine demand analysis. Note that regardless of sample size, the total volume of the dilution aliquot required is 50% more than the required volume of the GAC influent. After mixing, each of the seven dilution samples are analyzed for TOC and UV_{254}. Three chlorine doses for each dilution sample are determined by multiplying the measured TOC, TOC_{ds}, by the respective chlorine demand (CD) to TOC ratio

(CD:TOC) listed in Table 6-1 and adding to these values the chlorine residual required for the SDS test.

$$\text{Chlorine dose} = TOC_{ds\_}(CD:TOC) + \text{target chlorine residual}$$

Therefore, the chlorine dose for each dilution sample is bracketed with the goal of achieving a residual in one of the three samples that is near the target chlorine residual. Note that at low TOC concentrations, dilution samples 1 to 3, a wide range of chlorine demand to TOC ratios are used, since the inorganic demands may dominate.

All SDS conditions of pH, temperature, and incubation time that will be followed during the GAC study should be used for dilution study chlorination. The chlorine demand calculated from the dose that yielded a residual nearest to the target residual for each dilution is used to generate a plot of chlorine demand against TOC. The relationship found should be similar in form to those shown in Figure 6-1.

The results of the dilution study can now be used to estimate the chlorine demand of each GAC effluent sample, after TOC analysis. It is recommended that a small aliquot from each effluent sample be chlorinated at a dose based on the dilution study results and analyzed only for chlorine demand prior to chlorination for DBP analysis. Adjustments in the chlorine dose can then be made if needed, since the adsorbability or chlorine reactivity can naturally change with time.

6.2 Uniform Formation Conditions Approach

A standardized approach to representative chlorination conditions has been developed (Summers et al., 1996; Summers et al., 1994c; Hooper et al., 1994) and has resulted in a set of uniform formation conditions (UFC) for chlorination:

Incubation time:	24 ± 1 hours
Incubation temperature:	20.0 ± 1.0°C
pH:	8.0 ± 0.2
24-hour chlorine residual:	1.0 ± 0.4 mg Cl_2/L

These conditions are based on average conditions reported in the AWWA Water Industry Database, where the average mean residence time in the distribution system was reported as 1.3 days and the average mean chlorine residual in the distribution system was reported as 0.9 mg Cl_2/L. The UFC test pH was selected to represent the impact of the Lead and Copper Rule on distribution system pH. The incubation temperature was standardized so that variations in ambient laboratory temperatures would not affect DBP formation.

The UFC test may be used as described, or specific parameters may be changed as necessary to reflect specific distribution system conditions. For example, the incubation temperature for chlorination of an RSSCT operated during the winter could be set at 10°C to reflect seasonal conditions. The pH could be buffered to a different value, or allowed to

remain unbuffered to represent ambient conditions. The intent of the UFC test or a modified version of the UFC test is to provide constant chlorination conditions to allow for an accurate assessment of the breakthrough patterns of DBP precursors. The chlorination conditions (chlorine dose, chlorine residual, pH, incubation temperature, and incubation time) used for each sample should be recorded in Table 4-4 for pilot-scale studies or Tables 5-8 and 5-9 for bench-scale studies. The proposed standard operating procedure for the UFC test is included in Appendix 2-B.

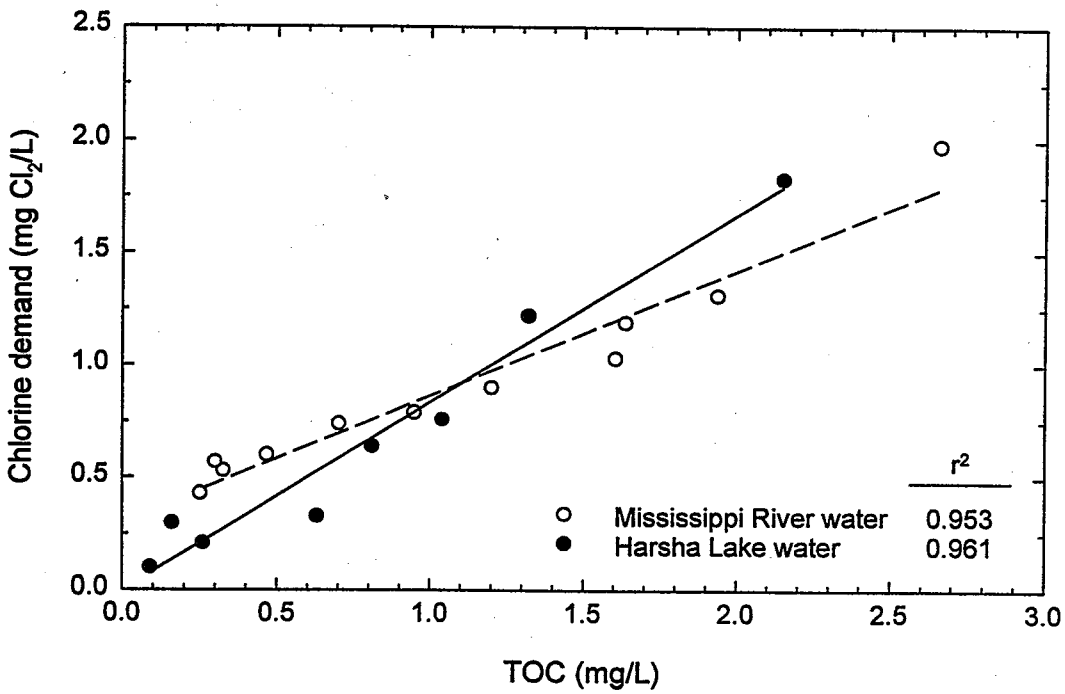

Figure 6-1 Correlation between chlorine demand and TOC for two waters

Table 6-1 Dilution study parameters

Sample number	Influent water	Dilution water	CD:TOC (mg Cl_2/mg C)		
			Low	Target	High
1	0%	100%	0.5	2.5	5.0
2	10%	90%	0.5	2.0	3.5
3	20%	80%	0.5	1.5	2.5
4	35%	65%	0.3	1.3	2.3
5	50%	50%	0.3	1.0	1.7
6	70%	30%	0.3	1.0	1.7
7	100%	0%	0.3	1.0	1.7

7.0 Cost Estimations

Using the breakthrough data from the pilot- and bench-scale DBP precursor removal studies, estimations of the run time to different effluent criteria will be made. These effluent criteria include, but are not limited to, the D/DBP Rule Stage 2 'place holders' of 40 and 30 μg/L for THM4 and HAA5, respectively. These run times can be used to calculate a carbon usage rate, GAC mass per volume of water treated (kg/m^3 or lbs/1000 gal). Using the carbon usage rate, costs estimates to achieve different effluent criteria can be made for different system sizes under several design options, e.g. on-site versus off-site reactivation or steel pressure vessels versus concrete gravity contactors. Cost estimates will be based on the use of GAC contactors placed after existing filters, termed post-filter adsorbers.

To better estimate the national costs for different effluent criteria, assessments of site-specific costs are needed. Site-specific cost information is requested from each utility performing pilot- or bench-scale DBP precursor removal studies. The requested cost information is listed in Table 7-1, along with example parameter values (Clark and Adams, 1991). If the specific value for a requested parameter is not available, then enter NA as its value in the table. In addition to the standard cost parameters, estimates of the costs of modifying the existing treatment plant to accommodate the addition of GAC post-filter adsorbers is requested.

Table 7-1 Input data for cost model

Cost Parameter	Example Values	Specific Utility Value
CAPITAL RECOVERY INTEREST RATE (%)	10	
CAPITAL RECOVERY PERIOD (YEARS)	20	
OVERHEAD & PROFIT FACTOR (% OF CONSTRUCTION COST)	5	
SPECIAL SITEWORK FACTOR (% OF CONSTRUCTION COST)	5	
CONSTRUCTION CONTINGENCIES (% OF CONSTRUCTION COST)	10	
ENGINEERING FEE FACTOR (% OF CONSTRUCTION COST)	10	
ENR CONSTRUCTION COST INDEX (CCI BASE YEAR 1913) (DATE)	4965 (May 92)	( )
PRODUCERS PRICE INDEX (PPI BASE YEAR 1967=100) (DATE)	326 (May 92)	( )
LABOR RATE + FRINGE ($/MANHOUR)	15	
LABOR OVERHEAD FACTOR (% OF LABOR)	10	
ELECTRIC RATE ($/KWH)	0.086	
FUEL OIL RATE ($/GALLON)	0.89	
NATURAL GAS RATE ($/CU.FT.)	0.0055	
PROCESS WATER RATE ($/1000 GAL)	0.35	
MODIFICATIONS TO EXISTING PLANT (% OF CONSTRUCTION COST)	5	

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Appendix 2-A
Sampling Activated Carbon

A sample tube, riffle splitter, sample reducer or coning and quartering technique should be used to obtain a representative sample of the activated carbon. The first three of the above mentioned techniques require mechanical devices, are only applicable for granular particles and can not handle small sample sizes. The coning and quartering technique does not have these limitations and therefore, can be applied to both GAC and ground GAC. However, it is labor intensive especially for obtaining very small samples from large samples. The coning and quartering procedure is illustrated in Figure A-1 and described below.

1) The total volume of the as-received GAC is taken from the original container and placed into a cone shape pile, scoop-by-scoop. Each scoop is added to the center of the pile and allowed to flow evenly in all directions (a).

2) The pile is then evenly flattened from above to form a shallow cylinder of uniform thickness (b).

3) This cylinder of carbon is then evenly divided into pie-shaped quarters as shown in Figure A-1 (c and d).

4) Two opposite quarters are removed (e).

5) The remaining two opposite quarters are piled into a cone again by taking scoops from alternate quarters (f).

6) Steps 2 through 5 are repeated until the desired sample size is obtained.

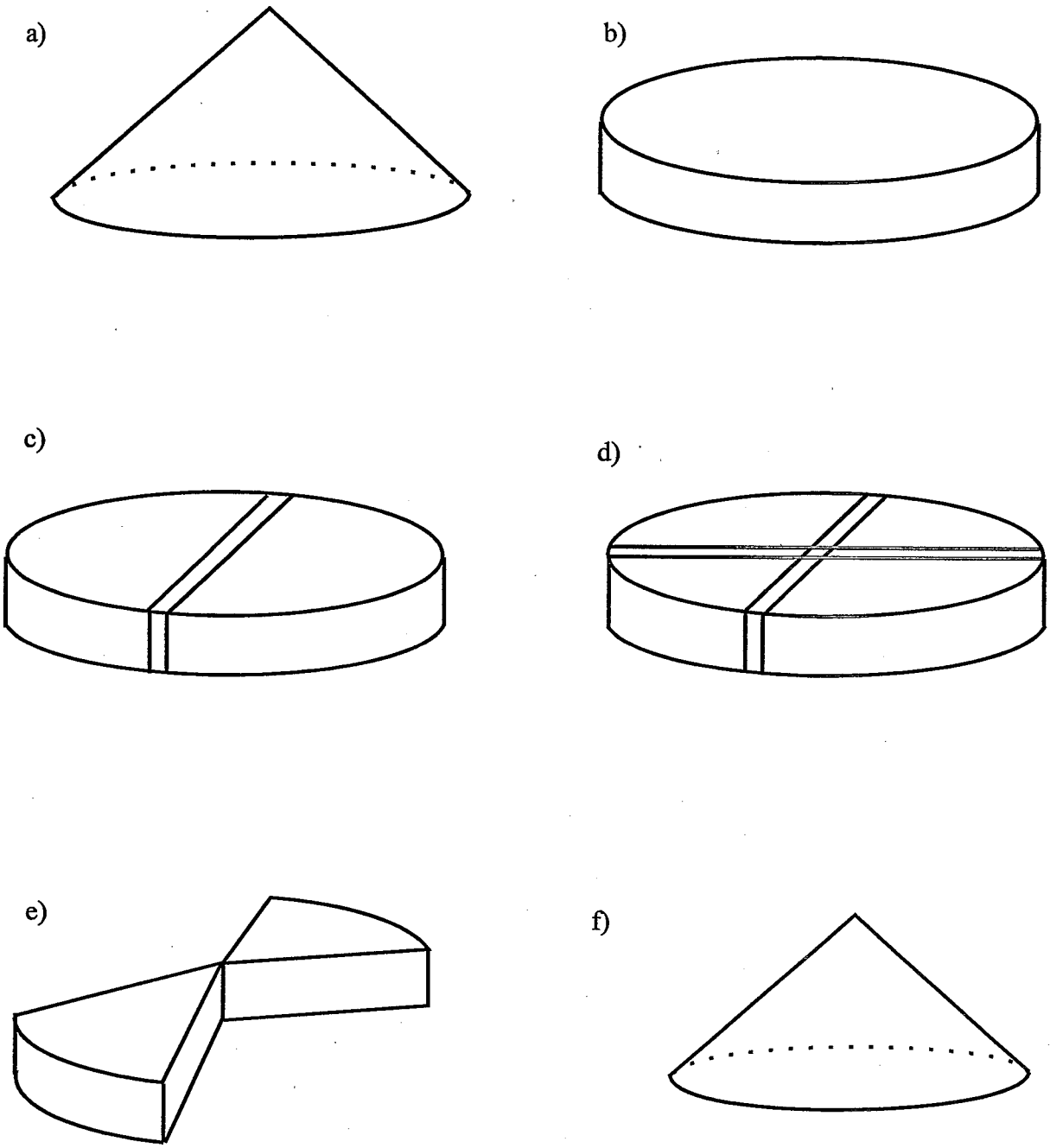

Figure A-1 Coning and Quartering Sampling Technique

Appendix 2-B
Uniform Formation Conditions (UFC) For DBP Formation
Proposed Standard Operating Procedure

Uniform Formation Conditions:

pH:	8.0 ± 0.2
temperature:	20.0 ± 1.0°C
incubation time:	24 ± 1 hr
chlorine residual:	1.0 ± 0.4 mg/L as free chlorine after 24 hr

Preliminary Study:

A 24-hour chlorine demand study on the water sample may be required before dosing under UFC to determine the applied dose that will yield a chlorine residual of 1.0 mg/L after 24 hours (procedure described below).

Materials:

- chlorine demand-free glassware
- pH 8.0 borate buffer
- pH 8.0 combined hypochlorite/buffer dosing solution

Methods:

Chlorine demand-free glassware:

Incubation bottles (amber, with TFE-faced caps): soak in detergent (Fisher FL-70, 4%) at least overnight, rinse 4x with hot tap water, 2x with DI water. Place in 10-20 mg/L chlorine solution (made with DI water) for at least 24 hours. Rinse 4x with DI water and then 1-2x with laboratory clean water; dry in 140°C oven at least overnight. Store dosing pipettes in ~50 mg/L Cl_2 (made with laboratory clean water). Rinse 3x with dosing solution prior to use, and return pipettes to storage in chlorine solution after use.

pH 8.0 borate buffer:

Before dosing, water samples are buffered to pH 8.0 with 2 mL/L borate buffer: 1.0M boric acid (ACS grade) and 0.26M sodium hydroxide (ACS grade) in boiled laboratory clean water (RO/IX/GAC).

pH 8.0 combined hypochlorite/buffer dosing solution:

A combined hypochlorite/buffer solution (based on method described in Koch et al., "A Simulated Distribution System Trihalomethane Formation Potential Method," 1987 AWWA WQTC) is made by buffering the hypochlorite solution to pH 8.0 with pH 6.7 borate buffer.

- pH 6.7 borate buffer: 1.0M boric acid (ACS grade) and 0.11M sodium hydroxide (ACS grade) in boiled laboratory clean water (RO/IX/GAC).

- add pH 6.7 borate buffer to chlorine solution (1000-4000 mg Cl_2/L) to yield a pH 8.0 dosing solution. (A 4-5:1 volume ratio of pH 11.2 hypochlorite solution to pH 6.7 borate buffer has been found to yield a pH 8.0 combined hypochlorite/buffer solution, with an approximately 20% drop in chlorine strength.)

The dosing solution (combined OCl^-/buffer) chlorine strength should allow for a dosing volume of < 0.5% of the water sample volume (e.g. 2.5 mL dosing solution in 1.0 L bottle).

Preliminary study:

Perform a 24-hour chlorine demand study (buffered at pH 8.0 and incubated in the dark at 20°C as described in the dosing procedure) using a series of three chlorine doses based on Cl_2:TOC ratios of 1.2:1, 1.8:1, and 2.5:1, after adjusting for inorganic demand. From the results of these tests, the chlorine dose for UFC is selected to yield a 24-hour residual of 1.0 mg/L free chlorine.

Dosing procedure:

1. Add 2.0 mL/L pH 8.0 borate buffer to water sample
2. Adjust to pH 8.0 with H_2SO_4/NaOH (if necessary)
3. Fill incubation bottle 3/4 full with buffered water sample
4. Dose with combined hypochlorite/buffer solution holding pipette Just above water surface
5. Cap bottle, invert twice
6. Fill to top with buffered water sample and cap headspace free
7. Invert 10 times
8. Incubate in dark at 20.0°C for 24 hours
9. After incubation period, measure chlorine residual, pH, and sample for DBPs

Appendix 2-C

AWWA Standard For Granular Activated Carbon

ANSI/AWWA B604-90

Contact AWWA, 6666 West Quincy Ave., Denver, CO 80235
(303) 794-7711 for information about revisions to this standard.

American Water Works Association
ANSI/AWWA B604-90
(Revision of AWWA B604-74)

AWWA STANDARD

FOR

GRANULAR ACTIVATED CARBON

AMERICAN NATIONAL STANDARD

Effective date: Feb. 1, 1991.
First edition approved by AWWA Board of Directors Jan. 28, 1974.
This edition approved June 17, 1990.
Approved by American National Standards Institute, Inc., Nov. 13, 1990.

AMERICAN WATER WORKS ASSOCIATION

6666 West Quincy Avenue, Denver, Colorado 80235

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Contents

Foreword

This foreword is for information only and is not a part of ANSI/AWWA B604.

I. History of Standard. The first edition of AWWA B604, Standard for Granular Activated Carbon, was approved by the AWWA Board of Directors on Jan. 28, 1974. This is the first revision to AWWA B604.

The purpose of ANSI/AWWA B604 is to provide a standard for use in preparing purchase specifications for the purchase of granular activated carbon to be used as adsorption media for the treatment of municipal and industrial water supplies. Powdered activated carbon is covered in ANSI/AWWA B600, Standard for Powdered Activated Carbon.

This standard does not cover the design of carbon handling facilities or adsorption processes. Design information may be found in the *Journal AWWA* and in other publications, some of which are listed in the bibliography (appendix A) to this standard.

II. Introductory Information.

Description. Activated carbon is a form of carbon that is activated by a carefully controlled oxidation process to develop a porous carbon structure with a surface area greater than 500 m^2/g. This surface area gives the activated carbon the adsorptive capacity to adsorb dissolved organic materials, many of which are taste- and odor-causing substances in water.

The major raw materials used in the manufacture of granular activated carbons are peat, bituminous coal, coconut shell, and lignite. After preliminary processing, these materials are heated to a high temperature and reacted with steam to develop the extensive internal pore structure required for adsorption. Subsequent processing includes crushing, grading, screening, and packaging.

Water treatment with granular activated carbon is usually accomplished by percolating the water to be treated through fixed-adsorption beds of granular activated carbon. The granular activated carbon may be crushed and screened to any particle size, but typical sizes used for water treatment range from No. 8 to No. 50 US standard sieve sizes.

Source of supply. Activated carbon to be used in water treatment should be obtained from manufacturers regularly engaged in the production of activated carbon found satisfactory for service in the water treatment field.

Caution in handling and storage. Activated carbon will readily adsorb oxygen from the air, creating an acute oxygen depletion hazard in confined areas. Appropriate safety measures for oxygen-deficient atmospheres should be strictly adhered to when entering enclosed or partially enclosed areas containing activated carbon.

In storing activated carbon, precautions must be taken to avoid direct contact with strong oxidizing agents, such as chlorine, hypochlorites, potassium permanganate, ozone, and peroxide.

Mixing carbon with hydrocarbons (such as oils, gasoline, diesel fuel, grease, paint thinners, and so forth) may cause spontaneous combustion. Therefore, activated carbon must be kept separated from hydrocarbon storage or spills.

Particle-size distribution. Granular activated carbons extending over a wide range of size distributions have given satisfactory results. The proper size distribution for a particular application cannot be specified without consideration of the

nature of the water to be treated, the particular treatment process in question, and other controlling factors.

In general, coarser particle-size distributions will permit higher hydraulic loading and backwash rates but will exhibit somewhat lower adsorption rates for certain specific organic chemicals.

The particle-size distribution for a particular grade of activated carbon is usually specified by particle-size range, effective-size range, and maximum uniformity coefficient. Commonly manufactured particle-size ranges for granular activated carbons, expressed in limiting US standard sieve sizes, include 8 × 16, 8 × 20, 8 × 30, 10 × 30, 12 × 40, 14 × 40, 20 × 40, and 20 × 50 with effective sizes ranging from 0.35 mm to 1.30 mm. The purchaser should specify a particular-size range and an effective-size range meeting site-specific requirements, which may include one or more of the manufactured size ranges previously enumerated. In general, the uniformity coefficient for granular activated carbon should not exceed 2.1 after backwashing in the filter.

Abrasion resistance. Granular activated carbons used for municipal water treatment are exposed to a variety of external forces during shipping, loading into adsorption beds, and backwashing. These forces can cause activated carbon granule crushing on impact, granule-to-granule abrasion, and the generation of undesirable fines. Because of difficulty in devising a test that simulates the various handling conditions that may be encountered, the industry has not yet agreed on any one standard test for predicting activated carbon durability.

Two tests, the stirring abrasion test and the Ro-Tap abrasion test, have been included in this standard for measuring granular activated carbon durability. It is recognized that differences in bulk density and other physical properties of the various manufactured activated carbons, which might not be related to durability, influence the results obtained in using these tests. For this reason, it is current practice to use the stirring abrasion test for lignite-based granular activated carbons and the Ro-Tap abrasion test for bituminous-based granular activated carbons.

Adsorptive capacity. The optimum method for determining the effectiveness of a granular activated carbon is by using water from the particular plant in question for the test. Other tests have been developed that give an indication of a granular activated carbon's performance under specific conditions. These tests use a very high concentration of adsorbate to reduce the amount of time required to complete the test. Various producers of activated carbon suggest different adsorbates to give an index of a carbon's performance. Examples are phenol, tannin, iodine, and molasses. Phenol adsorption is an index of a carbon's ability to remove some types of chemical taste and odor; tannin is representative of organic compounds added to water by decayed vegetation; and iodine adsorption is an index of the total surface area of a carbon. Iodine and molasses adsorption are often used to show if a carbon is activated. An iodine adsorption test is included in this standard. Information on tannin and phenol adsorptive capacity tests may be found in appendix B to this standard for those purchasers who want to include these requirements in their specifications.

III. Acceptance. Government legislative and regulatory bodies at national and state or provincial levels promulgate rules that may control the use of products described in ANSI/AWWA B604. AWWA does not obtain or provide information about all of the actual or proposed regulations in the many involved jurisdictions. The user of this standard is cautioned to determine that the use of products described in this standard conforms to all applicable laws and regulations.

Questions concerning laws and regulations should be referred to the appropriate regulatory agency.

Consensus standards have been developed for direct and indirect additives from products that come in contact with potable water. Manufactured products covered by ANSI/AWWA B604 eventually may be required to be certified to meet those standards. Questions regarding additives should be referred to the appropriate state regulatory agency.

IV. Information Regarding Use of This Standard. When purchasing activated carbon under the provisions of this standard, the purchaser should provide specifications covering the following:

1. Standard used—that is, ANSI/AWWA B604-90, Standard for Granular Activated Carbon.

2. Quantity of granular activated carbon to be purchased in cubic feet (cubic metres), backwashed, drained, and in place—or by weight. Activated carbon intended for immediate placement in an adsorption bed is typically purchased by volume, backwashed, drained, and in place—or by weight. Makeup activated carbon or other activated carbon intended for subsequent placement is purchased on a volume or weight basis.

3. Whether an affidavit of compliance is required (Sec. 1.3).

4. Reference sample and acceptance method (Sec. 1.4.1 and Sec. 1.4.4).

5. Particle-size range, effective size, and uniformity coefficient, if other than that specified (Sec. 2.1).

6. Special adsorptive capacity tests (Sec. 2.2.1 and Sec. 2.2.2).

7. Provisions for reaching agreement on sampling technique (Sec. 3.1.1).

8. Method of packaging and shipping (Sec. 3.2).

9. If shipment is to be in bulk: type of rail car or hopper truck (Sec. 3.2.4); and whether bulk shipments are to be accompanied by weight certificates of certified weighers (Sec. 3.2.5).

V. Modification to Standard. Any modification of the provisions, definitions, or terminology in this standard must be provided in the purchaser's specifications.

VI. Major Revisions. The following revisions were incorporated in this edition of ANSI/AWWA B604:

1. The standard has been revised to conform with the current style and content of AWWA standards.

2. An "Acceptance" section has been added in the Foreword.

3. The "Definitions" section has been revised and expanded.

4. All references to "contractor" have been changed to "supplier."

5. The "Basis for Shipment, Acceptance, and Rejection" section has been revised.

6. Impurities information from the *Water Chemicals Codex** has been added.

7. The minimum apparent density has been decreased to 0.25 g/cc (Sec. 2.1.2).

8. Minimum values for surface area and pore volume have been added (Sec. 2.1.7 and Sec. 2.1.8).

**Water Chemicals Codex*, National Academy Press, 2101 Constitution Ave., N.W., Washington, DC 20418.

9. A maximum value for water-soluble ash (Sec. 2.1.9) and a range of effective sizes (Sec. 2.1.4) have been added.

10. The iodine test procedure from the 1974 edition has been deleted. This edition of ANSI/AWWA B604 includes ASTM* D4607-86, Standard Test Method for Determination of Iodine Number of Activated Carbon. Minor changes in other test methods have also been made.

*American Society for Testing and Materials, 1916 Race St., Philadelphia, PA 19103.

American Water Works Association

ANSI/AWWA B604-90
(Revision of AWWA B604-74)

AWWA STANDARD FOR

GRANULAR ACTIVATED CARBON

SECTION 1: GENERAL

Sec. 1.1 Scope

This standard covers granular and extruded activated carbon for use as adsorption media in the treatment of municipal and industrial water supplies.

Sec. 1.2 Definitions

The following definitions shall apply to this standard:

1.2.1 *Activated carbon:* A family of carbonaceous substances manufactured by processes that develop internal porosity, thereby creating adsorptive properties.

1.2.2 *Adsorption:* A process in which fluid molecules are concentrated on a surface by chemical or physical forces or both.

1.2.3 *Effective size:* That size opening that will just pass 10 percent of a representative sample of a filter material; that is, if the size distribution of the particles is such that 10 percent of a sample is finer than 0.45 mm, the filter material has an effective size of 0.45 mm.

1.2.4 *Extruded activated carbon:* A form of granular activated carbon in which the particles are uniform cylinders or pellets in shape. Effective size and uniformity coefficient are not applicable for extruded carbons.

1.2.5 *Manufacturer:* The party that manufactures, fabricates, or produces materials or products.

1.2.6 *Purchaser:* The person, company, or organization that purchases any materials or work to be performed.

1.2.7 *Supplier:* The party who supplies materials or services. A supplier may or may not be the manufacturer.

1.2.8 *Uniformity coefficient:* A ratio of the size opening that will just pass 60 percent of a representative sample of the filter material divided by that opening that will just pass 10 percent of the same sample.

Sec. 1.3 Affidavit of Compliance

When requested by the purchaser, the supplier shall provide an affidavit of compliance stating that the activated carbon furnished complies with the applicable provisions of this standard and the purchaser's specifications.

Sec. 1.4 Basis for Shipment, Acceptance, and Rejection

1.4.1 *Reference sample.* When requested, a representative sample of the granular activated carbon shall be submitted to the purchaser for acceptance before shipment. The sample must be submitted in clean, vaporproof containers, clearly marked with the address of the supplier, and identified with the lot number of the contents. A duplicate sample shall be tested by the supplier and a certified test report shall be submitted to the purchaser with the purchaser's sample, showing compliance with the requirements of the purchaser's specifications, along with a statement certifying that the material for shipment is equal in quality to the sample submitted.

1.4.2 *Authorization for shipment.* The purchaser may authorize shipment on the basis of the supplier's certification of quality, or may test the reference sample submitted by the supplier to confirm compliance before shipment is authorized.

1.4.3 *Sampling and testing after delivery of shipment.* The purchaser may elect to collect a representative sample of the material after delivery. The procedure used shall be in accordance with Sec. 3.1. One of the three sample portions taken may be tested to determine compliance with the purchaser's specifications.

1.4.4 *Acceptance.* The purchaser may elect to accept the granular activated carbon on the basis of (1) the supplier's certified test report and an accompanying affidavit of compliance indicating the product proposed for use complies with this standard and with the purchaser's specifications with no exceptions; (2) the supplier's certified test report completed by a qualified third-party testing laboratory approved by the purchaser and an accompanying affidavit of compliance; (3) the purchaser's own testing of the reference sample submitted by the supplier and the required affidavit of compliance; or (4) the purchaser's own testing of the representative sample, collected according to Sec. 3.1 after receipt of shipment, showing compliance with this standard and the purchaser's specifications. (See note in Sec. 2.1.1.)

1.4.5 *Notice of nonconformance.* If the granular activated carbon delivered does not meet the requirements of this standard or the purchaser's specifications, a notice of nonconformance must be provided by the purchaser to the supplier within 15 working days* after receipt of the shipment at the point of destination. The results of the purchaser's test shall prevail unless the supplier notifies the purchaser within five working days of the notice of nonconformance that a retest is desired. On receipt of the request for a retest, the purchaser shall forward to the supplier one of the sealed samples taken according to Sec. 3.1. In the event the results obtained by the supplier on retesting do not agree with the test results obtained by the purchaser, the other sealed sample shall be forwarded, unopened, for analysis to a referee laboratory agreed on by both parties. The results of the referee's analysis shall be accepted as final. The cost of the referee's analysis shall be paid for by the supplier if the material does not meet the requirements of this

*If testing for the removal of a specific challenge compound is required by the purchaser's specifications, adequate time must be allowed for conformance testing.

standard and the purchaser's specifications, or by the purchaser if it does meet the requirements of this standard and the purchaser's specifications.

1.4.6 *Removal or price adjustment.* If the material does not meet the requirements of this standard and the purchaser's specifications, the supplier shall remove it from the premises of the purchaser and replace it with a like amount of satisfactory granular activated carbon or make a price adjustment acceptable to the purchaser.

SECTION 2: MATERIALS

Sec. 2.1 Physical Requirements

2.1.1 *Moisture.* The moisture content of granular activated carbon shall not exceed 8 percent, by weight, of the listed container contents as packaged or at the time of shipment by the supplier in the case of a bulk shipment. The moisture content shall be determined according to Sec. 4.3.

NOTE: Because ambient conditions may be beyond the control of the supplier, the moisture content of activated carbon may increase during bulk shipment. A moisture content exceeding 8 percent is permitted in the reference sample that is collected after receipt of shipment (Sec. 1.4.4 and Sec. 1.4.5).

2.1.2 *Apparent density.** The apparent density of the activated carbon shall be not less than 0.25 g/cc as determined according to Sec. 4.4.

2.1.3 *Particle-size distribution.* Particle-size distribution shall be determined according to Sec. 4.5. The particle-size range of the granular activated carbon shall be as specified by the purchaser. Not greater than 15 percent of the activated carbon shall be retained on the maximum-size sieve, and not greater than 5 percent of the activated carbon shall pass the minimum-size sieve.

2.1.4 *Effective size.* The effective size of the granular activated carbon shall be within the limits specified by the purchaser. A range from .35 mm to 1.5 mm is available. This parameter does not apply to extruded carbons.

2.1.5 *Uniformity coefficient.* Unless otherwise specified by the purchaser, granular activated carbon shall have a uniformity coefficient not greater than 2.1 after backwashing and draining in the filter. This parameter does not apply to extruded carbons.

2.1.6 *Abrasion resistance.* The retention of average particle size of granular activated carbon shall not be less than 70 percent as determined by either the stirring abrasion test or the Ro-Tap abrasion test, according to Sec. 4.6.

2.1.7 *Surface area.* The surface area of granular activated carbon shall not be less than 500 m^2/g as determined by the Nitrogen BET Surface Area Test, according to Sec. 4.8.

2.1.8 *Pore volume.* The total pore volume of granular activated carbon shall not be less than 0.80 cc/g as determined according to Sec. 4.9.

2.1.9 *Water-soluble ash.* The water-soluble ash shall not exceed 4 percent as determined according to Sec. 4.10, Water Extractables Test.

*Backwash and drained density (in pounds) is calculated by multiplying apparent density by 62.43 times 0.85 (for bituminous-based activated carbons).

Sec. 2.2 Performance Criteria

2.2.1 *Adsorptive capacity—iodine number.* The iodine number of the granular activated carbon shall not be less than 500 mg/g carbon as determined according to Sec. 4.7. (See Foreword, Adsorptive Capacity, for discussion of other tests to determine special adsorptive characteristics for color, taste, and odor and specific organics removal. These special test procedures should be specified if deemed advisable, and the purchaser's specifications should allow adequate time to complete testing and confirmation analysis.)

2.2.2 *Additional adsorptive capacity tests.* If the purchaser desires to use additional adsorptive capacity tests to measure adsorptive capacity, the purchaser shall notify the supplier which type of shipment sampling will be required (Sec. 1.4.4).

Sec. 2.3 Impurities

2.3.1 *General impurities.* The granular activated carbon supplied according to this standard shall contain no substances in quantities capable of producing deleterious or injurious effects on the health of those consuming water that has been properly treated with granular activated carbon.

2.3.2 *Specific impurity limits.* The granular activated carbon shall not contain specific impurities in excess of the limits listed in the *Water Chemicals Codex.**

SECTION 3: SAMPLING, PACKAGING AND SHIPPING, AND MARKING

Sec. 3.1 Sampling

3.1.1 *Sampling location.* If the purchaser elects to accept the material on the basis as required in Sec. 1.4.4(4), samples shall be taken at the point of destination. The technique of sample collection shall be agreed on by both the supplier and the purchaser before shipment.

3.1.2 *Mechanical sampling.* If the granular activated carbon is handled by conveyor or elevator or shipped in bulk, a mechanical sampling arrangement may be used.

3.1.3 *Package sampling.* If the material is packaged, 5 percent of the packages shall be sampled. No sample shall be taken from a broken package. If the packaged material is shipped in carload quantities, one package from each lot number should be selected for sampling, with a minimum of 20 bags sampled from each carload.

3.1.4 *Sampling tube.* Carbon may be sampled, by the use of a sampling tube of at least ¾ in. (19 mm) diameter, from bulk carload shipments or from packages. When taking samples from packages, the sampling tube shall be extended the full length of the package to obtain a representative sample. It should be noted that it is virtually impossible to avoid particle fracture when using a sampling tube. Extreme care should be taken to minimize the effect of this on particle-size distribution. Sampling bulk shipping containers after shipment from the manufacturer will be subject

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to error caused by stratification and compaction during shipment. Extreme care should be exercised in sampling bulk shipping containers after shipment.

3.1.5 *Sample size.* The gross sample shall be sealed in airtight, moistureproof containers. Each sample container shall be labeled to identify it, and the label shall be signed by the sampler. The gross sample shall be divided using one of the following methods:

3.1.5.1 Mix thoroughly and divide to provide three 1-lb (0.45 kg) samples, or

3.1.5.2 Pour through a sample riffler. Repeat as necessary using the split portions to provide three 1-lb (0.45 kg) samples.

Sec. 3.2 Packaging and Shipping

3.2.1 *Containers.* Granular activated carbon shall be in packages acceptable to the US Department of Transportation (USDOT) and shall contain from 35 to 150 lb (16 to 68 kg) in each package, or other quantity as agreed on between the purchaser and the supplier.

3.2.2 *Package shipments.* Paper bag packages used in shipments of activated carbon in less than carload lots shall be protected by an outer package of a resistant nature, to avoid tearing the bags. Complete protection from weather shall be provided for the individual packages or by the conveyance.

3.2.3 *Tolerances.* The net dry weight of the packages shall not deviate from the recorded weight by more than 5 percent, plus or minus. Objections to the weight of the material received shall be based on a certified unit weight of not less than 10 percent of the packages shipped, which are selected at random from the entire shipment.

3.2.4 *Bulk shipments.* Bulk shipments of activated carbon shall be in clean cars or trucks with tight closures to avoid loss and contamination of the material in transit. The interior of the cars or trucks shall be clean and free from dirt, corrosion–scale, and other sources of contamination. Shipments in open-top hopper bottom cars are acceptable only with adequate provision for covering the material and keeping it contained and protected during shipment. The type of rail car or hopper truck shall be agreed on by the supplier and the purchaser before shipment. The criteria for choosing a car or truck are the type of handling equipment and the unloading facilities at the destination.

3.2.5 *Weight certification (bulk).* Bulk shipments shall be accompanied by weight certificates of certified weighers, if specified by the purchaser; or the weights may be checked by certified weighers for the purchaser on delivery.

Sec. 3.3 Marking

Each shipment of the material shall carry with it some means of identification.

3.3.1 *Packaged material.* Each container of granular activated carbon shall have marked legibly on it the net weight of the contents, the name of the manufacturer, the lot number, a brand name, if any, and shall bear other markings as required by applicable regulations and laws.*

3.3.2 *Bulk material.* When shipped in bulk, the information required in Sec. 3.3.1 for packaged material shall accompany the bill of lading.

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*Because of frequent changes in these regulations, their specific provisions should not be included in the purchaser's specifications.

3.3.3 *Conformance with standard.* (Optional) Containers may bear the statement: "This material meets the requirements of AWWA B604, Standard for Granular Activated Carbon," provided that the requirements of this standard are met, and the material is not of a different quality in separate agreement between the supplier and the purchaser.

SECTION 4: TESTING METHODS

Sec. 4.1 Samples

If the purchaser elects to accept the material on the basis specified in Sec. 1.4.4(3), samples shall be taken from each shipment of granular activated carbon according to Sec. 3.1. The sample delivered to the laboratory shall be divided to provide approximately 1 lb (0.45 kg). After thorough mixing, this sample should be stored in an airtight container and weighed out of it rapidly to avoid change in moisture content.

Sec. 4.2 Testing Period

The laboratory examination of a sample shall be complete in time to meet the requirements of Sec. 1.4.5 for notification of the supplier in the event tests reveal that the material does not comply with this standard or the purchaser's specifications.

Sec. 4.3 Moisture

4.3.1 *Procedure.* In a tared weighing bottle, accurately weigh approximately 2 g of the sample. Dry in a drying oven at 140°C for 2 h or 110°C for 3 h; then cool in a desiccator and weigh rapidly.

4.3.2 *Calculation.*

$$\frac{\text{loss of weight}}{\text{weight of sample}} \times 100 = \% \text{ moisture}$$

Sec. 4.4 Apparent Density

4.4.1 *General.* The apparent density of a carbon is the weight in grams per cubic centimetres (g/cc) of the carbon in air. Carbons should have the density determined on an "as-received" basis with corrections made for moisture content.

4.4.2 *Apparatus.* Testing apparatus shall be as shown in Figure 1. Reservoir and feed funnels are glass or metal. The metal vibrator is 26-gauge galvanized sheet metal. A balance having a sensitivity of 0.1 g is required.

4.4.3 *Procedure.*

1. Carefully place a representative sample of the carbon into the reservoir funnel. If the material prematurely flows into the graduated cylinder, return the material to the reservoir funnel.

2. Add the sample to the cylinder by the vibrator feeder at a uniform rate not less than 0.75 mL/s nor greater than 1.0 mL/s up to the 100-mL mark. Adjust the rate by changing the slope of the metal vibrator or raising or lowering the reservoir

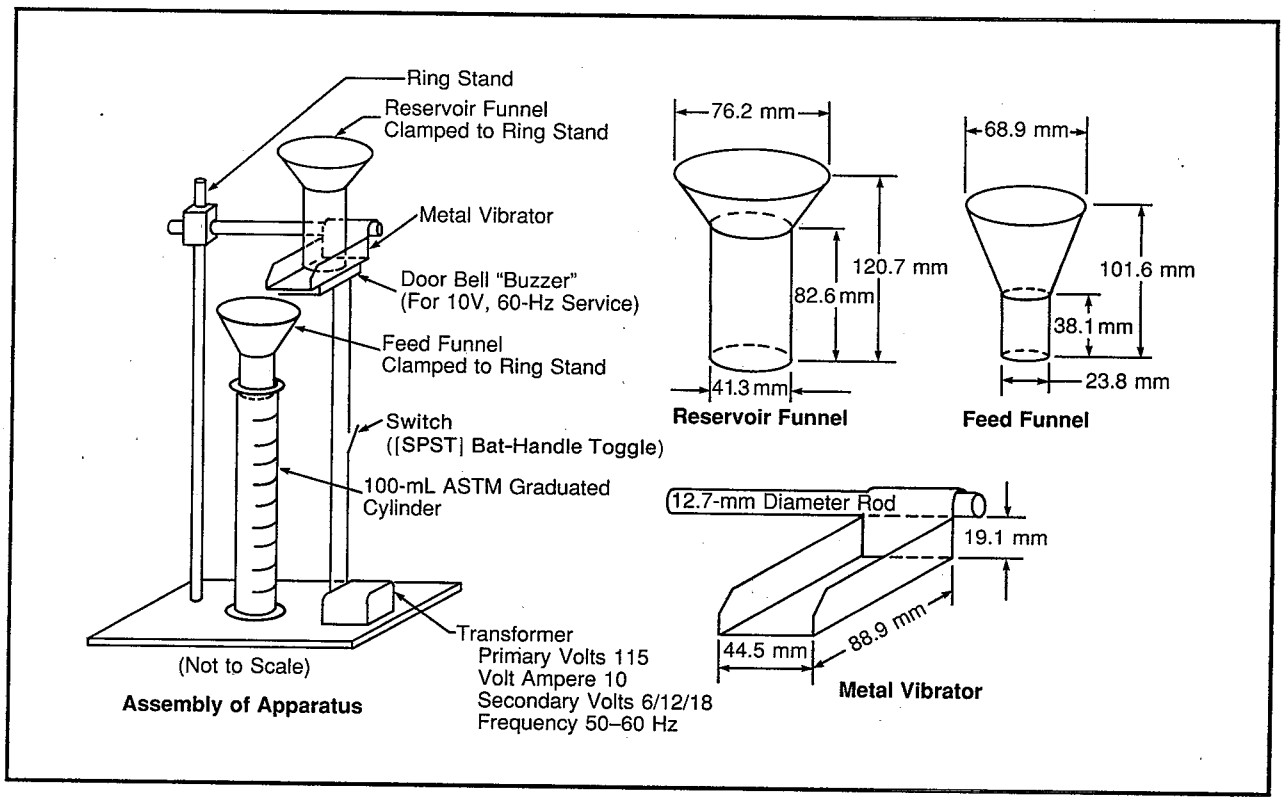

Figure 1 Apparent-density test apparatus.

funnel, or both, or by using a variable autotransformer to vary the current to the buzzer transformer.

3. Transfer the contents from the cylinder to a balance pan and weigh to the nearest 0.1 g.

4.4.4 *Calculation.* Calculate the apparent density in grams/millilitre on the dry basis:

$$\text{apparent density} = \frac{(\text{weight of carbon}) \times (100 - \%\ \text{moisture})}{10{,}000}$$

Sec. 4.5 Particle-Size Distribution

4.5.1 *General.* Determine the particle-size distribution of granular activated carbon by mechanically shaking a weighed amount of material through a series of US standard sieves and then determining the quantity retained on or passing through each sieve.

4.5.2 *Apparatus.*

- Sample splitter—similar to Jones riffler
- Sieve shaker, electrically driven, equipped with automatic timer similar to Ro-Tap

- Sieves—US standard sieves, 8 in. in diameter and 2 in. high
- Bottom receiver pan—8 in. diameter, full height
- Top sieve cover—8 in. diameter
- Balance—top loader with sensitivity of 0.1 g
- Brush—soft brass-wire brush

4.5.3 *Procedure.*

1. Assemble the sieves to be used on the bottom receiver pan in order of increasing sieve opening size from bottom to top. The smallest and largest opening size sieves should correspond to the limiting sizes for the grade of carbon specified; such as for 12 × 40 carbon, use sieve numbers 12, 14, 16, 20, 30, and 40. US standard sieves and opening sizes are tabulated in Table 1.

2. Mix the sample by passing the material through the riffle and recombining twice.

3. Carefully reduce the mixed sample by repeated passes through the riffle to obtain a test sample of 100 ± 5 g. No more than 5.0 g of activated carbon may be added or taken from the test sample without additional riffling.

4. Transfer the weighed sample to the top sieve. Install the sieve cover and sieve shaker cover and place the assembly on the sieve shaker.

5. Allow the sieve assembly to shake for 3 min ± 3 s with the hammer operating.

6. Remove the sieve assembly from the sieve shaker and quantitatively transfer the activated carbon retained on the top sieve to a tared balance pan and weigh to the nearest 0.1 g. Repeat this procedure for material retained on each subsequent sieve and the bottom receiver pan. Lightly brush the material from each sieve to free particles held in the screen.

7. Add the weights of each sieve fraction, and if the sum deviates more than 2.0 g from the test sample weight, repeat the analyses.

4.5.4 *Percentage retained on each sieve.*

$$\frac{\text{(sieve fraction weight) (100)}}{\text{(sum of sieve fraction weights)}} = \%\ \text{retained on each sieve}$$

Table 1 US Standard Sieves and Opening Sizes

US Standard Sieve Number	Sieve Opening *mm*
8	2.36
10	2.00
12	1.70
14	1.40
16	1.18
20	0.850
30	0.600
40	0.425
50	0.300

4.5.5 *Effective size and uniformity coefficient.*

a. From the percentage retained on each sieve, calculate the cumulative percentage passing each sieve. The cumulative percentage passing a sieve is the sum of all the percentages retained on subsequent (smaller) sieves plus the percentage retained on the pan.

b. Using probability × logarithmic paper or semilogarithmic paper, plot the sieve opening in millimetres on the ordinate or vertical scale versus the cumulative percentage passing each sieve on the abscissa or horizontal scale.

c. The effective size is the sieve opening in millimetres at which 10 percent of the material passes on the cumulative percentage passing scale.

d. The uniformity coefficient is determined by dividing the millimetre opening at which 60 percent passes by the millimetre opening at which 10 percent passes.

Sec. 4.6 Abrasion Resistance

4.6.1 *General.* Determine abrasion resistance either by the stirring abrasion test or by the Ro-Tap abrasion test as follows.

4.6.2 *Stirring abrasion test.* The stirring abrasion test measures percentage retention of the average particle size in the carbon after abrading the carbon by the action of a T-shaped stirrer in a specially fabricated abrasion unit. This test is used to measure abrasion resistance of lignite- and petroleum-coke-base granular activated carbons.

4.6.2.1 Sieving apparatus—stirring abrasion test.

- Sieve shaker, electrically driven, equipped with automatic timer—similar to Ro-Tap
- Sieves—US standard sieves, 8 in. diameter and 2 in. high; Table 2 indicates sieves that are required
- Bottom receiver pan—8 in. diameter, full height
- Top sieve cover—8 in. diameter
- Balance—top loader with sensitivity of 0.1 g
- Brush—soft brass-wire brush

4.6.2.2 Stirring abrasion unit. The abrasion unit is detailed in Figure 2. The apparatus includes a T-shaped stirrer made from ½-in. metal rod that is driven at 855 ± 15 rpm. The stirrer and cylinder may be made of any suitable material; for

Table 2 Sieving Apparatus Required for Stirring Abrasion Test

US Standard Sieve Number	Sieve Opening *mm*	Average Opening *mm* (D_i)
8	2.36	—
12	1.70	2.03
16	1.18	1.44
20	0.850	1.02
40	0.425	0.64
50	0.300	0.36
70	0.212	0.26
pan	—	0.15

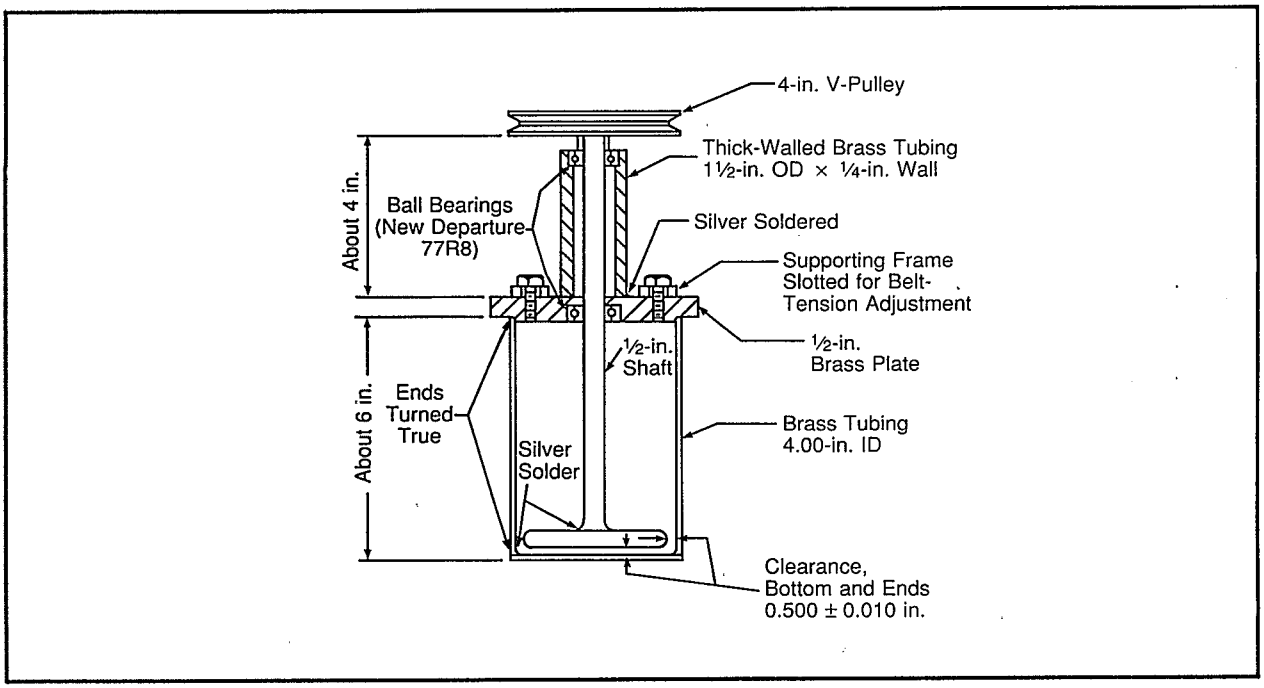

Figure 2 Stirring abrasion unit.

example, steel, stainless steel, or brass. The absence of burrs and rough welds is absolutely necessary. The T-bar stirrer should be replaced when the length of the cross bar is 0.02 in. less than the designed size or when the hemispherical ends show signs of serious wear; that is, when the length of the cross bar is more than 0.025 in. from the designed size. Such wear will show on the leading edge of the T-bar stirrer.

4.6.2.3 Procedure—stirring abrasion test.

1. Place a No. 8 sieve on top of a No. 70 sieve on the sieve shaker. Screen sufficient granular activated carbon sample to obtain 250–300 mL of 8 × 70 mesh carbon by shaking portions of the activated carbon on the sieve shaker for exactly 3 min ± 2 s with the hammer operating. Discard the material retained on the No. 8 sieve and the material passing the No. 70 sieve.

2. Place the 250–300-mL portion of granular activated carbon on the top screen of a nest of US standard sieves, numbers 12, 16, 20, 40, 50, and 70; and shake on the sieve shaker for 15 min ± 10 s with the hammer operating.

3. Remove the sieve assembly from the sieve shaker and quantitatively transfer the carbon retained on the top sieve to a tared balance pan and weigh to the nearest 0.1 g. Repeat this procedure for material retained on each subsequent sieve and the bottom receiver pan. The material should be lightly brushed from each sieve to free particles held in the screen. Record the weight of each sieve fraction and the total weight of carbon recovered.

4. Recombine and blend by tumbling the sieve fractions very gently in a quart fruit jar or similar container and place the carbon in the abrasion unit. Operate the abrasion unit for 1 h ± 1 min.

5. Remove the carbon from the abrasion unit and repeat the screening on a nest of US standard sieves, numbers 12, 16, 20, 40, 50, and 70, as in step 2. Use the same sieve shaker as was used for the initial sieve analysis. Record the weight of each sieve fraction and the total weight of carbon recovered.

4.6.2.4 Calculations—stirring abrasion test. Calculate the average particle size before and after stirring by using the following equation:

$$D_{avg} = \frac{\text{summation of } (W_i \times D_i)}{\text{summation of } (W_i)}$$

Where:

D_{avg} = the average particle size, in millimetres
W_i = the weight of a sieve fraction, in grams
D_i = the opening in millimetres that corresponds to the average of the openings in the two sieves that enclose that mesh fraction (See Table 2.)

Calculate the percentage retention of average particle size; adjust to 1 mm original particle size by using the following equation:

$$\%\ \text{retention/millimetre} = (100)\left[1 - \frac{(\text{original } D_{avg} - \text{final } D_{avg})}{(\text{original } D_{avg})^2}\right]$$

Report the value obtained as the percentage retention of particle size from the stirring abrasion test.

4.6.3 *Ro-Tap abrasion test.* The Ro-Tap abrasion test measures the percentage retention of original average particle size by the resistance of the particles to the action of steel balls in the Ro-Tap machine. This test is used to measure abrasion resistance of bituminous coal and petroleum-coke-base granular activated carbons.

4.6.3.1 Sieving apparatus—Ro-Tap abrasion test.

- Sample splitter—similar to Jones riffler
- Ro-Tap—sieve shaker, electrically driven, equipped with automatic timer
- Sieves—US standard sieves, 8 in. diameter and 2 in. high
- Bottom receiver pan—8 in. diameter, full height
- Top sieve cover—8 in. diameter
- Balance—top loader with sensitivity of 0.1 g
- Brush—soft brass-wire brush

4.6.3.2 Testing pan assembly. The abrasion pan assembly is detailed in Figure 3. The assembly consists of a Ro-Tap lid with cork insert, a half-height blank pan, a specially fabricated abrasion testing pan, and a bottom receiver pan. The abrasion testing pan is detailed in Figure 4. Ten ½-in. (12.7-mm) diameter and ten ¾-in. (19-mm) diameter smooth steel balls will also be required. The steel balls will be placed in the testing pan together with the carbon sample to be tested for the abrasion test.

4.6.3.3 Procedure—Ro-Tap abrasion test.

1. Assemble the sieves to be used on the bottom receiver pan in order of increasing sieve opening from bottom to top. Suggested sieve sizes to be used with various particle-size ranges are given in Table 3.

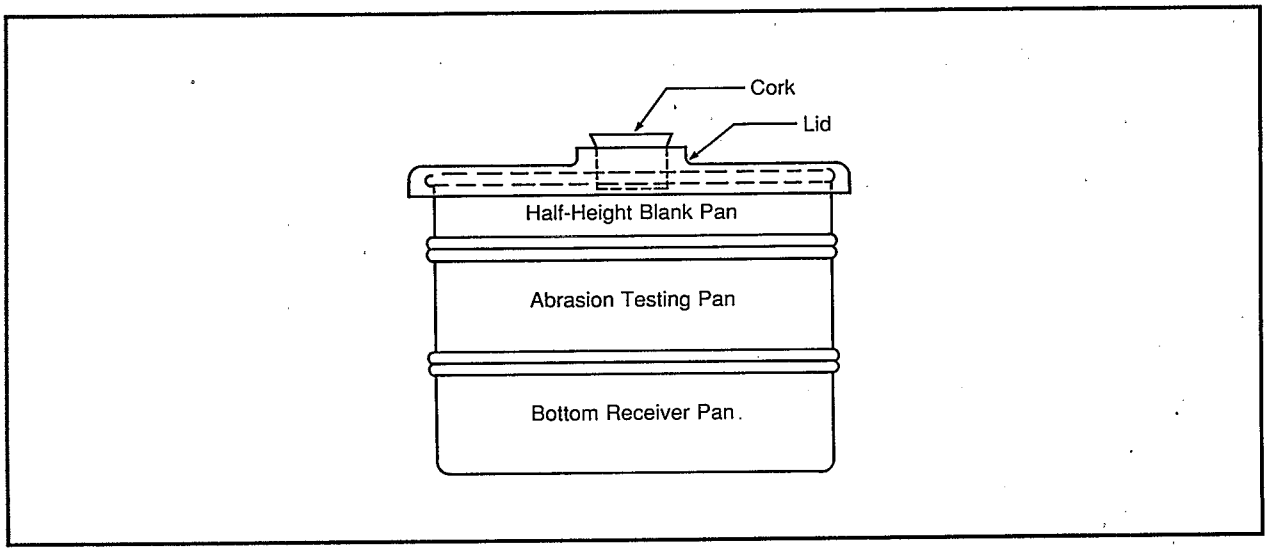

Figure 3 Testing pan assembly for Ro-Tap abrasion test (not to scale).

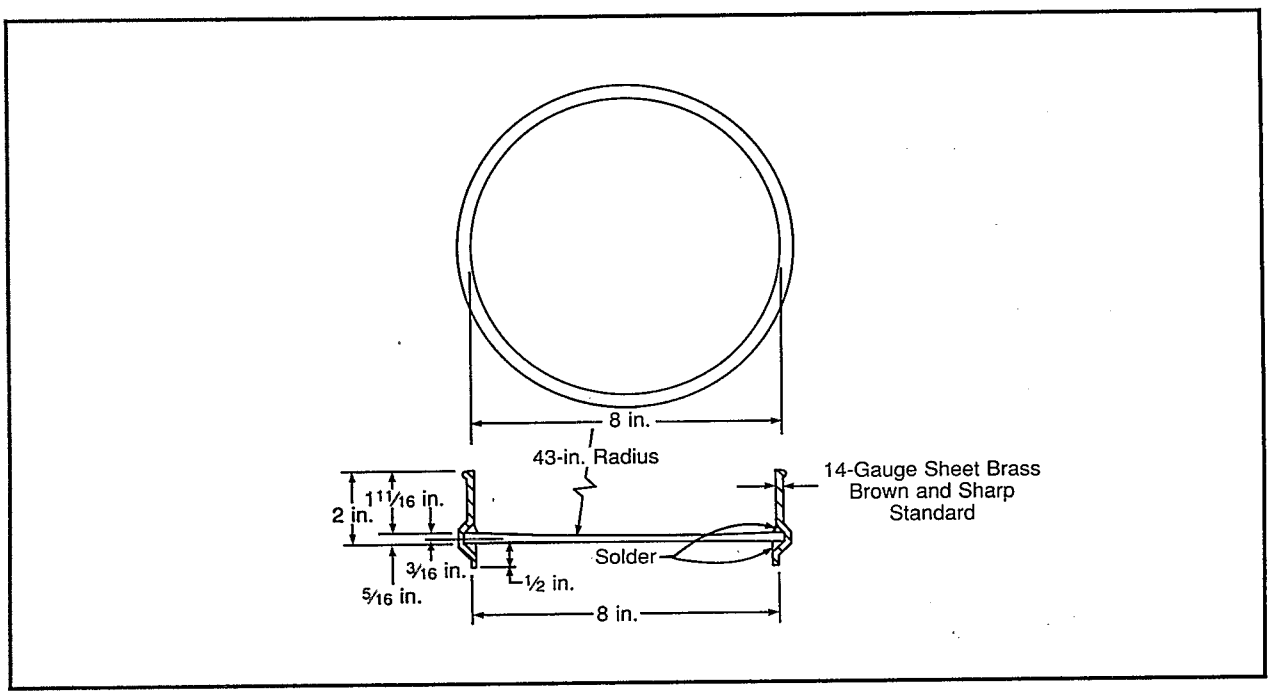

Figure 4 Abrasion testing pan for Ro-Tap abrasion test (not to scale).

Table 3 Recommended Particle Sieve Sizes

Particle-Size Range	US Standard Sieve Sizes
8 × 16	8, 12, 16, pan
8 × 20	8, 12, 16, 20, pan
8 × 30	8, 12, 16, 20, 30, pan
10 × 30	10, 12, 16, 20, 30, pan
12 × 40	12, 16, 20, 30, 40, pan
14 × 40	14, 16, 20, 30, 40, pan
20 × 40	20, 30, 40, pan
20 × 50	20, 30, 40, 50, pan

2. Mix the sample by passing the material through the riffle and recombining twice.

3. Carefully reduce the mixed sample by repeated passes through the riffle so as to obtain a test sample of 100 ± 5 g. Do not add to or take from the sample more than 5.0 g of carbon without additional riffling.

4. Transfer the weighed sample to the top sieve.

5. Install the sieve cover and Ro-Tap cover and place the assembly on the Ro-Tap sieve shaker.

6. Allow the sieve assembly to shake for 10 min ±10 s with the hammer operating.

7. Prepare the abrasion testing pan and count the steel balls to ensure that ten ½-in. (12.7-mm) and ten ¾-in. (19-mm) diameter smooth steel balls are contained in the pan.

8. Remove the sieve assembly from the Ro-Tap and quantitatively transfer the carbon retained on the top sieve to a tared balance pan and weigh to the nearest 0.1 g; then transfer to the abrasion testing pan. Repeat this procedure for material retained on each subsequent sieve and the bottom receiver pan. The material should be lightly brushed from each sieve to free particles held in the screen. Record the weight of each sieve fraction and the total weight of carbon recovered.

9. After the sieve fractions have been weighed and recombined in the abrasion testing pan, place the testing pan assembly on the Ro-Tap sieve shaker. The testing pan assembly must be level and fit snugly on the Ro-Tap.

10. Allow the testing pan assembly to shake for 20 min ± 2 s with the hammer operating. The time is critical, and if the automatic timer is not capable of the specified accuracy, the sieve shaker should be manually controlled and timed with a stopwatch.

11. Remove the abrasion pan from the Ro-Tap and quantitatively transfer the contents to the original set of sieves. A large-opening sieve may be temporarily nested into the top sieve to remove the steel balls from the carbon, or the balls may be removed by hand.

12. Repeat steps 5, 6, and 8 using the same Ro-Tap as was used for the initial sieve analysis. However, after this second sieve analysis, discard the individual screen fractions after weighing. Repeat the analysis if the sum of either sieve analysis deviates by more than 2.0 g from the test sample weight.

4.6.3.4 Calculations—Ro-Tap abrasion test.

(a) Calculate the original and final average particle size by using the following equation:

$$D_{avg} = \frac{\text{summation of } (W_i \times D_i)}{\text{summation of } (W_i)}$$

Where:

D_{avg} = the average particle size, in millimetres
W_i = the weight of a sieve fraction, in grams
D_i = the opening in millimetres that corresponds to the average of the openings in the two sieves that enclose that mesh fraction

Material caught on the pan is not considered in calculating the average particle diameter. Values for D_i are given in Table 4.

(b) Calculate average particle size; example calculation using a 12 × 30 mesh material.

US Standard Sieve No.	Retained *percent*	Average Opening D_i *mm*	Average*
+12	1.5	2.03†	3.0
12 × 16	25.0	1.44	36.0
16 × 20	50.0	1.02	51.0
20 × 30	22.5	0.725	16.3
+30	1.0	0.00	0.0
	100.0		106.3

$$D_{avg} = \frac{106.3}{100.0} = 1.063$$

(c) Calculate the percentage retention of average particle size by using the following equation:

$$\text{retention, } percentage = \frac{\text{final } D_{avg}}{\text{original } D_{avg}} \times 100$$

Report the value obtained as the percentage retention of average particle size from the Ro-Tap Abrasion Test.

*The 2.03 factor was used for material remaining on the No. 12 sieve because it was assumed this material would pass through a No. 8 sieve (generally the next larger sieve in the square root of two series).

†Weighted.

Table 4 D_i Values for Ro-Tap Abrasion Test

US Standard Sieve Numbers	Average Opening (D_i)—*mm*
6 × 8	2.86
8 × 10	2.18
8 × 12	2.03
10 × 12	1.85
12 × 14	1.55
12 × 16	1.44
14 × 16	1.29
16 × 20	1.02
20 × 30	0.725
30 × 40	0.513
40 × 50	0.360

Sec. 4.7 Test Method for Iodine Number

The procedure for determining the iodine number of activated carbon is ASTM* D4607, Standard Test Method for Determination of Iodine Number of Activated Carbon.

Sec. 4.8 Surface Area Determination

The procedure for determining the surface area of activated carbon is the Nitrogen BET Surface Area Test. The reference procedure to perform this test is ASTM D3037, Standard Test Methods for Carbon Black—Surface Area by Nitrogen Adsorption.

Sec. 4.9 Pore Volume Determination

The procedure for the determination of the total pore volume of an activated carbon employs a combination of mercury and helium displacement techniques. The reference procedure to perform this test is ASTM C699, Standard Methods for Chemical, Mass Spectrometric, and Spectrochemical Analysis of, and Physical Tests on, Beryllium Oxide Powder.

Sec. 4.10 Water Extractables Test

The method used for determining the water extractable content of activated carbon is found in the *Food Chemicals Codex*† procedure, under the category of Carbon, Activated.

*American Society for Testing and Materials, 1916 Race St., Philadelphia, PA 19103.

†*Food Chemicals Codex*, National Academy Press, 2101 Constitution Ave., N.W., Washington, DC 20418.

APPENDIX A
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APPENDIX B
Adsorptive Capacity Tests

This appendix is for information only and is not a part of ANSI/AWWA B604.

These tests were added because they are referred to in the Adsorptive Capacity section of the foreword, and they could aid some purchasers in the analysis of granular carbon used for water treatment.

SECTION B.1 TANNIN ADSORPTION TEST

Sec. B.1.1 Stock Tannic Acid Solution—500 mg/L

Dissolve exactly 1.00 g of NF grade tannic acid in distilled water and dilute to 2 L in a volumetric flask. Use tannic acid similar to Merck & Company, NF catalog number 04541 or equivalent.

Sec. B.1.2 Test Procedure

A piece of 0.75-in. (19-mm) inside diameter (ID) tubing* (glass or acrylic) about 7 in. (175 mm) long is fitted at the bottom with a one-hole rubber stopper, a short piece of rubber tubing, and an adjustable hose clamp. A piece of 80-mesh screen is used in the bottom of the tube to support the carbon. The tube is marked to indicate a carbon volume of 32 mL. A weighed amount of granular carbon is added to the tube to approximately the 32-mL mark, then gently washed upflow to remove any fines. If needed, additional carbon is added to the 32-mL mark, and the column is backwashed again. After backwashing, the water level is allowed to fill to the top of the carbon bed. Care should be taken so the carbon in the column is completely submerged at all times; otherwise, channeling will occur through the center of the bed.

One litre of 500-mg/L tannic acid solution is passed downflow through the column at the rate of 15 mL/min (assuming 0.75-in. [19-mm] tubing is used), and the entire effluent is collected in a receiving flask. If a suitable pump is not available, the tannic acid solution can be fed from a separatory funnel held above the column by adjusting the stopcock to give a flow of 15 mL/min.

The effluent is mixed and the concentration of tannin remaining is determined by either UV absorbance at 275 mμm by evaporation of a portion of the mixed filtrate or by the standard AWWA color method (see Sec. B1.3.3) for the tannin analysis.

Sec. B.1.3 Determination of Tannin in Effluent

B.1.3.1 *UV absorbance.* A sample of mixed effluent and of the original 500-mg/L tannin feed is read on a UV spectrophotometer at 275 mμm (maximum

*A larger diameter tube can be used with appropriate adjustments of carbon volume, flow rate, and total volume of tannic acid solution used.

Table B.1 Standard Curve of Tannin Dilution

Tannin—*mg/L*	500 mg/L Tannin—*mL*	Distilled Water *mL*
5	1	99
25	5	95
50	10	90
100	20	80
200	40	60
300	60	40
400	80	20

absorbance peak). Samples are diluted with distilled water until a direct instrument scale reading can be obtained and corrected for dilution. A standard curve is prepared by diluting the 500-mg/L tannin feed as shown above in Table B.1.

The optical density of each above dilution at 275 mμm is plotted against milligrams per litre tannin. From the standard curve, the milligrams per litre tannin in each effluent sample is determined.

Calculation:

$$\text{percentage tannin adsorbed} = 100\left[1 - \frac{\text{effluent tannin (in milligrams per litre)}}{\text{influent tannin (in milligrams per litre)}}\right]$$

$$\frac{\text{weight tannin adsorbed (in grams)}}{\text{100 g carbon}} = \frac{\text{percentage tannin adsorbed} \times 5\text{ g} \times \text{litres used}}{\text{weight carbon in column (in grams)}} \times 100$$

B.1.3.2 *Evaporation of mixed effluent.* Exactly 200 g of mixed effluent and a 200-g feed sample are evaporated in a 100°C convection oven to dryness and each residue weighed on an analytical balance to the nearest milligram.

Calculation:

$$\text{percentage tannin adsorbed} = 100\left[1 - \frac{\text{effluent residue (in grams)}}{\text{influent residue (in grams)}}\right]$$

$$\frac{\text{weight tannin adsorbed (in grams)}}{\text{100 g carbon}} = \frac{\text{percentage tannin adsorbed} \times 5\text{ g} \times \text{litres used}}{\text{weight carbon in column (in grams)}} \times 100$$

B.1.3.3 *AWWA–APHA–WPCF method.* The residual mg/L tannin is determined colorimetrically for the mixed effluent and feed using the AWWA–APHA–WPCF method for tannin and lignin. Reagents and apparatus required are given in method

number 5550 *Standard Methods for the Examination of Water and Wastewater.** Calculations are made in the same manner as previously described.

SECTION B.2 PHENOL ADSORPTION TEST

Sec. B.2.1 Reagents

a. Stock phenol solution—5000 mg/L. Dissolve 5.0 g reagent-grade phenol in distilled water and dilute to 1 L. Phenol should be weighed in a glass weighing dish. Rinse the dish several times with distilled water to ensure transfer of all phenol from the dish into the solution. Standardize. If the concentration of phenol is more than ± 200 mg/L, either dilute with distilled water or add more phenol to get the desired concentration. After two weeks, this solution should be discarded and fresh solution prepared. (Reagent-grade phenol should be stored in a refrigerator.)

b. Sodium thiosulfate solution—0.1*N*. Dissolve 25.0 g reagent-grade sodium thiosulfate and 1.0 g reagent-grade sodium carbonate (as a preservative) in boiled distilled water and make up to 1 L. Store in a brown bottle. Standardize.

c. Potassium bromate–bromide solution—0.1*N*. Dissolve 2.784 g of reagent-grade potassium bromate and 10.0 g reagent-grade potassium bromide (bromate-free) in distilled water and make up to 1 L. Store in a brown bottle.

d. Potassium biniodate solution—0.1*N*. Dissolve 3.2499 g potassium biniodate, primary standard, in distilled water and make up to 1 L.

e. Potassium iodide solution—12.5 percent. Dissolve 25 g reagent-grade potassium iodide in 175 mL distilled water. Store in a brown bottle. (Discard when it develops a yellow color.)

f. Starch solution. Dissolve 5.0 g soluble potato powder starch and 1.25 g reagent-grade salicylic acid in 50 mL distilled water. Add the dissolved starch and salicylic acid slowly, while stirring, to 950 mL boiling distilled water. Rinse the beaker with some of the hot starch solution to ensure removal of all the starch.

Sec. B.2.2 Standardization of Reagents

a. Sodium thiosulfate solution. Add 100 mL distilled water; 4 mL concentrated, reagent-grade hydrochloric acid; and 8 mL, 12.5 percent potassium iodide solution to a 500-mL iodine flask and mix. Rinse down sides of the flask with distilled water. Using a transfer pipette, add 25 mL 0.1*N* potassium biniodate solution to the flask. Mix and allow to stand for 3 min. Titrate with the 0.1*N* sodium thiosulfate solution using starch solution as the indicator.

Calculation:

$$\text{phenol concentration (in grams per litre)} = \frac{[(\text{millilitres bromate–bromide} \times \text{NF}) - (\text{millilitres thiosulfate} \times \text{NF})]}{\text{millilitres phenol solution titrated}} \times 15.685$$

Standard Methods for the Examination of Water and Wastewater. APHA, AWWA, WPCF. AWWA, Denver (17th ed., 1989).

b. Stock phenol solution. Pipette 25 mL stock phenol solution into a 500-mL iodine flask and add 15 mL concentrated, reagent-grade hydrochloric acid. Titrate with the potassium bromate–bromide solution to a slight yellow color. (For 5000 mg/L phenol concentration, it will require about 80–90 mL of solution to produce the yellow color.) Shake the flask and allow to stand for 3 min. Add 8 mL of 12.5 percent potassium iodide solution, shake, and allow to stand for 3 min. Titrate the liberated iodine with the standardized 0.1*N* sodium thiosulfate solution, using the starch solution as indicator.

Calculation:

$$\text{normality sodium thiosulfate solution} = \frac{\text{millilitres potassium biniodate} \times \text{NF biniodate}}{\text{millilitres sodium thiosulfate solution used}}$$

Sec. B.2.3 Test Procedure

a. Phenol adsorption. A piece of 0.75-in. (19-mm) ID tubing (glass or acrylic) about 7 in. (175 mm) long is fitted at the bottom with a one-hole rubber stopper, a short piece of rubber tubing, and an adjustable hose clamp. A piece of 80-mesh screen is used in the bottom of the tube to support the carbon. The tube is marked at such a height as to indicate a carbon volume of 32 mL. The granular carbon is added to the tube to about the 32-mL mark, then gently washed upflow to remove any fines. If needed, additional carbon is added to the 32-mL mark, and the column is backwashed again. After backwashing, the water level is allowed to fall to the top of the carbon bed.

One litre of phenol solution at 5000 mg/L is passed downflow through the column at the rate of 15 mL/min, and the entire effluent is collected in a receiving flask.

The effluent is mixed and the concentration of phenol determined.

b. Determination of phenol in effluent. A 25-mL aliquot of the mixed effluent is placed in a 500-mL iodine flask. The same procedure and calculation used to determine the concentration of the stock solution in B.2.2(b) is used to determine the phenol in effluent.

Calculation:

$$\text{percentage phenol adsorbed} = 100\left[1 - \frac{\text{effluent phenol (in milligrams per litre)}}{\text{influent phenol (in milligrams per litre)}}\right]$$

$$\frac{\text{weight phenol adsorbed (in grams)}}{\text{100 g carbon}} = \frac{\text{percentage phenol adsorbed} \times \text{5 g} \times \text{litres used}}{\text{weight carbon in column (in grams)}} \times 100$$

Part 3

Membrane Precursor Removal Studies

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Notice

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Contents

Figures

Tables

Symbols

A	Membrane area
B (subscript)	Bulk solution
b (subscript)	Blended water quality parameters (permeate:feed blend)
BCAA	Bromochloroacetic acid
C	Concentration
C (subscript)	Concentrate
CA	Cellulose acetate
$CaCO_3$	Calcium carbonate
CF	Cleaning frequency
cfs	Cubic feet per second
Cl_2	Chlorine
D-DBP	Disinfectants-Disinfection byproducts
DBAA	Dibromoacetic acid
DBP	Disinfection byproduct
DCAA	Dichloroacetic acid
$dMTC_W / dt$	Time rate of decline in the MTC_W
DV	Design value
e (subscript)	Element
EDR	Electrodialysis reversal
fps	Feet per second
F (subscript)	Feed
F_S	Solute flux
F_W	Water flux
F_W(Tavg°C)	F_W normalized to the average yearly water temperature
GAC	Granular activated carbon
gpd	Gallons per day
gfd	Gallons per day per square foot
HAAs	Haloacetic acids
HAA5	Sum of 5 HAAs: MCAA, DCAA, TCAA, MBAA & DBAA
HAA6	Sum of 6 HAAs: HAA5 & BCAA
I (subscript)	Influent
ICR	Information Collection Rule
PVD	Polyvinyl derivative
L_{cell}	Active length of membrane area in the bench-scale cell
MBAA	Monobromoacetic acid
MCAA	Monochloroacetic acid
MCL	Maximum contaminant level
MF	Microfiltration
MFI	Modified fouling index
MPFI	Mini plugging factor index
MW	Molecular weight
MWCO	Molecular weight cutoff
MTC_W	Water mass transfer coefficient

$MTC_{W(0)}$	Baseline MTC_W
N_e	Number of elements in a pressure vessel
N_v	Number of pressure vessels in a stage
NDP	Net driving pressure
NF	Nanofiltration
NOM	Natural organic matter
P	Pressure
p (subscript)	Permeate
Q	Flow rate
Q_T	Total product flow rate (sum of by-pass and permeate flows)
r	Recycle ratio
R	Recovery
R (subscript)	Recycle
R_B	Bulk rejection
R_F	Feed rejection
RBSMT	Rapid bench-scale membrane test
Rej_{TSD}	Manufacturer reported TDS rejection
RO	Reverse osmosis
RPD	Relative percent difference
s (subscript)	Stage
SDI	Silt density index
SEBST	Single element bench-scale test
sys (subscript)	System
T	Feed spacer thickness
T°C	Ambient temperature in degrees Celsius
Tavg°C	Average yearly water temperature in degrees Celsius
TCAA	Trichloroacetic acid
TDS	Total dissolved solids
TFC	Thin-film composite
THMs	Trihalomethanes
THM4	The sum of four trihalomethanes
TOC	Total organic carbon
TOX	Total organic halides
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
UV_{254}	Ultraviolet absorbance (wave length = 254 nm)
v_c	Cross-flow velocity
w_{cell}	Acitve width of membrane in the bench-scale cell
$w_{element}$	Scroll width of an element
W (subscript)	Waste
$\Delta\pi$	Osmotic pressure gradient
ΔP_c	The pressure drop through a membrane element
ΔP_s	The pressure drop through the stage hardware
Ω	Acceptable fractional loss in the MTC_W prior to cleaning
Γ	Stage flow weighted factor

1.0 Introduction

The Information Collection Rule (ICR) for Public Water Systems (PWSs) (Subpart M of the National Primary Drinking Water Regulations) will require PWSs to conduct disinfection byproduct (DBP) precursor removal studies if they meet the applicability criteria described in § 141.141 (e) of the ICR. The DBP precursor removal studies, referred to as treatment studies, are described in § 141.144 of the ICR. Part 1 of this manual provides a summary of the ICR treatment studies requirements.

Treatment studies must be performed on either membrane separations (i.e., nanofiltration or reverse osmosis), or granular activated carbon (GAC) using either bench-scale or pilot-scale procedures. Both of these technologies are effective for the removal of DBP precursors, and are potentially capable of meeting the maximum contaminant levels (MCLs) stated in the proposed Disinfectants/Disinfection Byproducts (D/DBP) Rule. Stage 1 of this rule establishes the MCLs for the sum of four trihalomethanes (THM4) and the sum of five haloacetic acids (HAA5) at 80 μg/L and 60 μg/L, respectively. The place holders for the Stage 2 MCLs are 40 μg/L and 30 μg/L for THM4 and HAA5, respectively. The objective of these treatment studies is to generate cost and performance data for membrane and GAC processes used to meet the proposed Stage 2 DBP MCLs when free chlorine is used as the disinfectant.

1.1 Organization Of Part 3

The purpose of this part of the manual is to provide guidance for the pilot- and bench-scale evaluation of membrane processes in accordance with the requirements of the ICR. This document provides guidance on three procedures for evaluating membrane performance, a flat-sheet test (the rapid bench-scale membrane test), a single element bench-scale approach, and a pilot-scale approach. Section 2.0 provides an overview of concepts and terminology used in nanofiltration. This section also sites the results of several membrane studies and provides a general indication of membrane performance in water treatment.

Section 3.0 presents an overview of the three procedures described in this manual: the rapid bench-scale membrane test (RBSMT), a single element bench-scale test (SEBST), and pilot-scale testing; and describes the advantages and limitations of each approach. Sections 4.0, 5.0 and 6.0 describe the details and specific requirements of the RBSMT, SEBST and pilot-scale testing, respectively. Section 7.0 requests specific cost information to develop cost estimates for this technology.

1.2 ICR Requirements For Membrane Studies

The ICR requires that treatment studies be conducted with the effluent from treatment processes already in place that remove DBP precursors but prior to the addition of chlorine-based oxidants that form halogenated DBPs. If chlorine-based oxidants are added prior to full-scale processes that remove DBP precursors, then bench- or pilot-scale treatment processes must be used to simulate these full-scale processes. These processes may be optimized, and additional processes employed, in order to provide an acceptable feed water for the membrane studies.

Judgment should be exercised when selecting the point at which water is sampled for the study and the treatment processes used prior to membrane separations.

The ICR has provisions for both quarterly studies using the RBSMT or SEBST procedures and long-term SEBST studies. For the quarterly bench-scale studies, the ICR requires that two different membranes with manufacturer reported molecular weight cutoffs less than 1000 Daltons be evaluated quarterly over one year to evaluate the impact of seasonal variation on membrane performance. If seasonal variation is not expected to be significant, then four tests must be run to evaluate the impact of other parameters. For the long-term SEBST studies, the ICR requires that one membrane with a manufacturer reported molecular weight cutoff less than 1000 Daltons be evaluated continuously for one year.

The ICR requires that pilot-scale systems be designed as a staged array of elements to yield information on fouling, pretreatment requirements, cleaning requirements and permeate quality. Only one membrane type with a manufacturer reported molecular weight cutoff less than 1000 Daltons must be evaluated during pilot-scale studies. The pilot-studies should be run continuously over a one year period for at least 6600 hours run time, regardless of seasonal variation.

This treatment studies manual is referenced in the ICR rule and contains specific requirements of the rule. The ICR requirements listed in this manual include sampling and reporting requirements for each type of study. This manual also provides guidance to assist in setting-up and conducting these studies, and this guidance should not be interpreted as specific requirements. Guidance is provided on selecting membranes, selecting pretreatment processes, and on the design of bench- and pilot-scale systems. In preparing this manual, an effort has been made to distinguish between specific ICR requirements and guidance.

2.0 Background Information

The growth of drinking water regulations, improved water quality analysis and advances in membrane technology have created applications for membranes that will change accepted drinking water treatment technology. Public notification of outbreaks of waterborne pathogens following scientific disclosure and reporting by national and local news media has raised the public and political awareness of drinking water quality to a point where drinking water suppliers must use the best available technology to meet drinking water regulations (Fox and Lytle, 1994; Fox and Lytle 1993). The resulting financial liability is justification enough for using the most reliable technology to produce drinking water. Membrane technology is clearly among the leading technologies for producing high quality drinking water and can be used to meet current and future drinking water regulations in the United States.

2.1 Fundamentals Of Membrane Processes

2.1.1 Terminology And Concepts

The basic definition of a synthetic membrane is a barrier which separates two phases and restricts the transport of various chemical species in a specific manner (Porter, 1990). Under this broad definition, membranes can vary widely in composition and characteristics; they can be polymeric or ceramic, charged or neutral, homogeneous or heterogeneous, and symmetric, asymmetric or thin-film composite (TFC). This wide range of characteristics yields a variety of membranes with different separation capabilities ranging from microfiltration (MF) membranes that remove suspended solids to nanofiltration (NF) and reverse osmosis (RO) membranes that remove molecules and ions. NF membranes are ideal for the control of disinfection byproducts (DBPs) as they can remove greater than 90% of the organic matter while operating at substantially lower pressures than RO membranes.

The resistance to transport imposed by the membrane barrier is termed the membrane permeability, which can be subdivided into water permeability and solute permeability (Gekas, 1988). Membrane permeability is a function of membrane properties such as the molecular weight cutoff (MWCO), charge, hydrophobicity and chemical structure; as well as environmental factors such as the properties and concentrations of individual solutes, pH, ionic strength and temperature. Of these properties, the MWCO is one of the most important; however, this is not an absolute cutoff since many parameters affect solute rejection.

A schematic of a membrane separation process is shown in Figure 2-1, and Tables 2-1 and 2-2 list basic terminology and definitions associated with membrane processes that will be used throughout this document. The system shown in Figure 2-1 is a tangential-flow system since the feed stream flows tangential to the membrane surface while permeation occurs perpendicular to the direction of feed flow. As a result of water permeation, the solution on the feed side of the membrane becomes concentrated with rejected solutes and is termed the concentrate stream when it exits the membrane system. Between the inlet and concentrate outlet, the solution on the high pressure side of the membrane will be referred to as the bulk solution or the feed/concentrate stream. This system employs recycle to increase productivity by returning some of the concentrate to the feed side of the membrane. In Figure 2-1 and

Table 2-2, Q refers to the volumetric flow rate, C refers to the concentration of a constituent, P refers to the pressure and $\Delta\pi$ refers to the osmotic pressure gradient; while the subscripts F, I, C, p, W, R, and B refer to the feed, influent, concentrate, permeate, waste, recycle and bulk, respectively.

The fluid velocity tangential to the membrane surface is defined as the cross-flow velocity, v_c, and will decrease in the direction of flow due to the loss of feed flow as permeate. The cross-flow velocity is reported in units of feet per second (fps). Recovery is the ratio of permeate flow to feed flow, and is a measure of the amount of product obtained per unit of feed water applied to the system. The system recovery, R_{sys}, is the total permeate flow divided by the total feed flow and defines the overall productivity of the system. The recovery of individual stages can also be calculated by dividing the stage permeate flow rate by the influent flow rate entering that stage. The permeate flow rate per unit of membrane area is the water flux, F_W, and is reported in gallons per day per square foot of active membrane area (gfd); while the mass flow rate of a solute through the membrane per unit area is the solute flux, F_S.

The water flux per unit of net driving pressure is the water mass transfer coefficient[1], MTC_W. The MTC_W normalizes the flux with respect to pressure and is a good indicator of membrane productivity. This parameter can be determined from a membrane characterization curve which is a plot of water flux as a function of net driving pressure. Characterization curves should be linear and pass through the origin under typical operating conditions encountered during drinking water treatment. The slope of the characterization curve is the MTC_W. Characterization curves are used to check the validity of calculating the MTC_W by dividing the flux by the net driving pressure.

In order to quantify the removal of solutes in a membrane system, the concept of rejection is employed; however, the rejection of solutes can be defined in three ways (Rosa and Pinho, 1994). The intrinsic rejection, R_i, is the concentration of solute rejected with respect to the solute concentration at the membrane-solution interface. The bulk rejection, R_B, is the concentration of solute rejected with respect to the solute concentration in bulk solution, C_B. The feed rejection, R_F, is the concentration of solute rejected with respect to the feed solute concentration, C_F. R_F is the most useful index for the practitioner, since it indicates removal with respect to feed water quality. Both feed and bulk rejections will be used to quantify removal in these bench- and pilot-scale studies. Unless specifically stated, the term "rejection" will refer to feed rejection throughout this document.

2.1.2 Membrane System Design

An understanding of the fundamentals of membrane applications is necessary to conduct and interpret bench- or pilot-scale membrane studies. A conventional NF or RO membrane system is defined as three separate sub-systems consisting of pretreatment, membrane filtration and post-treatment. A conventional RO/NF membrane system is shown in Figure 2-2.

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[1] Strictly speaking, a mass transfer coefficient should relate a mass flow rate to a driving force. The rational for using a volume flow rate to define a mass transfer coefficient is that the the volume flow rate is related to the mass flow rate through the density of water.

The purpose of pretreatment in these systems is to control membrane fouling or flux loss. Scaling is a type of fouling caused by the precipitation of an inorganic salt on the membrane surface and is controlled by the addition of an acid or antiscalant to either change the speciation of the anion or complex the metal involved in the formation of the precipitating salt. Typical limiting salts are $CaCO_3$ or $CaSO_4$. Other mechanisms that reduce productivity in membrane processes are colloidal fouling, biological fouling and chemical fouling.

The membrane process follows pretreatment and is where the majority of contaminants are removed. If the membrane surface is scaled or fouled then the productivity of the membrane system is reduced, and eventually the membranes must be chemically cleaned to restore productivity. Typical cleaning frequencies for RO/NF systems operating on ground waters are 3 months to 2 years and average about 6 months (Taylor et al., 1990). Surface water systems using additional pretreatment are termed integrated membrane systems (IMSs) and have only been piloted. The cleaning frequencies of surface water IMSs can be as low as 1 to 2 weeks resulting in more difficult plant operation.

Post-treatment consists of disinfection at a minimum and any other unit operations that are necessary before final distribution. Typical post-treatment unit operations are disinfection, aeration, stabilization and storage. Aeration may be required to strip dissolved gases such as hydrogen sulfide. Since membrane permeate can be corrosive, stabilization may be required to produce a non-corrosive product. Alkalinity recovery is an effective process for recovering dissolved inorganic carbon (DIC) in the permeate. Alkalinity can be recovered by lowering the pH prior to membrane filtration in order to convert alkalinity to CO_2, and then raising the pH of the permeate in a closed system to recover dissolved CO_2 as alkalinity. Blending membrane permeate with by-passed feed water can be another means of stabalizing the product stream; however, this practice negates the benefit of the membrane treatment system acting as a barrier to pathogens.

In addition to post-treatment, the concentrate stream from membrane processes must be treated and/or disposed of. Some concentrate disposal methods that may be viable include deep well injection, ocean discharge, discharge to sanitary sewers, land application and evaporation ponds; however, the most effective concentrate disposal method will depend on the concentrate water quality, local regulations and site specific factors. Additional information about concentrate disposal options can be found in Membrane Concentrate Disposal, 1993.

Membrane systems are configured in arrays which consists of stages. A typical two-stage, 2-1 membrane array is shown in Figure 2-3. The first stage shown in Figure 2-3 consists of two pressure vessels in parallel, and the second stage consists of one pressure vessel. Each pressure vessel typically contains from one to seven membrane elements. The most common membrane elements used for drinking water production are spiral wound membrane elements which have an 8" diameter, are 40" long and have 340 to 400 ft^2 of active membrane area. Membrane elements used for drinking water production can also be manufactured in a hollow-fiber configuration. If each of the pressure vessels in Figure 2-3 contained six 8" by 40" elements and were producing water at an average flux of 15 gfd, then each element would

produce 6000 gpd; 72,000 gpd would be produced from the first stage and 36,000 gpd would be produced from the second stage. The total permeate produced by the system would be 108,000 gpd.

This combination of stages is called a tapered or "Christmas tree" array and is used to increase recovery of the overall membrane system while maintaining acceptable hydraulic conditions within each element. As shown in Figure 2-3, the concentrate stream from the first stage is used as the feed stream to the second stage. By passing the concentrate from up-stream stages through membranes in down-stream stages additional permeate is produced resulting in an increase in the system recovery.

Hydraulics are important within the membrane elements and a minimum cross-flow velocity is recommended to avoid an excessive build-up of ions at the membrane/solution interface (a phenomena known as concentration polarization). For 8" elements, a flow of 12 to 30 gpm is typically sought in the last element in the pressure vessel to avoid concentration polarization. If 4" elements are used, a flow of 3 to 6 gpm is typically sought in the last element in the pressure vessel to avoid concentration polarization. The tapered design is used to decrease the number of parallel elements in down stream stages in order to maintain an acceptable cross-flow velocity. Staging and control of concentration polarization must be considered in pilot-scale or full-scale applications.

2.2 Membrane Technology To Meet Drinking Water Treatment Objectives

Reverse osmosis, nanofiltration, electro-dialysis reversal (EDR), ultrafiltration (UF) and microfiltration are the five membrane processes which have major application to the production of drinking water (Taylor et al., 1990). The basic characteristics of these processes are shown in Table 2-3. Although many factors affect solute rejection by these processes, a general understanding of drinking water application can be achieved by associating the minimum size of solute rejected by a membrane process with regulated contaminants.

One manner of interpreting the characteristics shown in Table 2-3 is to correctly assume that each membrane process has the capability of rejecting solutes that are larger than the size shown in the exclusion column. As shown in Table 2-3, regulated drinking water solutes can be simplified into categories of pathogen, organic solutes and inorganic solutes. Pathogens are subdivided into cysts, bacteria and viruses. Organic solutes are subdivided into disinfection byproduct precursors (DBPP) and synthetic organic compounds (SOCs). Inorganic solutes include general parameters such as total dissolved solids (TDS), total hardness, heavy metals and other inorganic contaminants. Three mechanisms of solute rejection are referenced: size exclusion (sieving), diffusion and charge repulsion.

EDR processes are capable of removing ions as small as 0.0001 μm, but a charge is required. Consequently EDR processes are limited to treatment of charged contaminants and are ineffective for the removal of pathogens and most organic solutes. RO and NF processes are capable of removing many organic contaminants by sieving, and many inorganic and

organic contaminants by diffusion. If the membrane seals are not compromised, RO and NF processes have the potential to remove all pathogens. RO and NF processes have the broadest span of treatment capability. UF and MF are sieving controlled and can remove most if not all pathogens from drinking water if the MWCO is tight enough. Consequently these processes are ideal for removing turbidity and microbiological contaminants, and they are ideal for treating the majority of drinking water sources in the United States. The application of UF/MF processes and conventional treatment is similar in that both processes are used to remove particulates from drinking water; however, UF and MF have a significant advantage over conventional processes in that a membrane is a solid film which provides a static barrier to pathogens which are simply too big to pass the membrane. Conventional processes are more dynamic since a solid must be formed and contact must occur between the floc and the particle, followed by floc growth and finally sedimentation before effective pathogen removal can be achieved. Although filtration is another barrier used in conventional treatment, numerous studies have shown that high settled turbidities can result in pathogenic breakthrough in the filtered water.

The surface water treatment rule (SWTR) has been in effect since 1993 and was developed to reduce the potential for pathogenic contamination of drinking water. The SWTR requires that all waters under the direct influence of surface water achieve a minimum of 3-log removal of Giarda cysts and 4-log removal of enteric viruses. The USEPA has recommended that well operated coagulation, sedimentation and filtration systems be given 2.5 log removal credit for Giarda and 3 log removal of viruses. Disinfection is required by the SWTR to meet a CT (mg/L disinfectant x disinfectant contact time) standard. The required CT depends on the type of disinfectant used, the pathogen and other water quality parameters. The expected CT requirements for Cryptosporidium will have a major impact on surface water treatment and may result in the large-scale use of ozone throughout the United States. The enhanced SWTR is expected to link the required log removal of pathogens, including cryptosporidium, to the source water quality. Studies have shown that the log removal of all pathogens achieved by hollow-fiber membrane processes is controlled by the pathogen concentration in the feed water and that membranes can achieve complete pathogen removal if the cutoff is tight enough (Jacangelo et al., 1991). The future ground water disinfection rule (GWDR) may require some level of microorganism removal or inactivation. Pressure driven membrane processes have the potential to remove all pathogens regardless of source and should be able to satisfy the primary inactivation/removal requirements of the GWDR. The least costly membrane processes, UF and MF, are ideally suited for pathogen removal and have been shown to consistently remove all pathogens from drinking water, with the exception of viruses which are removed by UF but not MF. Tighter RO and NF membranes should achieve the same degree of removal if the brine seals are not compromised. However, all of these membrane processes should be followed by disinfection to ensure acceptable distribution system water quality.

The improving methods of detection for biological pathogens have shown that contamination by water-borne, disease-causing agents may well be the most serious problem in providing safe drinking water. Specific contamination by Salmonella, Legionella, E. coli and Cryptosporidium has been documented in the United States. Indications are that the majority of incidents of water-borne disease are unidentified and unreported. Consequently, the need to

use the best treatment technology and maintain distribution system water quality has been emphasized in regulatory action. These biological contaminants should be partially if not totally rejected by most pressure driven membrane processes. NF and RO processes also remove much of the disinfectant demand and nutrients which can contribute to loss of integrity in the distribution system.

Inorganic compounds (IOCs), volatile organic compounds (VOCs) and SOCs are regulated by the amendments to the SDWA. The IOC, SOC and VOC regulations involve eighty-three specific compounds which have varying susceptibility to removal by membrane processes; however, some generalizations can be made. No commercially available membrane process is being used for VOC removal since VOCs are uncharged, have low molecular weights (MW), and pass through membranes with water.

MF and UF membranes don't have a low enough MWCO to reject SOCs or IOCs. RO and NF can achieve significant SOC rejection because the MWCO of these membranes is sufficiently low that many SOCs cannot pass or are diffusion controlled (Duranceau and Taylor, 1993). This is also the case with IOCs or radionuclides like uranium and radium. Although RO and NF have been shown to be among the most promising processes for SOC and IOC removal, not all SOCs or IOCs can be rejected by these processes. RO and NF use both sieving and diffusion mechanisms to reject SOCs and IOCs from drinking water, and rejection will increase as the MW and charge of the contaminant increases. Arsenic and sulfates will be removed by EDR, RO and NF but not by UF and MF. Typically, charged solutes and solutes with MWs greater than 200 are highly rejected by RO and NF. UF and MF can remove SOCs if powdered activated carbon (PAC) is used for SOC adsorption and UF or MF are used for PAC removal. EDR is a viable means of removing any charged solutes from drinking water but is not effective for the removal of uncharged contaminants such as pathogens, SOCs or natural organic material.

The lead and copper rule has been finalized since 1991 and is intended to control the lead and copper concentrations in drinking water. Since corrosion occurs in the distribution system, the chemistry of the finished water is very important, and corrosion is significantly affected by inorganic solutes such as sulfate, sodium, chloride and bicarbonate. Whenever the inorganic matrix of a finished water is altered there is a potential for water quality problems in the distribution system as equilibrium is reestablished between the finished water and the distribution system materials. This can result in unacceptable levels of lead and cadmium, aesthetic problems such as a metallic taste or red-brown stains, and increased operating costs due to infrastructure damage (Schock, 1990). UF and MF do not affect corrosivity because ions are not removed by these processes; however, RO and NF do remove inorganic solutes from water, and thus can impact the corrosivity of a finished water.

Post-treatment processes are designed to stabilize NF and RO product streams by partially reminalizing the permeate to minimize corrosion in the distribution system, and some research has indicated that post-treated product water from membranes can be less corrosive than conventionally treated finished water for new pipe materials (Taylor et al., 1992). Alkalinity recovery is a post-treatment process used to pass DIC from the feed stream to the permeate

stream during membrane treatment. The amount of DIC removed by a membrane process will depend on the carbonate speciation of the feed water which is a function of the feed water pH. Since many membrane processes are operated at a reduced pH to control scaling, much of the DIC can pass through the membrane as aqueous CO_2 or carbonic acid. Base is then added to the permeate to reconvert aqueous CO_2 or carbonic acid to bicarbonate or carbonate species. Since other water quality parameters in addition to alkalinity and DIC can affect the corrosivity of the water, additional post-treatment steps may be required for corrosion control. Guidance on corrosion and corrosion control is readily available through the USEPA Lead and Copper rule Guidance Manual Volume II: Corrosion Control Treatment, 1992; Lead Control Strategies, 1990; and Internal Corrosion of Water Distribution Systems, 1985.

The final rule for discussion is the Disinfectants-Disinfection byproducts (D-DBP) rule. EDR has not been shown to be effective for DBP control, and UF and MF have pores which are too large to reject significant amounts of DBP precursors. The existing DBP MCL is 100 μg/L for the sum of four trihalomethanes (THM4) but Stage 1 of the D/DBP rule has proposed MCLs of 80 μg/L for THM4 and 60 μg/L for the sum of five haloacetic acids (HAA5) which could be reduced further to 40 μg/L for THM4 and 30 μg/L for HAA5 after the turn of the century.

UF and MF can be used to control DBPs and TOC if these processes are preceded by coagulation. As with the SOC application, they replace sedimentation and filtration in conventional treatment and are limited to the 50% to 75% TOC removal that can be achieved by coagulation (Taylor et al., 1986). RO and NF can achieve greater than 90% TOC removal and are unmatched for effective TOC and DBP precursor removal in drinking water treatment (Taylor et al., 1990). Moreover, these processes reject so much of the disinfectant demand that even though the disinfectant dose is greatly reduced, maximum distribution system integrity can be achieved because the residual persists longer. A final major advantage of membranes is the removal of contaminants without producing any oxidation byproducts. All oxidants, including chloramines, produce disinfection byproducts which may be regulated in the future.

A summary of the applicability of membrane processes for meeting some of the regulations described above is provided in Table 2-4.

2.3 Literature Review

The literature describing DBP precursor removal by NF or RO is not extensive. However, work has been done on surface and ground waters that has shown NF and RO to be effective processes for the control of DBPs by removing the organic precursors. The following literature is selected to provide an overview of DBP precursor removal by these membrane processes.

Membrane material was shown to affect the rejection of TOC in membrane investigations (McCarty and Aieta, 1983). Cellulose acetate (CA) membranes were found to reject only 50% of the dissolved organic carbon (DOC), whereas polyamide (PA) membranes were found to

reject greater than 90% of the DOC for the same source and operating conditions. Even though the chemical characteristics of TOC are not well understood, this investigation showed that the surface chemistry of the membrane film affected TOC mass transfer through the film.

Bench scale experiments conducted at the University of Central Florida have shown that trihalomethane formation potential (THMFP) of the potable water supply (Lake Washington) for Melbourne, Florida could not be controlled to less than 100 μg/L by aluminum-, iron- or magnesium-based coagulation. Since chlorine was the only disinfectant used, THM4 in the distribution system was greater than 100 μg/L. Solute fractionation of raw and coagulated Lake Washington water demonstrated that the THMFP precursors were organic species with nominal molecular weights varying from less than 1000 to over 10,000. Coagulation was shown to remove most of the THMFP precursors with a MW above 10,000; however, the remaining THMFP precursors with a MW of less than 1000 resulted in THMFP concentrations which exceeded the MCL when only chlorine was used for disinfection. This work indicated that removal of organic matter with nominal MWs of less than 1000 was necessary to meet the THM4 MCL (Fouroozi, 1980) indicating that RO and NF processes with a MWCO less than 1000 Daltons would be effective for controlling DBPs.

Research has been conducted which demonstrated THM precursors could be removed from surface and ground waters with high THMFP by membrane processes. Membrane filtration of a highly organic ground water at the Village of Golf (VOG) water treatment plant was conducted with different membranes in short-term (2-6 hr) single element studies, and the study demonstrated that 10% to 90% of the THMFP precursors were removed from the water over a MWCO range of 10,000 to 500. No significant removal of THMFP precursors could be realized at lower MWCOs (Taylor et al., 1987). However, softening of VOG water to concentrations attainable by lime-softening required a membrane with a MWCO of 300. Identical results for THM precursor removal and softening were observed for the Acme Improvement District (AID) ground water and for the Caloosahatchee River surface water (Taylor et al., 1986). These waters were the potable water supplies for AID and Lee County, Florida, respectively. Based on these studies, a FilmTec NF 50 membrane was selected for long-term pilot plant operation because the membrane could be operated at lower pressures (100 psi) and normal recoveries (70% to 80%) while controlling THMFP to less than 100 μg/L.

A conventional nanofiltration pilot plant consisting of acid feed for scaling control, cartridge filtration and membrane filtration was used to investigate NF for THMFP control at the ground water sites. The pilot plant was operated for 300 to 600 hours at each site. These studies found that THMFP could be controlled to less than 100 μg/L while maintaining consistent production at the highly organic ground water sites. A single 4" x 40" NF element preceded by acid addition and cartridge filtration was used to investigate NF at the surface water site. Results from the surface water study indicated that while NF could attain the same high water quality as observed at the ground water sites, consistent productivity could not be maintained with conventional pretreatment. Significant organic fouling occurred at the surface water site, resulting in a rate of flux loss near 0.40 ft/d^2 which was more than three orders of magnitude higher than the fouling rate at the ground water sites. These results showed that

ground water treatment by NF was feasible, but that surface water treatment by NF would require additional pretreatment and more frequent cleaning.

In operational studies at the surface water site (Lee County) and the ground water sites (VOG and AID), the permeate concentrations of inorganic solutes were observed to increase as the net driving pressure decreased or as system recovery increased. This phenomenon would be expected when solute mass transfer in a membrane process is diffusion controlled. The corresponding permeate concentrations of organic solutes were observed to be independent of pressure and recovery. This phenomenon would be expected when solute mass transfer in a membrane process is controlled by sieving (Taylor et al., 1986).

A long-term investigation of THMFP control was conducted at the Flagler Beach, Florida water treatment plant (a ground water site) and at the Punta Gorda, Florida water treatment plant (a surface water site). Several membranes were investigated for use in short-term studies and found to control THMFP and provide softening. A MWCO of 300 was found to control THMFP and to provide softening to less than 100 mg/L as $CaCO_3$. These pilot studies were conducted for approximately one year at each site. A 15,000 gpd membrane pilot plant using FilmTec NF 70 membranes was operated for one year at Flagler Beach, Florida, and controlled THMFP to less than 100 μg/L while maintaining consistent production (Taylor et al., 1990). The Flagler Beach ground water is highly organic with a DOC concentration of 11 mg/L and a raw water THMFP in excess of 600 μg/L.

Another yearlong pilot study was conducted using the same membrane pilot plant to treat the highly organic surface water at Punta Gorda, Florida. Results of short-term membrane selection studies demonstrated the same 300 MWCO requirement to achieve THM4 control and softening as was observed at previous sites at Flager Beach, AID, VOG and Lee County, Florida. Advanced pretreatment processes of: (1) sand filtration; (2) alum coagulation and sand filtration; (3) dispersant addition coupled with the two previously noted pretreatment processes; (4) decreased pressure; and (5) increased cross-flow velocity were investigated. Although consistent control of permeate THMFP was achieved at the surface water site, the flux loss was again severe for all conditions tested. Membrane cleaning was conducted on 20 occasions in an attempt to sustain a water flux of 10 gfd. The operating system at the ground water site required prefiltration and acidification in order to sustain a flux of over 15 gfd with semiannual cleaning. These studies found, as had previously been shown, that the surface water was more difficult to treat by membrane processes than the ground water, but high water quality was produced at both sites. The work was the first successful demonstration of long-term, consistent production for THM control by membranes using a highly organic source (Taylor et al., 1990).

The removal of DBP precursors by membrane processes was found to be sieving controlled in these studies. Furthermore, over 90% of the DOC was removed by membranes with manufacturer reported MWCOs of 300 to 500 from both surface water and ground water supplies. Membranes with lower MWCOs removed very little additional DBP precursors. The THM4 and HAA5 concentrations in the permeate averaged 15 and 4 μg/L, respectively, which represented more than a 90% rejection of DBP precursors. Membranes treating surface

water supplies had to be cleaned every two weeks to maintain production, whereas ground water membrane systems required cleaning no more frequently than every six months. These results have found that membrane systems can be used effectively to remove natural organic contaminants from ground water supplies (Jones et al., 1992).

The results from a pesticide study using nanofiltration indicated the removal of uncharged organic contaminants such as pesticides and naturally occurring dissolved organic compounds by RO or NF was controlled by sieving (Duranceau and Taylor, 1990). This investigation clearly showed that both charge and molecular weight increased solute rejection by nanofiltration but that charge was far more significant to solute rejection than molecular weight for the solutes investigated. These investigations also found that for this water, increasing cross-flow velocity across the membrane surface within the range recommended by the manufacturer had no effect on the rate of fouling.

Work by Lozier and Carlson in 1991 and 1992 investigated the treatment of Dismal Swamp water in Virginia using CA and polyvinyl derivative (PVD) membranes and found that TOC removal did increase with increasing recovery for the CA membranes and did not vary with recovery for the PVD membranes. Hence the mass transfer mechanism for the TOC in this work was controlled by the membrane surface characteristics. These results demonstrate that generalizations about TOC removal in a membrane process cannot be made.

In 1993, Kohl et al. found that microfiltration could be used to reduce the fouling of both CA and polyamide membranes used to treat wastewater tertiary effluent that was being used as a recharge source for a recreational water body. RO cleaning frequencies exceeded one month for this integrated membrane system. This study and others indicate that surface water fouling is dependent on the source and membrane surface characteristics.

In a study by Laine, et al. (1993), the brominated THMFP was found to increase in the permeate from membrane processes as the MWCO increased. In this study, surface waters were processed through membranes with varying MWCOs, and bromide spiking studies were conducted to determine the effect of increased bromide concentrations and MWCO on DBP formation. NF was found to control brominated DBPs but pretreatment was necessary, and the concentration of brominated DBPs increased as the bromide concentration increased.

Membrane processes were found to be the most effective processes for removing color and DBP precursors from a low DOC ground water in the western United States (Lo Tan and Amy, 1991). The THMFP was reduced from 182 μg/L to 39 μg/L and the HAAFP from 77 μg/L to below the detection limit by a membrane with a 300 MWCO. Although membranes were found to be the most effective process for DBP control, concern was expressed about pretreatment requirements for this source.

Different performance for different types of nanofiltration membranes have been observed in membrane pilot studies on a highly organic California ground water (Fu et al., 1994). A membrane selection study was conducted comparing eight NF membranes, followed by a one year pilot study which compared a softening and a high permeability NF membrane. The

selection study found that all the membranes rejected more than 85% of the TOC but that some of the membranes passed more alkalinity to the permeate. The eight membranes were classified into a softening group that rejected more than 80% of the alkalinity and a high permeability group that rejected less than 40% of the alkalinity. The cited advantages of the high permeability membrane were a higher water mass transfer coefficient, higher finished water alkalinity and run times in excess of six months between cleanings. This study is significant in that it demonstrated that a high permeability membrane could operate at lower pressures, a lower scaling potential, a greater potential recovery, achieve a concentrate TDS concentration low enough to permit sewer discharge and still achieve high TOC rejection.

A bench-scale procedure, termed the rapid bench-scale membrane test (RBSMT), has been developed and tested using several different waters and membrane types (Allgeier and Summers, 1995). The RBSMT can be used to generate data quickly from several different films. Mesh feed spacers and cross-flow velocities representative of those used in practice are used to approximate the flow conditions in a actual spiral-wound element. The results of this study indicated that membranes could be used to meet the requirements of the D-DBP rule except for a Florida ground water based on the proposed Stage 2 MCLs, and that TOC mass transfer occurred by diffusion and/or convection. The water quality results were similar to those of other investigators, but this was one of the first studies that indicated TOC mass transfer was not controlled by a sieving mechanism. This finding is significant since diffusive and convective transport of DBP precursors may result in water recovery being limited by DBP formation in the finished water.

Existing literature on DBP control by membrane technology has shown that highly organic ground waters can be successfully treated by nanofiltration systems using conventional pretreatment and thin-film composite membranes with MWCOs less than 500. Cleaning frequencies for membrane systems treating ground waters are typically projected at 3 months to 2 years and have been demonstrated in large-scale pilot plant studies. Membrane systems treating highly organic surface waters have demonstrated successful TOC removal and DBP control very similar to ground water systems; however, several pilot studies on United States surface waters have indicated that cleaning frequencies of two weeks or less will be required to maintain consistent production. Although a pilot study treating a surface water with a TOC concentration of 10 mg/L showed cleaning frequencies of greater than two weeks for thin-film composite RO membranes and greater than two months for CA RO membranes.

There is a need to emphasize research on surface water systems as opposed to ground water systems for productivity or fouling control. However, the successful application of both conventional RO membranes and a high permeability NF membrane to surface waters has shown that high TOC rejection could be achieved while maintaining an acceptable productivity. Membrane developments by manufacturers are occurring rapidly which emphasizes the need for bench- and pilot-scale testing of membrane systems for the control of organic contaminants in drinking water systems.

2.4 Mechanisms And Control Of Membrane Fouling

There are different mechanisms that can reduce the productivity in a membrane process including scaling, colloidal fouling, biological fouling and organic or chemical fouling, and these fouling mechanisms require different control strategies.

2.4.1 Scaling

Scaling occurs when a sparingly soluble salt is concentrated to its solubility limit and precipitates onto the feed side of the membrane. A diffusion controlled membrane process will naturally concentrate salts on the feed side of the membrane, and if excessive water is passed through the membrane, this concentration process will continue until a salt precipitates and scaling occurs. Scaling will reduce membrane productivity and consequently recovery is limited by the allowable concentration just before the limiting salt precipitates. The limiting salt and maximum recovery can be determined from the solubility products of potential limiting salts and the feed stream water quality. Ionic strength must also be considered in these calculations.

Scaling control is essential in RO/NF membrane processes. Control of scaling within the membrane element requires identification of a limiting salt, acid addition and possibly the addition of an antiscalant. Calcium carbonate scaling is commonly controlled by sulfuric acid addition; however, other salts such as sulfates can also be the limiting salt. Commercially available antiscalants can be used to control scaling by complexing the metal ions in the feed stream and preventing precipitation. Equilibrium constants for these antiscalants are not available which prohibits direct calculation of the required dose. However, manufacturer provided computer programs are available for estimating the required antiscalant dose for a given recovery, water quality and membrane.

To determine the potential for calcium carbonate precipitation, the Langlier Saturation Index (LSI) should be calculated using an estimate of the concentrate water quality. $CaCO_3$ scaling can be controlled by lowering the pH until the LSI is negative. A conservative approximation for the maximum allowable pH to achieve scaling control for softening membranes is given by Equation 2.1.

$$\textbf{pH for } CaCO_3 \textbf{ scaling control} < -\log[2.4\times10^{-12}\times CH_{FEED}\times ALK_{FEED}] \quad (2.1)$$
$$\textbf{(for softening membranes)}$$

where CH_{FEED} is the feed calcium hardness in mg/L as $CaCO_3$ and ALK_{FEED} is the feed alkalinity in mg/L as $CaCO_3$. For membranes that do not remove hardness, the maximum allowable pH for scale control can be estimated as:

$$\textbf{pH for } CaCO_3 \textbf{ scaling control} < -\log[8\times10^{-13}\times CH_{FEED}\times ALK_{FEED}] \quad (2.2)$$
$$\textbf{(for non-softening membranes)}$$

These approximations account for the increase in the concentration of the alkalinity and calcium on the feed side of the membrane, but do not account for concentration polarization

and actual salt concentrations at the membrane surface and should be checked against more detailed calculations or a manufacturer's computer program. Also, the LSI only indicates the potential for calcium carbonate scaling, and the potential for precipitation of other salts must be checked through consultation or computer programs.

2.4.2 Colloidal, Biological And Chemical Fouling

Colloidal fouling is defined as fouling by particles that exist in the influent stream to the membrane elements. The particles or colloids are smaller than the exclusion size of the cartridge filter that is commonly used for pretreatment in a membrane process. The typical pore size of the cartridge filter used in pretreatment is 1 to 20 μm. The colloids can build-up on the surface of the membrane and form a cake which is eventually compressed and reduces flow through the membrane. The resulting phenomena is similar to models that have been used to describe cake filtration in vacuum filters. Initially during cake formation and build-up, productivity is not diminished. When the cake collapses or compresses, the resistance to filtration is increased and the cake must be removed. RO and NF membranes, unlike MF or UF membranes, cannot be back-washed, and chemical cleaning is required to remove the cake. Colloidal fouling can be reduced by additional pretreatment such as MF and UF. The common fouling indices, which are described in Section 2.5, are indicators of the potential for colloidal fouling.

Biological fouling is defined as biological growth in the membrane element that results in a reduction in membrane productivity or an increase in the pressure drop through an element. Unfortunately, no reliable methods have been demonstrated for the prediction of biofouling. Biological growth can occur in the feed spacers or on the membrane surface. Biological growth will always occur in a membrane system as it is practically impossible to maintain sterile conditions in a plant environment; however, this growth will not always result in a significant productivity loss in a membrane process. It should be possible to control biological fouling with additional or advanced pretreatment processes such as disinfection, MF or UF.

Chemical fouling is defined as the interaction of dissolved solutes in the feed stream with the membrane surface that results in a reduction in membrane productivity. Examples of such interaction would be the adsorption of polysaccharides on the surface of a thin-film composite membrane. Chemical interaction between solutes and the membrane surface will always occur to some degree, but membrane productivity may not be reduced. In general, fouling by organic matter can be reduced by removing a portion of the TOC prior to membrane filtration through processes such as enhanced coagulation.

2.5 Fouling Indices

Fouling indices can be quickly developed from simple filtration tests and are used to qualitatively estimate pretreatment requirements. The silt density index (SDI), modified fouling index (MFI) and mini plugging factor index (MPFI) are the most common fouling indices, and are determined by monitoring flow through a commercially available Millipore test apparatus. The water must be passed through a 0.45 μm Millipore filter with a 47 mm diameter at 30 psi to determine any of the indices. Because of the effects of different filters,

only 47 mm diameter, 0.45 μm pore size Millipore filters should be used to generate accurate index measurements. The time required to complete data collection for these tests varies from 15 minutes to 2 hours depending on the fouling nature of the water. Although similar data is collected for each index, there are significant differences among these indices. These filtration indices are primarily indicators of the potential for particulate or colloidal fouling.

2.5.1 Silt Density Index

The SDI (ASTM D-4189-82) is the most widely used fouling index and is shown in Equation 2.3. The Millipore test apparatus is used to determine two time intervals, the times to collect an initial 500 mL and a final 500 mL. The time between these two sample collection periods is 5, 10 or 15 minutes. The 15 minute interval is used unless the water is so highly fouling that the filter plugs before the 15 minute interval is realized. In this case, the time between the initial and final sample collection is decreased until a final 500 mL sample can be collected.

$$SDI = \frac{100 \times (1 - t_i/t_f)}{t_t} \qquad (2.3)$$

where t_i is the time to collect the initial 500 mL of sample, t_f is the time to collect the final 500 mL of sample and t_t is the total running time of the test.

The SDI is a static measurement of resistance which is determined by samples taken at the beginning and the end of the test. The SDI does not measure the rate of change of resistance during the test and is the least sensitive fouling index.

2.5.2 Modified Fouling Index

The MFI is determined using the same equipment and procedure used to determine the SDI, except that the volume is recorded every 30 seconds over a 15 minute filtration period (Schippers and Verdouw, 1980). The development of the MFI is consistent with Darcy's Law in that the thickness of the cake layer formed on the membrane surface is assumed to be directly proportional to the filtrate volume. The total resistance is the sum of the filter and cake resistance. The MFI is derived in Equations 2.4 to 2.6 and is defined graphically in Figure 2-4 as the slope of an inverse flow verses cumulative volume curve.

$$\frac{dV}{dt} = \frac{\Delta P}{\mu} \frac{A}{(R_f + R_k)} \qquad (2.4)$$

$$t = \frac{\mu V R_f}{\Delta P A} + \frac{\mu V^2 I}{2 \Delta P A^2} \qquad (2.5)$$

$$\frac{1}{Q} = a + MFI \; x \; V \qquad (2.6)$$

where $\mathbf{R_f}$ is the resistance of the filter, $\mathbf{R_k}$ is the resistance of the cake, **I** is a measure of fouling potential **V** is the volume of filtrate (L), **Q** is the average flow (L/s), and **a** is a constant.

Based on the work of Schippers and Verdouw (1980), Morris determined an instantaneous MFI by calculating the ratio of flow over volume in 30 second increments to increase the sensitivity of the test (Morris, 1990). Typically, the cake formation, cake build up and cake compaction or failure can be seen in three distinct regions on a MFI plot, as shown in Figure 2-4. The regions corresponding to blocking filtration and cake filtration represent productive operation, whereas compaction would be indicative of the end of a productive cycle.

2.5.3 Mini Plugging Factor Index

The MPFI is defined as the ratio of flow to time and is shown in Figure 2-5 for the same tap water as was used to determine the MFI (Figure 2-4). The MPFI is stated mathematically in Equation 2.7.

$$\mathbf{Q' = a + MPFI \times t} \qquad \textbf{(2.7)}$$

where **Q'** is the flow at 30 second increments, **t** is the time of operation and **a** is a constant.

The MPFI curve ideally shows regions of blocking filtration, cake filtration and cake compaction as does the MFI curve. The MPFI is actually the change in the MTC_W as a function of time since membrane pressure and area are constant. The MPFI would seemingly be the best indicator of membrane fouling as the change in the MTC_W with time is the exact measurement of productivity decline. However since there is very little flow when fouling occurs, it is very difficult to collect flow and time data that accurately reflects fouling.

2.5.4 Index Guidelines

Some approximations for the feed water fouling indices required to control membrane fouling are given in Table 2-5. These numbers are only approximations and do not replace the need for pilot or bench studies. Pretreatment requirements cannot be determined for most installation without a pilot study unless actual plant operating data can be obtained on a very similar water. Pilot studies have been omitted in the design of some brackish water reverse osmosis plants using waters that have TOC concentrations and SDI values less than 1. However, membrane manufacturers typically permit SDIs in the range of 3 to 4 for spiral-wound elements.

2.6 Membrane System Design And Operational Factors For Precursor Removal

Membrane systems are affected by the membrane type selected and the conditions under which the system is operated. Conventional pretreatment is necessary in all systems, and advanced pretreatment may be necessary in some systems, to control fouling. Following membrane treatment, post-treatment and concentrate disposal may be required. All of these factors must be considered to develop an accurate cost estimate for membrane treatment. In some instances, blending of membrane permeate with raw, partially treated or other process

treated streams may be possible and should be evaluated for water quality and cost impact. However, any pathogen control is compromised if blending is used.

2.6.1 Membrane Selection

Membranes can be selected using many different parameters. The primary parameters for membrane selection are percent NaCl rejection, the MWCO, the water mass transfer coefficient, resistance to fouling mechanisms of significance and water quality.

Membrane systems can be categorized according to the level of total dissolved solids (TDS) in the raw water. The suggested levels of TDS classification would be (A) < 1000 mg/L, (B) between 1000 mg/L and 10,000 mg/L and (C) > 10,000 mg/L. Level A systems are essentially freshwater systems and could be treated by a NF membrane system unless the majority of the TDS is composed of monovalent ions. Level B systems are brackish water systems and could be treated by low pressure RO or EDR membrane systems. Level C systems are salt water systems and require high pressure RO. Membrane application programs are available from membrane manufacturers or consulting engineers and can be used to determine the potential recovery and general finished water quality. Consequently the first step in membrane selection would be based on raw water quality parameters such as TDS.

Manufacturers generally categorize membranes by percent NaCl rejection or MWCO. Percent NaCl rejection will only be applicable for membranes selected for treatment of (B) brackish or (C) salt waters. These waters are generally not highly organic but will require membranes capable of rejecting greater than 97% NaCl which should be the primary basis for selection. However, if membranes are used specifically for TOC or precursor control then a high flux membrane with a higher MWCO can be utilized. Current research has shown that a MWCO of 1000 Daltons or less is required to achieve greater than 70% TOC rejection and control DBPs to less than 80 μg/L THM4 and 60 μg/L HAA5. If softening is desired then a MWCO of 300 or less is usually required. Pilot studies in Florida have shown that a membrane with a MWCO of 500 only removed 30% of the hardness whereas a membrane with a MWCO of 300 removed 60% of the hardness. However, these are general statements, and investigators considering membranes for TOC and DBP control can evaluate membranes with varying MWCOs from 1000 to 100 Daltons. Not all manufacturers measure the MWCO of membranes, and the method of measuring MWCO varies among manufacturers; thus, the MWCO is not an absolute performance index.

The water quality of any source must be characterized and the treatment objectives identified for membranes to be selected. The water quality characterization will be based on fundamental measurements of fouling indices, inorganic contaminants, organic contaminants and biological water quality:

- The SDI, MFI or MPFI of the raw water should be determined to estimate pretreatment requirements.

- Typical inorganic water quality parameters include turbidity, TDS, total hardness, calcium hardness, Fe, Mn, Si, Sr, Ba, Na, Cl, SO_4, Br, NO_3 and other inorganic solutes that are regulated drinking water parameters.

- Typical organic water quality parameters include TOC; simulated distribution system (SDS) samples for THM4, HAA6 and TOX; and other organic solutes such as pesticides or other SOCs that are regulated and may be applicable to the particular drinking water source. UV_{254} is a useful surrogate parameter for TOC and DBP precursors.

- Typical biological water quality parameters include standard plate count, heterotrophic plate count, biodegradable dissolved organic carbon, assimilable organic carbon, E-coli, particle count and other biological parameters that may be applicable to a given drinking water source.

It is possible that a given source may have one contaminant that will control membrane selection. Such a contaminant could be nitrates, chlorides, or bromides; however, this contaminant would be identified in the water quality analysis of the raw water and the ability of the membrane to reject this contaminant should be considered when membranes are selected for testing.

The second category for membrane selection will be drinking water source. If the source is a ground water, then the chemical and biological water quality will allow a relatively accurate estimation of the potential hindrances to membrane production. Biological activity and foulants are typically low in ground water systems, and a ground water would typically be successfully treated by conventional membrane systems; however, some contaminants might require advanced pretreatment for ground water systems. For example, high concentrations of Fe and Mn would indicate that the system must either be kept chemically anaerobic or that the Fe and Mn must be removed by advanced pretreatment prior to the NF or RO membrane system. Surface water systems will likely require advanced pretreatment or an integrated membrane system to maintain productivity. If a surface water is being treated, then membranes that are resistant to biological fouling, biological degradation, particulate fouling and chemical fouling should be considered. Cellulose acetate membranes are more susceptible to biological degradation relative to thin-film composite membranes; however, cellulose acetate membranes are less costly than other membranes. Membranes that can accommodate high cross-flow velocities or that have feed spacers that produce hydraulic turbulence and are designed to minimize particulate fouling would be desirable in some applications.

Membranes can be selected on the basis of membrane surface characteristics. Many manufacturers categorize membranes with respect to the hydrophobic or hydrophilic nature of the surface. Hydrophilic surfaces would be expected to pass water with the least resistance and be the least susceptible to chemical fouling but may be more susceptible to biological fouling. Membrane manufacturers can rank their own products relative to hydrophobicity, but there is no common ranking among manufacturers.

A summary of general membrane selection criteria in shown in Table 2-6. Membrane selection should be discussed with membrane manufacturers and consultants. Additionally, membrane screening studies can be conducted to quickly evaluate several membranes and choose the most appropriate film for a given application. The information presented herein provides general guidelines for membrane selection.

Cost information for pilot studies is difficult to obtain because of the way in which membranes are typically purchased. Typically, membranes are bid to a set of specifications supplied by a consultant working for a utility. Membrane manufacturers choose to bid or not bid following a review of the bid criteria. In many cases there are several membranes which can be successfully used to treat a given water.

2.6.2 Pretreatment

Scaling control is defined as conventional pretreatment and has been presented earlier. Advanced pretreatment processes may be necessary to treat surface waters prior to membrane processes and can be classified by the type of foulant that they remove. For example pretreatment by UF or MF would be expected to greatly reduce the tendency for biofouling or fouling by particles larger than 0.01 μm or 0.2 μm, respectively. Categories of pretreatment are shown in Table 2-7 for control of various fouling mechanisms.

Advanced pretreatment would be unit operations that precede scaling control and cartridge filtration. Examples of advanced pretreatment would be coagulation, oxidation followed by green sand filtration, ground water recharge, continuous microfiltration and GAC filtration. Any other unit operations that precede conventional pretreatment are advanced pretreatment by definition. In some pretreatment unit operations, such as alum coagulation, the feed water is saturated with a salt such as aluminum hydroxide. In such instances the solubility of such salts must be accounted for in the feed water stream to avoid precipitation onto the membrane. Finally advanced pretreatment is a costly addition to a RO/NF membrane process (i.e., the addition of coagulation, sedimentation and filtration prior to a NF membrane process could easily increase the cost of treatment by $1/1000 gal or more).

This information is only a guide, and there are many more pretreatment processes than shown in Table 2-7. Additionally, pretreatment processes can be successfully combined to achieve other water treatment objectives while reducing the rate of membrane fouling.

2.6.3 Impact Of Operating Parameters On Performance

The effect of six independent variables on permeate water quality can be considered as shown in Table 2-8. These parameters are feed stream concentration (C_F), recovery (R), net driving pressure (NDP), solute mass transfer coefficient (K_S), recycle ratio (r) and the water mass transfer coefficient (MTC_W). The effects of these operating parameters on the permeate stream solute concentration are summarized in Table 2-8 for sieving and diffusion controlled mass transfer mechanisms. Table 2-8 should be read as all other variables are constant with the exception of the noted variable. For example, the terms $C_F\uparrow$ $C_p\uparrow$ indicate an increase in the permeate concentration due to an increase in the feed stream concentration, while $R\uparrow$ C_pO indicates no change in the permeate concentration with increasing recovery. Decreasing the

feed stream concentration results in lower permeate concentrations in both diffusion and sieving controlled processes; consequently, pretreatment to reduce the feed stream concentration may be an option for decreasing the permeate stream concentration. If the net driving pressure (NDP) is increased and all other variables are held constant, then the permeate concentration will decrease for diffusion controlled species and remain constant for sieving controlled species. If recovery is increased and all other variables are held constant, then the permeate concentration will increase for diffusion controlled species and remain constant for sieving controlled species. These effects may be hard to realize if an existing membrane array is considered, for it is impossible to increase pressure without increasing recovery in such an environment.

The maximum obtainable recovery for a system can be controlled either by the precipitation of a limiting salt or by a diffusion controlled contaminant. For example, assume that a recovery of 90% could be achieved without reaching the solubility limit of a sparingly soluble salt, but bench or pilot studies showed that TOC was diffusion controlled. If the permeate TOC was not low enough to meet the treatment objectives (i.e., the proposed Stage 2 DBP MCLs) at a recovery of 90%, then the system recovery would have to be decreased until an acceptable permeate TOC was achieved. This is possible with any species and can be established through bench or pilot studies.

Membrane characteristics such as the solute and solvent mass transfer coefficients will also affect permeate quality. An increase in the solute mass transfer coefficient will always lead to an increase in the permeate concentration regardless of the transport mechanism. In general, the solute mass transfer coefficient will decrease with decreasing MWCO, but this will not always be the case. The impact of the water mass transfer coefficient on permeate concentration is identical to the impact of NDP on permeate concentration.

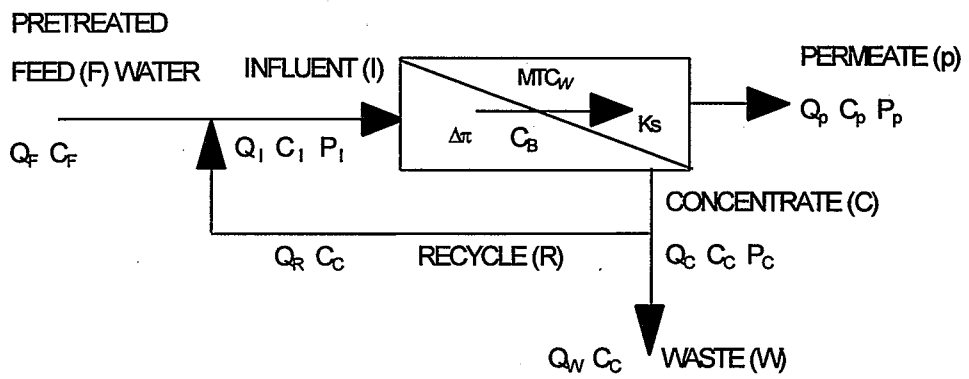

Figure 2-1 Basic Diagram Of A Membrane Separation Process

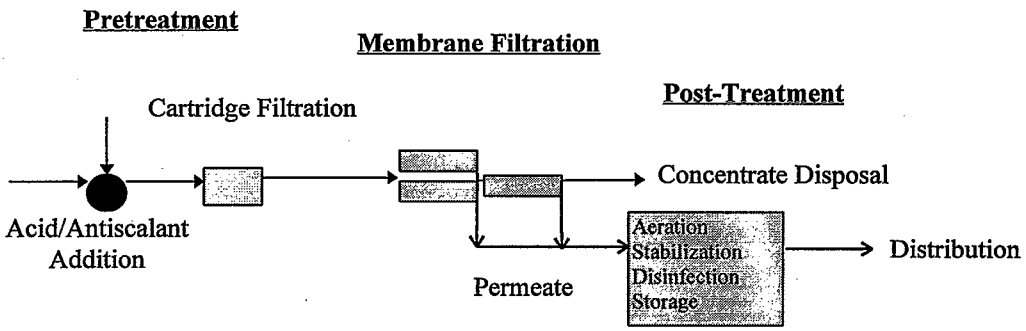

Figure 2-2 Conventional NF/RO Systems Showing Pretreatment, Membrane Filtration And Post-treatment

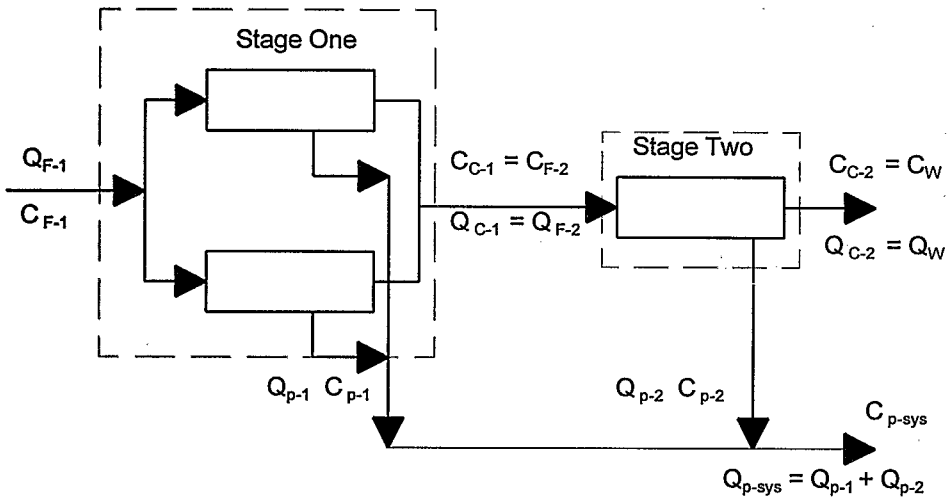

Figure 2-3 Two Stage (One Array) Membrane System

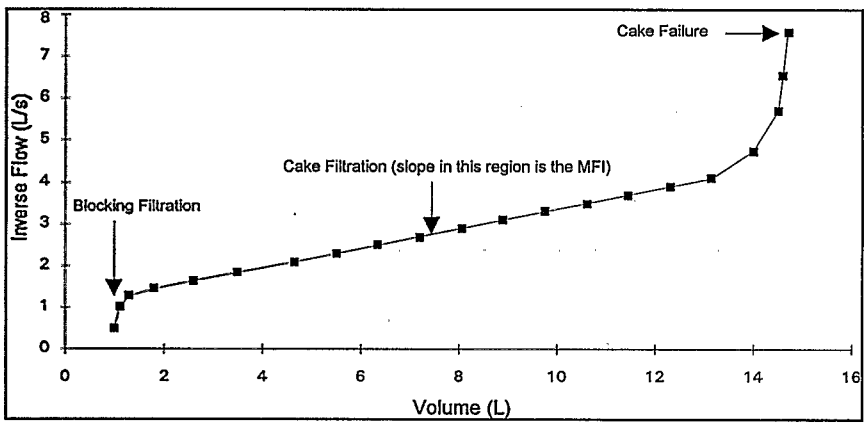

Figure 2-4 Definition Curve For The Modified Fouling Index

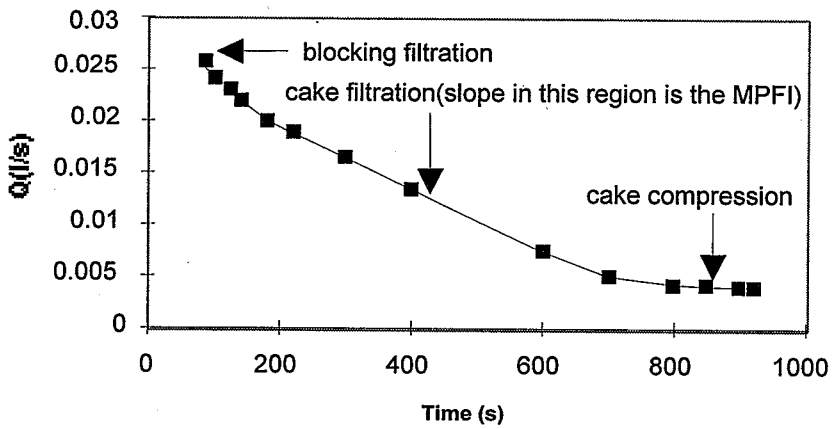

Figure 2-5 Typical Curve For The Mini Plugging Factor Index

Table 2-1 Terminology Used In RO/NF Membrane Processes

Array or Train	Multiple interconnected stages in series.
Bulk rejection	Percent solute concentration retained by the membrane relative to the bulk stream concentration.
Bulk solution	The solution on the high pressure side of the membrane that has a water quality between that of the influent and concentrate streams.
Concentrate	One of the membrane output streams that has a poorer water quality than the feed stream.
Conventional RO/NF Process	A treatment system consisting of acid or antiscalant addition for scaling control, cartridge filtration, RO/NF membrane filtration, aeration, chlorination and corrosion control.
Feed	Input stream to the membrane array after pretreatment.
Feed rejection or Rejection	Percent solute concentration retained by the membrane relative to the feed stream concentration.
Flux	Mass (lb/ft^2day) or volume (gal/ft^2day, gsfd, gfd) rate of transfer through membrane surface.
Fouling	Reduction of productivity measured by a decrease in the temperature normalized MTC_W.
High Recovery Array	Arrays where the concentrate stream from preceding arrays is fed to down-stream arrays to increase recovery.
Influent	Input stream to the membrane array after the recycle stream has been blended with the feed stream. If there is no concentrate recycle then the feed and influent streams are identical.
Mass Transfer Coefficient (MTC)	Mass or volume unit transfer through membrane based on driving force (gfd/psi).
Membrane element	A single membrane unit containing a bound group of spiral wound or hollow-fiber membranes to provide a nominal surface area.
Permeate or Product	One of the membrane output streams that has a better water quality than the feed stream.
Productivity	The efficiency with which a membrane system produces permeate over time.
Pressure vessel	A single tube that contains several membrane elements in series.
Raw	Input stream to the membrane process prior to any pretreatment.
Recovery	The ratio of permeate flow to feed flow.
Scaling	Precipitation of solids onto the membrane surface due to solute concentrations on the feed side of the membrane (i.e. in bulk solution).
Solute	Dissolved constituent in any process stream.
Solvent	Liquid containing solutes; usually water.
Stage or Bank	Parallel pressure vessels.
System Arrays	Several arrays that produce the required plant flow.
Waste	The concentrate stream that exits the membrane system and must be treated or disposed.

Table 2-2 Definitions Commonly Used In Membrane Processes

Parameter	Symbol	Definition
Recovery	R	$(Q_p/Q_F) \times 100\%$
Cross-flow velocity	v_c	$Q_I/(w \times T)$
Total scroll width	w	Width of flow channel in element or cell
Feed spacer thickness	T	Thickness of flow channel in element or
Active area	A	Membrane area available for permeation
Water flux	F_W	Q_p/A
Solute flux	F_S	$C_p \times F_W$
Influent concentration	C_I	$(Q_F \times C_F + (Q_I - Q_F) \times C_C)/Q_I$
Bulk concentration	C_B	$(C_I + C_C)/2$
Bulk rejection	R_B	$[(C_B - C_p)/C_B] \times 100\%$
Feed rejection	R_F	$[(C_F - C_p)/C_F] \times 100\%$
Osmotic pressure gradient (psi)	$\Delta\pi$	$(TDS_B - TDS_p)/100$
Total dissolved solids	TDS	Total dissolved solids in mg/L
Net driving pressure	NDP	$(P_I + P_C)/2 - P_p - \Delta\pi$
Concentration gradient	ΔC	$C_B - C_p$
Water mass transfer coefficient	MTC_W	F_W/NDP
Solute mass transfer coefficient	K_S	$F_S/\Delta C$

Table 2-3 Characteristics Of Membrane Processes

Process	Mechanism	Exclusion	Regulated solutes rejected by process		
			Pathogens	Organics	Inorganics
EDR	C	0.0001 μm	None	None	Most
RO	S, D	0.0001 μm	C, B, V	DBPPs, SOCs	Most
NF	S, D	0.001 μm	C, B, V	DBPPs, SOCs	Some
UF	S	0.001 μm	C, B, V	None	None
MF	S	0.01 μm	C, B	None	None

Mechanism: *C=charge, S=size exclusion, D=diffusion*
Pathogens: *C=cysts, B=bacteria, V=viruses*
Organics: *DBPPs=disinfection by-product precursors, SOCs=Synthetic Organic Compounds*

Table 2-4 Summary Of Membrane Applications For Regulated Contaminants

Rule	Membrane Process			
	EDR	RO/NF	UF	MF
SWTR/ESWTR* (Giardia/Crypto)	no	yes	yes	yes
IOC	yes	yes	no	no
SOC	no	yes	Poss. (w/PAC)	Poss. (w/PAC)
Radionuclides	yes (not Rn)	yes (not Rn)	no	no
DBP precursors	no	yes	Poss. (w/PAC or coagulants)	Poss. (w/PAC or coagulants)
GWDR** (bacteria/viruses)	no	yes	yes	bacteria yes viruses no
Arsenic	yes	yes	no	no
Sulfates**	yes	yes	no	no

*: proposed regulation
**: to be proposed in the future

Table 2-5 Fouling Index Approximations For RO/NF

Fouling Index	Range	Application
MFI	0 - 2 s/L^2	Reverse Osmosis
	0 - 10 s/L^2	Nanofiltration
MPFI	0 - 3 x 10^{-5} L/s^2	Reverse Osmosis
	0 - 1.5 x 10^{-4} L/s^2	Nanofiltration
SDI	0 - 2	Reverse Osmosis
	0 - 4	Nanofiltration

Table 2-6 Membrane Selection Characteristics

Raw water TDS mg/L	Source Water	% NaCl Rejection	MWCO Daltons	% DOC Rejection	% Hardness Removal
>10,000	GW/SW	>97%	<100	80%+	100%
10,000-1,000	GW/SW	>95%	<150	80%+	100%
<1,000	GW/SW	NA	1,000-300	70%+	0% to 70%

Membrane characteristic	Resistance to Fouling Mechanism			
	Scaling	Plugging	Biofilm	Chemical
Hydrophobic	NA	NA	yes	no
Hydrophilic	NA	NA	no	yes
Spacer type	NA	variable	variable	NA

Table 2-7 Advanced Pretreatment For Various Fouling Mechanisms

Advanced Pretreatment Process	Fouling Mechanism			
	Scaling	Plugging	Biofilm	Chemical
Coag.-Sed-Fil	no	yes	no	possible
Bank Filtration	no	yes	yes	yes
Soil Filtration	no	yes	yes	yes
Slow Sand Filtration	no	yes	yes	yes
GAC Filtration	no	no	possible	yes
Microfiltration	no	yes	yes	no
Ultrafiltration	no	yes	yes	no
Ion-Exchange	yes	no	no	no
Oxidation-Filtration	possible	yes	possible	possible

Table 2-8 Effect Of Independent Variable On Solute Permeate Concentration By Mass Transfer Mechanism (↑Increase,↓ Decrease, O No Effect)

Mechanism	Independent Variable					
Diffusion	C_F↑ C_p↑	R↑ C_p↑	NDP↑ C_p↓	MTC_W↑ C_p↓	K_s↑ C_p↑	r↑ C_p↑
	C_F↓ C_p↓	R↓ C_p↓	NDP↓ C_p↑	MTC_W↓ C_p↑	K_s↓ C_p↓	r↓ C_p↓
Sieving	C_F↑ C_p↑	R↑ C_pO	NDP↑ C_pO	MTC_W↑ C_pO	K_s↑ C_p↑	r↑ C_pO
	C_F↓ C_p↓	R↓ C_pO	NDP↓ C_pO	MTC_W↓ C_pO	K_s↓ C_p↓	r↓ C_pO

3.0 Membrane Test Systems

This section describes three procedures for evaluating membranes that can be used to meet the ICR. Although any of the procedures can be used to meet the ICR requirements (with the exception of plants serving more than 500,000 people, which must conduct pilot studies), each procedure does provide different data or a different level of detail. The advantages, limitations and ICR requirements of each approach are described here in order to help utilities decide on the most appropriate procedure for their individual circumstances.

The three systems described in this section provide different information and judgment must be exercised when interpreting the results of these studies. The rapid bench-scale membrane test is the most flexible system but is farthest removed from a full-scale plant, single element bench-scale tests sacrifice some flexibility in order to evaluate a spiral-wound element, and pilot systems have the least flexibility but can be scaled to simulate full-scale performance. All three procedures provide important information, and in an integrated membrane study (i.e., a study used to develop data sufficient for full-scale design) information is obtained from a progression of studies starting with bench-scale studies to select a membrane for use in pilot-scale studies where detailed design information is developed.

3.1 The Rapid Bench-Scale Membrane Test

3.1.1 General Description And ICR Requirements

The rapid bench-scale membrane test (RBSMT) is a systematic bench-scale procedure for the evaluation of membranes used in a spiral-wound configuration. The test uses a tangential-flow cell with mesh feed spacers and permeate carriers to approximate a differential element of a full-scale, spiral-wound module. The cell is operated in a range of cross-flow velocities used in practice to simulate the hydrodynamic conditions within a full-scale element. Concentrate recycle is used to increase the recovery of the bench system, producing a permeate quality more representative of practice than that obtained at lower recoveries. Operating at a high recovery also greatly reduces the test water volume requirements.

Although dead-end stirred cells have been used to evaluate membrane performance in the past, these dead-end cells can not be used for bench-scale ICR experiments. Since these cells are operated without a concentrate waste, the concentration of rejected solutes at the membrane surface will never reach steady-state. Also, these systems are not operated in a tangential flow and are operated without the mesh feed spacers used in full-scale spiral-wound elements. These operating conditions are not representative of conditions in full-scale spiral-wound elements, and therefore cannot be used in an ICR treatment study.

To meet ICR requirements, four RBSMT runs must be conducted with two different membranes with manufacturer reported MWCOs less than 1000 Daltons. These two membranes must be evaluated each quarter for four quarters, resulting in a total of thirty-two runs over one year. The purpose of the four RBSMT runs is to evaluate the impact of recovery on permeate quality, and two membranes are evaluated in order to compare their performance. Quarterly experiments are required to evaluate the impact of seasonal variation

on membrane performance. These requirements are summarized in Table 3-1, and the detailed requirements are described in Section 4.2.

If seasonal variation can be evaluated in less than four quarters, or if seasonal variation is not significant, then the remaining quarterly experiments can be used to investigate other parameters. Possible investigations include additional membrane types, different pretreatments, different operating parameters and long-term RBSMT studies. These options are discussed in Section 4.2.

3.1.2 Advantages And Limitations Of The RBSMT

The RBSMT has several advantages over larger systems. The small test water volume requirement (e.g., 200 liters) of the RBSMT allows the procedure to be conducted off-site. Furthermore, the influent to the membrane study may be batch pretreated eliminating the potential need for costly, continuous-flow pretreatment. The small membrane area requirement for this test allows several membranes to be quickly evaluated at a minimal cost since most manufacturers will provide a sample of membrane material at no charge. The RBSMT also maintains a great deal of operational flexibility allowing the recovery, pressure and cross-flow velocity to be independently varied. Thus, this procedure can be used to investigate the impact of operating parameters on membrane performance.

The RBSMT also has some important limitations. This short-term, bench-scale test does not provide data on long-term fouling and performance, and the duration of the test will usually be too short to demonstrate problems due to biofouling. Also, the small test water volumes will not capture variations that exist in natural waters; however, this can be addressed by collecting a sample representative of the average water quality for a given source and season, and conducting multiple runs to capture seasonal variations. Finally, membrane variability can impact results if precautions are not taken to insure that the membrane sample is representative of the product being tested.

The RBSMT is a new procedure and only a limited amount of verification data is available at this time. This limited verification data indicates that the RBSMT can provide reasonable estimates of: (1) initial membrane productivity (i.e., the productivity after a few days of operation) within 10% of the initial productivity observed in pilot studies, (2) solute rejections within 2% to 20% of rejections observed in pilot studies, (3) cleaning frequencies within 40% of those observed on the pilot-scale, (4) the potential for severe and rapid membrane fouling, and (5) concentrate water quality (Allgeier et al., 1996). This verification work is continuing, and will further define the applicability and limitations of this test.

These advantages and limitations must be appreciated when using this procedure. The flexibility of this test, along with the small test water volume and membrane area requirements make this procedure ideal as a screening tool prior to a pilot-scale investigation. The RBSMT can be used to compare different membranes, pretreatments and other operating conditions. Even if a pilot-scale study is planned for the ICR, the information provided by the RBSMT approach could be useful when designing the pilot study. If only bench-scale tests are to be

conducted, the results should be interpreted conservatively as the RBSMT is not a substitute for a thorough pilot-scale study and does not provide sufficient data for full-scale plant design.

3.2 Single Element Bench-Scale Tests

3.2.1 General Description And ICR Requirements

A single element bench-scale test (SEBST) uses a single membrane element in a continuous flow mode. Thus, this approach is actually a pilot-scale procedure, but will be considered a bench-scale test for the purposes of the ICR. The SEBST employs concentrate recycle to increase the recovery to 75% while the system is being operated at a cross-flow velocity and pressure within the manufacturer's specifications. The minimum element size to be used in a SEBST is a 2.5" diameter by a 40" length (2.5" x 40") element. Larger elements can be used, and standard 4" x 40" elements used in practice are commonly used in SEBSTs. The performance of 4" x 40" elements may better represent full-scale operation than smaller elements, and it is typically easier to control the concentrate waste flow rate, and thus the recovery, for a 4" x 40" element. The SEBST can also use hollow-fiber nanofiltration or reverse osmosis elements to meet the requirements of the ICR bench-scale membrane studies; however, hollow-fiber technology is not recommended for surface waters.

All SEBSTs must be run at a recovery of 75 $\pm$ 5% and at operating parameters, such as pressure, flux and influent flow rate, within the manufacturer's specifications. The high recovery is used to challenge the membrane, since permeate quality can decrease with increasing recovery. Each SEBST must be run continuously for four weeks with allowances for down-time due to membrane cleaning and minor maintenance.

One option to meet the ICR using the SEBST requires that two different membranes with manufacturer reported MWCOs less than 1000 Daltons be evaluated each quarter for four quarters. Two membranes are evaluated in order to compare their performance. It is recommended that the two membranes be evaluated simultaneously in parallel, which would require two separate systems; however, one membrane can be evaluated after the other using a single system. The quarterly experiments are required to evaluate the impact of seasonal variation on membrane performance. The impact of recovery does not need to be evaluated each quarter, as is the case for the RBSMT studies; however, four permeate SDS-DBP samples must be collected from each membrane each quarter. The detailed requirements of the SEBST are described in Section 5.0.

If seasonal variation can be evaluated in fewer than four quarters, or if seasonal variation is not significant, then the remaining quarterly experiments can be used to investigate other parameters. Possible investigations include, additional membrane types, different pretreatments and different operating parameters. These options are discussed in Section 5.2.

There is also an option to conduct long-term SEBST studies. Long-term SEBST studies must be run for a one year period, and only one membrane with a MWCO less than 1000 Daltons needs to be evaluated. The sampling requirements for long-term SEBST studies are similar to the requirements for the pilot studies. This option is provided to allow small

utilities to develop data from a long-term study without incurring the expense of a large pilot system; however, this study is classified as a bench-scale study for the purposes of the ICR.

3.2.2 Advantages And Limitations Of SEBSTs

With respect to scalability, a SEBST falls between the RBSMT and larger pilot-scale systems. The use of a full-scale, spiral-wound element may provide better data than the tangential-flow cell used in the RBSMT but provides less information than a pilot-scale study. A single element bench-scale test is ideal for conducting long-term studies, which can provide a better estimate of the fouling rate and required cleaning frequency than short-term bench-scale studies. Similar to the RBSMT, the SEBST uses concentrate recycle to obtain a recovery more representative of practice. However, the use of recycle does not capture the detail of pilot systems which provide data on inter-stage performance.

The use of concentrate recycle in the SEBST provides some operational flexibility allowing the recovery, cross-flow velocity and pressure to be varied; however, it does not facilitate the rapid evaluation of several different membrane types or non-destructive membrane autopsies, while the RBSMT maintains these advantages.

A potential limitation of the SEBST is that it must be conducted on-site due to the high flow requirements relative to the RBSMT. Thus, any pretreatment required for the membrane system must be continuous-flow, as opposed to batch pretreatment which can be used for the RBSMT studies.

These advantages and limitations must be appreciated when using this procedure. Since this procedure is an on-site test, it is ideal for conducting long-term performance studies; however, this also requires continuous pretreatment processes and staff to monitor the system. Single element tests have been performed for several years, and currently there is more confidence in the data produced by SEBSTs than the data produced by the relatively new RBSMT procedure. However, the correlation between single element performance and pilot-scale performance has not been sufficiently demonstrated to make the SEBST a substitute for a thorough pilot-scale study, and this procedure does not provide sufficient data for full-scale plant design. Thus, SEBST results must be used conservatively. In an integrated membrane study, a single element test would follow initial RBSMT studies, and be used to demonstrate sustained performance and provide an estimate of the fouling rate and cleaning frequency.

3.3 Pilot-Scale Testing

3.3.1 General Description And ICR Requirements

Pilot-scale systems typically consist of multiple, staged elements similar to full-scale plants. Thus, properly designed pilot systems provide the most accurate simulation of full-scale membrane performance.

Pilot-scale systems can vary widely in their complexity and cost, but minimum constraints must be placed on pilot-scale systems to be used in the ICR studies. The system must consist of at least two stages with at least two pressure vessels in the first stage and one pressure

vessel in the second stage (i.e., a 2-1 array); furthermore, each pressure vessel shall contain no fewer than three elements. The system must be designed to achieve a recovery of at least 75%, while meeting the design specifications set forth by the membrane manufacturer, such as the minimum and maximum flow rate to an element and the design pressure range. Concentrate recycle may be used if high cross-flow velocities are required to minimize fouling. The minimum element size that can be used is a 2.5" x 40" module, and larger elements such as 4" x 40", 8" x 40" or 4" x 60" elements can also be used. Although not required, it is strongly suggested that the smallest standard elements used in practice (i.e., 4" x 40" elements for the spiral-wound configuration) be used in the pilot system in order to minimize costs but provide appropriate design data.

The ICR requires the evaluation of only one membrane type, so caution must be used when selecting the membrane for investigation. It is strongly recommended that multiple membrane types be evaluated using the RBSMT prior to selecting one for pilot testing. This preliminary membrane screening should be conducted several months prior to the deadline to begin the pilot-scale treatment study. The membrane investigated must have a manufacturer reported MWCO less than 1000 Daltons. The pilot study shall be run continuously over a period of one year, with allowances for down-time due to membrane cleaning, maintenance or other reasons. The pilot-scale run time should be no less than 6600 hours which represents approximately 75% of a calendar year. In this manner, the sustained performance of the system will be demonstrated, and the potential impact of seasonal variation will be realized.

The sampling and analytical requirements for pilot-scale studies are described in Section 6.0. Some inter-stage monitoring is required for pilot studies in order to demonstrate any differences in stage performance.

Depending on the size and complexity of a pilot system, the costs can become substantial. For this reason, a pilot study should be carefully planned to insure that it will meet the objectives of the PWS as well as the ICR. Bench-scale studies such as the RBSMT or single element tests can demonstrate the ability of a membrane to meet a treatment objective or identify the need for additional pretreatment. A pilot-scale investigation is the final step in an integrated membrane study, conducted after bench-scale pre-studies have provided enough information to select an appropriate membrane and pretreatment scheme. For this reason, it is strongly suggested that some sort of pre-study be conducted prior to a pilot study. The large investment for a thorough pilot study should not be made without some preliminary information obtained from a pre-study.

3.3.2 Advantages And Limitations Of Pilot Systems

Pilot-scale systems potentially provide the most accurate data and the most detail. If a pilot system is properly scaled, it can provide data sufficient for full-scale plant design. However, the objective of the ICR is not to generate detailed design data, but to develop data sufficient to estimate costs and demonstrate technical feasibility. Thus, a pilot system that meets the minimum requirements of a 2-1 array operated at 75% recovery may not be sufficient to generate design data, and caution must be exercised when applying the results of pilot-scale studies.

The size and complexity of pilot systems limits their flexibility. Operational parameters can only be varied within a small range, but this is somewhat countered by the ability to monitor performance between stages. Also, the evaluation of different membrane types on the pilot-scale can be very expensive, and it is recommended that membrane screening be done with one of the bench-scale procedures described previously. An alternative that requires a moderate additional investment is to operate one or more additional membrane types in single element systems parallel to the staged pilot system. These parallel, single-element tests afford a comparison of front end system performance for different membrane types.

The limitations of pilot systems are not detrimental to an integrated membrane study. Flexibility is required in bench-scale studies where the details of a pilot study can be worked out. By the time a pilot study is started, the membrane type should be selected, a range of acceptable operating parameters chosen, adequate pretreatment schemes identified and a basic design decided upon. The pilot study is then used to demonstrate sustained performance and develop additional information such as cleaning frequency, stage performance, pressure losses through a system, membrane replacement frequency and other design parameters.

Table 3-1 Summary Of The RBSMT-ICR Requirements

First quarter				
Membrane 1	Run 1 Recovery = 70%	Run 2 Recovery = 90%	Run 3 Recovery = 50%	Run 4 Recovery = 30%
Membrane 2	Run 1 Recovery = 70%	Run 2 Recovery = 90%	Run 3 Recovery = 50%	Run 4 Recovery = 30%
Second quarter				
Membrane 1	Run 1 Recovery = 70%	Run 2 Recovery = 90%	Run 3 Recovery = 50%	Run 4 Recovery = 30%
Membrane 2	Run 1 Recovery = 70%	Run 2 Recovery = 90%	Run 3 Recovery = 50%	Run 4 Recovery = 30%
Third quarter				
Membrane 1	Run 1 Recovery = 70%	Run 2 Recovery = 90%	Run 3 Recovery = 50%	Run 4 Recovery = 30%
Membrane 2	Run 1 Recovery = 70%	Run 2 Recovery = 90%	Run 3 Recovery = 50%	Run 4 Recovery = 30%
Fourth quarter				
Membrane 1	Run 1 Recovery = 70%	Run 2 Recovery = 90%	Run 3 Recovery = 50%	Run 4 Recovery = 30%
Membrane 2	Run 1 Recovery = 70%	Run 2 Recovery = 90%	Run 3 Recovery = 50%	Run 4 Recovery = 30%

4.0 Rapid Bench-Scale Membrane Test

4.1 RBSMT System

This section describes the system used in the RBSMT procedure and is divided into the following subsections: RBSMT Definitions, System Design, System Start-up, System Shut-down, and System Cleaning.

4.1.1 RBSMT Definitions

The RBSMT procedure is centered around a tangential-flow cell with concentrate recycle. A schematic of the RBSMT system is shown in Figure 4-1 using the same terminology listed in Tables 2-1 and 2-2 and Figure 2-1. Table 4-1 lists nomenclature specific to this test, and many of these terms are used in the design equations presented in Section 4.2.2.

This is a tangential-flow system since the feed stream flows tangential to the membrane surface, while permeation occurs perpendicular to the direction of feed/concentrate flow. The cross-flow velocity is controlled by the influent flow rate (Q_I), which is the combined feed flow (Q_F) and recycle flow (Q_R). The concentration of this influent stream (C_I) is higher than the feed concentration (C_F) but lower than the concentrate concentration (C_C); furthermore, the influent concentration increases as the system recovery is increased. As the influent stream flows through the membrane cell, the bulk solution is concentrated until it exits the cell as the concentrate stream. The average concentration of the bulk solution (C_B) is calculated as the average of the influent (C_I) and concentrate (C_C) concentrations.

4.1.2 System Design

A schematic of a typical system for use with the RBSMT procedure is shown in Figure 4-2. This system was designed with consideration to full-scale parameters such as recovery, pressure and cross-flow velocity. The central element of the system is a tangential-flow membrane cell operated with a feed spacer and permeate carrier typical of those used in full-scale, spiral-wound elements. A typical tangential-flow cell is shown in Figure 4-3. The bulk solution flows through the cell-body bottom, tangential to the membrane surface and through the feed spacer, making the unit hydrodynamically similar to a spiral-wound element. After permeating the membrane, the permeate flows through the permeate carrier to a central collection channel where it exits the cell. A small area (24 in^2 typical) membrane sheet is sandwiched between the two halves of the cell-body and placed into a cell-holder (not shown). The cell-holder seals the cell body either pneumatically or mechanically. The membrane cell should be capable of operating up to pressures of at least 50 psi for high flux membranes; however, pressures as high as 125 psi may be required for lose RO membranes or if the system is to be operated in a constant flux mode with varying pressure. It is recommended that the cell-body be constructed of a chemical resistant material such as stainless steel or plastic. Cells that meet these criteria are readily available from manufacturers.

The dimensions of the active membrane area (i.e., the area available for permeation) are shown in Figure 4-3 (in the cell-body bottom) and must be determined to calculate some operating parameters. The length of active membrane area (L_{cell}) is measured parallel to the

direction of feed/concentrate flow and the width of active membrane area (w_{cell}) is measured perpendicular to the direction of feed/concentrate flow. The active membrane area is defined as that portion within the sealing surface of the cell, and will typically be identical to the dimensions of the mesh feed spacer.

The system can be operated in either a constant pressure or a constant flux mode. Constant flux operation is more typical of full-scale operation, but will cause the pressure to increase during operation, and the system must designed to allow the pressure to vary. If constant pressure operation is used, the pressure can be maintained by setting a pressure relief valve, located just downstream of the feed pump, at the desired feed pressure.

This system is equipped with a recycle loop so that a portion of the concentrate can be recycled, enabling the system to be operated at a representative recovery and cross-flow velocity. Other important features are described below by numbered paragraphs which correspond to the boxed numbers in Figure 4-2.

1. The feed pump should be capable of providing pressures at least 10% greater than the maximum estimated operating pressure (e.g., 50 to 130 psi for NF membranes) and a range of flow rates anticipated during operation (e.g., 0.16 gph to 3.1 gph for a 24 in^2 membrane). The pump does not need to be sized exactly since some of the pump effluent can be returned to the feed tank via the by-pass line, or a variable speed drive can be used to obtain the desired flow rate. (If constant flux operation is to be used, a variable speed drive may be required since by-pass may prevent the pressure from increasing as the membrane fouls). Pulseless flow is also desired since membrane performance can be affected by rapid pressure fluctuations. Rotary vane and gear pumps are capable of meeting these requirements. However, if a rotary vane pump with graphite vanes is used, it may be necessary to use a 1 μm in-line filter just downstream of the pump to prevent graphite from depositing on the membrane.

2. An adjustable pressure relief valve is placed just downstream of the feed pump to control the system pressure and minimize the risk of over-pressurizing the system. For constant pressure operation this valve is set to maintain the desired feed pressure, and only the permeate water flux is allowed to vary with time. An alternate mode of operation will allow the system to operate at a constant flux and varying pressure. If the system is designed to operate at high pressures (e.g., 130 psi), the pressure relief valve can be set to crack at a high pressure and the system operated in a constant flux mode. The advantage of operating at a constant flux is that it is more representative of full-scale operation. The disadvantage is that a high pressure system may be more expensive.

3. A flow meter can be placed downstream of the feed pump but upstream of the recycle loop to monitor the feed flow entering the system. This flow meter is optional since the actual feed flow rate will be calculated by adding the volumetrically measured permeate and waste flow rates; however, this flow meter may be useful when setting the operating conditions during an experiment.

4. A flow meter must be placed downstream of the junction where the feed flow is blended with concentrate recycle. This flow meter measures the influent flow rate to the membrane cell which is used to calculate the cross-flow velocity.

5. Gauges should be placed just upstream of the membrane cell to monitor the temperature and pressure of the influent stream. The temperature gauge should be able to read values 20°C above ambient temperature. The feed pressure gauge should be able to read values at least 10% higher than the maximum estimated operating pressure. Accurate temperatures are required to correct the water fluxes to a common temperature, and accurate pressures are required to calculate the water mass transfer coefficient which normalizes flux with respect to pressure.

6. The requirements of the tangential-flow cell have been described earlier, and several manufacturers provide acceptable cells.

7. For some tangential-flow cells, a compressed gas will be required to pneumatically seal the system. The gas should be non-combustible, such as nitrogen or argon.

8. A pressure gauge on the permeate line is optional since the permeate pressure will be close to atmospheric pressure.

9. An optional flow meter placed on the permeate line is useful for setting operating parameters; however, the flow rate must be measured with a graduated cylinder and stopwatch to confirm the system settings and obtain accurate flow measurements.

10. A pressure gauge should be placed on the concentrate line and should have the same pressure range as the feed pressure gauge.

11. The concentrate stream should be split with a union tee so that a portion of the concentrate stream can be wasted while the remainder of the concentrate flow is recycled.

12. A fine needle valve should be used to control the waste flow rate which will control the system recovery.

13. An optional flow meter placed on the concentrate waste line is useful for setting operating parameters; however, the flow rate must be measured with a graduated cylinder and stopwatch to confirm the system settings and obtain accurate flow measurements.

14. A recycle pump should be placed in the recycle line to boost the pressure of the recycle stream. The pump only needs to provide a differential pressure of about 5 to 30 psi, but should be capable of providing flow rates up to 0.4 gpm. This pump should produce pulseless flow and should not shed particles, since these particles would accumulate in the recycle loop. A gear pump with Teflon or stainless steel gears is

suitable for this application. Either a variable speed pump or a needle valve (at location #15) can be used to control the recycle flow rate.

15. A needle valve will be required to control the recycle flow rate if a variable speed pump is not used at location #14.

16. A check valve is required at this location to prevent feed flow from by-passing the membrane cell and going directly to waste.

It is recommended that all parts of the system in contact with water be constructed of stainless steel, Teflon or glass. The tubing used in the system can be 1/4" or 3/8" stainless steel or Teflon that is rated for the system pressures. The cost of the system will be reduced by bending the tubing instead of using unnecessary fittings such as elbows.

The system design presented in this section does not have to be followed exactly, but presents the critical elements of the system: concentrate recycle, a tangential-flow cell using mesh spacers, and a separate pump for feed and recycle flows. Any design that utilizes tangential-flow through mesh spacers at representative cross-flow velocities, recoveries, pressures and fluxes can be used.

4.1.3 System Start-up

The following section will describe the general steps to follow during initialization and start-up for the RBSMT system described in Section 4.1.2. The numbers in parentheses refer to components labeled by the boxed numbers in Figure 4-2.

1. Select a membrane type and obtain a membrane sample or a small membrane element that can by cut apart, and the manufacturer's specification sheet for that membrane.

2. Conduct a thorough analysis of the source water to evaluate the inorganic chemical matrix and determine limiting salts by calculation or manufacturer computer program.

3. Conduct fouling index tests, calculate indices and determine the potential for fouling problems. If a fouling problem is indicated, additional pretreatment alternatives may need to be evaluated.

4. Select a membrane flux rate consistent with the fouling potential of the water.

5. Calculate or consult manufacturer computer programs for feed water acid and/or antiscalant dose.

6. Cut out a membrane sheet using a template to ensure a proper fit within the cell. A straight edge and utility knife are suitable for this task. Care must be taken when cutting the membrane to avoid damage to the film. Membranes are sometimes stored in a preservative that can be harmful if ingested, so caution should be used when working with new membranes. After the initial wetting of a new membrane, it should

not be allowed to dry out and should be stored in water, or a solution recommended by the membrane manufacturer, and kept at 4°C.

7. Cut out a permeate carrier and feed spacer for use in the membrane cell. These mesh spacers must fit snugly within the cell cavities without extending beyond the boundaries of the cavities. These spacers can be obtained from membrane manufacturers and reused indefinitely as long as they are not damaged. Each membrane type should be used with its corresponding spacers when possible; however, most cells will be limited to a specific spacer thickness, such as 34 mils (0.0028 ft).

8. Place the feed spacer in the cell-body bottom and place the membrane over the feed spacer. The active side of the membrane, typically the shiny side, should face the feed spacer. Avoid touching the active side of the membrane.

9. Wet the permeate carrier with laboratory clean water, and place it in the cell-body top.

10. Assemble the cell-body. The adhesive forces between the water and the cell-body will keep the permeate carrier in place when the cell-body top is turned over.

11. Place the cell-body into the cell-holder and open the valve on top of the cell-holder to pressurize the pneumatic ram that seals the cell-body.

12. Attach the concentrate, influent and permeate cell fittings to the corresponding system connections.

13. Open the pressure relief (#2) and recovery (#12) valves so that upon start-up the system pressure will be low, and water will flow freely to waste.

14. Place the feed line into the feed tank and turn on the feed pump (#1).

15. If operating in a constant pressure mode, adjust the pressure relief valve (#2) until the feed pressure is close to the desired setting. If constant flux operation is used, set the pump feed rate to achieve the desired flux, and set the pressure relief valve to crack at a pressure below the maximum operating pressure for the system.

16. Turn on the recycle pump (#14).

17. Slowly adjust the recovery valve (#12) until the waste flow rate is close to the desired setting.

18. Adjust the flow rate on the recycle pump (#14) or the needle valve (#15) until the desired influent flow rate to the cell is achieved.

19. Repeat steps 15, 17, and 18 until the desired waste flow rate, feed pressure (or permeate flux), and influent flow rate are achieved. Throughout the run, these valves and variable speed controllers can be manipulated to maintain the desired settings.

20. Take initial readings, but wait one hour to take any permeate water quality samples.

4.1.4 System Shut-down

1. Take final readings and samples.

2. Open the recovery valve (#12).

3. Slowly open the pressure relief valve (#2) to relieve the system pressure.

4. Turn off the recycle pump (#14).

5. Turn off the feed pump (#1). If the membrane is to be cleaned, follow the procedure discussed in section 4.1.5 at this point.

6. When the system pressure is zero, disconnect the concentrate, permeate and influent lines from the membrane cell.

7. Slowly release the pressure in the pneumatic cell-holder and remove the cell.

8. Carefully remove the membrane from the cell and store it in an appropriate solution at 4°C.

4.1.5 System Cleaning

After the membrane has been operated with a test water, the MTC_W will decrease due to fouling. Some of this lost productivity can be recovered by cleaning the membrane with agents recommended by the manufacturer. Membranes are usually cleaned when the temperature-normalized MTC_W has decreased by 10 to 15% from the baseline at the beginning of the study or the baseline established after the most recent cleaning.

Since membranes are made from many different materials, membrane manufacturers specify chemicals, chemical strengths, temperatures and pH values for cleaning solutions. Membrane compatibility with a specific cleaning solution must be verified with the membrane manufacturer to avoid damage to the film. There are two basic categories of membrane cleaning solutions, alkaline and acidic solutions. In general, alkaline solutions such as a 0.1% solution of sodium EDTA and a 0.1% solution of sodium hydroxide are effective for removing organic and biological fouling agents. Alkaline solutions are typically used in conjunction with surfactants and detergents such as sodium lauryl sulfate or Triton-X. Acidic solutions such as a 0.5% solution of phosphoric acid are effective for removing inorganic foulants. When the exact nature of the foulant is not known, the manufacturer's recommendation for an appropriate cleaning procedure should be solicited.

In practice, spiral-wound elements are cleaned in their housings by recirculating the cleaning solution. To simulate this practice, the membrane in the bench-scale cell should be cleaned within the cell-holder. Figure 4-4 shows how the membrane can be cleaned while in the sealed (pressurized) cell-holder. With the system pumps off, the influent and effluent lines for the recycle pump and the influent, concentrate and permeate lines on the membrane cell should all be disconnected. Flexible tubing should be attached to the influent, concentrate and permeate fittings on the membrane cell. The tubing on the influent port of the membrane cell should be connected to the discharge side of the recycle pump. Tubing from the suction side of the recycle pump should be placed into a reservoir containing the cleaning solution (a 1 liter volume should be sufficient). The free ends of the concentrate and permeate lines should be placed into the cleaning reservoir so that the cleaning solution can be completely recycled.

The recycle pump should then be operated at a high cross-flow velocity (e.g., 0.5 to 1 fps) for a period of time recommended by the manufacturer which could range from 0.5 to 24 hours. Membranes may also be soaked in a cleaning solution for a period of time, and for highly fouled membranes, some manufacturers will recommend heating the cleaning solution. After the cleaning is complete, the membrane cell should be flushed with laboratory clean water. All chemicals should be disposed of in a safe and approved manner.

4.2 RBSMT Procedure

This section describes the RBSMT procedure with respect to the requirements of the ICR. Figure 4-5 presents the steps of the RBSMT studies to meet the ICR requirements. This section is divided into the following subsections: Obtaining Membrane Samples And Manufacturer Data, Selecting Operating Parameters, Membrane Pretreatment And Treatment Study Influent, Steps Of The RBSMT Procedure, Monitoring And Sampling Requirements, Seasonal (Quarterly) Variation, Data Sheets, and Interpretation Of The Results. The data sheets, referenced in this section as Tables 4-5 through 4-17, are described in Section 4.2.7. Utilities electing to conduct RBSMT experiments will be provided with data collection software that can be used to record and report the data elements presented in these data sheets.

The requirements of the ICR when using the RBSMT procedure are: (1) at least two membranes must be evaluated to compare their performance, (2) four recoveries must be investigated for each membrane to evaluate the impact of recovery on permeate quality, and (3) four sets of quarterly experiments on each membrane must be conducted to evaluate the impact of seasonal variation on membrane performance, or if a source is not subject to significant seasonal variation, to evaluate the effects of other parameters on membrane performance.

4.2.1 Obtaining Membrane Samples And Manufacturer Data

According to § 141.144(b)(1)(ii) of the ICR rule, a minimum of two different membrane types with manufacturer reported MWCOs less than 1000 Daltons shall be investigated during RBSMT studies. The membranes should be selected in accordance with the following treatment objectives: (1) removal of organic matter to levels that would enable the plant to meet the proposed Stage 2 DBP MCLs when free chlorine is used as the disinfectant, (2) a

high MTC_W per unit cost of membrane material, (3) minimal pre- and post-treatment requirements, (4) minimization of unnecessary contaminant removal (e.g., removal of total hardness when softening is not a treatment objective), and (5) minimization of concentrate disposal costs. Section 2.6.1 provides additional guidance on membrane selection.

Membrane manufacturers will be able to suggest appropriate membranes to meet the desired treatment objectives. The manufacturer should also be able to assist in determining the pretreatment requirements and appropriate cleaning procedures. Many manufacturers will provide a few square feet of membrane material at no charge. The membrane area should be large enough to produce at least four sheets for use in the bench-scale membrane cell. Mesh feed spacers and permeate carriers should be requested at a size sufficient for the membrane cell being used.

Membrane variability is an important consideration when conducting bench-scale studies with a small membrane area. Membranes of the same type and from the same manufacturer can vary significantly from batch to batch making scale-up difficult, and the most significant variations are typically with respect to water flux. If pilot or full-scale investigations are to follow bench-scale studies, then all membranes should be obtained from the same batch. Membrane variation can be assessed on the bench-scale by evaluating the MTC_W of the membrane with laboratory clean water, or the manufacturer's standard testing solution, and comparing this value to a range specified by the manufacturer. In this manner the flux characteristics of the membrane sample can be compared to the average value reported by the manufacturer.

The use of a representative membrane sample is critical for obtaining useful data from the RBSMT. Sample representativeness can be verified by comparing the observed clean-water MTC_W and the rejection of an easily measured parameter, such as total dissolved solids, with the manufacturer's specifications. The MTC_W values must be normalized to a common temperature for an accurate comparison. If a membrane sheet is outside of the manufacturer's specifications, then a new sheet should be cut from a different area of the membrane sample. If the entire sample is outside of specifications, then a new sample should be requested from the manufacturer.

The information that should be obtained from the manufacturer is listed in the data sheet presented in Table 4-5. This information will be used to design the bench-scale membrane studies.

4.2.2 Selecting Operating Parameters

There are several operating parameters that must be selected for the RBSMT. These include pressure, flux, cross-flow velocity and recovery. Table 4-2 presents four sets of operating conditions designed to achieve various simulations: (1) a conservative average system recovery for a full-scale plant, 70%; (2) the recovery in the final stage of a full-scale plant, 90%; (3) an average recovery for a full-scale plant, 50%; and (4) the first stage of a full-scale plant, 30%. If the precipitation of a sparingly soluble salt limits the recovery, then the highest obtainable recovery should be investigated for the second simulation. The

pressure/flux and cross-flow velocity should be held constant over these four runs to isolate the effect of recovery on permeate quality. These four sets of conditions must be evaluated for each membrane during each quarter.

The only specific values listed in Table 4-2 are the recoveries. The design cross-flow velocity (or minimum flow rate to an element), the design flux and pressure must be obtained from the manufacturer to complete the experimental matrix.

Typical pressures in nanofiltration range from 50 psi to 125 psi, and typical fluxes range from 10 gfd to 20 gfd but should not exceed 15 gfd for a high fouling surface water. The design flux and pressure are interdependent, and either the flux or the pressure should be held constant over the study. In either case the data will be normalized to a common measure of productivity, the temperature-normalized MTC_W.

Typical cross-flow velocities range from 0.15 to 1.0 fps, and the design cross-flow velocity or minimum feed flow rate to an element can be obtained from the manufacturer. Typical minimum influent flow rates to a 4" x 40" element range from 3 to 6 gpm. Lower cross-flow velocities will typically lead to a greater degree of fouling and produce more conservative data. The required influent flow rate to the membrane cell can be calculated from the design cross-flow velocity and the following equation:

$$Q_{I\text{-}cell} = v_{c\text{-}design} \times (T \times w_{cell}) \qquad (4.1)$$

where $Q_{I\text{-}cell}$ is the influent flow rate to the bench-scale membrane cell required to achieve the design cross-flow velocity, $v_{c\text{-}design}$ is the design cross-flow velocity obtained from the manufacturer, T is the feed spacer thickness obtained from the manufacturer, and w_{cell} is the active width of membrane in the membrane cell. Any consistent set of units can be used with this equation.

Most manufacturers will specify a minimum influent flow rate to be applied to the element instead of a design cross-flow velocity. The required influent flow rate to the membrane cell can be related to the influent flow rate to the element by the following equation:

$$Q_{I-cell} = Q_{I-element} \times \frac{w_{cell}}{w_{element}} \qquad (4.2)$$

where $Q_{I\text{-}element}$ is the minimum influent flow rate to the element as specified by the manufacturer, and $w_{element}$ is the total scroll width of the element as specified by the manufacturer.

A representative recovery is more difficult to obtain since the recovery increases in the direction of flow in a full-scale plant. Furthermore, downstream stages typically produce a smaller fraction of the total permeate flow than the lead stage. One approach to reduce these variable recoveries to an average system recovery is by weighting the recoveries of each stage

of a full-scale plant with the percentage of the total permeate flow produced by that stage. Representative average system recoveries range from 40% to 60%. Thus, the 50% recovery in Table 4-2 is intended to produce an average permeate quality for a large-scale system while the 70% recovery is designed to produce a more conservative estimate of the average permeate quality.

The osmotic pressure gradient must be estimated in order to calculate the flux. Equation 4.3 can be used to approximate the osmotic pressure gradient from the TDS concentration in the feed water and other system parameters:

$$\Delta\pi = \mathbf{0.01}\times\mathbf{TDS_F}\times(\mathbf{1} - \mathbf{R}\times(\mathbf{1} - \mathbf{Rej_{TDS}})) / (\mathbf{1} - \mathbf{R}) \qquad \mathbf{(4.3)}$$

where is $\Delta\pi$ an estimate of the osmotic pressure gradient in psi, **0.01** is the factor to convert from mg/L of TDS to osmotic pressure in psi, $\mathbf{TDS_F}$ is the TDS concentration in the feed water in mg/L, **R** is the fractional recovery and $\mathbf{Rej_{TDS}}$ is the TDS rejection of the membrane as reported by the manufacturer.

The operational parameters listed in Table 4-2 can be used to estimate the appropriate flow rates for each simulation. For constant pressure operation, the initial permeate water flux can be estimated from the feed pressure, an estimate of the osmotic pressure gradient and the MTC_W using Equation 4.4; however, this flux will decrease as the membrane fouls. If the system is to be operated in a constant flux mode, a design flux is selected and Equation 4.4 is rearranged to solve for the initial feed pressure; however, this pressure will increase as the membrane fouls:

$$\mathbf{F_W} = \mathbf{MTC_W}\times(\mathbf{P_F} - \Delta\pi) \qquad \mathbf{(4.4)}$$

where $\mathbf{F_W}$ is the permeate water flux in gfd, $\mathbf{MTC_W}$ is the water mass transfer coefficient in gfd/psi and $\mathbf{P_F}$ is the feed pressure in psi.

The permeate flow rate is calculated using the water flux and the active area of the membrane sheet used in the bench-scale cell:

$$\mathbf{Q_p} = \mathbf{F_W}\times\mathbf{A_{cell}} \qquad \mathbf{(4.5)}$$

where $\mathbf{Q_p}$ is the permeate flow rate and $\mathbf{A_{cell}}$ is the active area of membrane in the bench-scale cell.

The feed flow rate is estimated from the permeate flow rate and the fractional recovery using Equation 4.6:

$$\mathbf{Q_F} = \mathbf{Q_p} / \mathbf{R} \qquad \mathbf{(4.6)}$$

where $\mathbf{Q_F}$ is the feed flow rate.

The concentrate waste flow rate is the difference between the feed and the permeate flow rates as shown in Equation 4.7:

$$Q_W = Q_F - Q_p \qquad (4.7)$$

where Q_W is the concentrate waste flow rate.

The flow estimates calculated according to Equations 4.5 through 4.7 are only intended to provide a starting point for the simulation. The flows will have to be modified during the actual experiments to maintain the desired operating conditions. Table 4-6 should be used to report the specific values of the experimental matrix.

The following example demonstrates the use of these equations to design an RBSMT study. For the purposes of this example, assume the following information has been obtained from the cell manufacturer and the membrane manufacturer. Also, this system will be operated in a constant pressure mode at a feed pressure of 85 psi, and at a recovery of 0.70.

$w_{cell} = 0.33$ ft
$A_{cell} = 0.167$ ft^2
$T = 0.0025$ ft
$v_{c\text{-}design} = 0.30$ fps
$w_{element} = 12$ ft
$Q_{I\text{-}element} = 4$ gpm
$MTC_W = 0.20$ gfd/psi
$TDS_F = 300$ mg/L
$Rej_{TDS} = 0.90$

The minimum required influent flow rate to the cell can be calculated according to either Equation 4.1 or 4.2.

$$Q_{I\text{-}cell} = v_{c\text{-}design} \times T \times w_{cell} = 0.3 \text{ fps} \times 0.0025 \text{ ft} \times 0.33 \text{ ft}$$
$$= 0.0002475 \text{ ft}^3/\text{s}$$
$$= 420 \text{ mL/min}$$

$$Q_{I\text{-}cell} = Q_{I\text{-}element} \times (w_{cell}/w_{element}) = 4 \text{ gpm} \times (0.33 \text{ ft} / 12 \text{ ft})$$
$$= 0.11 \text{ gpm}$$
$$= 420 \text{ mL/min}$$

Thus, both approaches yield the same answer, and either Equation 4.1 or 4.2 can be used depending on the available information.

Equation 4.3 can be used to approximate the osmotic pressure gradient for the system which will then be used to estimate the flux.

$$\Delta\pi = 0.01 \times TDS_F \times (1 - R \times (1 - Rej_{TDS})) / (1 - R)$$
$$= 0.01 \times 300 \text{ mg/L} \times (1 - 0.70 \times (1 - 0.90)) / (1 - 0.70)$$
$$= 9 \text{ psi}$$

Equation 4.4 can be used to calculate the permeate flux. For this calculation it will be assumed that the temperature at which the MTC_W was determined is close to the temperature at which the RBSMT studies will be conducted. (If this is not the case, then the MTC_W should be corrected to the temperature at which the study will be conducted using an appropriate temperature correction equation, such as Equation 4.11.)

$$F_W = MTC_W \times (P_F - \Delta\pi) = 0.20 \text{ gfd/psi} \times (85 \text{ psi} - 9 \text{ psi})$$
$$= 15.2 \text{ gfd}$$

The permeate flux and the active area of the membrane sheet can be used with Equation 4.5 to calculate the permeate flow rate.

$$Q_p = F_W \times A_{cell} = 15.2 \text{ gfd} \times 0.167 \text{ ft}^2$$
$$= 2.53 \text{ gpd}$$
$$= 6.7 \text{ mL/min}$$

The feed flow rate is then calculated from Equation 4.6 and the system recovery.

$$Q_F = Q_p / R = 6.7 \text{ mL/min} / 0.70$$
$$= 9.6 \text{ mL/min}$$

The concentrate waste flow rate is calculated by subtracting the permeate flow rate from the feed flow rate using Equation 4.7.

$$Q_W = Q_F - Q_p = 9.6 \text{ mL/ min} - 6.7 \text{ mL/min}$$
$$= 2.9 \text{ mL/min}$$

These calculations have established the system operation parameters that need to be set for an experiment. The feed pressure will be set at 85 psi using the pressure relief valve. The influent flow rate will be set at 420 mL/min using the controller on the recycle pump or a needle valve in the recycle line. The concentrate waste flow rate will be set at 2.9 mL/min with the needle valve on the waste line. The remaining parameters will be set by these three operating parameters. The system will need to be adjusted over the course of a run to maintain the desired recovery, cross-flow velocity and pressure.

4.2.3 Membrane Pretreatment And Treatment Study Influent

The requirements of the treatment study influent are described in Part 1, Section 4.0 of this manual. Typically, 150 liters of influent will be sufficient to evaluate a single membrane; thus, a 300 liter batch of water can be used to conduct a set of quarterly experiments. A better estimate of the feed water volume requirements is provided by Equation 4.8.

$$V = 3.785 \times F_W \times A_{cell} \times [(t_1/R_1) + (t_2/R_2) + (t_3/R_3) + (t_4/R_4)] \quad (4.8)$$

where **V** is the test water volume requirement (liters) and t_n is the number of days during which the cell is operated at a recovery of R_n. The recoveries that are listed in Table 4-2 are: $R_1 = 0.70$, $R_2 = 0.90$, $R_3 = 0.50$, and $R_4 = 0.30$. Reasonable estimates of the times are: $t_1 = 3.5$ days and $t_2 = t_3 = t_4 = 0.5$ days. Using these values, Equation 4.8 reduces to:

$$V = 3.785 \times F_W \times A_{cell} \times 8.22 \quad (4.9)$$

This equation provides a quick estimate of the feed water volume requirements; however, Equation 4.8 should be used when there are significant deviations from the assumed times or recoveries.

The treatment study feed water must be representative of the source under investigation. For example, experiments on an anaerobic ground water should be conducted in a way to maintain anaerobic conditions. This is important as the introduction of oxygen into an anaerobic ground water can increase fouling. Anaerobic conditions can be maintained by conducting the test on-site, or shipping and handling the water in a manner that does not introduce oxygen into the sample.

As discussed in Section 2.0, appropriate pretreatment must be used prior to a membrane process to prevent excessive flux loss due to fouling. Pretreatment for membrane processes commonly includes chemical addition to prevent inorganic precipitation and cartridge filtration to reduce colloidal fouling. The most common chemical pretreatment is sulfuric acid addition to reduce the pH to prevent calcium carbonate precipitation. In some cases hydrochloric acid is substituted for sulfuric acid. The potential for calcium carbonate precipitation can be checked by calculating the Langlier Saturation Index for the concentrate stream. Some applications may require the addition of a chemical antiscalant to control such inorganic precipitants as calcium sulfate, barium sulfate or strontium sulfate. The use of an antiscalant can often eliminate the need for acid addition all together, and many antiscalants can prevent scaling in systems with a concentrate LSI $\leq +1.5$. The required chemical doses are determined by limiting salt calculations or manufacturer computer programs, both of which typically require a preliminary and comprehensive chemical analysis of the raw water. The required chemical dose will typically increase with increasing recovery, and this must be considered when conducting the RBSMT experiments over a range of recoveries from 30% to 90%. Additionally, the fouling potential of the feed water should be evaluated using one or more of the methods presented in Section 2.5.

The feed water must also be passed through a cartridge filter to remove larger suspended solids or colloidal material. Polypropylene cartridge filters with a size exclusion of 5 μm are acceptable for membrane pretreatment.

For feed waters which have excessive fouling as indicated by fouling indices or other factors, the water can be pretreated by advanced processes which may include enhanced coagulation and sand filtration with reduced pH. An example of this would be collecting the

membrane feed water from a conventional treatment plant after sand filtration and prior to the addition of any chlorine-based disinfectant. If alum is used as the coagulant, the pH of the feed water may need to be reduced to around 4.5 (or just above the minimum operational pH as specified by the manufacturer) to ensure the solubility of aluminum hydroxide. However, operating at a low pH may increase fouling by high molecular weight organic matter. Additional advanced pretreatment schemes may include microfiltration to control particulate or microbial fouling.

As mentioned in Section 3.1, one advantage of the RBSMT procedure is that batch pretreatment can be used, eliminating the need for continuous-flow pretreatment systems and allowing for greater flexibility in the pretreatment processes investigated. A large reservoir of water can be batch coagulated, settled, pumped through a cartridge filter and adjusted to the proper pH to provide a pretreated influent for the bench-scale membrane studies. Advanced pretreatment such as microfiltration, ultrafiltration, enhanced coagulation, or ozonation/biofiltration can also be applied in a batch mode. In any case, the choice of pretreatment is left up to the discretion of the utility as long as the influent sample meets the requirements of the ICR as discussed in Section 4.2 of Part 1 of this document. The final treatment study report must include design information for all full-, pilot- or bench-scale processes preceding membrane treatment and any costs associated with pretreatment processes not currently used in the full-scale plant. Table 4-7 requests information about foulants and membrane pretreatment used during the RBSMT experiments.

After the feed sample has received appropriate pretreatment, it can be analyzed for the water quality parameters listed in Table 4-8.

4.2.4 Steps Of The RBSMT Procedure

Once the membrane, pretreatment and operating parameters have been selected, the runs can be started. The experiments should be performed in the order listed in Table 4-2, starting with run #1. Running at a high recovery, 70%, during the first run minimizes the test water volume requirements, and evaluating the recoveries in neither ascending nor descending order partially randomizes the experiments. Below is a step-by-step procedure for conducting a set of RBSMT experiments.

1. Operate the membrane with laboratory clean water[1,2] until the change in the MTC_W over a 12 hour period is less than 4%. This period of operation with laboratory clean water is referred to as setting, and the cumulative run time should be set at 0:00 at the start of

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[1]An example of laboratory clean water suitable for setting is deionized water with a TOC concentration below 0.2 mg/L.

[2]As an alternative to laboratory clean water, the test solution used by the manufacturer (i.e., a 2000 mg/L of $MgSO_4$ dissolved in deionized water) can be used during setting. Using the manufacturer's standard testing solution allows direct comparison of the flux and rejection characteristics of the membrane sample with manufacturer specifications. The setting process is not affected by most salt solutions used by manufacturers for product evaluation.

setting. The operating parameters used during setting should be identical to the operating parameters to be used in the first experiment. If a manufacturer's testing solution is being used during setting, then the standard testing parameters, specified by the manufacturer, should be used. The important point in this step is to obtain a MTC_W after the clean water flux has stabilized so that decline observed in the MTC_W during operation with the test water can be attributed to water quality and fouling and not to membrane setting. The stable MTC_W obtained at this point can be compared to the value reported by the manufacturer to determine the representativeness of the membrane sheet. The operating parameters monitored during setting should be reported in Table 4-9.

2. After the test water has been pretreated and has equilibrated with room temperature, the test water can be applied to the membrane. The cumulative run time should be reset to 0:00 at the start of operation with the test water. When the test water is not being used, it should be kept in cold storage. During operation with the test water the permeate UV_{254} and TDS should be monitored with time. TOC can be monitored instead of, or in addition to UV_{254} if desired; however, it is usually easier and less expensive to analyze UV_{254}. The concentrate UV_{254} and TDS should also be sampled with time but less frequently than the permeate samples. A reasonable sampling frequency is three times a day (i.e., once every eight hours) for the permeate samples and once a day for the concentrate samples.

3. Permeate quality can vary during the beginning of a RBSMT run, and composite permeate and composite concentrate samples should not be collected until stable permeate quality has been achieved. Use real time measurements of permeate UV_{254} as an indicator of stable solute rejections. Permeate conductivity (or TDS) has been shown to follow the same temporal trends as permeate UV_{254} and TOC for a softening membrane (Allgeier and Summers, 1995). Thus, permeate conductivity (or TDS) can also be used as an indicator of stable permeate quality for softening membranes, but this approach may not work for NF membranes with TDS rejections lower than approximately 30%, and the permeate UV_{254} may need to be used for these membranes. The data obtained during operation with the test water should be reported in Table 4-10 for all four runs.

4. Once the change in the permeate water quality (UV_{254} or TDS) over a 10 hour period is less than 3%, or within the variability of the analysis, begin collecting one-gallon (approximate volume) permeate and concentrate samples for a complete water quality analysis. The permeate sample should be collected in a clean glass container, such as a one-gallon jug. The first experiment (at 70% recovery) should be run for at least 78 hours beyond setting to insure stable performance.

5. The one-gallon permeate sample should be analyzed for pH, alkalinity, TDS, turbidity, temperature, total and calcium hardness, bromide, TOC, UV_{254}, and SDS for THM4, HAA6, TOX and chlorine demand. If the SDS sample cannot be immediately chlorinated then it should be stored at 4°C until chlorination. It may be advantageous to collect two one-gallon permeate samples, so that the experiment will not need to be repeated if there is an error during the SDS test. The permeate water quality and

chlorination conditions should be reported in Tables 4-11 through 4-15 for run IDs 1 through 4.

6. The one-gallon concentrate sample should be analyzed for TOC, UV_{254}, TDS, turbidity, pH, alkalinity, total hardness and calcium hardness. These concentrate water quality parameters are reported in Table 4-16 and can be used to check mass balance closure errors as described in Section 4.2.8.

7. After collection of one-gallon permeate and concentrate samples at the first set of operating conditions has been completed, operate the membrane system at the next set of operating parameters and repeat steps 2 through 6 for each set of conditions. The membrane does not need to be operated with laboratory clean water between sets of operating conditions. Since the membrane has achieved stable performance during the run at 70% recovery, the remaining three recoveries can all be evaluated in 24 to 48 hours (i.e., 8 to 16 hours for each of the three remaining runs). The permeate UV_{254} (or TDS for softening membranes) should be monitored at 20 to 30 minute intervals over the first 2 hours to insure stable permeate quality (less than a 2% change over 1 hour) before collecting one-gallon permeate and composite concentrate samples; the system should stabilize within one to two hours.

8. After the fourth experiment, clean the membrane according to the procedure described in Section 4.1.5, and reevaluate the MTC_W at the final recovery investigated (e.g., 30%) using the test water. The data from this step indicates the relative amounts of reversible and irreversible fouling. The data collected for the cleaned membrane should be reported in Table 4-10.

The RBSMT does not need to be run continuously and can be shut-down during short periods when it cannot be monitored; however, the membrane should remain sealed in the cell during these intermittent shut-down periods. When possible, it is recommended that the test be run continuously.

4.2.5 Monitoring And Sampling Requirements

Operating parameters must be monitored to assess membrane performance and the parameters and recommended monitoring frequencies are summarized in Table 4-3. These operating parameters include: permeate, waste and influent flow rates; influent, concentrate and permeate pressures; and the influent temperature. These parameters should be monitored approximately every four hours with more frequent monitoring at the beginning of the run (i.e., during the first 12 hours) and less frequent monitoring at the end of the run.

In addition to these monitoring requirements, Table 4-3 also lists monitoring requirements for TDS, pH and UV_{245}. The membrane permeate must be sampled for TDS, pH and UV_{254} approximately three times each day. The TDS and UV_{254} measurements are used to monitor for stable permeate quality. As stated earlier, at least one of these parameters should be evaluated in real time to verify attainment of stable performance when collection of the one-

gallon permeate sample should commence. These parameters should also be monitored for the feed and concentrate, but less frequently (i.e., once each day).

Table 4-4 summarizes the water quality parameters that must be sampled during RBSMT experiments. The analyses for the feed to the membrane system should be conducted on the feed water after it has received appropriate membrane pretreatment and the results reported in Table 4-8. The membrane feed should be sampled twice, once immediately before the experiments and once at the end of the experiments, for the following parameters: alkalinity, TDS, total and calcium hardness, bromide, pH, turbidity, temperature, TOC, UV_{254}, and SDS for THM4, HAA6, TOX, and chlorine demand. If enough feed water is generated to conduct the experiments on both membranes, then the sampling requirements for the feed only need to be met for the single batch (i.e., the feed water would only have to be analyzed for the water quality parameters in Table 4-4 twice in one quarter). In this case, analytes should be evaluated prior to the first experiment with the first membrane and after the final experiment with the second membrane.

A one-gallon permeate sample should be collected for each run (i.e., at each recovery) with each membrane for the following analyses: pH, alkalinity, TDS, turbidity, temperature, total and calcium hardness, bromide, TOC, UV_{254}, and SDS for THM4, HAA6, TOX, and chlorine demand. Duplicate analyses are required for the permeate sample from the run at 70% recovery (run ID# 1 in Table 4-2) for each membrane. The analytical results for the membrane permeate should be reported in Tables 4-11 to 4-15 for run IDs 1, $1_{duplicate}$, 2, 3 and 4, respectively.

A one-gallon concentrate sample should be collected for each run and analyzed for TOC, UV_{254}, TDS, turbidity, pH, alkalinity, total hardness and calcium hardness. Data from these composite concentrate samples should be reported in Table 4-16.

Sampling, in terms of holding times, preservation, and sampling techniques, should be conducted in accordance with the "ICR Sampling Manual" (EPA 814-B-96-001). Approved methods for analysis are listed in Table 7, § 141.142 of the ICR Rule. The analyses for the treatment studies must be conducted according to the analytical and quality control procedures contained in the "DBP/ICR Analytical Methods Manual" (EPA 814-B-96-002).

4.2.6 Seasonal (Quarterly) Variation

In order to evaluate the performance of membranes treating surface waters under the range of conditions anticipated over the course of a year, bench-scale membrane studies must be performed quarterly. Furthermore, it is critical that each quarterly batch of treatment study feed water be representative of the season being evaluated.

The two membranes selected for the study must be evaluated each quarter. The sample of each membrane type obtained from manufacturers should be large enough to yield at least four membrane sheets for use in the bench-scale membrane cell. Each quarterly study should be conducted with a fresh membrane sheet from the same membrane sample. The use of a fresh membrane insures that fouling from previous runs does not affect membrane productivity in

following runs. The use of sheets from the same membrane sample minimizes the effects of membrane variation over the four seasons. The characteristics of the membrane will not change over a period of one year if the membranes are kept in cold storage and kept wet after the initial wetting. (If the membrane sample is not received in a moist condition, then it can be kept in dry storage until it is used.)

The variability of some source waters may be captured in fewer than four quarters. For example, many ground waters do not exhibit significant seasonal variations. In general, seasonal variation only needs to be evaluated when it is significant; however, four sets of experiments evaluating at least two membranes must be performed to meet the ICR requirements. These four sets of experiments can be used to evaluate any variables of interest such as additional membranes, different pretreatments or different operating parameters. For example, during the second quarter the experimental matrix in Table 4-2 could be repeated for the same two membranes using different pretreatment. In a following quarter, two different membranes could be evaluated according to the conditions listed in Table 4-2. Different operational parameters could also be investigated. For example, the recovery could be held constant and four fluxes or cross-flow velocities could be evaluated during a quarter.

Another option that may provide additional productivity data is a long-term RBSMT study. These studies should be conducted for at least 480 hours with cleaning performed when the MTC_W drops by a pre-determined percentage, such as 15%. A utility electing to perform a long-term bench study must evaluate two membrane at only one recovery, 70%, during that quarter and sample the permeate for the analytes listed in Table 4-4 four times over the run for each membrane. The analyses on one of the four permeate sample sets must be duplicated. The feed must be sampled twice over each membrane run for the analytes listed in Table 4-4. Also, monitoring of pH, TDS and UV_{254} can be reduced to once per day for the permeate and once every other day for the feed and concentrate. However, flow rates, pressures and temperatures should still be monitored six times per day.

If the water is not subject to seasonal variations, then the RBSMT experiments can be performed in any convenient time frame as long as they are completed within a year of the starting date.

4.2.7 Data Sheets

This section describes the data sheets that can be used to record the appropriate data from the RBSMT procedure for the ICR. Corresponding data collection software will be sent to utilities electing to conduct RBSMT experiments after the plant submits a study concept form to EPA.

The data sheet in Table 4-5 is used to report the characteristics of each membrane used for the ICR membrane studies. These are the membrane characteristics as reported by the manufacturer, and this information will be required for the experimental design reported in Table 4-6. Some of this information may not be available, but the data sheet should be filled out as completely as possible. The area and cost of an 8" x 40" element are requested for use in the cost analysis.

The data sheet in Table 4-6 is used to develop and report the experimental design for each membrane. The corresponding spreadsheet file uses input parameters to estimate the required flow rates for each set of conditions. These flow rates are only intended to provide a starting point and will need to be adjusted to achieve the desired simulation. The matrix in this data sheet can be modified for the 2nd, 3rd, and 4th quarters if seasonal variation is not significant as discussed in Section 4.2.6.

The data sheet in Table 4-7 requests information on the foulants in the feed water and the pretreatment processes used to control fouling. The first section of this table requests concentrations of foulants and fouling indices for the feed water. Only the foulants and indices relevant to the water being investigated need to be measured and reported. The blank rows should be used to report additional foulants that were measured but not listed in this table. This information should be used as a guide to selecting appropriate pretreatment processes. During the run, the relevant fouling indices and inorganic solutes should be periodically measured to insure that pretreatment processes are performing properly and that the proper chemical doses are being applied to the feed water.

The second half of this table requests information about the pretreatment processes used prior to nanofiltration. All pretreatment processes used should be reported here including processes in the existing full-scale treatment train, upstream of the point where the feed to the bench-scale system is collected; and processes that are added specifically for membrane pretreatment. Existing full-scale treatment processes used as membrane pretreatment should be marked with an "E", modifications to processes in the existing plant treatment train (e.g., an increase in the coagulant dose) should be indicated by an "M" and pretreatment processes used in addition to the existing treatment train (e.g., acid or antiscalant addition) should be indicated with an "A". This table can be used to provide some of the pretreatment information required in the final treatment study report.

The data sheet in Table 4-8 is used to report the feed water quality after membrane pretreatment. These water quality parameters must be evaluated twice for each batch of feed water.

Table 4-9 contains the parameters that should be monitored and reported during setting with laboratory clean water. Water fluxes at ambient temperature and normalized to the average yearly water temperature experienced at the plant should be reported. The recovery can be calculated by a spreadsheet; however, the recovery should also be manually calculated during the run to insure that the desired simulation is achieved. The cumulative time should be set at 0:00 at the start of setting, and reset at 0:00 at the start of operation with the test water and continued over the four runs. Down time for the system must be subtracted from the cumulative time (i.e., by stopping the timer when the system is turned off).

Table 4-10 contains the parameters that should be monitored and reported during operation with the test water. The time at which collection of the one-gallon permeate and composite concentrate samples begins should be indicated in this table. Temperature normalized fluxes, the MTC_W, and both feed and bulk rejections will be calculated by the data collection software.

The feed rejection is calculated from the feed and permeate concentrations; thus, the average feed values from Table 4-8 must be entered in the appropriate cells in Table 4-10. To calculate the bulk rejection, the permeate and feed concentrations and the recovery are used to first estimate the bulk concentration which is then used to calculate the bulk rejection. Spreadsheet calculations can also be used to determine the mass balance closure errors for all sample sets that include permeate, feed and concentrate values.

The water quality parameters for the one-gallon permeate samples from runs 1, 2, 3 and 4 should be reported in Tables 4-11, 4-13, 4-14 and 4-15, respectively. The analyses for run ID 1 should be duplicated and reported in Table 4-12.

Results from the analyses of the one-gallon concentrate samples for all four runs should be reported in Table 4-16 along with corresponding composite permeate and average feed concentrations. The concentrate concentrations can be calculated from the feed and permeate concentrations and the recovery. The calculated and measured concentrate values are then used to calculate the mass balance closure errors.

Since permeate quality often exceeds the treatment objectives, permeate can be blended with by-passed feed water. This can substantially reduce the required membrane area and post-treatment requirements and thus the cost. By calculating the water quality for different blending ratios, costs for different levels of treatment can be estimated. Tables 4-17 (a and b) use the average feed and the permeate water quality parameters evaluated at each recovery to calculate the amount of flow that must be treated by membranes to achieve the Stage 1 MCLs (Table 4-17a) and the proposed Stage 2 MCLs (Table 4-17b). Water quality parameters that impact post-treatment requirements are also calculated for the blended waters. In these two tables, Q_T is the total blended flow, and the ratio Q_p/Q_T is the fraction of flow that must be treated by membranes to meet the treatment objectives. This ratio is calculated for both THM4 and HAA5 as either of these water quality parameters can control the blend ratio. The subscript **b** in these tables denotes blended water quality.

4.2.8 Interpretation Of The Results

The parameters measured during an RBSMT run need to be transformed into standard parameters such as feed and bulk rejections and water mass transfer coefficients. These calculated parameters can then be plotted to facilitate data interpretation. This section presents an approach for plotting and interpreting the data generated in these experiments along with examples.

Calculating the temperature-normalized MTC_W. The permeate flow rates, influent (feed) and concentrate pressures and the influent temperature are used to calculate the temperature-normalized MTC_W which is used as a standard measure of membrane productivity. The permeate flux is calculated by dividing the permeate flow rate by the active area of membrane in the cell.

$$F_W = Q_P / A_{cell} \qquad (4.10)$$

Since water fluxes are sensitive to temperature, the flux values must be normalized to a common temperature. For the purposes of developing an average cost estimate, the average yearly water temperature experienced at the plant conducting the study will be used. Different membranes use different temperature correction factors and equations, but an equation that works well for most membranes is given below.

$$F_W(\text{Tavg°C}) = F_W(\text{T°C}) \times 1.03^{(\text{Tavg°-T°})} \qquad (4.11)$$

where F_W(**Tavg°C**) is the flux corrected to the average yearly water temperature experienced at the plant conducting the study, F_W(**T°C**) is the flux measured at ambient temperature, **T°** is the temperature at which the flux was measured in °C, and **Tavg°** is the average yearly water temperature experienced at the plant conducting the study in °C.

In order to determine the net driving pressure (NDP) that will be used to calculate the MTC_W, the osmotic pressure gradient must first be estimated from the influent, concentrate and permeate TDS values using Equation 4.12. An osmotic pressure gradient must be calculated for each recovery evaluated since the influent and permeate TDS concentrations will increase with increasing recovery.

$$\Delta\pi = ([(TDS_I + TDS_C)/2] - TDS_p) \times (0.01 \text{ psi / mg/L}) \qquad (4.12)$$

where $\Delta\pi$ is the osmotic pressure gradient in psi, TDS_I is the influent TDS concentration in mg/L, TDS_C is the concentrate TDS concentration in mg/L and TDS_p is the permeate TDS concentration in mg/L.

The influent TDS concentration is calculated from a mass balance using measured feed and concentrate TDS concentrations according to Equation 4.13.

$$TDS_I = (Q_F \times TDS_F + (Q_I - Q_F) \times TDS_C) / Q_I \qquad (4.13)$$

where Q_F is the feed flow rate, TDS_F is the feed TDS concentration in mg/L and Q_I is the influent flow rate.

Once the osmotic pressure gradient has been estimated, the net driving pressure is calculated according to Equation 4.14.

$$NDP = [(P_I + P_C)/2] - P_p - \Delta\pi \qquad (4.14)$$

where **NDP** is the net driving pressure, P_I is the influent pressure, P_C is the concentrate pressure and P_p is the permeate pressure which will usually equal zero in RBSMT experiments.

The temperature-normalized MTC_W is determined by dividing the temperature-normalized-flux by the net driving pressure according to Equation 4.15.

$$\mathbf{MTC_W(Tavg°C) = F_W(Tavg°C) / NDP} \qquad \mathbf{(4.15)}$$

where $\mathbf{MTC_W(Tavg°C)}$ is the temperature-normalized MTC_W.

MTC_W as a function of time. After the temperature-normalized MTC_W has been calculated for each data set, the data can be plotted as a function of operating time as shown in Figure 4-6 for a Fluid Systems TFCS membrane treating Ohio River water. During setting, the MTC_W was observed to increase slightly over the first few hours after which it leveled out to a value of 0.219 gfd/psi, shown as point **a** in Figure 4-6. This value is within 12% of the manufacturer's reported value of 0.193 gfd/psi. If the MTC_W at the end of setting is outside of an acceptable range reported by the manufacturer, it would be prudent to obtain another membrane sample for testing.

In this case, the MTC_W increased slightly during setting; however, other membranes have exhibited a sharp decline in the MTC_W during setting. Whether a membrane exhibits an increase or a decrease in the MTC_W during setting is not important. The purpose of setting is to obtain a stable MTC_W with clean water for comparison with the manufacturer's value and to serve as a baseline for the assessment of flux loss.

The MTC_W curve during operation with the test water can be divided into two sections, a rapid initial MTC_W decline followed by a more moderate MTC_W decline. The inflection point where the slope of the MTC_W curve rapidly changes (point **b** in Figure 4-6) can serve as a baseline for membrane performance treating a specific test water. In Figure 4-6, the value of this baseline MTC_W is 0.211 gfd/psi. The second portion of the MTC_W curve can be approximated as a line, and the slope of this line can be used as an estimate of the rate of MTC_W decline. This rate of MTC_W decline can be used to estimate the required cleaning frequency according to Equation 4.16.

$$\mathbf{CF} = \frac{\Omega \times \mathbf{MTC_{W(o)}}}{\mathbf{dMTC_W / dt}} \qquad \mathbf{(4.16)}$$

where **CF** is the cleaning frequency, Ω is the acceptable fractional loss in the MTC_W prior to cleaning (e.g., 0.15), $\mathbf{MTC_{W(o)}}$ is the baseline MTC_W during operation with the test water, and $\mathbf{dMTC_W/dt}$ is the rate of MTC_W decline determined from a linear regression of the flux data. If the r^2 value of the regression line is less than approximately 0.90, the fit may not accurately predict the rate of MTC_W decline. In this case other models can be used to predict the rate of MTC_W decline, such as a linear regression for a plot of the log of time versus the log of the MTC_W.

For this experiment, $dMTC_W/dt$ was -0.0023 gfd/psi/day, and using 0.15 for Ω, the cleaning frequency is calculated to be 14 days. This cleaning frequency is excessive, but it is likely that many surface waters will exhibit high fouling rates and require frequent cleaning without advanced pretreatment. This calculation also assumes a constant rate of flux decline which may not be a valid assumption over the life of a membrane.

After 100 hours of operation, the membrane was chemically cleaned first with a solution of HCl at pH = 2.0 followed by a solution of NaOH at pH = 10.5. The MTC_W after cleaning is indicated as point **c** in Figure 4-6. Immediately prior to cleaning, the MTC_W had declined 5% from the baseline MTC_W, and cleaning restored 50% of the flux lost relative to the baseline MTC_W.

The long-term flux study with the FilmTec NF-90 membrane treating Ohio River water shown in Figure 4-7 shows the continued fouling experienced by a membrane treating a conventionally treated surface water. It also demonstrates that the rate of MTC_W decline can decrease with time, and long-term studies may provide a better estimate of the rate of MTC_W decline.

At this time, the rate of fouling and the cleaning frequency determined according to the RBSMT has not been verified with sufficient pilot-scale data. However, this work is in progress, and a significant amount of verification data will be amassed and published prior to commencement of the treatment studies. Preliminary verification data indicates that the baseline MTC_W and rate of MTC_W decline obtained using the RBSMT may be reasonable estimates of single element or pilot-scale performance. Until the relationship between single element and bench-scale MTC_W data has been established, the fouling rate and cleaning frequency must only be used on a relative basis to compare different bench-scale studies and should not be inferred to predict single element performance.

Membrane characterization curves. Under most operating conditions used in practice, the permeate flux is directly proportional to the net driving pressure, and the proportionality constant is the MTC_W. However, it is possible for this relationship to fail under extreme conditions. At very high net driving pressures, a limiting flux is approached and the linear relationship between flux and the net driving pressure is no longer valid.

One method for verifying the validity of this relationship is to conduct a membrane characterization study. In a characterization study, the flux is evaluated at several pressures using the test water, recovery and cross-flow velocity under investigation. The pressures must encompass the operating pressure and cover a wide range (e.g., 40 psi to 95 psi). The permeate flux plotted as a function of net driving pressure should exhibit a linear relationship passing through the origin. The slope of this line is the MTC_W, and if the relationship is linear over the entire range, than the MTC_W can be calculated by dividing the flux by NDP.

The four characterization curves shown in Figure 4-8 demonstrate a linear relationship. The membrane was characterized when it was new, after setting, after it was fouled and after it was cleaned. In every case the linear relationship between flux and NDP was shown to be valid as will be the case under most reasonable operating conditions.

Rejection as a function of time. Permeate UV_{254} and TDS are monitored as a function of time to insure stable performance before permeate and concentrate samples are collected for a complete water quality analysis. Using the average feed water quality, the feed rejection of UV_{254} and TDS can be calculated and plotted as a function of time of operation with the test

water. An example of this type of data is shown in Figure 4-9 (in this figure conductivity rejection is plotted instead of TDS rejection).

For this experiment, the rejection of TOC, UV_{254} and conductivity increased with time due to an increase in the mass transfer resistance of the system. After 34 hours, the change in permeate conductivity was less than 3% per 10 hours; thus, collection of one-gallon permeate and concentrate samples could commence at this point. However, the first run, at 70% recovery, should be continued for at least 78 hours to insure stable performance and to obtain a more accurate slope from the MTC_W curve.

For this softening membrane, the temporal rejection trends were similar for all three parameters, and real time measurements of any of these parameters could have been used to monitor for stable performance. However, TDS rejection may not follow TOC and UV_{254} rejection for some membranes. In these cases, either UV_{254} or TOC rejection must be used to monitor system performance.

Rejection as a function of recovery. For each set of experiments with each membrane, permeate quality is evaluated at four recoveries. The average feed water quality parameters can be used to calculate the feed and bulk rejections for each recovery, and these rejections can be plotted as a function of recovery as shown in Figure 4-10.

In this figure, only TOC, UV_{254} and conductivity rejections are plotted. The feed rejection of all three parameters decreased with increasing recovery demonstrating that permeate quality can deteriorate at higher recoveries (as could be experienced in the down-stream stages of a full-scale plant). In cases where the solute is rejected on the basis of size (i.e., sieving), the permeate quality will be independent of recovery. This has been shown to be the case for TOC in some natural waters treated by softening membranes. However, the impact of recovery on membrane performance will be a function of solute and membrane characteristics and must be evaluated on a site specific basis.

Increasing the recovery in a recycle system will increase the bulk concentration in the membrane feed channel. The bulk rejection normalizes for the effect of recovery since the bulk concentration is used to calculate the rejection. In Figure 4-10, the bulk rejection of all three parameters remained relatively constant with recovery. This indicates that the membrane was performing consistently, and the decrease in permeate quality was due to the increase in the bulk concentration.

Rejection summary chart. Figure 4-11 is a bar chart showing the feed rejection of several water quality parameters. The feed rejection at 50% recovery is used since this is a reasonable estimate of the average system recovery for a full-scale plant. These charts present a quick summary of membrane performance and can be used to make rough comparisons; however, summary tables are more useful for assessing detailed membrane performance to determine if the treatment objectives have been met.

Mass balance closure errors. Any data set that contains values for feed, permeate, and concentrate water quality parameters can be used to check the mass balance on the system. The mass balance closure error can be used to assess sampling and analytical techniques. Mass balance closure errors on common parameters (e.g., TOC, UV_{254}, TDS, alkalinity, hardness, etc.) are typically less than a few percent.

The mass balance closure error is calculated in two steps. First the concentrate concentration is calculated from the feed and permeate concentrations and the fractional recovery using Equation 4.17.

$$\mathbf{C_{C(calc)} = \frac{C_F - (C_p \times R)}{(1 - R)}} \qquad \textbf{(4.17)}$$

where $\mathbf{C_{C(calc)}}$ is the calculated concentrate concentration. Next the mass balance closure error is determined by comparing calculated and measured concentrate values:

$$\mathbf{Error_{MB} = \frac{C_{C(meas)} - C_{C(calc)}}{C_{C(meas)}} \times 100\%} \qquad \textbf{(4.18)}$$

where $\mathbf{Error_{MB}}$ is the mass balance closure error expressed as a percentage and $\mathbf{C_{C(meas)}}$ is the measured concentrate concentration.

Permeate/feed blending. When the permeate quality exceeds the treatment objectives, feed can be blended with permeate to reduce the required membrane area and possibly minimize post-treatment requirements. The required permeate flow to total flow ratio (Q_p/Q_T) can be calculated from the feed and permeate concentrations and the treatment goal. These calculations can be performed automatically in spreadsheets for Tables 4-17a and 4-17b for the Stage 1 and proposed Stage 2 DBP MCLs, respectively. These calculations are only valid if the permeate DBPs are below 90% of the THM4 / HAA5 MCLs (i.e., 72 / 54 for Stage 1 and 36 / 27 for Stage 2). Since either THM4 or HAA5 can control, the user must compare the Q_p/Q_T flow ratios for each case and choose the higher of the two ratios as the controlling case. The blended concentrations of other water quality parameters such as alkalinity and hardness can also be calculated by a spreadsheet.

The concentration of various water quality parameters can be plotted as a function of the Q_p/Q_T flow ratio to show the range of water qualities obtainable through blending.

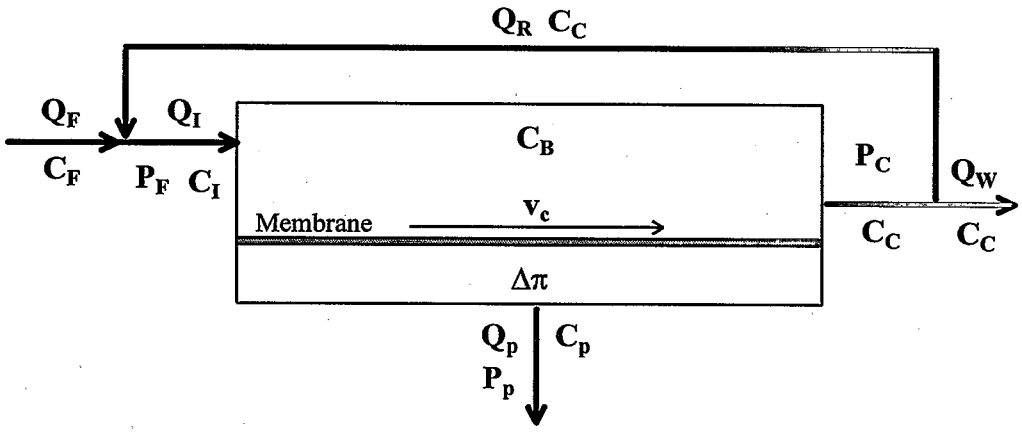

Figure 4-1 Definition Sketch Of A Tangential-Flow Membrane-Cell With Recycle

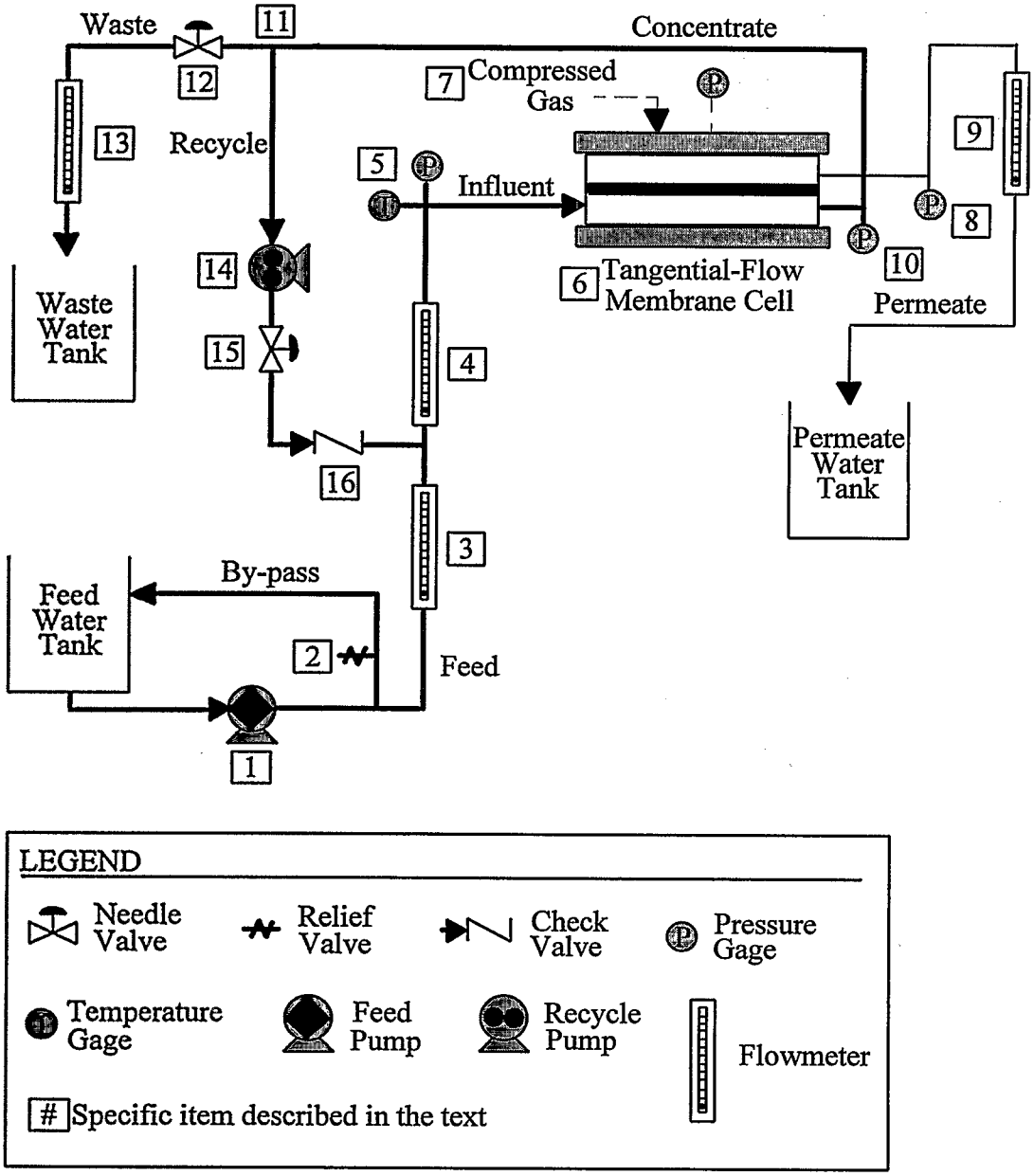

Figure 4-2 Bench-Scale Tangential-Flow Membrane System With Recycle

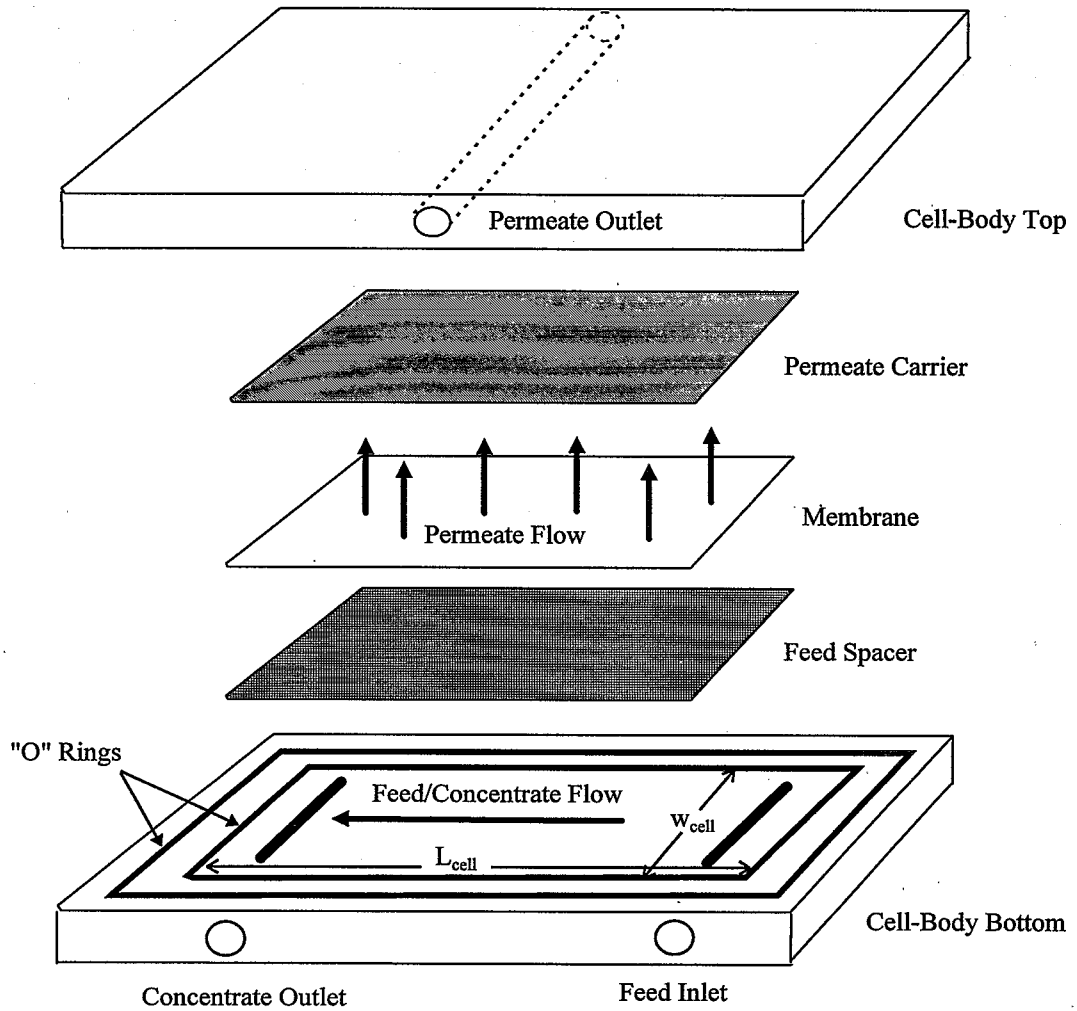

Figure 4-3 Schematic Of The Tangential-Flow Flat-Sheet Cell Used In The RBSMT

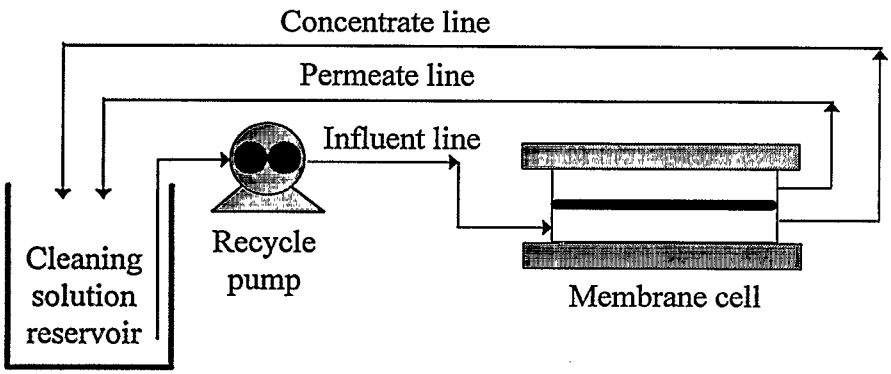

Figure 4-4 Set-Up For Membrane Cleaning Procedure

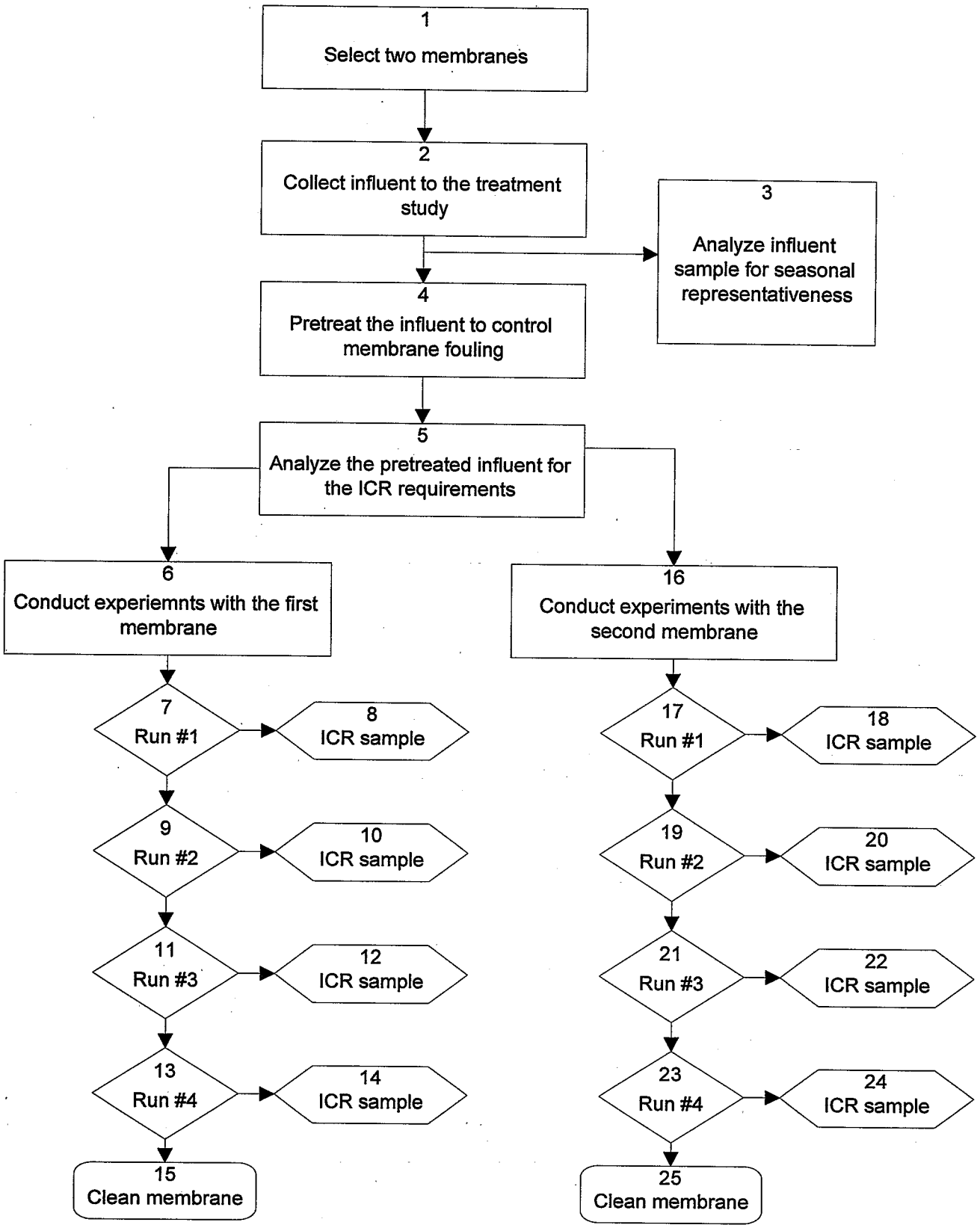

Figure 4-5 Flow Chart For The Quarterly RBSMT Membrane Studies

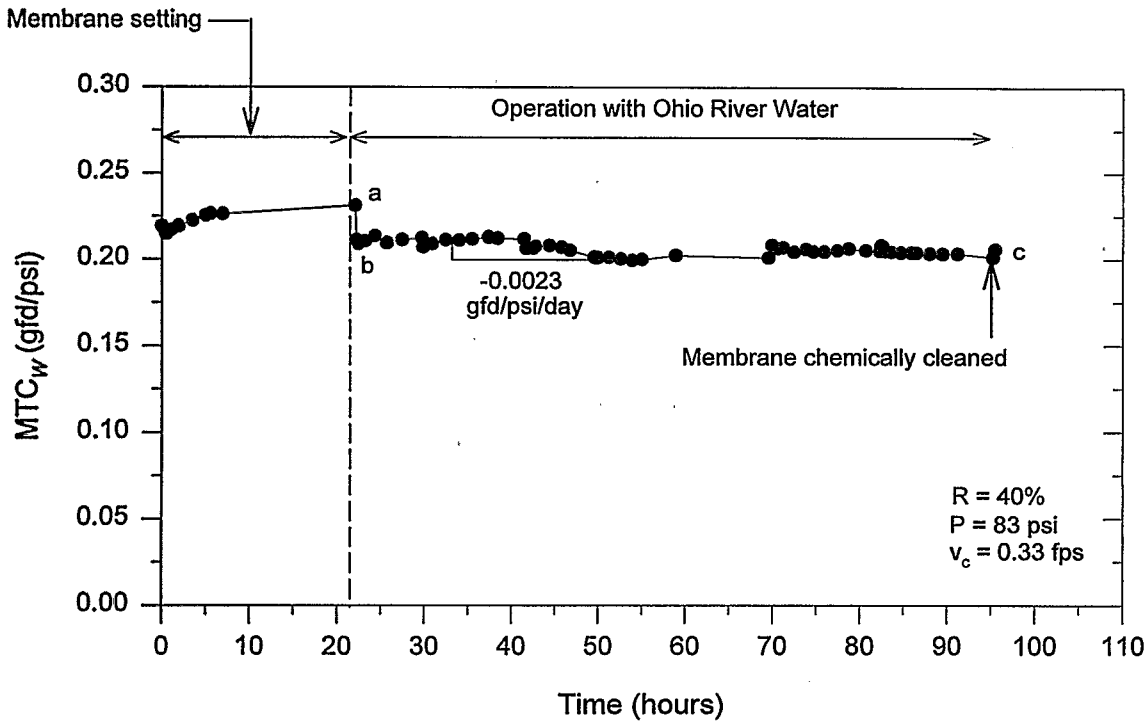

Figure 4-6 MTC_W as a function of time for a Fluid Systems TFCS membrane treating sand filtered Ohio River water from the Cincinnati Water Works

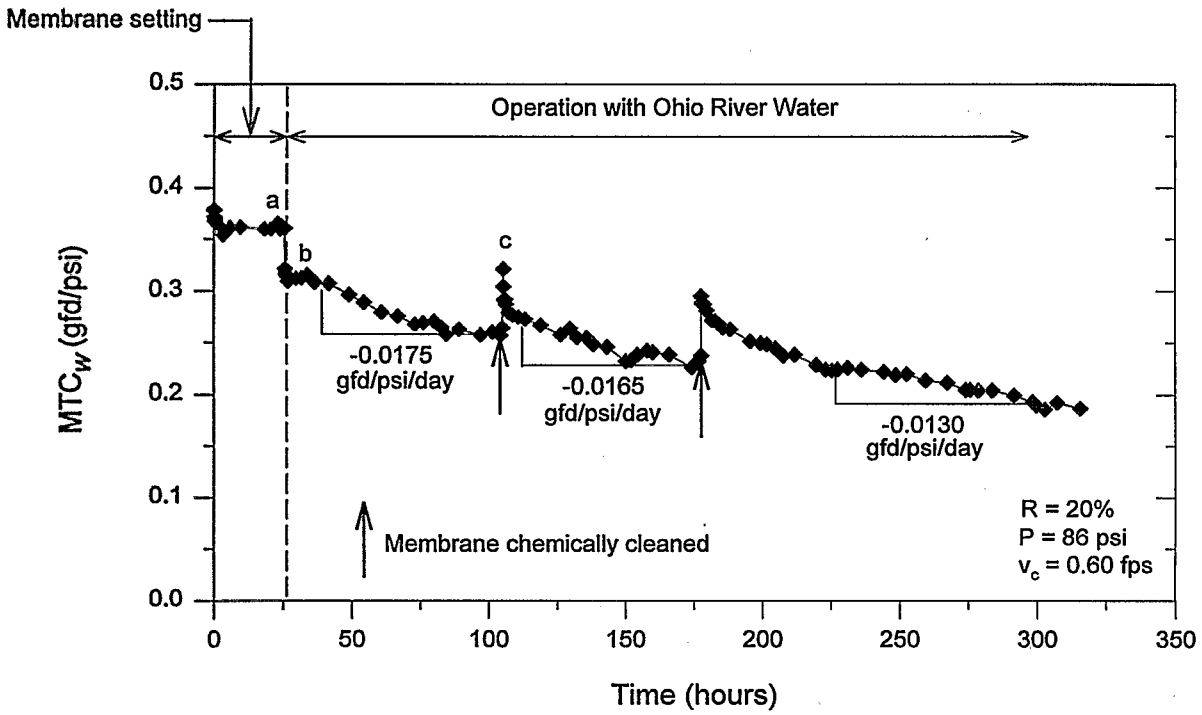

Figure 4-7 Long-term MTC_W study for a FilmTec NF-90 membrane treating sand filtered Ohio River water from the Cincinnati Water Works

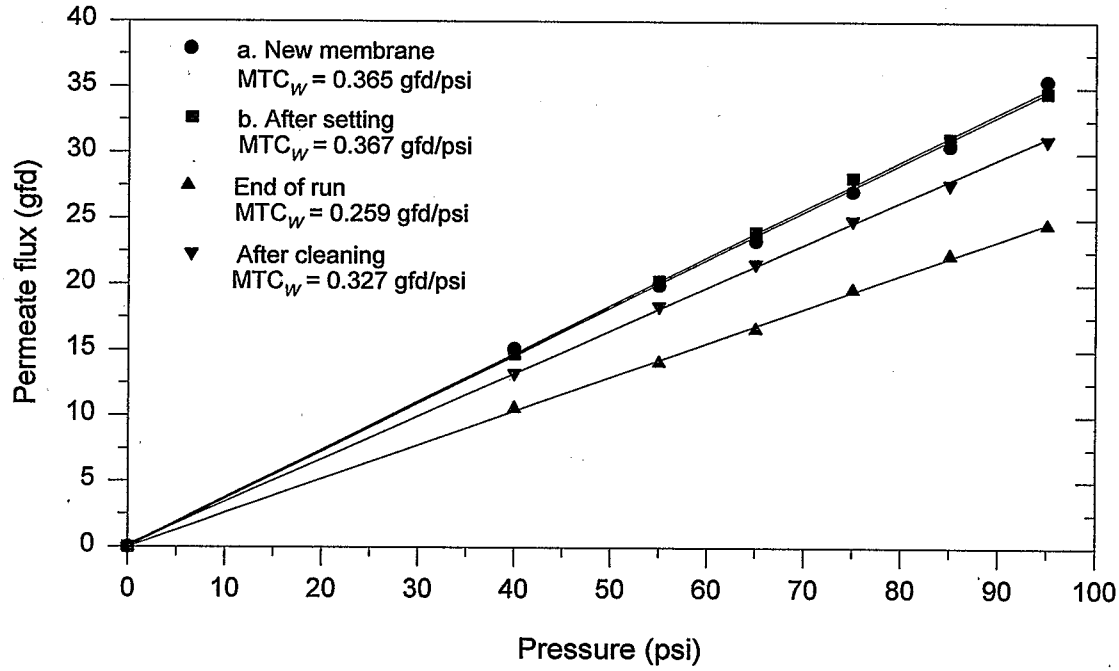

Figure 4-8 Membrane characterization curves for the FilmTec NF-90 membrane treating sand filtered Ohio River water from the Cincinnati Water Works

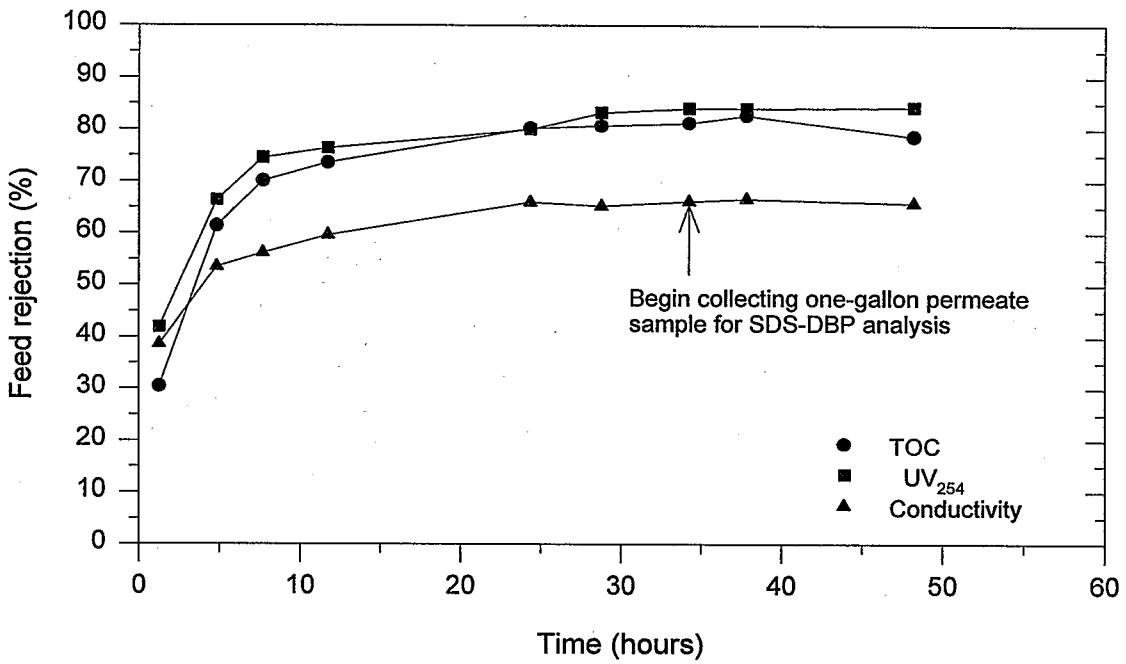

Figure 4-9 Rejection of TOC, UV_{254} and conductivity with time for the FilmTec NF-90 treating sand filtered Ohio River water from the Cincinnati Water Works

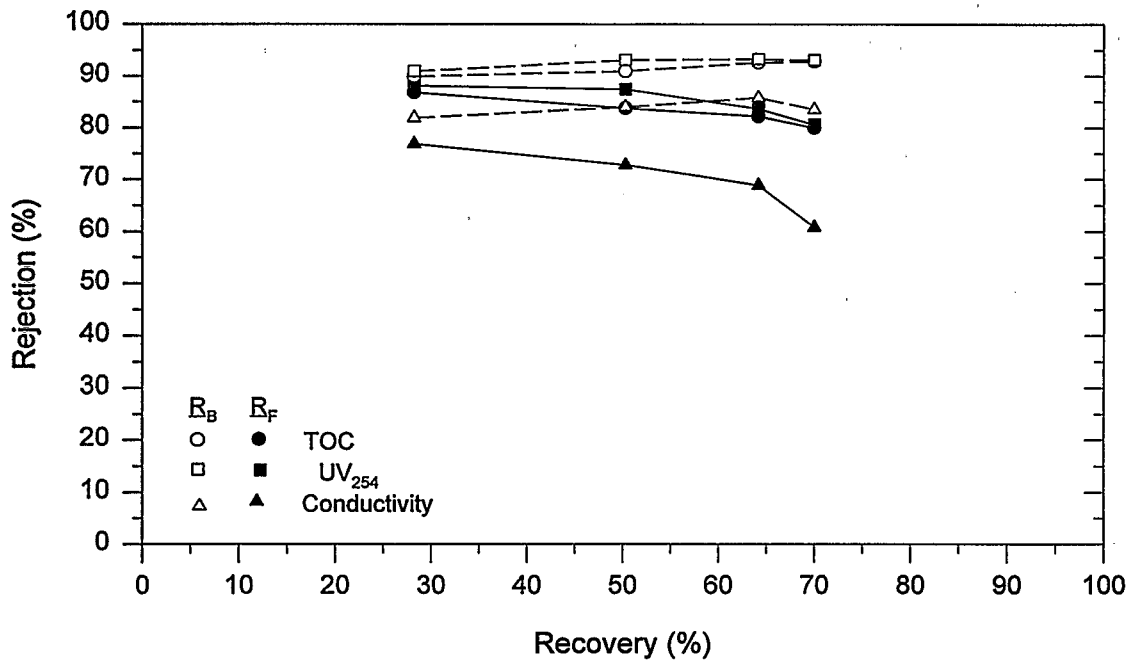

Figure 4-10 Bulk and feed rejections of TOC, UV_{254} and conductivity as a function of recovery for an NF-90 treating sand filtered Ohio River water

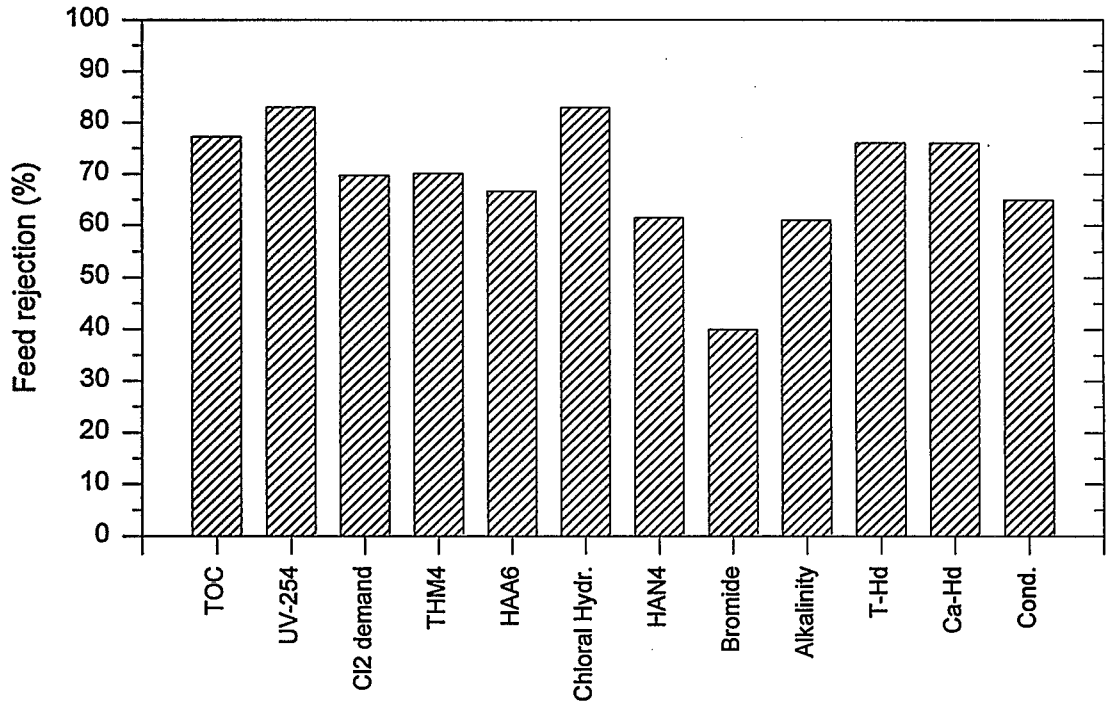

Figure 4-11 Rejections summary for an NF-90 membrane treating sand filtered Ohio River water

Table 4-1 Definitions Used In The RBSMT Procedure

Symbol	Definition
L_{cell}	Active length of membrane in the cell
w_{cell}	Active width of membrane in the cell
A_{cell}	Active area of membrane in the cell
T	Spacer thickness
$v_{c\text{-}design}$	Design cross-flow velocity (minimum)
$Q_{I\text{-}cell}$	Minimum influent flow rate to the cell to achieve $v_{c\text{-}design}$
$L_{element}$	Length of one membrane envelope in a full-scale element
$w_{element}$	Width of all envelopes in a full-scale element (total scroll width)
$Q_{I\text{-}element}$	Minimum influent flow rate to a full-scale membrane element
V	Estimate of the volume requirements for a RBSMT study
Ω	Acceptable fractional loss in the MTC_W prior to cleaning
CF	Cleaning frequency

Table 4-2 Experimental Matrix For The RBSMT-ICR Membrane Studies

ID #	Simulation	Recovery	Cross-flow velocity	Pressure (or Flux)
1	**Conservative system average**	70%	DV	DV
2	**Final stage of a full-scale NF plant**	90%	DV	DV
3	**System average for full-scale plant**	50%	DV	DV
4	**First stage of a full-scale NF plant**	30%	DV	DV

DV: Design values obtained from the membrane manufacturer (see Table 4-5)

Table 4-3 Recommended Minimum Monitoring Frequencies For The RBSMT

Routine RBSMT Study Monitoring Requirements					
Parameter	**Feed**	**Permeate**	**Concentrate**	**Influent**	**Recycle**
Flow	none	6xD	6xD	6xD	none
Pressure	none	none	6xD	6xD	none
Temperature	none	none	none	6xD	none
TDS	1xD	3xD	1xD	none	none
pH	1xD	3xD	1xD	none	none
UV_{254}	1xD	3xD	1xD	none	none

1xD - once per 24 hours
3xD - three time per 24 hours
6xD - six times per 24 hours

Table 4-4 RBSMT Water Quality Monitoring Requirements

Water Quality Parameters To Be Evaluated At Each Recovery			
Parameter	**Feed**	**Permeate**	**Concentrate**
pH	TPR	FTPR	FTPR
Total Hardness	TPR	FTPR	FTPR
Calcium Hardness	TPR	FTPR	FTPR
Alkalinity	TPR	FTPR	FTPR
Total Dissolved Solids	TPR	FTPR	FTPR
Turbidity	TPR	FTPR	FTPR
Total Organic Carbon	TPR	FTPR	FTPR
UV_{254}	TPR	FTPR	FTPR
Bromide	TPR	FTPR	none
SDS - THM4	TPR	FTPR	none
SDS - HAA6	TPR	FTPR	none
SDS - TOX	TPR	FTPR	none
SDS - Cl_2 demand	TPR	FTPR	none

TPR - twice per run.
FTPR - five times per run (i.e., once at each recovery and one duplicate).

Table 4-5 Membrane Characteristics As Reported By The Manufacturer

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Characteristics for a standard 8" x 40" element

Membrane manufacturer	
Membrane module model number	
Active membrane area of an equivalent 8" x 40" element	
Purchase price for an equivalent 8" x 40 " element ($)	
Molecular weight cutoff (Daltons)	
Membrane material / construction	
Membrane hydrophobicity (circle one)	Hydrophilic Hydrophobic
Membrane charge (circle one)	Negative Neutral Positive
Design pressure (psi)	
Design flux at the design pressure (gfd)	
Variability of design flux (%)	
MTC_W (gfd/psi)	
Standard testing recovery (%)	
Standard testing pH	
Standard testing temperature (°C)	
Design cross-flow velocity (fps)	
Maximum flow rate to the element (gpm)	
Minimum flow rate to the element (gpm)	
Required feed flow to permeate flow rate ratio	
Maximum element recovery (%)	
Rejection of reference solute and conditions of test (e.g. solute type and concentration)	
Variability of rejection of reference solute (%)	
Spacer thickness (ft)	
Scroll width (ft)	
Acceptable range of operating pressures	
Acceptable range of operating pH values	
Typical pressure drop across a single element	
Maximum permissible SDI	
Maximum permissible turbidity (ntu)	
Chlorine/oxidant tolerance	
Suggested cleaning procedures	

Note: Some of this information may not be available, but this table should be filled out as completely as possible for each membrane tested.

Table 4-6 RBSMT Design Parameters

Utility name and address _____

_____

ICR plant number _____

Contact person _____

Contact phone number _____ FAX number _____

Membrane trade name and manufacturer _____

8" by 40" Membrane Element Characteristics (from Table 4-5)

Membrane area (ft^2) [ ] Spacer thickness (ft) [ ] Scroll width (ft) [ ]

Design pressure (psi) [ ] Design permeate flux (gfd) [ ] Design MTC_W (gfd/psi) [ ]

Minimum flow rate to an element (gpm) [ ] Design cross-flow velocity (fps) [ ]

Bench-Scale System Characteristics

Membrane area (ft^2) [ ] Membrane width (ft) [ ] Operating temperature (^oC) [ ]

Experimental design[+]

ID#[*]	Recovery (%)	F_W (gfd)	P_F (psi)	v_c (fps)	Q_I (mL/min)	Q_P[**] (mL/min)	Q_F[**] (mL/min)	Q_W[**] (mL/min)
1	70							
2	90							
3	50							
4	30							

Notes: + The values in the shaded cells can be calculated by a spreadsheet.

* For experimental conditions see Table 4-2.

** The flow rates calculated in the above table are approximate values intended to provide a starting point for the experiments. The waste and feed flow rates will need to be adjusted to obtain the target recovery based on the actual permeate flow rate.

Table 4-7 Membrane Pretreatment Data

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Foulants and fouling indices of the feed water prior to pretreatment[1]

Alkalinity (mg $CaCO_3$/L)	
Ca Hardness (mg $CaCO_3$/L)	
LSI	
Dissolved iron (mg/L)	
Total iron (mg/L)	
Dissolved aluminum (mg/L)	
Total aluminum (mg/L)	
Fluoride (mg/L)	
Phosphate (mg/L)	
Sulfate (mg/L)	
Calcium (mg/L)	
Barium (mg/L)	
Strontium (mg/L)	
Reactive silica (mg/L as SiO_2)	
Turbidity (ntu)	
SDI	
MFI	
MPFI	

1: Only those foulants and fouling indices relevant to the water being tested need to be evaluated.
Additional foulants and indices can be listed in the blank rows or on an attached sheet.

Pretreatment processes used prior to nanofiltration or reverse osmosis[2]

Pre-filter exclusion size (μm)	
Type of acid used	
Acid concentration (units)	
mL of acid per L of feed	
Type of antiscalant used	
Antiscalant concentration (units)	
mL of antiscalant per L of feed	
Type of coagulant used	
Coagulant dose (mg/L)	
Type of polymer used during coag.	
Polymer dose (mg/L)	

2: Use an "E" to indicate a pretreatment process that is currently part of the plant treatment train, an "M" to indicate a modification to a process that is currently part of the plant treatment train, and an "A" to indicate an addition to the current treatment train.
Additional pretreatment processes, such as MF, can be listed in the blank rows or on an attached sheet.

Table 4-8 Membrane Feed Water Quality (After Membrane Pretreatment)

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Membrane trade name _____

Water quality parameter	Units	1st sample	2nd sample	Average	RPD
Sampling date	MM/DD/YY				
Sampling time	hh:mm				
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---				
Turbidity	ntu				
Temperature	°C				
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L				
Chlorine residual	mg/L				
Chlorine demand	mg/L				
Chlorination temperature	°C				
Chlorination pH	---				
Incubation time	hours				
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
*MCAA**	µg/L				
*DCAA**	µg/L				
*TCAA**	µg/L				
*MBAA**	µg/L				
*DBAA**	µg/L				
*BCAA**	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

Note: RPD is the relative percent difference between the two samples.

* These six species make up HAA6.

The other three HAA species should be reported if measured.

Table 4-9 Membrane Setting Data (Operation With Laboratory Clean Water)

Utility name and address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____ Membrane sheet area (ft^2) _____ Average Temperature (°C) _____

Operational parameters monitored with time during membrane setting

Date	Cumulative time (hr)	Influent Temp. (°C)	P_I (psi)	P_C (psi)	Q_I (mL/min)	Q_p (mL/min)	Q_W (mL/min)	Q_F (mL/min)	Recovery (decimal)	F_W (gfd)	F_W (Tavg°C) (gfd)	NDP (psi)	MTC_W (gfd/psi)

Notes: Shaded cells can be calculated by a spreadsheet.

Nomenclature is defined in Figure 2-1 and Table 2-2.

Table 4-10 Membrane Performance Data Monitored During Operation With The Pretreated Test Water (page 1)

Utility name and address ______________________________ Phone number ______________

______________________________ FAX number ______________

ICR plant number ____________________ Contact person ____________________

Membrane trade name ______________________________

Operational parameters monitored with time during operation with the test water

Date	Time (hr)	Cumulative time (hr)	P_I (psi)	P_C (psi)	Influent Temp. (°C)	Q_I (mL/min)	Q_P (mL/min)	Q_W (mL/min)	Q_F (mL/min)	Recovery (decimal)

Notes: Shaded cells can be calculated by a spreadsheet, but should also be manually calculated during the run.
Nomenclature is defined in Figure 2-1 and Table 2-2.

Table 4-10 Membrane performance data monitored during operation with the pretreated test water (page 2)

Utility name & address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____

Water quality parameters monitored with time during operation with the test water

Date	Time (hr)	Cumulative time (hr)	pH			TDS (mg/L)		
			Feed C_F	Permeate C_p	Concentrate C_C	Feed C_F	Permeate C_p	Concentrate C_C

Notes: Nomenclature is defined in Figure 2-1 and Table 2-2.

Table 4-10 Membrane performance data monitored during operation with the pretreated test water (page 3)

Utility name & address ______________________________ Phone number __________

______________________________ FAX number __________

ICR plant number ____________________ Contact person ______________

Membrane trade name ______________________________

Water quality parameters monitored with time during operation with the test water

Date	Time (hr)	Cumulative time (hr)	UV_{254} (cm^{-1})			TOC (mg/L), optional analysis		
			Feed C_F	Permeate C_p	Concentrate C_C	Feed C_F	Permeate C_p	Concentrate C_C

Notes: Nomenclature is defined in Figure 2-1 and Table 2-2.

Table 4-11 Membrane Permeate Water Quality For Run ID# 1

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Q_p (mL/min) _____ Q_F (mL/min) _____ Q_I (mL/min) _____

Water quality parameter	Units	$C_{F(average)}$	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
*MCAA**	µg/L				
*DCAA**	µg/L				
*TCAA**	µg/L				
*MBAA**	µg/L				
*DBAA**	µg/L				
*BCAA**	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.

Shaded cells can be calculated by a spreadsheet.

Table 4-12 Duplicate Analysis Of The Membrane Permeate Water Quality For Run ID# 1

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name

Q_p (mL/min) _____ Q_F (mL/min) _____ Q_I (mL/min) _____

Water quality parameter	Units	$C_{F(average)}$	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
*MCAA**	µg/L				
*DCAA**	µg/L				
*TCAA**	µg/L				
*MBAA**	µg/L				
*DBAA**	µg/L				
*BCAA**	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.
Shaded cells can be calculated by a spreadsheet.

Table 4-13 Membrane Permeate Water Quality For Run ID# 2

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name

Q_p (mL/min) _____ Q_F (mL/min) _____ Q_I (mL/min) _____

Water quality parameter	Units	$C_{F(average)}$	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
*MCAA**	µg/L				
*DCAA**	µg/L				
*TCAA**	µg/L				
*MBAA**	µg/L				
*DBAA**	µg/L				
*BCAA**	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.
Shaded cells can be calculated by a spreadsheet.

Table 4-14 Membrane Permeate Water Quality For Run ID# 3

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name

Q_p (mL/min) _____ Q_F (mL/min) _____ Q_I (mL/min) _____

Water quality parameter	Units	$C_{F(average)}$	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
*MCAA**	µg/L				
*DCAA**	µg/L				
*TCAA**	µg/L				
*MBAA**	µg/L				
*DBAA**	µg/L				
*BCAA**	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.
Shaded cells can be calculated by a spreadsheet.

Table 4-15 Membrane Permeate Water Quality For Run ID# 4

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name

Q_p (mL/min) _____ Q_F (mL/min) _____ Q_I (mL/min) _____

Water quality parameter	Units	$C_{F(average)}$	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
*MCAA**	µg/L				
*DCAA**	µg/L				
*TCAA**	µg/L				
*MBAA**	µg/L				
*DBAA**	µg/L				
*BCAA**	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.

Shaded cells can be calculated by a spreadsheet.

Table 4-16 Composite Concentrate Water Quality Parameters And Mass Balance Closure Errors

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Membrane trade name _____

Composite sample for run ID#1 Date _____ Time _____ Recovery (decimal) _____

Parameter	Units	$C_{F(average)}$	C_p	$C_{C(meas)}$	$C_{C(calc)}$	$Error_{MB}$ (%)
pH	---					
Turbidity	ntu					
TDS	mg/L					
TOC	mg/L					
UV_{254}	cm^{-1}					
Alkalinity	mg $CaCO_3$/L					
Total hardness	mg $CaCO_3$/L					
Calcium hardness	mg $CaCO_3$/L					

Composite sample for run ID#2 Date _____ Time _____ Recovery (decimal) _____

Parameter	Units	$C_{F(average)}$	C_p	$C_{C(meas)}$	$C_{C(calc)}$	$Error_{MB}$ (%)
pH	---					
Turbidity	ntu					
TDS	mg/L					
TOC	mg/L					
UV_{254}	cm^{-1}					
Alkalinity	mg $CaCO_3$/L					
Total hardness	mg $CaCO_3$/L					
Calcium hardness	mg $CaCO_3$/L					

Composite sample for run ID#3 Date _____ Time _____ Recovery (decimal) _____

Parameter	Units	$C_{F(average)}$	C_p	$C_{C(meas)}$	$C_{C(calc)}$	$Error_{MB}$ (%)
pH	---					
Turbidity	ntu					
TDS	mg/L					
TOC	mg/L					
UV_{254}	cm^{-1}					
Alkalinity	mg $CaCO_3$/L					
Total hardness	mg $CaCO_3$/L					
Calcium hardness	mg $CaCO_3$/L					

Composite sample for run ID#4 Date _____ Time _____ Recovery (decimal) _____

Parameter	Units	$C_{F(average)}$	C_p	$C_{C(meas)}$	$C_{C(calc)}$	$Error_{MB}$ (%)
pH	---					
Turbidity	ntu					
TDS	mg/L					
TOC	mg/L					
UV_{254}	cm^{-1}					
Alkalinity	mg $CaCO_3$/L					
Total hardness	mg $CaCO_3$/L					
Calcium hardness	mg $CaCO_3$/L					

Table 4-17a Blending Calculations To Determine The Fraction Of Flow That Requires NF Treatment To Meet The Stage I DBP Regulations

Utility name and address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____

	RUN ID #			
Parameter	**1**	**2**	**3**	**4**
$THM4_F$, µg/L				
$THM4_p$, µg/L				
$HAA5_F$, µg/L				
$HAA5_p$, µg/L				
Alk_F, mg/L $CaCO_3$				
Alk_p, mg/L $CaCO_3$				
$T\text{-}Hd_F$, mg/L $CaCO_3$				
$T\text{-}Hd_p$, mg/L $CaCO_3$				
$Ca\text{-}Hd_F$, mg/L $CaCO_3$				
$Ca\text{-}Hd_p$, mg/L $CaCO_3$				

THM4 Controls

Q_p/Q_T (THM4), %				
Alk_b, mg/L $CaCO_3$				
$T\text{-}Hd_b$, mg/L $CaCO_3$				
$Ca\text{-}Hd_b$, mg/L CaCO3				
$THM4_b$, µg/L				
$HAA5_b$, µg/L				

HAA5 Controls

Q_p/Q_T (HAA5), %				
Alk_b, mg/L $CaCO_3$				
$T\text{-}Hd_b$, mg/L $CaCO_3$				
$Ca\text{-}Hd_b$, mg/L CaCO3				
$THM4_b$, µg/L				
$HAA5_b$, µg/L				

Notes: In the first section of this table, the feed and permeate concentrations are entered for each run. The spreadsheet uses these values to calculate the flow that must be treated to meet the stage I DBP MCLs with a 10% factor of safety (i.e.72/54 µg/L - THM4/HAA5). The higher of the two Q_p/Q_I flow ratios (i.e. permeate flow to total flow) based on either THM4 or HAA5 controls the design. The blended water quality parameters are also calculated for the feed / permeate blends. If the permeate quality does not meet the MCLs prior to blending, then these calculations are meaningless.

Table 4-17b Blending Calculations To Determine The Fraction Of Flow That Requires NF Treatment To Meet The Stage II DBP Regulations

Utility name and address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____

	RUN ID #			
Parameter	**1**	**2**	**3**	**4**
$THM4_F$, µg/L				
$THM4_p$, µg/L				
$HAA5_F$, µg/L				
$HAA5_p$, µg/L				
Alk_F, mg/L $CaCO_3$				
Alk_p, mg/L $CaCO_3$				
$T\text{-}Hd_F$, mg/L $CaCO_3$				
$T\text{-}Hd_p$, mg/L $CaCO_3$				
$Ca\text{-}Hd_F$, mg/L $CaCO_3$				
$Ca\text{-}Hd_p$, mg/L $CaCO_3$				

THM4 Controls

Q_p/Q_T (THM4), %				
Alk_b, mg/L $CaCO_3$				
$T\text{-}Hd_b$, mg/L $CaCO_3$				
$Ca\text{-}Hd_b$, mg/L CaCO3				
$THM4_b$, µg/L				
$HAA5_b$, µg/L				

HAA5 Controls

Q_p/Q_T (HAA5), %				
Alk_b, mg/L $CaCO_3$				
$T\text{-}Hd_b$, mg/L $CaCO_3$				
$Ca\text{-}Hd_b$, mg/L CaCO3				
$THM4_b$, µg/L				
$HAA5_b$, µg/L				

Notes: In the first section of this table, the feed and permeate concentrations are entered for each run. The spreadsheet uses these values to calculate the flow that must be treated to meet the stage II DBP MCLs with a 10% factor of safety (i.e.36/27 µg/L - THM4/HAA5). The higher of the two Q_p/Q_f flow ratios (i.e. permeate flow to total flow) based on either THM4 or HAA5 controls the design. The blended water quality parameters are also calculated for the feed / permeate blends. If the permeate quality does not meet the MCLs prior to blending, then these calculations are meaningless.

5.0 Single Element Bench-Scale Test

5.1 SEBST System

The following section presents the general design, equipment and procedures to be used with the single element bench-scale test (SEBST). Section 5.1 is divided into the following sub-sections: SEBST Requirements And Options, System Design, Continuous-flow Pretreatment, System Start-up, System Shut-down, and Membrane Cleaning And Preservation.

5.1.1 SEBST Requirements And Options

The SEBST is a bench-scale procedure, and can only be used to meet the requirements of the ICR by plants serving under 500,000 persons (with the exception of some joint study options as described in Part 1). Two options are available to plants using the SEBST procedure (1) quarterly tests on two membrane types or (2) a yearlong study on a single membrane type.

General SEBST Requirements

The following list of requirements applies to both the quarterly and yearlong SEBST options:

- The minimum element size to be evaluated is a 2.5" x 40" element. If hollow-fiber technology is to be investigated, the smallest standard production size hollow-fiber element should be investigated.

- The experiments must be run at a recovery of 75% $\pm$ 5% using concentrate recycle. If the precipitation of a sparingly soluble salt limits the recovery of the system, then the highest obtainable recovery should be used after appropriate pretreatment steps have been taken. Other operating parameters, such as pressure, flux, influent flow rate, temperature and pH must be within the membrane manufacturer's specifications.

- Only membranes with manufacturer reported molecular weight cutoffs less than 1000 Daltons may be investigated.

- The monitoring and sampling requirements for the SEBST are described in Sections 5.2.2 and 5.2.3, respectively.

Quarterly Studies On Two Membranes

Plants may elect to conduct four quarterly studies on two different membranes using the SEBST procedure. The requirements for this option are as follows:

- The study will evaluate two membranes for no less than four weeks per membrane each quarter of one year with allowances for down-time due to membrane cleaning and minor maintenance. Thus, each membrane must be evaluated for approximately 112 days over the course of one year. This will enable the impact of seasonal variation on membrane performance to be evaluated.

- The two membranes may be evaluated simultaneously using two parallel systems or they may be evaluated sequentially using a single SEBST system. However, the membranes cannot be evaluated in series.

- The same two membrane elements should be used for all four quarters when possible. However, the membranes must be properly cleaned and stored according to the manufacturer's specifications between quarterly runs. This insures that fouling from previous runs does not affect membrane productivity in following runs. If the MTC_W can not be restored to at least 80% of its initial value after cleaning, or if the rejection changes by more than 15% during operation, the membrane may need to be replaced during subsequent runs.

The purpose of quarterly studies is to evaluate the impact of seasonal variation on membrane performance; however, the variability of some source waters may be captured in fewer than four quarters. For example, many ground waters do not exhibit significant seasonal variation. In general, seasonal variation only needs to be evaluated when it is significant, but four quarterly runs evaluating at least two membranes must be performed to meet the ICR requirements. These four runs can be used to evaluate any variables of interest such as additional membranes, different pretreatments or different operating parameters. For example, during the second quarter the same two membranes can be evaluated using different pretreatment. In a following quarter, two different membranes could be evaluated using the optimal pretreatment scheme as determined during the previous two quarters. Different operational parameters could also be investigated.

If the water is not subject to seasonal variations, then the quarterly SEBST runs can be performed in any convenient time frame as long as they are completed within a year of the starting date.

Yearlong Study On A Single Membrane

As an alternative to quarterly studies, the utility may evaluate a single element continuously for one year using the SEBST. This option requires that a single membrane type be run continuously over a period of one year, with allowances for down-time due to membrane cleaning, maintenance or other reasons. The run time should be no less than 6600 hours which represents approximately 75% of a calendar year. Since only one membrane is to be investigated, it is recommended that a preliminary evaluation be conducted to select an appropriate membrane type. A membrane could be selected through a membrane selection study, a literature review, discussions with manufacturers or based on experience with membranes applied to a similar water source. The RBSMT procedure presented in Section 4.0 could be used to rapidly screen a number of membranes prior to a yearlong SEBST study.

5.1.2 System Design

The following section will present the guidelines and equipment to be used in the design and construction of single element bench-scale units. These guidelines are general, and individual equipment for a specific design should be sized and verified for compatibility with

individual membrane specifications. The terminology and definitions used in this section are described in Tables 2-1 and 2-2 and Figure 2-1.

The minimum element size to be evaluated is 2.5" x 40". The only other common size that is available for evaluation on a bench-scale would be a 4" x 40" element; however, larger elements such as 8" x 40" elements can also be evaluated. The 2.5" x 40" element will typically have an active membrane area of 17 to 23 ft^2 and will require an influent flow rate of approximately 0.75 to 1.5 gpm. The 4" x 40" element will have an active membrane area of 70 to 90 ft^2 and will require an influent flow rate of 3 to 6 gpm.

The flow diagram of a SEBST unit showing its major components, system control points and sampling locations is shown in Figure 5-1. The basic design depicted in the flow diagram would apply to either the 2.5" x 40" or 4" x 40" membrane element, but the flow meters, booster pump and pressure vessel would need to be sized based on the dimensions of the element used. Most 2.5" x 40" elements are manufactured in similar lengths and are compatible with standard 2.5" x 40" pressure vessels. However, 4" x 40" element lengths are not necessarily standard between manufacturers, and a product water tube adapter is typically needed for length compatibility with standard 4" x 40" pressure vessels. Table 5-1 presents approximate ranges for pumps and measurement devices to be used on a SEBST system.

Feed water is pretreated to prevent membrane fouling. As shown in the flow diagram, the chemically treated feed water is supplied to the prefilter at a pressure (20 to 40 psi) sufficient to push the water through the prefilter and prevent the booster pump from cavitating. The pretreated water can be combined with recycled concentrate water just after the prefilter on the suction side of the booster pump. The combined feed and concentrate recycle flow is termed the influent stream, and the influent flow rate sets the cross-flow velocity of the system. The filtered water then enters the booster pump. Two pumps types that can be used as booster pumps are positive displacement pumps or multi-stage centrifugal pumps, and the choice of an appropriate pump depends on the pressure and influent flow rate requirements. The booster pump must be sized to meet the membrane manufacturer's pressure and flow requirements for the specific membrane element used; however, a pump recirculate line and valve can be used to adjust the feed pressure. The pump recirculate line transfers influent water from the high pressure side of the booster pump to the suction side of the pump. In this manner, the feed pressure can be controlled with the recirculate valve allowing the pump to be slightly oversized, providing some flexibility.

The pressurized influent stream flows into the membrane pressure vessel and enters through the end of the spiral-wound membrane element. The influent stream is separated into a permeate stream which results from passage through the membrane film, and a concentrated stream (i.e., bulk stream) which flows across the membrane surface. The permeate is collected into a center collection tube and passed out of the membrane pressure vessel. The permeate flow rate is measured with a flow meter, and discharged through an outlet tube at atmospheric pressure. The permeate flow rate should also be measured with a graduated container and a stopwatch to verify and correct flow meter readings.

The concentrate flow can be recycled or wasted. The concentrate waste is passed through a flow meter, a valve and then discharged at atmospheric pressure. The concentrate waste flow rate should also be measured with a graduated container and a stopwatch. The flow meter and valve on the concentrate waste line are used to set the system recovery. A portion of the concentrate stream is returned to the suction side of the booster pump and recycled to obtain a system recovery of 75% and to meet manufacturer specifications for a minimum influent flow rate to an element or a maximum element recovery (i.e., single-pass recovery). The recycle flow rate is controlled with a valve and in-line flow meter.

The following procedure was used to develop these equipment and size ranges for a recovery of 75%. The design at 15% recovery is presented in Table 5-1 to demonstrate a single-pass system (i.e., no recycle), but all SEBST studies are to be conducted at 75% ± 5% recovery or the highest obtainable recovery if the design is controlled by the precipitation of a limiting salt after adequate pretreatment steps have been taken.

1. Obtain the membrane manufacturer's specification sheet for the specific membrane film and element size to be used. The equipment presented in Table 5-1 was sized based on nanofiltration membrane specifications of: a flux of 15 gfd, maximum operating pressure of 250 psi, and membrane surface areas of 20 ft^2 for the 2.5" x 40" element and 70 ft^2 for the 4" x 40" element. Table 5-2 presents the membrane manufacturer information used for this design.

2. The design permeate flux must be selected on the basis of feed water quality and manufacturer specifications. Typically, a flux of 10 to 20 gfd is reasonable for a ground water, and fluxes from 10 to 15 gfd or lower are recommended for surface waters. In this example a ground water is being treated, so a flux of 15 gfd will be used as the design flux. Once the design flux is selected, the permeate flow rate can be calculated using Equation 5.1.

$$\mathbf{Q_p = F_W \times A_e} \qquad \textbf{(5.1)}$$

where $\mathbf{Q_p}$ is the permeate flow rate $\mathbf{F_W}$ is the design flux and $\mathbf{A_e}$ is the active membrane area of the element.

For the 4" x 40" element the permeate flow rate is calculated as:

$$Q_p = F_W \times A_e = 15 \text{ gfd} \times 70 \text{ ft}^2 = 1{,}050 \text{ gpd} = 0.73 \text{ gpm}$$

3. The feed flow rate is calculated from the permeate flow rate and the recovery using Equation 5.2.

$$\mathbf{Q_F = Q_p / R} \qquad \textbf{(5.2)}$$

where $\mathbf{Q_F}$ is the feed flow rate and **R** is the fractional recovery.

For the 4" x 40" element at a recovery of 75% the feed flow rate is calculated as:

$$Q_F = Q_p / R = 0.73 \text{ gpm} / 0.75 = 0.97 \text{ gpm}$$

4. The concentrate waste flow rate is determined by subtracting the permeate flow from the feed flow using Equation 5.3.

$$\mathbf{Q_W = Q_F - Q_p} \qquad \textbf{(5.3)}$$

where $\mathbf{Q_W}$ is the concentrate waste flow rate.

For the 4" x 40" element at 75% recovery, the concentrate waste flow rate is calculated as:

$$Q_W = Q_F - Q_p = 0.97 \text{ gpm} - 0.73 \text{ gpm} = 0.24 \text{ gpm}$$

5. The feed flow rate of 0.97 gpm is below the manufacturer's minimum flow rate of 4 gpm per element. To obtain an acceptable influent flow rate at this recovery, concentrate recycle must be employed. The required recycle flow rate is calculated from the desired influent flow rate and the feed flow rate according to Equation 5.4.

$$\mathbf{Q_R = Q_I - Q_F} \qquad \textbf{(5.4)}$$

where $\mathbf{Q_R}$ is the recycle flow rate and $\mathbf{Q_I}$ is the influent flow rate. The system can be designed for any influent flow rate within the manufacturer's specifications.

In this example, for a single 4" x 40" element, the manufacturer's recommended single-pass recovery is 15%; thus, the required influent flow rate can be calculated by dividing the permeate flow rate by the single-pass recovery (0.73 gpm / 0.15 = 4.9 gpm). This influent flow rate of 4.9 gpm is within the manufacturer's specifications (a minimum flow rate of 4 gpm and a maximum flow rate of 16 gpm), and the recycle flow rate is calculated as:

$$Q_R = Q_I - Q_F = 4.9 \text{ gpm} - 0.97 \text{ gpm} = 3.93 \text{ gpm}$$

6. The recycle ratio can be calculated by dividing the recycle flow rate by the feed flow rate according to Equation 5.5.

$$\mathbf{r = Q_R / Q_F} \qquad \textbf{(5.5)}$$

where **r** is the recycle ratio.

In this example, the recycle ratio is calculated as:

$$r = Q_R / Q_F = 3.93 \text{ gpm} / 0.97 \text{ gpm} = 4$$

7. In order to estimate the required feed pressure, first the osmotic pressure gradient must be estimated. This requires that the TDS concentration be estimated in the waste, permeate and influent streams using Equations 5.6 through 5.8.

$$\mathbf{TDS_W = TDS_F \times [1 + r - R + (R \times Rej_{TDS})] / [1 + r - R - (r \times R \times Rej_{TDS})]} \quad \mathbf{(5.6)}$$

$$\mathbf{TDS_p = (Q_F \times TDS_F - Q_W \times TDS_W) / Q_p} \quad \mathbf{(5.7)}$$

$$\mathbf{TDS_I = (Q_F \times TDS_F + Q_R \times TDS_W) / Q_I} \quad \mathbf{(5.8)}$$

where $\mathbf{TDS_p}$, $\mathbf{TDS_F}$, $\mathbf{TDS_W}$ and $\mathbf{TDS_I}$ are the TDS concentrations in mg/L in the permeate, feed, waste and influent streams, respectively; and $\mathbf{Rej_{TDS}}$ is the manufacturer reported TDS rejection expressed as a decimal fraction.

In this example, the feed TDS concentration is 300 mg/L and the manufacturer reported TDS rejection is 0.70. The TDS concentrations in the waste, permeate and influent streams are:

$$TDS_W = TDS_F \times [1 + r - R + (R \times Rej_{TDS})] / [1 + r - R - (r \times R \times Rej_{TDS})] =$$
$$300 \text{ mg/L} \times [1 + 4 - 0.75 + (0.75 \times 0.70)] / [1 + 4 - 0.75 - (4 \times 0.75 \times 0.70)] =$$
$$666 \text{ mg/L}$$

$$TDS_p = (Q_F \times TDS_F - Q_W \times TDS_W) / Q_p =$$
$$(0.97 \text{ gpm} \times 300 \text{ mg/L} - 0.24 \text{ gpm} \times 666 \text{ mg/L}) / 0.73 \text{ gpm} = 180 \text{ mg/L}$$

$$TDS_I = (Q_F \times TDS_F + Q_R \times TDS_W) / Q_I =$$
$$(0.97 \text{ gpm} \times 300 \text{ mg/L} + 3.93 \text{ gpm} \times 666 \text{ mg/L}) / 4.9 \text{ gpm} = 593 \text{ mg/L}$$

8. The TDS concentrations calculated in the preceding step can now be used to estimate the osmotic pressure gradient using Equation 5.9.

$$\mathbf{\Delta\pi = [((TDS_I + TDS_W) / 2) - TDS_p] \times 0.01} \quad \mathbf{(5.9)}$$

where $\Delta\pi$ is an estimate of the average osmotic pressure gradient in psi, and **0.01** is the factor to convert TDS (mg/L) to pressure (psi).

In this example, the osmotic pressure gradient is calculated as:

$$\Delta\pi = [((TDS_I + TDS_W) / 2) - TDS_p] \times 0.01 =$$
$$[((593 \text{ mg/L} + 666 \text{ mg/L}) / 2) - 180 \text{ mg/L}] \times 0.01 \text{ psi per mg/L} = 4.5 \text{ psi}$$

9. The net driving pressure is estimated from the design permeate flux and the water mass transfer coefficient using Equation 5.10. (Note that the MCT_W may have to be corrected to the temperature at which the study will be conducted using Equation 5.16).

$$\mathbf{NDP = F_W / MTC_W} \qquad \mathbf{(5.10)}$$

where $\mathbf{F_W}$ is the permeate flux, $\mathbf{MTC_W}$ is the water mass transfer coefficient for the membrane under investigation and **NDP** is the net driving pressure for the specific membrane and flux.

In this example, the net driving pressure is calculated as:

$$NDP = F_W / MTC_W = 15 \text{ gfd} / (0.20 \text{ gfd / psi}) = 75 \text{ psi}$$

10. The required feed pressure can be calculated by summing the osmotic pressure gradient, the NDP and any additional losses in the system.

$$\mathbf{P_F = NDP + \Delta\pi + \Delta P_{loss}} \qquad \mathbf{(5.11)}$$

where $\mathbf{P_F}$ is the feed pressure that must be supplied by the booster pressure pump and $\mathbf{\Delta P_{loss}}$ is the summation of additional pressure losses that occur through the membrane element and system hardware such as pipes, valves, flow meters, etc.

For this example, assuming system losses of 7 psi, the feed pressure requirement is calculated as:

$$P_F = NDP + \Delta\pi + \Delta P_{loss} = 75 \text{ psi} + 4.5 \text{ psi} + 7 \text{ psi} = 86.5 \text{ psi}$$

Thus, the high pressure pump should be sized for optimal operation near 87 psi and at a flow rate of 5 gpm. However, the pump should be able to operate over a range of pressures from 80 to 100 psi so that the membrane can be operated in a constant flux mode.

11. From these calculations, flow meters can be sized to measure these flows at the approximate mid-range of the gauges. Table 5-1 presents typical flow gauge ranges for this particular design for both 2.5" and 4" diameter elements. In most single element units, the permeate and concentrate flows are added to determine the feed flow rate; thus it is only necessary to have a recycle flow meter since the permeate and concentrate flows are measured directly by timed volumetric displacement.

5.1.3 Continuous-flow Pretreatment

Pretreatment for membrane processes commonly includes chemical addition to prevent inorganic precipitation and cartridge filtration to reduce colloidal fouling. The most common chemical pretreatment is sulfuric acid addition to reduce the pH to prevent calcium carbonate precipitation. In some cases hydrochloric acid is substituted for sulfuric acid. The potential for calcium carbonate precipitation can be checked by calculating the Langlier Saturation Index

for the concentrate stream. Some applications may require the addition of a chemical antiscalant to control such inorganic precipitants as calcium sulfate, barium sulfate or strontium sulfate. The use of an antiscalant can eliminate the need for acid addition in some cases, and many antiscalants can prevent scaling in systems with a concentrate LSI $\leq +1.5$. The required chemical doses are determined by limiting salt calculations or manufacturer computer programs, both of which typically require a preliminary and comprehensive chemical analysis of the raw water. Additionally, the fouling potential of the feed water should be evaluated using one or more of the methods presented in Section 2.5.

Since they have relatively small flows, the concentrated chemicals used for pretreatment are generally diluted into 20 to 50 gallon containers before injection into the feed stream. The injection point for pretreatment chemicals shown in Figure 5-1 was chosen so that the cartridge filter and booster pump will assist in mixing the pretreatment chemicals. In some cases an in-line static mixer may be used before the cartridge filter to insure proper mixing.

After chemical addition, the water is passed through a cartridge filter to remove larger suspended solids or colloidal material, mix the pretreatment chemicals and protect the booster pump and membrane element from sand or other foreign materials. Polypropylene cartridge filters with a size exclusion of 5 μm are acceptable for membrane pretreatment. The filter cartridges should be cleaned or replaced when the pressure drop across the prefilter increases by a predetermined percentage (e.g., 50%).

For feed waters which have excessive fouling as indicated by fouling indices or other factors, advanced pretreatment will need to be incorporated into the system. Advanced pretreatment may include enhanced coagulation and sand filtration with reduced pH. An example of this would be operating the membrane system using water from a conventional treatment plant after sand filtration and prior to the addition of any oxidant or disinfectant. If alum is used as the coagulant, the pH of the feed water may need to be reduced to around 4.0 (or just above the minimum operational pH as specified by the manufacturer) to ensure the solubility of aluminum hydroxide. However, operating at a low pH may increase fouling by high molecular weight organic matter. Additional advanced pretreatment schemes may include microfiltration to control particulate or microbial fouling.

5.1.4 System Start-up

The following section will describe the general steps to follow during initialization and start-up of a single element test unit.

1. Select a membrane type and obtain the appropriate element size and the manufacturer's specification sheet for that element.

2. Conduct a thorough analysis of the source water to evaluate the inorganic chemical matrix and determine limiting salts by calculation or manufacturer computer program.

3. Conduct fouling index tests on the feed water, calculate indices and determine the potential for fouling problems. If a fouling problem is indicated, additional pretreatment alternatives may need to be evaluated.

4. Select a membrane flux rate consistent with the fouling potential of the water and the manufacturer's recommendations.

5. Calculate or consult manufacturer computer programs for feed water acid and/or antiscalant dose. Calculate the dilution needed for the chemical feed tank capacity and the chemical pump feed rate.

6. Load the element into the pressure vessel and carefully secure the end caps.

7. Flush the feed line upstream of the first stage of the membrane system, but downstream of any pretreatment processes to remove debris and other contaminants. Flushing should be continued for several minutes.

8. Connect the feed line of membrane unit to a pressurized (20 to 40 psi) source water transmission line and open feed valve to allow water to enter the membrane prefilter.

9. Open all valves including permeate, concentrate waste, concentrate recycle, and pump recirculate valves. This is to allow water to flow through the system, displace any trapped air and flow to waste upon start-up.

10. Verify that the feed water is at the prefilter and release trapped air by depressing the bleed button located at the top of the prefilter (if available).

11. Verify that there are proper and secure connections for the chemical feed system, and energize the chemical feed pump. If the unit is going to be operated unattended for significant periods of time, some consideration should be given to controls to shut-down the unit if chemical dosing is interrupted.

12. Connect the power cord of the membrane unit to a compatible power supply and energize the booster pump. Verify that water is passing through the unit by observing the waste flow meter. Adjust the concentrate waste valve so that the concentrate flow does not exceed the manufacturer's maximum recommended flow rate per element.

13. While continuously monitoring the feed pressure to prevent exceeding the unit or membrane manufacturer's specifications, slowly close the concentrate waste valve to set the system recovery at 75%.

14. While continuously monitoring the feed pressure to prevent exceeding the unit or membrane manufacturer's specifications, slowly close the concentrate recycle valve to obtain the selected recycle and influent flow rates.

15. Slowly close the pump recirculate valve to set the permeate flow at the design flux rate.

16. Adjust the concentrate waste, concentrate recycle and pump recirculate valves to set the recovery, influent flow rate and flux rate at the desired values. These parameters must be consistent with the requirements of the ICR and the specifications of the manufacturer.

17. Confirm the proper feed rate for acid by measuring pH or antiscalant by calibrating the chemical pump feed rate.

18. Use the data sheet in Table 5-8 to record the initial system conditions, including the feed, concentrate and permeate flow rates and pressures, the recycle flow rate, and the influent temperature.

5.1.5 System Shut-down

The following section will describe the general steps to follow during shut-down of a single element test unit. The single element studies should be conducted with the objective of operating continuously from start-up to finish; however, continuous operation is not a requirement as long as the run time meets the requirements of the ICR. The system may be shut-down for brief periods (i.e., not to exceed 48 hours) if it cannot be monitored or if the feed stream from the plant needs to be shut-off. If unit operation is interrupted for more than 24 hours, the element should be flushed with feed water once per day for 30 minutes to minimize biological growth.

1. Use the data sheet in Table 5-8 to record the final system conditions, including the feed, concentrate and permeate flow rates and pressures, the recycle flow rate, and the influent temperature.

2. Collect approximately 20 gallons of permeate to use for membrane preservation and cleaning solutions.

3. Open the waste, recycle, pump recirculate and permeate valves to full open.

4. Turn the membrane booster pump to the off position.

5. Turn the chemical feed pumps to the off position.

6. Close the valve from the feed water source.

7. If the system is to be shut-down for more than 24 hours but less than one week, the previously collected permeate water should be used to flush the feed/concentrate side of the membrane. If the membrane is to be shut-down for longer than one week, it should be preserved according to the manufacturer's recommended procedure.

8. The permeate valve should not be closed during shut-down in order in order to avoid osmotic flow from the permeate to the feed side of the membrane. This "reverse flow" can result in membrane damage.

5.1.6 Membrane Cleaning And Preservation

The following section will provide general procedures to be followed during the cleaning and preservation of membranes used in the SEBST. Membranes are usually cleaned when the temperature-normalized MTC_W has decreased by 10 to 15% from the baseline at the beginning of the study or the baseline established after the most recent cleaning. It should be noted that the MTC_W has to be normalized for temperature, since a drop in temperature will cause an increase in the net driving pressure required to maintain a constant flux. The equation used to normalize the MTC_W to a common temperature (i.e., the average yearly water temperature at the plant conducting the study) is presented in Section 5.2.5 as Equation 5.16.

Membrane cleaning frequencies greater than once per month have been suggested to be limiting because of the associated cost and lack of automation. However, there is no reason that membrane cleaning cannot be highly automated and made a routine part of membrane plant operation. Unfortunately, that technology is not widely used today, and the impact of cleaning frequency must be considered in the overall cost and performance of a membrane process.

Since membranes are made from many different materials, membrane manufacturers specify chemicals, chemical strengths, temperatures and pH values for cleaning solutions. Membrane compatibility with a specific cleaning solution must be verified with the membrane manufacturer to avoid damage to the film. There are two basic categories of membrane cleaning solutions, alkaline and acidic solutions. In general, alkaline solutions such as a 0.1% solution of sodium EDTA and a 0.1% solution of sodium hydroxide are effective for removing organic and biological fouling agents. Alkaline solutions are typically used in conjunction with surfactants and detergents such as sodium lauryl sulfate or Triton-X. Acidic solutions such as 0.5% phosphoric acid are effective for removing inorganic foulants. When the exact nature of the foulant is not known, the manufacturer's recommendation for an appropriate cleaning procedure should be solicited.

During membrane cleaning, the single element unit is operated as a closed loop system. The feed line from the suction side of the booster pump is connected or submerged in the cleaning solution tank along with the permeate and waste discharge lines. With the permeate and concentrate waste valves completely open, the cleaning solution is recirculated through the pressure vessel. In situations were the membranes are highly fouled, the cleaning solution may need to be pre-heated and the membranes may need to be soaked in the pre-heated cleaning solution for 1 to 24 hours. It is also noted that some manufacturers require low pressures during cleaning which might require a separate low pressure pump for cleaning; most manufacturers limit the pressure to 60 psi during cleaning. Once the cleaning cycle has been completed, the membranes should be flushed with previously collected permeate water. Permeate should also be used to flush the cleaning tank and system between cleanings with acidic and alkaline solutions.

To preserve the membranes for storage, follow membrane manufacturer specifications for type and strength of preservative. Membranes should always be cleaned prior to preservation and storage. Use previously collected membrane permeate and mix with preservative chemicals to achieve the proper concentration. Connect a suction line from the booster pump to the preservative solution tank, the same tank used for cleaning can be used for membrane preservation solutions, and energize the booster pump long enough to replace the feed and concentrate water left from previous operation with the preservative solution. Turn off the booster pump and close all valves to trap the preservative solution within the membrane pressure vessel. If the membrane is to be stored separately from the pressure vessel, then it may be wetted in the preservative solution and placed into a sealed plastic bag.

Handle, dispose and store all chemicals used in the membrane study in a safe and approved method.

5.2 SEBST Procedure

The following section will present the procedures for monitoring membrane performance during SEBST runs. It will present the parameters and frequency of monitoring as well as sheets for recording data. This section will also present an example of the methodology used to calculate and predict membrane productivity. The section is divided into the following subsections: Selecting Operating Parameters, Monitoring Requirements, Sampling Requirements, Data Sheets, and Membrane Productivity.

5.2.1 Selecting Operating Parameters

There are several operating parameters which must be selected and maintained to conduct a successful membrane study, and Section 5.1.2 describes the procedure for calculating these operating parameters. The recovery must be set and maintained at 75% ± 5%. A lower recovery can be used if the recovery is limited by the precipitation of a sparingly soluble salt after appropriate pretreatment steps have been taken. Membrane manufacturers recommend a minimum influent flow rate (or cross-flow velocity) to avoid excessive ion build up at the membrane film surface (concentration polarization). For 4" diameter membranes, this equates to an influent flow rate of 3 to 6 gpm. The concentrate waste valve is set to achieve a recovery of 75% while the concentrate recycle valve must be set to produce a flow which combined with the feed flow maintains the desired influent flow rate. Additionally, there are manufacturer specifications for a recommended water flux range, a maximum allowable influent flow rate to an element and a maximum allowable pressure. The water flux range usually falls between 10 and 25 gfd. Lower flux (< 15 gfd) and lower single-pass recoveries (< 10% per element) have achieved increased water productivity in some surface water pilot studies (Taylor et al., 1990; Taylor et al., 1992). Although the system recovery is set at 75 ± 5%, the single-pass recovery can be reduced to 10 to 15% by recycling a portion of the concentrate stream.

Pretreatment chemical addition and the appropriate feed pH must also be constantly maintained to prevent inorganic fouling. In addition, the membrane manufacturer may list additional specifications that must be met to prevent damage to the membrane film or element.

For example, most thin-film composite membranes cannot tolerate any chlorine-based disinfectants.

5.2.2 Monitoring Requirements

The flux, net driving pressure and temperature must be monitored during the entire study to calculate the MTC_W and evaluate the rate of MTC_W decline. Since the flux and recovery are maintained at constant levels, fouling will be identified with an increase in net driving pressure, and the drop in productivity can be quantified by calculating the MTC_W. Additionally, some general water quality parameters must be routinely monitored to assess variations in permeate quality.

The sites in Figure 5-1 that need to be monitored are the feed stream before joining with the recycle stream, as well as the permeate, concentrate waste and concentrate recycle streams. The parameters that must be monitored at these sites are pressure, flow rate, temperature, pH and TDS. The feed and permeate TOC and/or UV_{254} may also be measured and reported as part of routine monitoring if desired. The sensor for monitoring temperature should be positioned to monitor the influent stream just before it enters the pressure vessel.

These parameters must be monitored daily at the sites listed in Table 5-3 for both quarterly and yearlong SEBST studies. In addition to monitoring and recording the gauge readings, the permeate and concentrate flow rates should be measured directly to calibrate or verify the flow meters. Table 5-8 presents a data sheet for recording the SEBST monitoring data.

5.2.3 Sampling Requirements

The feed, permeate and concentrate streams should be sampled at the locations shown in Figure 5-1. Table 5-4 presents the analyses to be conducted on the samples collected from each site for both the quarterly and yearlong SEBST studies. The THM4, HAA6 and TOX samples should be formed under SDS conditions that represent the average distribution system conditions at the plant. The chlorine dose and SDS conditions should be reported along with the results of the DBP analyses.

The parameters listed in Table 5-4 must be sampled weekly from each membrane for the quarterly studies. For yearlong studies, the analytes listed in Table 5-4 must be sampled biweekly.

The analyses for the feed should be conducted after it has received appropriate membrane pretreatment, but prior to joining with any recycled concentrate. The feed should be sampled far enough upstream of the junction where the feed joins the recycled concentrate to prevent any back-flow of concentrate into the feed sample. In some cases a check valve may be required to prevent back-flow of concentrate into the feed sample. If the two membranes are evaluated concurrently during quarterly studies, then the feed only needs to be sampled once per week for the analytes listed in Table 5-4.

Sampling, in terms of holding times, preservation, and sampling techniques, should be conducted in accordance with the "ICR Sampling Manual" (EPA 814-B-96-001). Approved

methods for analysis are listed in Table 7, § 141.142 of the ICR Rule, and the analyses for the treatment studies must be conducted according to the analytical and quality control procedures contained in the "DBP/ICR Analytical Methods Manual" (EPA 814-B-96-002).

5.2.4 Data Sheets

This section describes data sheets that can be used to record the appropriate data from the SEBST procedure for the ICR. Corresponding data collection software will be sent to utilities electing to conduct SEBST experiments after the plant submits a study concept form to EPA. Some of these data sheets will have to be modified for the long-term SEBST.

The data sheet in Table 5-6 is used to report the characteristics of each membrane used during the treatment study. These are the membrane characteristics as reported by the manufacturer, and although some of this information may not be available, the data sheet should be filled out as completely as possible. The area and cost of an 8" x 40" element are requested for use in the cost analysis.

The data sheet in Table 5-7 requests information on the foulants in the feed water and the pretreatment processes used to control fouling. The first section of this table requests concentrations of foulants and fouling indices for the feed water. Only the foulants and indices relevant to the water being investigated need to be measured and reported. The blank rows should be used to report additional foulants that were measured but not listed in this table. This information should be used as a guide to selecting appropriate pretreatment processes. During the run, the relevant fouling indices and water quality parameters should be periodically measured to insure that pretreatment processes are performing properly and that the proper chemical doses are being applied to the feed water.

The second half of this table requests information about the pretreatment processes used prior to nanofiltration. All pretreatment processes used should be reported here including processes in the existing full-scale treatment train, upstream of the feed to the SEBST system; and processes that are added specifically for membrane pretreatment. Existing full-scale treatment processes used as membrane pretreatment should be marked with an "E", modifications to processes in the existing plant treatment train (e.g., an increase in the coagulant dose) should be indicated by an "M" and pretreatment processes used in addition to the existing treatment train (e.g., acid or antiscalant addition) should be indicated with an "A". This table can be used to provide some of the pretreatment information required in the final treatment study report.

Table 5-8 contains the parameters that should be monitored with time for each membrane. Temperature normalized fluxes, the MTC_W, and both feed and bulk rejections will be calculated by the data collection software. The feed rejection is calculated from the feed and permeate concentrations. To calculate the bulk rejection, the permeate and feed concentrations and the recovery are used to first estimate the bulk concentration, which is then used to calculate the bulk rejection. The cumulative run time in this data sheet should be set at 0:00 at the start of the run and continued over each four week run or over the yearlong study. Down

time for the system must be subtracted from the cumulative run time (i.e., by stopping the timer when the system is turned off).

The water quality parameters listed in Table 5-4 must be measured once each week for each membrane during the quarterly studies, and this data should be reported in Tables 5-9 through 5-12. For each membrane, the analyses for one set of weekly samples must be duplicated each quarter and reported in Table 5-13.

For the yearlong SEBST studies, the water quality parameters listed in Table 5-4 must be sampled biweekly and reported on data sheet similar to Tables 5-9 through 5-12. The date of sample collection should be listed at the top of the data sheet along with the week number (e.g., week 2, week 4, week 6, ... week 52). Thus at least twenty (20), but no more than twenty-six (26), sample sets are required for both the feed and the permeate. The analysis on every fifth set of samples (feed and permeate) should be duplicated, resulting in four to five sets of duplicate analyses over the course of the yearlong study.

Results from analysis of the concentrate samples sets should be reported in Table 5-14 along with corresponding permeate and feed concentrations. Table 5-14 will need to be extended to include twenty (20) to twenty-six (26) sample sets for the yearlong study. These complete data sets can be used to calculate the mass balance closure errors which can be used to assess sampling and analytical techniques. Mass balance closure errors on common parameters (e.g., TOC, UV_{254}, TDS, alkalinity, hardness, etc.) are typically less than a few percent.

The mass balance closure error is calculated in two steps. First the concentrate concentration is calculated from the feed and permeate concentrations and the fractional recovery using Equation 5.12.

$$C_{C(calc)} = \frac{C_F - (C_p \times R)}{(1 - R)} \qquad (5.12)$$

where $C_{C(calc)}$ is the calculated concentrate concentration. Next the mass balance closure error is determined by comparing calculated and measured concentrate values:

$$Error_{MB} = \frac{C_{C(meas)} - C_{C(calc)}}{C_{C(meas)}} \times 100\% \qquad (5.13)$$

where $Error_{MB}$ is the mass balance closure error expressed as a percentage and $C_{C(meas)}$ is the measured concentrate concentration.

Since permeate quality often exceeds the treatment objectives, permeate can be blended with by-passed feed water. This can substantially reduce the required membrane area and post-treatment requirements, and thus the cost. However, any removal of pathogens that the

membrane is capable of will be negated by blending permeate and feed water, unless the pathogens were removed or inactivated by a process upstream of the membrane process. By calculating the water quality for different blending ratios, costs for different levels of treatment can be estimated. Tables 5-15 (a and b) use the average feed and permeate water quality parameters to calculate the amount of flow that must be treated by membranes to achieve the Stage 1 MCLs (Table 5-15a) and the proposed Stage 2 MCLs (Table 5-15b). Water quality parameters that impact post-treatment requirements are also calculated for the blended waters. In these two tables, Q_T is the total blended flow, and the ratio Q_p/Q_T is the fraction of flow that must be treated by membranes to meet the treatment objectives. This ratio is calculated for both THM4 and HAA5 as either of these water quality parameters can control the blend ratio. The subscript **b** in these tables denotes blended water quality.

5.2.5 Membrane Productivity

Membrane productivity is assessed by the MTC_W decline with time of operation. All membranes foul during operation, and constant production is achieved in full-scale membrane plants by increasing pressure. To develop the cleaning frequency or rate of fouling for a SEBST, the following procedure is presented:

The MTC_W is calculated by using the following equations and data recorded from a short-term single element bench-scale study shown in Table 5-5. Using the definitions for permeate flux and the water mass transfer coefficient from Table 2-2:

$$\mathbf{F_W = Q_P/A_e = MTC_W \times NDP} \qquad \mathbf{(5.14)}$$

Rearranging the equation for water flux and solving for MTC_W:

$$\mathbf{MTC_W = F_W / NDP} \qquad \mathbf{(5.15)}$$

The flux of water is calculated using a permeate flow of 784 gpd and single 4" x 40" element membrane area of 70 ft^2:

$$F_W = Q_P/A_e = (784 \text{ gpd}) / (70 \text{ ft}^2) = 11.2 \text{ gfd}$$

The flux is normalized to a common temperature. Equation 5.16 can be used to normalize the flux to the average yearly water temperature experienced at the plant conducting the study if a manufacture does not specify a temperature correction equation.

$$\mathbf{F_W(Tavg°C) = F_W(T°C) \times 1.03^{(Tavg°-T°)}} \qquad \mathbf{(5.16)}$$

where $\mathbf{F_W(Tavg°C)}$ is the flux corrected to the average yearly water temperature at the plant conducting the study, $\mathbf{F_W(T°C)}$ is the flux measured at ambient temperature, **T°** is the temperature at which the flux was measured in °C, and **Tavg°** is the average yearly water temperature at the plant conducting the study in °C.

The temperature correction equation was not used in this particular case since the temperature at which the study was performed was equivalent to the average temperature of the source.

In order to determine the NDP, the osmotic pressure gradient must first be estimated from the influent, concentrate waste and permeate TDS values using Equation 5.9 which was first presented in Section 5.1.2.

For this example TDS_p is 100 mg/L, TDS_I is 200 mg/L and TDS_W is 500 mg/L.

$$\Delta\pi = ([(TDS_I+TDS_W)/2]-TDS_p)\times(1\text{ psi} / 100\text{ mg/L}) =$$
$$[(200\text{ mg/L}+500\text{ mg/L})/2]-100\text{ mg/L})(1\text{psi} / 100\text{ mg/L TDS}) = 2.5\text{ psi}$$

The net driving pressure is calculated according to Equation 5.17.

$$\mathbf{NDP} = [(P_I + P_C) / 2] - P_p - \Delta\pi \qquad \textbf{(5.17)}$$

where **NDP** is the net driving pressure, $\mathbf{P_I}$ is the influent pressure, $\mathbf{P_C}$ is the concentrate pressure and $\mathbf{P_p}$ is the permeate pressure.

For this example, P_I is 45 psi, P_C is 35 psi and P_p is 5.5 psi.

$$NDP = [(P_I+P_C)/2]-P_p-\Delta\pi = [(45\text{psi}+35\text{psi})/2]-5.5\text{psi}-2.5\text{psi} = 32\text{psi}$$

Using these results the MTC_W can be calculated from Equation 5.14 as:

$$MTC_W = F_W/NDP = 11.2\text{ gfd} / 32\text{ psi} = 0.35\text{ gfd/psi}$$

The MTC_W is calculated for each set of operational data and plotted versus the cumulative time of operation. A spreadsheet incorporating these equations can calculate the net driving pressure, the temperature normalized flux and the MTC_W using the data recorded in Table 5-8.

The data summarized in Table 5-5 is presented graphically in Figure 5-2. The slope of a linear least squares fit of the plotted data is the change in the MTC_W with time and this slope is used to predict the rate of fouling and the required cleaning frequency. From the data summarized in Table 5-5 and presented graphically in Figure 5-2, the linear regression line calculated from a spreadsheet is:

$$MTC_W = -0.0005 \times \text{time} + 0.355$$

Equation 5.18 can be used to estimate the cleaning frequency from the rate of MTC_W decline and the acceptable loss in the MTC_W.

$$\mathbf{CF} = \frac{\Omega \times \mathbf{MTC}_{W(o)}}{\mathbf{dMTC}_W / \mathbf{dt}} \qquad \textbf{(5.18)}$$

where **CF** is the cleaning frequency, Ω is the acceptable fractional loss in the MTC_W prior to cleaning (e.g., 0.15), $\mathbf{MTC}_{W(o)}$ is the baseline MTC_W established at the start of the run or after the most recent cleaning, and $\mathbf{dMTC}_W/\mathbf{dt}$ is the rate of MTC_W decline determined from a linear regression of the flux data.

The data used to develop Figure 5-2 came from an actual short-term pilot study. Note the baseline MTC_W is 0.35 gfd/psi, and the acceptable 15 % MTC_W loss is 0.054 gfd/psi. The calculated cleaning frequency using the linear rate of decline is 105 days or 3.5 months. The rate of MTC_W decline in this example was estimated from a linear regression which worked well for this data. However, the rate of MTC_W decline may not always follow a linear model, and the best model of MTC_W decline over time of production should be used to estimate the rate of MTC_W decline. In general, if the r^2 value of the regression line is less than approximately 0.90, the fit may not accurately predict the rate of MTC_W decline. In this case, another model for MTC_W decline should be used. For example a linear regression for a plot of the log of time versus the log of the MTC_W may be used to predict the rate of MTC_W decline.

A CF of 105 days is not considered an unreasonable rate of cleaning for a membrane plant treating a highly organic ground water. This SEBST study showed that chemical fouling was not prohibitive. Furthermore, this bench study showed that this source is treatable by a conventional membrane process and that a more extensive pilot study could be undertaken to develop design data. However, due to its short time of operation, this study did not measure the potential for biofouling which is one of the reasons a more thorough pilot study is justified. This point must be appreciated when interpreting data from short-term studies, since biofouling may control the cleaning frequency in some situations.

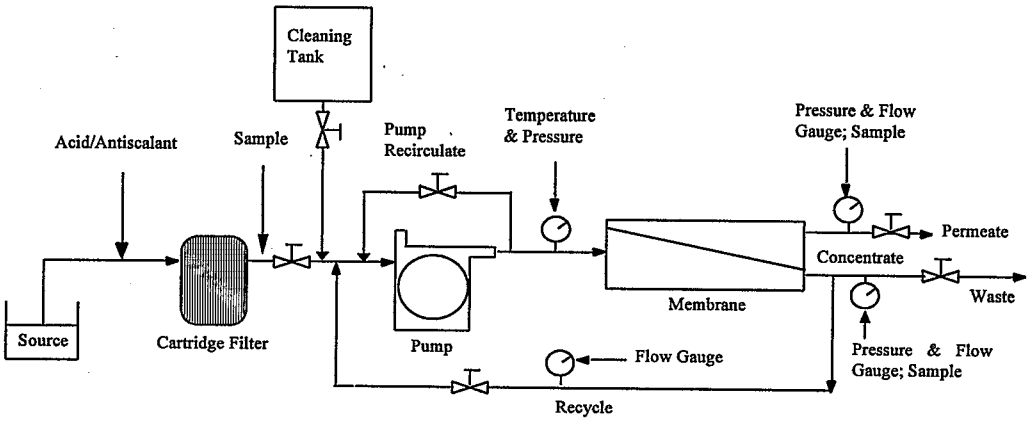

Figure 5-1 Schematic Of A Single Element Bench-Scale Unit

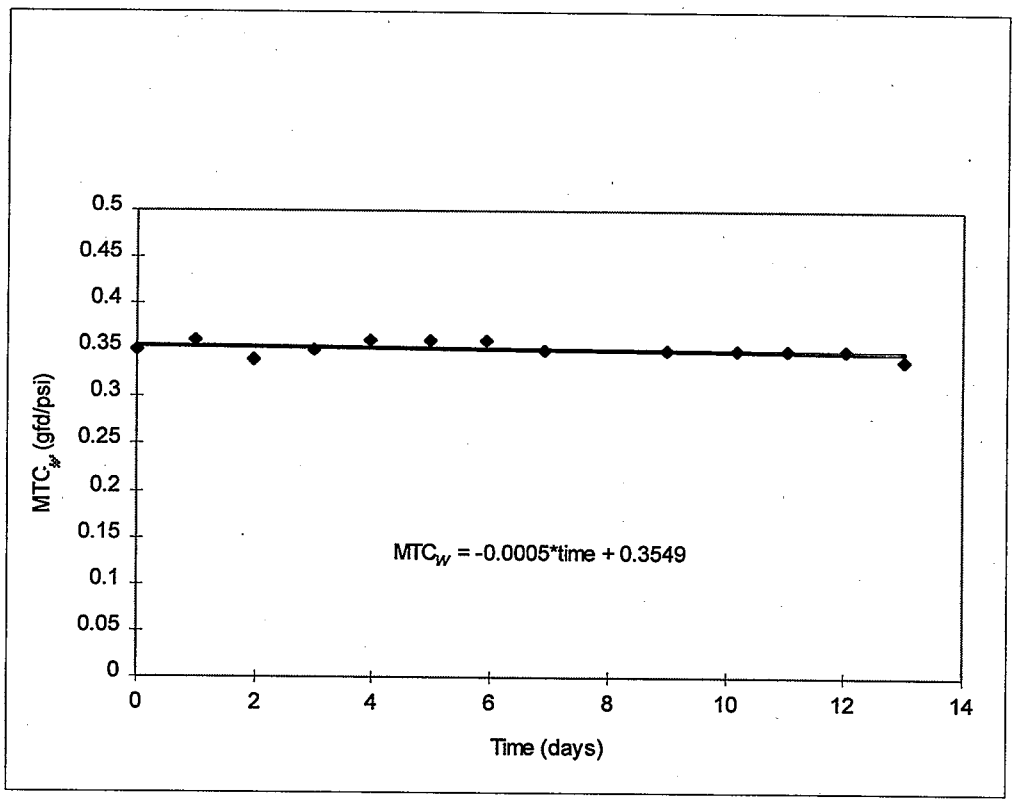

Figure 5-2 Temperature Normalized MTC_W Plotted As A Function Of Time

Table 5-1 Example Design Parameters For Single Element Units

Recovery	75% (with recycle)		15% (single-pass)	
Element size	**2.5" x 40"**	**4" x 40"**	2.5" x 40"	4" x 40"
Feed				
Flow (gpm)	**0.28**	**0.97**	1.39	4.9
Pump Flow (gpm)	**1.39**	**4.9**	1.39	4.9
Pressure (psi)	**87**	**87**	87	87
Permeate				
Flow (gpm)	**0.21**	**0.73**	0.21	0.73
Pressure (psi)	**0**	**0**	0	0
Concentrate				
Flow (gpm)	**0.07**	**0.24**	1.18	4.2
Pressure (psi)	**80**	**80**	80	80
Recycle				
Flow (gpm)	**1.11**	**3.96**	0	0

Table 5-2 Design Characteristics For The Membrane Used In The Design Example

Parameter	Value
Manufacturer	**********
Membrane trade name	**********
Element size	4 inch diameter by 40 inch length
Membrane material / construction	PVD / thin-film composite
Continuous operational pH range	3 to 9
Short-term cleaning pH range	1 to 11
Molecular weight cutoff, Daltons	500
Membrane area, ft^2	70
Maximum operating temperature, ^oC	35
Maximum flow to element, gpm	16
Minimum flow to element, gpm	4
Maximum pressure, psi	250
Design pressure, psi	80
Design flux, gfd	15
Single element recovery, %	15
MTC_W (T^oC), gfd/psi	0.20 at (20^oC)
Max. pressure drop across element, psi	10
TDS rejection, %	70

Table 5-3 SEBST Routine Monitoring Requirements

Quarterly SEBST Study Monitoring Requirements					
Parameter	**Feed**	**Permeate**	**Concentrate**	**Influent**	**Recycle**
Flow	none	D	D	none	D
Pressure	none	D	D	D	none
Temperature	none	none	none	D	none
TDS	D	D	D	none	none
pH	D	D	D	none	none

Yearlong SEBST Study Monitoring Requirements					
Parameter	**Feed**	**Permeate**	**Concentrate**	**Influent**	**Recycle**
Flow	none	D	D	none	D
Pressure	none	D	D	D	none
Temperature	none	none	none	D	none
TDS	D	D	D	none	none
pH	D	D	D	none	none

D - daily (once per shift)

Table 5-4 SEBST Water Quality Monitoring Requirements

Quarterly SEBST Study Sampling Requirements			
Parameter	**Feed**	**Permeate**	**Concentrate**
pH	W	W	W
Total Hardness	W	W	W
Calcium Hardness	W	W	W
Alkalinity	W	W	W
Total Dissolved Solids	W	W	W
Turbidity	W	W	W
Total Organic Carbon	W	W	W
UV_{254}	W	W	W
Bromide	W	W	none
SDS - THM4	W	W	none
SDS - HAA6	W	W	none
SDS - TOX	W	W	none
SDS - Cl_2 demand	W	W	none

Yearlong SEBST Study Sampling Requirements			
Parameter	**Feed**	**Permeate**	**Concentrate**
pH	BW	BW	BW
Total Hardness	BW	BW	BW
Calcium Hardness	BW	BW	BW
Alkalinity	BW	BW	BW
Total Dissolved Solids	BW	BW	BW
Turbidity	BW	BW	BW
Total Organic Carbon	BW	BW	BW
UV_{254}	BW	BW	BW
Bromide	BW	BW	none
SDS - THM4	BW	BW	none
SDS - HAA6	BW	BW	none
SDS - TOX	BW	BW	none
SDS - Cl_2 demand	BW	BW	none

W - weekly
BW - biweekly

Table 5-5 Short-term Membrane Productivity Study

Time Days	NDP (psi)	Recovery (%)	Flux (gfd)	MTC_W (gfd/psi)
0.00	32	15	11.20	0.35
0.99	31	15	11.16	0.36
1.98	33	14	11.22	0.34
2.99	32	15	11.20	0.35
3.94	31	15	11.16	0.36
4.96	31	15	11.16	0.36
5.91	31	16	11.16	0.36
6.90	32	14	11.20	0.35
8.99	30	15	10.50	0.35
10.02	30	15	10.50	0.35
11.04	30	15	10.50	0.35
12.02	30	14	10.50	0.35
13.02	30	14	10.20	0.34
14.02	30	11	10.50	0.35

Table 5-6 Membrane Characteristics As Reported By The Manufacturer

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Characteristics of the membrane element used in the study

Membrane manufacturer	
Membrane module model number	
Size of element used in study (e.g. 4" x 40")	
Active membrane area of element used in study	
Active membrane area of an equivalent 8" x 40" element	
Purchase price for an equivalent 8" x 40 " element ($)	
Molecular weight cutoff (Daltons)	
Membrane material / construction	
Membrane hydrophobicity (circle one)	Hydrophilic Hydrophobic
Membrane charge (circle one)	Negative Neutral Positive
Design pressure (psi)	
Design flux at the design pressure (gfd)	
Variability of design flux (%)	
MTC_W (gfd/psi)	
Standard testing recovery (%)	
Standard testing pH	
Standard testing temperature (°C)	
Design cross-flow velocity (fps)	
Maximum flow rate to the element (gpm)	
Minimum flow rate to the element (gpm)	
Required feed flow to permeate flow rate ratio	
Maximum element recovery (%)	
Rejection of reference solute and conditions of test (e.g. solute type and concentration)	
Variability of rejection of reference solute (%)	
Spacer thickness (ft)	
Scroll width (ft)	
Acceptable range of operating pressures	
Acceptable range of operating pH values	
Typical pressure drop across a single element	
Maximum permissible SDI	
Maximum permissible turbidity (ntu)	
Chlorine/oxidant tolerance	
Suggested cleaning procedures	

Note: Some of this information may not be available, but this table should be filled out as completely as possible for each membrane tested.

Table 5-7 Membrane Pretreatment Data

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Foulants and fouling indices of the feed water prior to pretreatment[1]

Alkalinity (mg $CaCO_3$/L)	
Ca Hardness (mg $CaCO_3$/L)	
LSI	
Dissolved iron (mg/L)	
Total iron (mg/L)	
Dissolved aluminum (mg/L)	
Total aluminum (mg/L)	
Fluoride (mg/L)	
Phosphate (mg/L)	
Sulfate (mg/L)	
Calcium (mg/L)	
Barium (mg/L)	
Strontium (mg/L)	
Reactive silica (mg/L as SiO_2)	
Turbidity (ntu)	
SDI	
MFI	
MPFI	

1: Only those foulants and fouling indices relevant to the water being tested need to be evaluated.
Additional foulants and indices can be listed in the blank rows or on an attached sheet.

Pretreatment processes used prior to nanofiltration or reverse osmosis[2]

Pre-filter exclusion size (μm)	
Type of acid used	
Acid concentration (units)	
mL of acid per L of feed	
Type of antiscalant used	
Antiscalant concentration (units)	
mL of antiscalant per L of feed	
Type of coagulant used	
Coagulant dose (mg/L)	
Type of polymer used during coag.	
Polymer dose (mg/L)	

2: Use an "E" to indicate a pretreatment process that is currently part of the plant treatment train, an "M" to indicate a modification to a process that is currently part of the plant treatment train, and an "A" to indicate an addition to the current treatment train.
Additional pretreatment processes, such as MF, can be listed in the blank rows or on an attached sheet.

Table 5-8 Membrane Operational And Performance Data Monitoring With Time (page 1)

Utility name and address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____

Operational parameters monitored with time

Date	Time (hr)	Cumulative time (hr)	P_I (psi)	P_C (psi)	P_p (psi)	Influent Temp (°C)	Q_R (gpm)	Q_P (gpm)	Q_W (gpm)	Q_F (gpm)	Recovery (decimal)

Notes: Shaded cells can be calculated by a spreadsheet, but should also be manually calculated during the run.
Nomenclature is defined in Figure 2-1 and Table 2-2.

Table 5-8 Membrane Operational And Performance Data Monitoring With Time (page 2)

Utility name & address ______________________________ Phone number __________

______________________________ FAX number __________

ICR plant number ____________________ Contact person ______________

Membrane trade name ______________________________

Water quality parameters monitored with time

Date	Time	Cumulative time	**pH**			**TDS (mg/L)**		
	(hr)	(hr)	Feed C_F	Permeate C_p	Concentrate C_C	Feed C_F	Permeate C_p	Concentrate C_C

Notes: Nomenclature is defined in Figure 2-1 and Table 2-2.

Table 5-8 Membrane Operational And Performance Data Monitoring With Time (page 3)

Utility name & address ________________________________ Phone number __________

________________________________ FAX number __________

ICR plant number ____________________ Contact person ______________

Membrane trade name ________________________________

Water quality parameters monitored with time

Date	Time	Cumulative time	UV_{254} (cm^{-1}), optional analysis			TOC (mg/L), optional analysis		
	(hr)	(hr)	Feed C_F	Permeate C_p	Concentrate C_C	Feed C_F	Permeate C_p	Concentrate C_C

Notes: Nomenclature is defined in Figure 2-1 and Table 2-2.

Table 5-9 Membrane Feed And Permeate Water Quality For Week One

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name

Q_p (gpm) _____ Q_F (gpm) _____ Q_I (gpm) _____

Water quality parameter	Units	C_F	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
MCAA *	µg/L				
DCAA *	µg/L				
TCAA *	µg/L				
MBAA *	µg/L				
DBAA *	µg/L				
BCAA *	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.
Shaded cells can be calculated by a spreadsheet.

Table 5-10 Membrane Feed And Permeate Water Quality For Week Two

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name

Q_p (gpm) _____ Q_F (gpm) _____ Q_I (gpm) _____

Water quality parameter	Units	C_F	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
*MCAA**	µg/L				
*DCAA**	µg/L				
*TCAA**	µg/L				
*MBAA**	µg/L				
*DBAA**	µg/L				
*BCAA**	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.

Shaded cells can be calculated by a spreadsheet.

Table 5-11 Membrane Feed And Permeate Water Quality For Week Three

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name

Q_p (gpm) _____ Q_F (gpm) _____ Q_I (gpm) _____

Water quality parameter	Units	C_F	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
MCAA*	µg/L				
DCAA*	µg/L				
TCAA*	µg/L				
MBAA*	µg/L				
DBAA*	µg/L				
BCAA*	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.
Shaded cells can be calculated by a spreadsheet.

Table 5-12 Membrane Feed And Permeate Water Quality For Week Four

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name

Q_p (gpm) _____ Q_F (gpm) _____ Q_I (gpm) _____

Water quality parameter	Units	C_F	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
*MCAA**	µg/L				
*DCAA**	µg/L				
*TCAA**	µg/L				
*MBAA**	µg/L				
*DBAA**	µg/L				
*BCAA**	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.
Shaded cells can be calculated by a spreadsheet.

Table 5-13 Duplicate Analysis Of Membrane Feed And Permeate Water Quality For Week ___

Week for which water quality analyses are being duplicated _____

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name

Q_p (gpm) _____ Q_F (gpm) _____ Q_I (gpm) _____

Water quality parameter	Units	C_F	C_p	R_F	R_B
Sampling date	MM/DD/YY			---	---
Sampling time	hh:mm			---	---
Alkalinity	mg/L as $CaCO_3$				
Total dissolved solids	mg/L				
Total hardness	mg/L as $CaCO_3$				
Calcium hardness	mg/L as $CaCO_3$				
Bromide	µg/L				
pH	---			---	---
Turbidity	ntu				
Temperature	°C			---	---
Total organic carbon	mg/L				
UV_{254}	cm^{-1}				
SDS samples					
Chlorine dose	mg/L			---	---
Chlorine residual	mg/L			---	---
Chlorine demand	mg/L				
Chlorination temperature	°C			---	---
Chlorination pH	---			---	---
Incubation time	hours			---	---
TOX	µg/L				
$CHCl_3$	µg/L				
$CHBrCl_2$	µg/L				
$CHBr_2Cl$	µg/L				
$CHBr_3$	µg/L				
THM4	µg/L				
*MCAA**	µg/L				
*DCAA**	µg/L				
*TCAA**	µg/L				
*MBAA**	µg/L				
*DBAA**	µg/L				
*BCAA**	µg/L				
TBAA	µg/L				
CDBAA	µg/L				
DCBAA	µg/L				
HAA6	µg/L				

* These six species make up HAA6. The other three HAA species should be reported if measured.
Shaded cells can be calculated by a spreadsheet.

Table 5-14 Concentrate Water Quality Parameters And Mass Balance Closure Errors

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Membrane trade name _____

Concentrate sample from week 1 Date _____ Time _____ Fractional recovery [ ]

Parameter	Units	C_F	C_p	$C_{C(meas)}$	$C_{C(calc)}$	$Error_{MB}$ (%)
TDS	mg/L					
TOC	mg/L					
UV_{254}	cm^{-1}					
Alkalinity	mg $CaCO_3$/L					
Total hardness	mg $CaCO_3$/L					
Calcium hardness	mg $CaCO_3$/L					

Concentrate sample from week 2 Date _____ Time _____ Fractional recovery [ ]

Parameter	Units	C_F	C_p	$C_{C(meas)}$	$C_{C(calc)}$	$Error_{MB}$ (%)
TDS	mg/L					
TOC	mg/L					
UV_{254}	cm^{-1}					
Alkalinity	mg $CaCO_3$/L					
Total hardness	mg $CaCO_3$/L					
Calcium hardness	mg $CaCO_3$/L					

Concentrate sample from week 3 Date _____ Time _____ Fractional recovery [ ]

Parameter	Units	C_F	C_p	$C_{C(meas)}$	$C_{C(calc)}$	$Error_{MB}$ (%)
TDS	mg/L					
TOC	mg/L					
UV_{254}	cm^{-1}					
Alkalinity	mg $CaCO_3$/L					
Total hardness	mg $CaCO_3$/L					
Calcium hardness	mg $CaCO_3$/L					

Concentrate sample from week 4 Date _____ Time _____ Fractional recovery [ ]

Parameter	Units	C_F	C_p	$C_{C(meas)}$	$C_{C(calc)}$	$Error_{MB}$ (%)
TDS	mg/L					
TOC	mg/L					
UV_{254}	cm^{-1}					
Alkalinity	mg $CaCO_3$/L					
Total hardness	mg $CaCO_3$/L					
Calcium hardness	mg $CaCO_3$/L					

Notes: Shaded cells can be calculated by a spreadsheet.
Nomenclature is defined in Figure 2-1 and Table 2-2.

Table 5-15a Blending Calculations To Determine The Fraction Of Flow That Requires NF Treatment To Meet The Stage I DBP Regulations

Utility name and address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____

	RUN ID #			
Parameter	**1**	**2**	**3**	**4**
$THM4_F$, µg/L				
$THM4_p$, µg/L				
$HAA5_F$, µg/L				
$HAA5_p$, µg/L				
Alk_F, mg/L $CaCO_3$				
Alk_p, mg/L $CaCO_3$				
T-Hd_F, mg/L $CaCO_3$				
T-Hd_p, mg/L $CaCO_3$				
Ca-Hd_F, mg/L $CaCO_3$				
Ca-Hd_p, mg/L $CaCO_3$				

THM4 Controls

Q_p/Q_T (THM4), %				
Alk_b, mg/L $CaCO_3$				
T-Hd_b, mg/L $CaCO_3$				
Ca-Hd_b, mg/L CaCO3				
$THM4_b$, µg/L				
$HAA5_b$, µg/L				

HAA5 Controls

Q_p/Q_T (HAA5), %				
Alk_b, mg/L $CaCO_3$				
T-Hd_b, mg/L $CaCO_3$				
Ca-Hd_b, mg/L CaCO3				
$THM4_b$, µg/L				
$HAA5_b$, µg/L				

Notes: In the first section of this table, the feed and permeate concentrations are entered for each run. The spreadsheet uses these values to calculate the flow that must be treated to meet the stage I DBP MCLs with a 10% factor of safety (i.e.72/54 µg/L - THM4/HAA5). The higher of the two Q_p/Q_I flow ratios (i.e. permeate flow to total flow) based on either THM4 or HAA5 controls the design. The blended water quality parameters are also calculated for the feed / permeate blends. If the permeate quality does not meet the MCLs prior to blending, then these calculations are meaningless.

Table 5-15b Blending Calculations To Determine The Fraction Of Flow That Requires NF Treatment To Meet The Stage II DBP Regulations

Utility name and address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____

	RUN ID #			
Parameter	**1**	**2**	**3**	**4**
$THM4_F$, µg/L				
$THM4_p$, µg/L				
$HAA5_F$, µg/L				
$HAA5_p$, µg/L				
Alk_F, mg/L $CaCO_3$				
Alk_p, mg/L $CaCO_3$				
$T\text{-}Hd_F$, mg/L $CaCO_3$				
$T\text{-}Hd_p$, mg/L $CaCO_3$				
$Ca\text{-}Hd_F$, mg/L $CaCO_3$				
$Ca\text{-}Hd_p$, mg/L $CaCO_3$				

THM4 Controls

Q_p/Q_T (THM4), %				
Alk_b, mg/L $CaCO_3$				
$T\text{-}Hd_b$, mg/L $CaCO_3$				
$Ca\text{-}Hd_b$, mg/L CaCO3				
$THM4_b$, µg/L				
$HAA5_b$, µg/L				

HAA5 Controls

Q_p/Q_T (HAA5), %				
Alk_b, mg/L $CaCO_3$				
$T\text{-}Hd_b$, mg/L $CaCO_3$				
$Ca\text{-}Hd_b$, mg/L CaCO3				
$THM4_b$, µg/L				
$HAA5_b$, µg/L				

Notes: In the first section of this table, the feed and permeate concentrations are entered for each run. The spreadsheet uses these values to calculate the flow that must be treated to meet the stage II DBP MCLs with a 10% factor of safety (i.e.36/27 µg/L - THM4/HAA5). The higher of the two Q_p/Q_I flow ratios (i.e. permeate flow to total flow) based on either THM4 or HAA5 controls the design. The blended water quality parameters are also calculated for the feed / permeate blends. If the permeate quality does not meet the MCLs prior to blending, then these calculations are meaningless.

6.0 Pilot-Scale Evaluation Of Membrane Processes

6.1 Design Considerations

The design of membrane pilot systems typically follows the same guidelines used in the design of full-scale systems, making the results of a pilot study directly scalable to full-scale operation. Thus, the results of a properly designed pilot-study can be used to design a full-scale plant; however, factors such as membrane variability and process upsets will lead to some variation between the performance of full-scale and pilot-scale systems.

The design of membrane pilot systems can vary depending on the objectives of the study and the availability of resources. A pilot study is also a learning experience, and operating conditions within the pilot plant will need to be varied to optimize performance. For these reasons a single, specific protocol for pilot-scale membrane studies will not be provided. Instead, general guidelines for conducting a pilot-scale study to evaluate membrane performance will be described in this section. Since this document is rule referenced, it also contains specific requirements of the pilot-scale membrane studies for compliance with the ICR.

6.1.1 Minimum Requirements For A Pilot-Scale Study

The objectives of a pilot-scale membrane study are to demonstrate sustained performance and to develop an estimate of the costs associated with membrane technology used to remove DBP precursors from source waters. Additional objectives, such as pre-qualification of membrane products and production of a representative concentrate stream water quality for evaluating concentrate disposal options may be incorporated based on site-specific considerations.

The ICR requires that only a single membrane type be investigated during a pilot study, and for this reason the membrane should be carefully selected. Although not an ICR requirement for pilot-scale membrane studies, it is recommended that utilities use a bench-scale procedure to screen at least two membranes prior to the pilot-scale study. A utility interested in pursuing membrane technology beyond the requirements of the ICR may want to consider evaluating additional membrane types in single element studies parallel to the pilot system. This is especially important when a utility wants to promote competitive membrane procurement during bidding of full-scale facilities construction.

The pilot study shall be run continuously over a period of one year, with allowances for down-time due to membrane cleaning, maintenance or other reasons. The pilot-scale run time shall be no less than 6600 hours which represents approximately 75% of a calendar year. If a membrane system fails over the one year period, a new membrane run shall be started as soon as possible after the failure. In general, a failure is defined as (1) an irreversible decrease in system productivity to an unacceptable level or (2) an irreversible degradation in permeate quality to an unacceptable level when the membrane was originally demonstrated to meet the treatment objective. Irreversible implies that attempts, primarily chemical cleaning or

modifications to pretreatment processes, consistent with the manufacturer's recommendations were made to correct the problem but were unsuccessful.

The membrane pilot study should be redesigned to prevent the second run from failing, and the same membrane type used in the first study should be used in the second study unless it can be demonstrated that the membrane type was responsible for failure of the first run.

Flexibility will be permitted in the design of a membrane pilot system so that it can be tailored to the specific objectives of a utility; however, certain minimum requirements must be imposed to insure that the objectives of the ICR are met. The pilot system shall consist of standard spiral-wound elements no smaller than 2.5" diameter by 40" long. The pilot plant must, as a minimum configuration, be composed of a two stage array with two pressure vessels in the first stage and one pressure vessel in the second stage. Each pressure vessel shall contain at least three spiral-wound membrane elements. This would require at least nine membrane elements for the pilot system. The pilot plant shall be designed to achieve a system recovery of at least 75% while meeting membrane manufacturer's specifications for pressure, flux, minimum and maximum influent flow rates, etc. Concentrate recycle can be used to meet the minimum membrane element flow specification for pilot systems. If high recoveries are feasible for a given water supply, (80 to 95%), serious consideration should be given to the use of additional stages or concentrate recycle to achieve these recoveries during piloting. Such operation will provide greater confidence with respect to achieving water quality objectives. Membrane manufacturers also specify a maximum feed flow rate to be applied to a single element. Exceeding this maximum flow rate may result in damage to an element or seals which could result in a deterioration in performance. Any design that meets these requirements can be used for the ICR.

Hollow fiber membranes are also used in NF applications, but are less common and not recommended for surface waters. If hollow-fiber technology is being investigated for the ICR, then standard-production, hollow-fiber elements should be used in the pilot system. The system must be staged to achieve a system recovery of at least 75% while being operated at a pressure, cross-flow velocity and feed flow rate within the manufacturer's specifications.

Finally, there are specific sampling and analytical requirements that must be met for the ICR pilot studies which are described in Section 6.3.

6.1.2 Pilot Plant Description

Pilot membrane systems are typically designed as a staged array of elements similar to the design of full-scale membrane plants. Staging is used to increase the system recovery by feeding the concentrate from previous stages to downstream stages. A minimum cross-flow velocity must be maintained through all stages in order to minimize concentration polarization and inorganic precipitation at the membrane surface. Since some of the flow exits the system as permeate in upstream stages, the area available for flow must be decreased in downstream stages to maintain the desired cross-flow velocity. This is accomplished by reducing the number of parallel pressure vessels in downstream stages. Since the cross-sectional area available for flow is difficult to quantify for membrane elements, manufacturers typically

specify a minimum feed flow to a single element instead of a minimum cross-flow velocity. The feed flow rate to the last element in a pressure vessel in a pressure vessel must be greater than this minimum flow rate to a single element specified by the manufacturer.

The minimum acceptable feed flow per element is directly related to the specified recovery and flux for a single element. For a 4" x 40" element the specified single-element-recovery can vary from 5% to 20%, and a typical flux is 15 gfd for low fouling waters and may be reduced to less than 10 gfd for high fouling waters. Assuming a membrane area of 70 ft^2, a permeate flow of 0.73 gpm, and a 15% single-element-recovery, the feed flow rate is 4.9 gpm and the concentrate flow is 4.2 gpm per element. Concentrate recycle may be used to increase the recovery while maintaining an acceptable flow rate through the system.

Figure 6-1 is a flow diagram of a two-stage membrane pilot plant which could be used to meet the ICR requirements for a pilot-scale membrane system. This flow diagram includes a numbering system to identify selected monitoring and/or sampling points, and Table 6-1 presents a description of these monitoring sites. This particular pilot plant design is skid mounted and occupies a space of approximately 5 ft tall x 4 ft wide x 14 ft long, and a single electrical cable provides the necessary power from a 220 volt, three phase source.

A low pressure centrifugal pump is used to increase the feed stream pressure to approximately 40 psi in order to maintain sufficient pressure through the cartridge filters to prevent high pressure pump cavitation. The chemicals used for pretreatment are added between the feed water pump and the prefilter. Mixing is provided by the prefilter and static mixers. From the prefilter the feed stream is directed to a high pressure pump, such as a multi-stage centrifugal pump, which provides the necessary pressure for the membrane process.

The two-stage membrane system consists of three pressure vessels in a 2-1 array. Pressure vessels one and two are in the first stage and pressure vessel three is the second stage. Each pressure vessel houses three 4" x 40" spiral-wound elements. For this pilot plant the total number of membrane elements used is nine and the total membrane area is 630 ft^2 at 70 ft^2 per element.

The pressurized influent stream is directed through a manifold to pressure vessels one and two in the first stage. The permeate water is collected in the connected product water tubes of each element and routed to a permeate water collection manifold at the end of the pressure vessel. The concentrate from pressure vessels one and two of stage one is combined and routed to the influent end of pressure vessel three in stage two. The permeate water from stage two is routed to the permeate collection manifold and combined with the permeate from stage one. Most systems typically use one flow meter and one valve to measure and control the combined permeate stream from stage one. However, valves or flow controlling devices may be required on the permeate discharge line from each pressure vessel of the first stage in order to balance the permeate flows and maintain equal fluxes in each pressure vessel. If there are no anomalies between the pressure vessel configuration or individual elements of stage one, then the differences between the parallel pressure vessels should be insignificant. After

stage 2 the concentrate waste is routed through a valve and flow meter before being discharged as waste. The ability to recycle a portion of the concentrate back to the suction side of the high pressure pump is included in this design and may be necessary to maintain the desired flow rate through all membrane elements.

The system utilizes an electrical control panel which monitors feed pressure, TDS of the feed and permeate streams, feed temperature and hours of high pressure pump operation. If the pressure between the prefilter and the high pressure pump drops to a level of approximately 10 psi, the system will automatically shut down to protect the high pressure pump. In addition, a pH monitor and chemical feed pump controller can be added to control the influent pH and shut-down the system to prevent damage to the membranes if chemical feed is interrupted.

In some cases excessive hydraulic losses through the mesh feed spacers and system plumbing result in an excessive decrease in the feed pressure through a system. This results in a lower permeate flux and an under utilization of available membrane area in subsequent stages. In order to maintain the design permeate flux throughout a system, inter-stage pumping may be required. Pumps can be placed between stages to boost the pressure of the influent stream to the next stage. Booster pumps must have a capacity that can handle the total concentrate flow from the upstream stage while providing the desired differential pressure. Inter-stage pumping also provides the flexibility to recycle around an individual stage.

Major problems associated with the design of membrane systems are excessive flux or permeate production in the first stage, inadequate inter-stage feed pressure, and inadequate feed flow to the last element in a pressure vessel. Excessive flux or permeate flow from a stage can be controlled by incorporating valves on the permeate lines from the stage or pressure vessels. This restricts the flow, creates a back-pressure and allows the flux for each stage to be controlled, there-by balancing the stage production. If permeate back-pressure is used, it must be measured and used to calculate the net driving pressure. Inadequate inter-stage feed pressure can be increased with the use of inter-stage booster pumps. Inadequate flow to the last element in any stage or pressure vessel can be increased by incorporating concentrate recycle around the system or around a single stage to increase the influent flow rate.

6.1.3 Sampling And Monitoring Locations

The following section summarizes the locations and frequencies at which selected operating and water quality parameters should be monitored for pilot-scale membrane studies. Section 6.3 provides an explanation of the monitoring requirements as well as formats for recording and reporting the data. Figure 6-1 and Table 6-1 describe the location of selected monitoring sites for pilot-scale membrane studies. Table 6-2 presents a matrix showing the location and frequency at which operating and water quality parameters must be monitored for pilot-scale studies, and Table 6-3 can be used to record daily readings of flow rates, pressures, temperatures, pH and TDS concentrations.

The sampling and monitoring requirements described in this section are only intended to meet the requirements of the ICR and may not be adequate to develop the information necessary for the design of a full-scale plant. For example, if recoveries higher than 75% are achievable for a given water source, then the design recovery proposed for a full-scale plant is suggested for use in the pilot-scale study in order to produce the most representative concentrate and permeate water quality data. This is of critical importance when investigating concentrate water quality in order to assess concentrate disposal options. In addition, permeate water quality parameters of particular concern to the treatment objectives of a specific utility are suggested for consideration in the membrane investigation.

Temperature and pH

Temperature and pH measurements must be monitored at least once per shift each day of operation. The temperature should be measured using an in-line temperature gauge located at the influent to the system (i.e., location #4 in Figure 6-1). The pH of the feed water, the pretreated feed stream, and the system concentrate waste stream should also be measured as part of the shift monitoring.

Flow rates

Flow rates are measured by reading in-line flow meters at the following points: the permeate flow from each stage, the permeate flow from the system, the concentrate waste flow rate from the system, and the concentrate recycle flow rate. These monitoring points are listed as locations 12, 13, 14, 15 and 16 in Table 6-2. All other flow rates in the system can be determined from these flow measurements. The system permeate and system waste flows should also be measured by manually timed volumetric displacement. These manual measurements are used to verify and calibrate the flow meters.

Additional flow meters can be placed in the pilot plant to monitor the performance of individual pressure vessels if desired. For the pilot plant shown in Figure 6-1 and described in Section 6.1.2, panel mounted flow meters with an approximate range of 2 to 20 gpm were used to measure the influent flow rate to each pressure vessel. Flow meters with a range of 1 to 10 gpm were used to measure the concentrate flows from each pressure vessel and the system permeate and concentrate recycle flow rates. Flow meters with a range of approximately 0.5 to 5 gpm were used to measure permeate flow from each pressure vessel and the concentrate waste flow rate from the system. The ranges of the flow meters will vary with the size and type of membranes.

Pressure

The locations and frequency of pressure measurement are also shown in Table 6-2. The gauges should have a range of approximately 0 to 200 psi for influent and concentrate lines and 0 to 60 psi for permeate lines. The gauges should be liquid filled and calibrated before installation onto a common front panel of the pilot plant.

Hours of operation

The membrane pilot plant should be designed to operate on a continuous basis. The actual hours of operation for the unit are recorded by an hour meter mounted on the front panel,

which should record only when the pilot plant is operating. This is accomplished by tying the hour meter operation to the high pressure pump motor's operation. If the pilot plant is shut-down due to mechanical failure or cleaning, the down-time should be recorded on a daily operating log sheet similar to the one presented in Table 6-3, along with a description of the event. The time to complete any maintenance as well as the restart time should also be recorded.

6.1.4 Design Calculations

The design of the membrane pilot plant shown in Figure 6-1 is based on criteria presented in Table 6-4.

The first step in determining the operating pressure and feed stream flow of a membrane pilot plant is to determine the permeate produced by each element by using the flux and membrane area as shown in Equation 6.1.

$$Q_{p\text{-}e} = F_W \times A_e \qquad (6.1)$$

where $Q_{p\text{-}e}$ is the permeate flow rate produced by a single element, F_W is the design flux and A_e is the area of a single element.

The permeate flow from each pressure vessel can be determined by multiplying the number of elements per pressure vessel by the permeate flow produced by a single element using Equation 6.2.

$$Q_{p\text{-}v} = N_e \times Q_{p\text{-}e} \qquad (6.2)$$

where $Q_{p\text{-}v}$ is the permeate flow rate produced by a pressure vessel and N_e is the number of elements in one pressure vessel.

The permeate flow from each stage is calculated by multiplying the number of pressure vessels in each stage by the flow produced by a single pressure vessel using Equation 6.3.

$$Q_{p\text{-}s} = N_v \times Q_{p\text{-}v} \qquad (6.3)$$

where $Q_{p\text{-}s}$ is the permeate flow rate produced by a stage and N_v is the number of pressure vessel in the stage.

The stage permeate flows can be added together to calculate the permeate flow produced by the system using Equation 6.4.

$$Q_{p\text{-}sys} = Q_{p\text{-}s(1)} + Q_{p\text{-}s(2)} + \ldots + Q_{p\text{-}s(n)} \qquad (6.4)$$

where $Q_{p\text{-}sys}$ is the permeate flow rate produced by the system, which is equal to the sum of the permeate flows from all stages in a system with **n** stages, $Q_{p\text{-}s(1)}$ is the permeate flow rate

produced by stage one, $Q_{p\text{-}s(2)}$ is the permeate flow rate produced by stage two, and $Q_{p\text{-}s(n)}$ is the permeate flow rate produced by stage n.

The feed flow rate to a pressure vessel, a stage, or the system can now be estimated by dividing the associated permeate flow by the associated recovery as shown in Equation 6.5.

$$Q_{F\text{-}\#} = Q_{P\text{-}\#} / R_{\#} \qquad (6.5)$$

where $Q_{F\text{-}\#}$ is the feed stream flow to either a pressure vessel ($Q_{F\text{-}v}$), a stage ($Q_{F\text{-}s}$), or the system ($Q_{F\text{-}sys}$); $Q_{p\text{-}\#}$ is the permeate flow produced by the pressure vessel ($Q_{p\text{-}v}$), stage ($Q_{p\text{-}s}$) or system ($Q_{p\text{-}sys}$) and $R_{\#}$ is the fractional recovery for either the pressure vessel (R_v), stage (R_s) or system (R_{sys}).

The concentrate waste flow rate from the system is calculated as the difference between the feed flow rate to the system and the permeate flow produced by the system as shown in Equation 6.6.

$$Q_{W\text{-}sys} = Q_{F\text{-}sys} - Q_{p\text{-}sys} \qquad (6.6)$$

where $Q_{W\text{-}sys}$ is the concentrate waste flow rate from the system.

The manufacturer's recommended minimum and maximum element flow rates can be used to determine if recycle is necessary to maintain the minimum required flow rate through the final element in a pressure vessel, or if the feed flow rate to the front end of a pressure vessel must be reduced. In order to determine if recycle is required, the feed flow rate to the last element in each stage must be calculated according to Equation 6.7. The last element is used because this element experiences the lowest feed flow in a pressure vessel.

$$(Q_{F\text{-}s})_{end} = Q_{F\text{-}s} - N_v \times Q_{p\text{-}e} \times (N_e - 1) \qquad (6.7)$$

where $(Q_{F\text{-}s})_{end}$ is the feed flow rate to the last element in a stage, N_v is the number of pressure vessels in a stage, $Q_{F\text{-}s}$ is the feed flow rate to the respective stage, N_e is the number of elements in the respective pressure vessel, and $Q_{p\text{-}e}$ is the permeate flow produced per element.

The minimum required recycle flow for a stage is determined from the manufacturer's recommended minimum flow rate and the flow entering the last element in a stage as shown in Equation 6.8. If calculated recycle flow rate is negative, then the flow into the last element is greater than the minimum required flow and recycle is not required. This calculation must be made for each stage in the system, and the recycle flow rate used in the system must provide adequate flow in all stages (i.e., the system recycle flow rate must be equal to or greater than the largest minimum recycle flow rate calculated according to Equation 6.8). The most critical element is typically the last element in the first stage.

$$(Q_{R\text{-}s})_{min} = N_v \times (Q_{F\text{-}e})_{min} - (Q_{F\text{-}s})_{end} \quad (6.8)$$

where $(Q_{R\text{-}s})_{min}$ is the minimum required recycle flow rate for a stage and $(Q_{F\text{-}e})_{min}$ is the manufacturer's recommended minimum feed flow rate to a single element.

Once an acceptable system recycle flow rate has been calculated, the influent flow rate to a pressure vessel, stage or the system can be determined by adding the corresponding feed flow rate, calculated from Equation 6.5, to the recycle flow rate as shown in Equation 6.9.

$$Q_{I\text{-}\#} = Q_{F\text{-}\#} + Q_{R\text{-}sys} \quad (6.9)$$

where $Q_{I\text{-}\#}$ is the influent flow rate to a pressure vessel ($Q_{I\text{-}v}$), a stage ($Q_{I\text{-}s}$) or the system ($Q_{I\text{-}sys}$). If recycle is not used, the influent flow rate is equal to the feed flow rate.

The flow rate entering each stage must be compared to the maximum allowable feed flow rate for each stage, which is calculated from the manufacturer's recommended maximum flow rate to an element and the number of pressure vessels in a stage using Equation 6.10. If the influent flow rate entering any stage exceeds the maximum allowable flow rate for that stage then the influent flow rate must be reduced.

$$(Q_{I\text{-}s})_{max} = (Q_{F\text{-}e})_{max} \times N_v \quad (6.10)$$

where $(Q_{I\text{-}s})_{max}$ is the maximum allowable influent flow rate to a stage and $(Q_{F\text{-}e})_{max}$ is the maximum allowable feed flow rate to a single element as specified by the manufacturer.

The maximum recycle flow rate for each stage can be calculated as the difference between the maximum allowable influent flow rate to the stage and the feed flow rate to the stage using Equation 6.11. The maximum allowable flow rates must be calculated for each stage and the lowest value is the maximum allowable recycle flow rate for the system.

$$(Q_{R\text{-}s})_{max} = (Q_{I\text{-}s})_{max} - Q_{F\text{-}s} \quad (6.11)$$

where $(Q_{R\text{-}s})_{max}$ is the maximum allowable recycle flow rate for a stage.

The concentrate flow rate from a pressure vessel, a stage or system is calculated from the corresponding influent flow rate, the corresponding permeate flow rate and the system recycle flow rate as shown in Equation 6.12.

$$Q_{C\text{-}\#} = Q_{F\text{-}\#} + Q_{R\text{-}sys} - Q_{P\text{-}\#} \quad (6.12)$$

where $Q_{C\text{-}\#}$ is the concentrate flow rate from either a pressure vessel ($Q_{C\text{-}v}$), a stage ($Q_{C\text{-}s}$) or the system ($Q_{C\text{-}sys}$).

The recycle ratio is calculated as the ratio of the recycle flow rate to the feed flow rate according to Equation 6.13.

$$r = Q_{R\text{-}sys} / Q_{F\text{-}sys} \qquad (6.13)$$

where **r** is the recycle ratio.

The required feed stream pressure can be determined once the osmotic pressure gradient for each stage is estimated and hydraulic losses through stage hardware and membrane elements are accounted for. The osmotic pressure gradient is estimated from the TDS of the influent, waste and permeate streams as shown in Equation 6.14.

$$\Delta\pi_s = [((TDS_I + TDS_C) / 2) - TDS_p] \times 0.01 \qquad (6.14)$$

where $\Delta\pi_s$ is an estimate of the average osmotic pressure gradient for a stage in psi, TDS_I is the influent TDS concentration in mg/L, TDS_C is the concentrate TDS concentration in mg/L, TDS_p is the permeate TDS concentration in mg/L and **0.01** is an approximation factor for converting TDS (mg/L) to pressure (psi).

To determine the approximate osmotic pressure for each stage, the TDS of all flow streams must be predicted, using a manufacturer reported TDS rejection. This method uses a sequential iterative mass balance approach around each element of a stage within a system. Appendix 3-A presents the equations used to predict the TDS concentration of the influent, permeate and concentrate for each stage. These equations incorporate recycle around the system (not individual stages), recovery and the manufacturer reported TDS rejection. It assumes an equal number of elements per pressure vessel with constant and equal per element flux.

Since the equations presented in Appendix 3-A can be cumbersome, they were solved for a typical pilot system that could be used in the ICR (i.e., a two stage system with three elements per pressure vessel operated at 75% recovery). The resulting osmotic pressures are presented in Table 6-5. This table presents osmotic pressures for each stage of a two stage system for five different recycle ratios, seven different manufacturer reported TDS rejections and four different feed TDS concentrations. To use this table, select a recycle ratio, manufacturer reported TDS rejection and feed TDS concentration representative of the testing conditions to be used during the study. Next, use these parameters to read the stage one and stage two osmotic pressures from Table 6-5.

The results presented in this table were calculated for a two stage system similar to the one described in Section 6.1.2. Systems that differ significantly from the 2-1 array described in this section may need to use the equations is Appendix 3-A or a manufacturer's computer program to estimate the osmotic pressure for use in the design calculations.

Once the osmotic pressure has been estimated, the feed stream pressure that must be supplied by the high pressure pump can be estimated. The flux equation shown in Equation 6.15 can be rearranged to solve for the required feed stream pressure as shown in Equation 6.16. In words Equation 6.16 is: (the required system feed pressure) **is equal to** (the pressure required for permeation) **plus** (the pressure of the permeate stream) **plus** (pressure losses

through the membranes and stage hardware) **plus** (the osmotic pressure gradient). The losses through the elements and stage piping cumulate throughout the system; therefore, the losses in each stage must be a summation of all losses in the preceding stages in addition to the losses in that stage.

$$F_W = MTC_W \times \sum_{i=1}^{n} \Gamma_i \times \left[\left\{(2 \times P_F - (2 \times i - 1) \times L)/2\right\} - P_p - \Delta\pi_i\right] \quad (6.15)$$

$$P_F = \left(\frac{F_W}{MTC_W}\right) + (P_p) + \left(L \times \sum_{i=1}^{n} \Gamma_i \times (i - 0.5)\right) + \left(\sum_{i=1}^{n} \Gamma_i \times \Delta\pi_i\right) \quad (6.16)$$

$$\Gamma_i = Q_{p\text{-}s(i)}/Q_{p\text{-}sys} \quad (6.17)$$

$$L = \Delta P_s + N_e \times \Delta P_e \quad (6.18)$$

where **i** is the stage number in a system consisting of **n** stages; Γ_i is the stage flow weighted factor (defined in Equation 6.17 as the permeate flow produced by stage **i** divided the permeate flow produced by the system); P_F is the required system feed pressure; P_p is the system permeate pressure; $\Delta\pi_i$ is the osmotic pressure gradient associated with stage **i**; **L** is the pressure loss term associated with the stage hardware and elements; ΔP_s is pressure loss term associated with stage hardware; ΔP_e is pressure loss term associated with membrane elements; and N_e is the number of elements in a pressure vessel.

6.1.5 Design Example

A design for a nanofiltration pilot plant is shown to clarify system design procedure described in Section 6.1.4. Basic assumptions used in this design are shown in Table 6-6. Note the recovery per stage is based on the influent flow to and permeate flow from each individual stage.

The permeate produced per element, pressure vessel, stage and by the system can be determined from the average flux, number of elements per pressure vessel and the system configuration using Equations 6.1 through 6.4.

Equation 6.1 is used to calculate the permeate flow produced by a single element.

$$Q_{p\text{-}e} = F_W \times A_e = 15 \text{ gfd} \times 70 \text{ ft}^2 = 1{,}050 \text{ gpd per element}$$

Equation 6.2 is used to calculate the permeate flow produced by a single pressure vessel.

$$Q_{p\text{-}v} = N_e \times Q_{p\text{-}e} = 3 \times 1{,}050 \text{ gpd} = 3{,}150 \text{ gpd per pressure vessel}$$

Equation 6.3 is used to calculate the permeate flow produced by each stage.

$$Q_{p\text{-}s\,(1)} = N_{v\,(1)} \times Q_{p\text{-}v} = 2 \times 3{,}150 \text{ gpd} = 6{,}300 \text{ gpd from stage one}$$

$$Q_{p\text{-}s\,(2)} = N_{v\,(2)} \times Q_{p\text{-}v} = 1 \times 3{,}150 \text{ gpd} = 3{,}150 \text{ gpd from stage two}$$

Equation 6.4 is used to calculate the permeate flow produced by the system.

$$Q_{p\text{-}sys} = Q_{p\text{-}s\,(1)} + Q_{p\text{-}s\,(2)} = 6{,}300 \text{ gpd} + 3{,}150 \text{ gpd} = 9{,}450 \text{ gpd}$$

Equation 6.5 is used to calculate the feed flow to the system based on a design system recovery of 75%.

$$Q_{F\text{-}sys} = Q_{p\text{-}sys} / R_{sys} = 9{,}450 \text{ gpd} / 0.75 = 12{,}600 \text{ gpd}$$

Equation 6.6 is used to calculate the concentrate waste flow rate from the system, and it is this waste flow rate along with the system permeate flow rate that controls the recovery of the system.

$$Q_{W\text{-}sys} = Q_{F\text{-}sys} - Q_{p\text{-}sys} = 12{,}600 \text{ gpd} - 9{,}450 \text{ gpd} = 3{,}150 \text{ gpd}$$

The feed flow rate to the first stage is identical to the feed flow rate to the system.

$$Q_{F\text{-}s\,(1)} = Q_{F\text{-}sys} = 12{,}600 \text{ gpd}$$

The feed flow rate to the second stage is calculated using Equation 6.5 (or alternatively, as the difference between the feed flow to the first stage and the permeate flow from the first stage).

$$Q_{F\text{-}s\,(2)} = Q_{p\text{-}s\,(2)} / R_{s\,(2)} = 3{,}150 \text{ gpd} / 0.50 = 6{,}300 \text{ gpd}$$

In order to determine if there is adequate feed flow going to each element in a stage, the feed flow rate to the last element in each stage must be calculated using Equation 6.7.

The feed flow rate to the last element in each of the two parallel pressure vessels of stage one is calculated as:

$$(Q_{F\text{-}s\,(1)})_{end} = Q_{F\text{-}s\,(1)} - N_{v\,(1)} \times Q_{p\text{-}e} \times (N_{e\,(1)} - 1) = 12{,}600 \text{ gpd} - 2 \times 1{,}050 \text{ gpd} \times (3\text{-}1)$$
$$= 8{,}400 \text{ gpd}$$

The feed flow rate to the last element in the single pressure vessel of stage two is calculated as:

$$(Q_{F\text{-}s\,(2)})_{end} = Q_{F\text{-}s\,(2)} - N_{v\,(2)} \times Q_{p\text{-}e} \times (N_{e\,(2)} - 1) = 6{,}300 \text{ gpd} - 1 \times 1{,}050 \text{ gpd} \times (3\text{-}1)$$
$$= 4{,}200 \text{ gpd}$$

Equation 6.8 can be used to determine the minimum required concentrate recycle flow rate. Recycle will be required if the flow rate to the last element in any pressure vessel is less

than the minimum flow rate to a single element, specified by the manufacturer as 4 gpm or 5,760 in this example.

The minimum required recycle flow rate for stage one is calculated as:

$$(Q_{R\text{-}s\,(1)})_{min} = N_{v\,(1)} \times (Q_{F\text{-}e})_{min} - (Q_{F\text{-}s\,(1)})_{end} = 2 \times 5{,}760 \text{ gpd} - 8{,}400 \text{ gpd} = 3{,}120 \text{ gpd}$$

The minimum required recycle flow rate for stage two is calculated as:

$$(Q_{R\text{-}s\,(2)})_{min} = N_{v\,(2)} \times (Q_{F\text{-}e})_{min} - (Q_{F\text{-}s\,(2)})_{end} = 1 \times 5{,}760 \text{ gpd} - 4{,}200 \text{ gpd} = 1{,}560 \text{ gpd}$$

Since the recycle flow rates calculated according to Equation 6.8 are positive, concentrate recycle is required. Furthermore, the recycle flow rate required for stage one is greater than the recycle flow rate required for stage two, and thus controls the design. The minimum recycle flow rate for the system is:

$$(Q_{R\text{-}sys})_{min} = 3{,}120 \text{ gpd}$$

The minimum influent flow rate to the system, which is equal to the influent flow rate to stage one, is calculated by adding the feed flow rate to the minimum recycle flow rate for the system using Equation 6.9.

$$Q_{I\text{-}sys} = Q_{I\text{-}s\,(1)} = Q_{F\text{-}sys} + (Q_{R\text{-}sys})_{min} = 12{,}600 \text{ gpd} + 3{,}120 \text{ gpd} = 15{,}720 \text{ gpd}$$

The corresponding influent flow rate to stage two can also be calculated using Equation 6.9.

$$Q_{I\text{-}s\,(2)} = Q_{F\text{-}s\,(2)} + (Q_{R\text{-}sys})_{min} = 6{,}300 \text{ gpd} + 3{,}120 \text{ gpd} = 9{,}420 \text{ gpd}$$

The maximum allowable influent flow rate to each stage must be calculated using Equation 6.10 and the maximum allowable flow rate to a single element, specified by the manufacturer as 16 gpm or 23,040 in this example.

The maximum allowable influent flow rate to stage one is:

$$(Q_{I\text{-}s\,(1)})_{max} = (Q_{F\text{-}e})_{max} \times N_{v\,(1)} = 23{,}040 \text{ gpd} \times 2 = 46{,}080$$

The maximum allowable influent flow rate to stage two is:

$$(Q_{I\text{-}s\,(2)})_{max} = (Q_{F\text{-}e})_{max} \times N_{v\,(2)} = 23{,}040 \text{ gpd} \times 1 = 23{,}040$$

Next, the influent flow rate to each stage must be compared to the maximum allowable flow rate to each stage.

$$Q_{I\text{-}s\,(1)} = 15{,}720 \text{ gpd} < (Q_{F\text{-}s\,(1)})_{max} = 46{,}080 \text{ gpd}$$

$$Q_{I\text{-}s\,(2)} = 9{,}420 \text{ gpd} < (Q_{F\text{-}s\,(2)})_{max} = 23{,}040 \text{ gpd}$$

Since the influent flow rates to each stage are below the corresponding maximum allowable flow rates to each stage, this design is acceptable.

In some cases, a recycle flow rate larger than the minimum recycle flow rate for the system, $(Q_{R\text{-}sys})_{min}$, may be desired to minimize fouling. The maximum allowable recycle flow rate for the system must be determined by calculating the maximum allowable recycle flow rates for each stage according to Equation 6.11.

$$(Q_{R\text{-}s\,(1)})_{max} = (Q_{I\text{-}s\,(1)})_{max} - Q_{F\text{-}s\,(1)} = 46{,}080 \text{ gpd} - 12{,}600 \text{ gpd} = 33{,}480 \text{ gpd}$$

$$(Q_{R\text{-}s\,(2)})_{max} = (Q_{I\text{-}s\,(2)})_{max} - Q_{F\text{-}s\,(1)} = 23{,}040 \text{ gpd} - 6{,}300 \text{ gpd} = 16{,}740 \text{ gpd}$$

The maximum allowable recycle flow rate for stage two is lower than that for stage one. Thus, the maximum allowable recycle flow rate for the system is the maximum recycle flow rate for stage two, 16,740 gpd, since a recycle flow rate greater than this value would result in a flow rate in stage two outside of the manufacturer's specifications.

The recycle ratio can calculated for both the maximum and minimum recycle flow requirements in this example using Equation 6.13.

$$r_{max} = (Q_{R\text{-}sys})_{max}/Q_{F\text{-}sys} = 16{,}740 \text{ gpd} / 12{,}600 \text{ gpd} = 1.33$$

$$r_{min} = (Q_{R\text{-}sys})_{min}/Q_{F\text{-}sys} = 3{,}120 \text{ gpd} / 12{,}600 \text{ gpd} = 0.25$$

The minimum concentrate flow rates from each stage and the system can be calculated using Equation 6.12 using the minimum system recycle flow rate, 3,120 gpd:

$$Q_{C\text{-}s\,(1)} = Q_{F\text{-}s\,(1)} + (Q_{R\text{-}sys})_{min} - Q_{p\text{-}s\,(1)} = 12{,}600 \text{ gpd} + 3{,}120 \text{ gpd} - 6{,}300 \text{ gpd} = 9{,}420 \text{ gpd}$$

$$Q_{C\text{-}s\,(2)} = Q_{F\text{-}s\,(2)} + (Q_{R\text{-}sys})_{min} - Q_{p\text{-}s\,(2)} = 6{,}300 \text{ gpd} + 3{,}120 \text{ gpd} - 3{,}150 \text{ gpd} = 6{,}270 \text{ gpd}$$

$$Q_{C\text{-}sys} = Q_{F\text{-}sys} + (Q_{R\text{-}sys})_{min} - Q_{p\text{-}sys} = 12{,}600 \text{ gpd} + 3{,}120 \text{ gpd} - 9{,}450 \text{ gpd} = 6{,}270 \text{ gpd}$$

The maximum concentrate flow rates are calculated using Equation 6.12 and the maximum system recycle flow rate, 16,740 gpd:

$$Q_{C\text{-}s\,(1)} = Q_{F\text{-}s\,(1)} + (Q_{R\text{-}sys})_{max} - Q_{p\text{-}s\,(1)} = 12{,}600 \text{ gpd} + 16{,}740 \text{ gpd} - 6{,}300 \text{ gpd} = 23{,}040 \text{ gpd}$$

$$Q_{C\text{-}s\,(2)} = Q_{F\text{-}s\,(2)} + (Q_{R\text{-}sys})_{max} - Q_{p\text{-}s\,(2)} = 6{,}300 \text{ gpd} + 16{,}740 \text{ gpd} - 3{,}150 \text{ gpd} = 19{,}890 \text{ gpd}$$

$$Q_{C\text{-}sys} = Q_{F\text{-}sys} + (Q_{R\text{-}sys})_{max} - Q_{p\text{-}sys} = 12{,}600 \text{ gpd} + 16{,}740 \text{ gpd} - 9{,}450 \text{ gpd} = 19{,}890 \text{ gpd}$$

Note that the concentrate flow rate from the system is always equal to the sum of the concentrate waste flow rate and the concentrate recycle flow rate.

For this design example, the feed flow rate is 12,600 gpd with a minimum recycle needed of 3,120 gpd producing a minimum influent flow to the system of 15,720 gpd. If higher recycle flow rates are to be tested, the maximum concentrate flow that should be recycled is 16,740 gpd, which corresponds to a total maximum influent flow to the system of 29,340 gpd.

Once the system flows have been calculated, the pressure requirements can be determined for the membrane system using the basic flux equation on a flow weighted basis and accounting for the entrance and exit pressure losses, element pressure losses and osmotic pressure.

Using a feed TDS of 300 mg/L, an element TDS rejection of 0.70, a recovery of 75 % and a recycle ratio of 0.25 the approximate osmotic pressure for each stage was selected from Table 6-5. The values for the osmotic pressure can be interpolated between the recycle ratios of 0 and 1 and rounded to the nearest 1 psi. For stage one the $\Delta\pi_1$ is 3 psi and for stage two the $\Delta\pi_2$ is 5 psi. Equations 6.16 through 6.18 are used to calculate the pressure required to drive the membrane process.

Using Equation 6.18 the mechanical losses are calculated:

$$L = \Delta P_s + N_e \times \Delta P_e = 5 \text{ psi} + 3 \times 3 \text{ psi} = 14 \text{ psi}$$

Using Equation 6.17 the stage flow weighted factor for stage one and two are calculated as 0.67 and 0.33, respectively:

$$\Gamma_1 = Q_{p\text{-}s(1)} / Q_{p\text{-}sys} = 6{,}300 \text{ gpd} / 9{,}450 \text{ gpd} = 0.67$$

$$\Gamma_2 = Q_{p\text{-}s(2)} / Q_{p\text{-}sys} = 3{,}150 \text{ gpd} / 9{,}450 \text{ gpd} = 0.33$$

Using Equation 6.16 the feed pressure is calculated by breaking up the equation for clarity, solving for each part and then solving for P_F. A permeate stream pressure of 30 psi will be assumed for this example.

$$P_F = \left(F_W / MTC_W\right) + \left(P_p\right) + \left(L \times \sum_{i=1}^{n} \Gamma_i \times (i - 0.5)\right) + \left(\sum_{i=1}^{n} \Gamma_i \times \Delta\pi_i\right)$$

$$F_W/MTC_W = (15 \text{ gfd} / 0.30 \text{ gfd/psi}) = 50 \text{ psi}$$

$$P_P = 30 \text{ psi}$$

$$L \times \sum_{i=1}^{n} \Gamma_i \times (i - 0.5) = 14 \text{ psi} \times [0.67 \times (1 - 0.5) + 0.33 \times (2 - 0.5)] = 11.6 \text{ psi}$$

$$\sum_{i=1}^{n} \Gamma_i \times \Delta\pi_i = (0.67 \times 3 \text{ psi}) + (0.33 \times 5 \text{ psi}) = 3.7 \text{ psi}$$

$$P_F = 50 \text{ psi} + 30 \text{ psi} + 11.6 \text{ psi} + 3.7 \text{ psi} = 95 \text{ psi}$$

All of the parameters necessary for a system design have been calculated or estimated, and a summary of this design is presented in Table 6-7. The flows can be used to size flow meters and system plumbing, and the pressures can be used to select pressure gauges. When sizing the flow meters for the stage influent and stage concentrate lines, the flow contribution from the recycle stream must be accounted for. In this design the high pressure pump should be selected so that optimum operation occurs at approximately 95 psi at a flow rate of approximately 15,7200 to 29,340 gpd. However, the pump should be capable of operating over a range of pressures from 80 to 110 psi so that the pressure can be varied to maintain a constant flux during operation.

6.1.6 Pretreatment

Pretreatment for membrane processes commonly includes chemical addition to prevent inorganic precipitation and cartridge filtration to reduce colloidal fouling. The most common chemical pretreatment is sulfuric acid addition to reduce the pH to prevent calcium carbonate precipitation. In some cases hydrochloric acid is substituted for sulfuric acid. The potential for calcium carbonate precipitation can be checked by calculating the Langlier Saturation Index for the concentrate stream. Some applications may require the addition of a chemical antiscalant to control such inorganic precipitants as calcium sulfate, barium sulfate or strontium sulfate. The use of an antiscalant can often eliminate the need for acid addition all together, and many antiscalants can prevent scaling in systems with a concentrate LSI $\leq +1.5$. The required chemical doses are determined by limiting salt calculations or manufacturer computer programs, both of which typically require a preliminary and comprehensive chemical analysis of the raw water. Additionally, the fouling potential of the feed water should be evaluated using one or more of the methods presented in Section 2.5.

Multi-stage pilot systems with fouling indices within an acceptable range should require minimal pretreatment equipment. Generally, concentrated sulfuric acid is pumped through an injection port connected directly to the feed water line between the feed water pump and the prefilter. The injection point for pretreatment chemicals is typically chosen so the prefilter and booster pump will assist in mixing the chemicals with the feed water, as shown in Figure 6-1. In some cases an in-line static mixer may be used to insure proper mixing. A chemical feed pump made of resistant materials is used to inject the acid from storage barrels. If

antiscalants are evaluated, they are generally highly concentrated and must be diluted into 30 to 50 gallon containers before injection into the feed water stream.

After chemical addition, the water is passed through a cartridge filter to remove larger suspended solids or colloidal material and protect the booster pump and membrane elements from sand or other foreign materials. Polypropylene cartridge filters with a size exclusion of 5 μm are acceptable for membrane pretreatment. The filter cartridges should be cleaned or replaced when the pressure drop across the prefilters increases by a predetermined percentage (e.g., 50%).

For feed waters which have excessive fouling as indicated by fouling indices or other factors, advanced pretreatment will need to be incorporated into the system. Advanced pretreatment may include enhanced coagulation and sand filtration with reduced pH. An example of this would be operating the membrane system using water from a conventional treatment plant after sand filtration and prior to the addition of any oxidant or disinfectant. If alum is used as the coagulant, the pH of the feed water may need to be reduced to around 4.5 (or just above the minimum operational pH as specified by the manufacturer) to ensure the solubility of aluminum hydroxide. However, operating at a low pH may increase fouling by high molecular weight organic matter. Additional advanced pretreatment schemes may include microfiltration to control particulate or microbial fouling.

6.2 System Operation

6.2.1 System Start-up

If the proper sequence is not followed during start-up of a membrane system, the membranes could be damaged by overfeeding, over pressurizing, or hydraulic shock. Although the specific start-up procedure will vary from system to system, a typical initialization and start-up sequence is provided in this section.

1. Select a membrane type and obtain the appropriate element size and the manufacturer's specification sheet for that element.

2. Conduct a thorough analysis of the source water to evaluate the inorganic chemical matrix and determine limiting salts by calculation or manufacturer computer program.

3. Conduct fouling index tests on the feed water, calculate indices and determine the potential for fouling problems. If a fouling problem is indicated, additional pretreatment alternatives may need to be evaluated.

4. Select a membrane flux rate consistent with the fouling potential of the water and recommendations of the manufacturer.

5. Calculate or consult manufacturer computer programs for feed water acid and/or antiscalant dose. Calculate the dilution needed for the chemical feed tank capacity and the chemical pump feed rate.

6. Load the elements into the pressure vessels, coupling elements in a common pressure vessel, and carefully secure the end caps.

7. Flush the influent line upstream of the first stage of the membrane system, but downstream of any pretreatment processes to remove debris and other contaminants. Flushing should be continued for several minutes.

8. Connect the feed line of membrane unit to a pressurized (20 to 40 psi) source water transmission line and open feed valve to allow water to enter the membrane prefilter.

9. Open all valves, including permeate, concentrate waste, concentrate recycle, and pump recirculate valves. This is to allow water to flow through the system, displace any trapped air and flow to waste upon start-up.

10. Verify that the feed water is at the prefilter and release trapped air by depressing the bleed button located at the top of the prefilter (if available).

11. Verify that there are proper and secure connections for the chemical feed system, and energize the chemical feed pump. If the unit is going to be operated unattended for significant periods of time, some consideration should be given to controls to shutdown the unit if chemical dosing is interrupted.

12. Allow water to flow through the system to waste in order to purge trapped air from the system. When all of the air has been purged from the system, slowly increase the system pressure by opening the feed valve and turn on the high pressure pump. Adjust the concentrate waste valve so that the concentrate flow does not exceed the manufacturer's maximum recommended flow rate per element.

13. Continue to open the feed valve to increase the system pressure and feed flow rate until the design permeate flux is achieved.

14. Making sure that the recirculate valves on the inter-stage pumps are open, turn on the inter-stage pumps.

15. Slowly close the concentrate waste valve on the final stage until the desired concentrate waste flow rate is achieved while making sure not to overpressurize the first stage.

16. While monitoring the pressure, slowly close the concentrate recycle valve (if used) to obtain the proper recycle flow rate.

17. Adjust the recirculate valves on the inter-stage pumps to achieve the desired stage pressures and fluxes.

18. Repeat steps 13, 15, 16 and 17 as necessary until the desired flows and fluxes are achieved.

19. Confirm the proper feed rate for acid by measuring pH or antiscalant by calibrating the chemical pump feed rate.

20. After one hour of operation, take an initial set of readings (i.e., flow rates, pressures, influent temperature, pH and TDS) to insure that the system is performing according to specifications.

6.2.2 System Shut-down

The following section will describe the general steps to follow during shut-down of a pilot system. Pilot-scale studies should be operated continuously; however, the system will need to be periodically shut-down for cleaning and other maintenance. The system may be shut-down for brief periods (i.e., not to exceed 48 hours) if it cannot be monitored or if the feed stream from the plant needs to be shut-off. If unit operation is interrupted for more than 24 hours, the system should be flushed with feed water once per day for 30 minutes to minimize biological growth.

1. Record the system readings and collect any samples necessary.

2. Collect 50 to 500 gallons of permeate to use for membrane preservation and cleaning solutions.

3. Open the recirculate valves on the inter-stage pumps and turn off the pumps.

4. Open the concentrate waste, recycle and permeate valves.

5. Slowly close the feed valve, and turn off the high pressure pump before completely closing the feed valve.

6. Turn the chemical feed pumps to the off position.

7. Close the valve from the feed water source.

8. If the system is to be shut-down for more than 24 hours but less than one week, the previously collected permeate water should be used to flush the feed/concentrate side of the membrane. If the membrane is to be shut-down for longer than one week, it should be preserved according to the manufacturer's recommended procedure.

6.2.3 Membrane Cleaning And Preservation

The following section will provide general procedures to be followed during the cleaning and preservation of membranes used during the operation of a membrane pilot plant. Membranes are usually cleaned when the temperature-normalized MTC_W has decreased by 10 to 15% from the baseline at the beginning of the study or the baseline established after the

most recent cleaning. Membranes should also be cleaned if the pressure drop across a pressure vessel increases by more than 20%. It should be noted that the MTC_W has to be normalized for temperature, since a drop in temperature will cause an increase in the net driving pressure required to maintain a constant flux. The equation used to normalize the MTC_W to a common temperature (i.e., the average yearly water temperature experienced at the plant) is presented in Section 6.2.4 as Equation 6.21. Membrane cleaning frequencies greater than once per month have been suggested to be limiting because of the associated cost and lack of automation. However, there is no reason to believe that membrane cleaning cannot be highly automated and made a routine part of membrane plant operation. Unfortunately, that technology does not exist today, and the impact of cleaning frequency must be considered in the overall cost and performance of a membrane process.

Since membranes are made from many different materials, membrane manufacturers specify chemicals, chemical strengths, temperatures and pH values for cleaning solutions. Membrane compatibility with a specific cleaning solution must be verified with the membrane manufacturer to avoid damage to the film. There are two basic categories of membrane cleaning solutions, alkaline and acidic solutions. In general, alkaline solutions such as a 0.1% solution of sodium EDTA and a 0.1% solution of sodium hydroxide are effective for removing organic and biological fouling agents, and are typically used in conjunction with detergents such as sodium lauryl sulfate or Triton-X. Acidic solutions such as 0.5% phosphoric acid are effective for removing inorganic foulants. When the exact nature of the foulant is not known, the manufacturer's recommendation for an appropriate cleaning procedure should be solicited.

To clean the membranes, the pilot plant is generally modified to form a closed loop system. The pilot plant is isolated from the raw water source, and the pretreatment chemical pumps are turned off. The cleaning solution can be made in a 50 to 100 gallon chemical resistant tank using the previously collected permeate. In some cases pre-heating the cleaning solution may be necessary to properly clean fouled membranes. A hose is connected to the feed line before the prefilters and the cleaning solution is pumped throughout the pilot plant using a low pressure pump. The first flush of cleaning solution from the membrane pilot plant generally contains the highest concentration of foulants and is wasted for the first five to ten minutes of the cleaning procedure. The cleaning solution is then pumped through the pilot plant to fill the membrane pressure vessels after which the pumps can be turned off to allow the membranes to soak for one to several hours. The cleaning solution used during soaking is flushed out of the system and replaced by fresh cleaning solution. After this second flush, the remaining cleaning solution is directed back to the cleaning tank so it can be recirculated through the membrane system for one to two hours. This procedure can be repeated with a new cleaning solution if needed. Once the cleaning cycle has been completed, the membranes should be flushed with previously collected permeate water.

To preserve the membranes for storage, follow membrane manufacturer specifications for type and strength of preservative. Membranes should always be cleaned prior to preservation and storage. Use previously collected membrane permeate to dilute the preservative chemicals to the proper concentration. Connect a suction line from the booster pump to the preservative solution tank. The same tank used for cleaning can be used for membrane preservation

solutions. Energize the booster pump long enough to replace the feed and concentrate water left from previous operation with the preservative solution. Turn off the booster pump and close all valves to trap the preservative solution within the membrane pressure vessel. If the membranes are to be stored separately from the pressure vessels, then they may be wetted in the preservative solution and placed into sealed plastic bags.

Handle, dispose and store all chemicals used in the membrane study in a safe and approved method.

6.2.4 Membrane Productivity

Membrane productivity is assessed by the rate of MTC_W decline with time of operation. All membranes foul during operation and constant production is achieved in full-scale membrane plants by increasing pressure to maintain a constant flux, and membrane pilot plants should be operated in the same fashion.

The following section presents the procedure for determining the fouling rates for each stage, and a flow weighted approach to determine the overall fouling rate for the system. This procedure could also be used to determine the fouling rates for individual pressure vessels. Determination of the fouling rate and cleaning frequency for a multi-stage membrane pilot system is presented here.

The MTC_W is calculated by using the following equations, and data recorded from a pilot-scale study shown in Table 6-8. Using the definitions for permeate flux and the water mass transfer coefficient from Table 2-2:

$$\mathbf{F_W = Q_P/A = MTC_W \times NDP} \qquad \mathbf{(6.19)}$$

Rearranging the equation for water flux and solving for MTC_W:

$$\mathbf{MTC_W = F_W/NDP} \qquad \mathbf{(6.20)}$$

The flux of water for each stage is first calculated using the permeate flow from each stage and dividing by the membrane area associated with the each stage. For this example stage one contained six 4" x 40" membrane elements with an area of 70 ft^2 per element and produced 5,628 gpd of permeate at the initial data recording. Stage two contained three membrane elements and produced 2814 gpd of permeate.

The flux for stage one is:

$$F_W = Q_p/A = (5{,}628 \text{ gpd})/(6 \text{ elements} \times 70 \text{ ft}^2 \text{ per element}) = 13.4 \text{ gfd}$$

The flux for stage two is:

$$F_W = Q_p/A = (2{,}814 \text{ gpd})/(3 \text{ elements} \times 70 \text{ ft}^2 \text{ per element}) = 13.4 \text{ gfd}$$

The flux is normalized to a common temperature so that water production can be compared on an equivalent basis. Equation 6.21 can be used to normalize the flux to the average yearly water temperature experienced at the plant conducting the study. If a manufacturer specifies a temperature correction equation, then the specific equation should be used instead of Equation 6.21.

$$\mathbf{F_W(Tavg°C) = F_W(T°C) \times 1.03^{(Tavg°-T°)}} \qquad \mathbf{(6.21)}$$

where $\mathbf{F_W(Tavg°C)}$ is the flux corrected to the average yearly water temperature experienced at the plant conducting the study, $\mathbf{F_W(T°C)}$ is the flux measured at ambient temperature, **T°** is the temperature at which the flux was measured in °C, and **Tavg°** is the average yearly water temperature at the plant conducting the study in °C.

The temperature correction equation was not used in this particular case since the feed was a ground water source with a constant temperature of 20°C

In order to determine the NDP, the osmotic pressure gradient must first be estimated from the feed, concentrate and permeate TDS values using Equation 6.14.

$$\mathbf{\Delta\pi_s = ([(TDS_I + TDS_C) / 2] - TDS_p) \times (1\ psi / 100\ mg/L)}$$

For this example and stage one: TDS_p = 60 mg/L, TDS_I = 300 mg/L and TDS_C = 500 mg/L; for stage two: TDS_p = 100 mg/L, TDS_I = 500 mg/L and TDS_C = 700 mg/L.

The osmotic pressure gradient for stage one is:

$$\Delta\pi_1 = ([(300\ mg/L + 500\ mg/L)/2] - 60\ mg/L) \times (1\ psi/100\ mg/L) = 3.4\ psi$$

The osmotic pressure gradient for stage two is:

$$\Delta\pi_2 = ([(500\ mg/L + 700\ mg/L)/2] - 100\ mg/L) \times (1\ psi/100\ mg/L) = 5.0\ psi$$

The net driving pressure is calculated according to Equation 6.22.

$$\mathbf{NDP = [(P_I + P_C) / 2] - P_p - \Delta\pi} \qquad \mathbf{(6.22)}$$

where **NDP** is the net driving pressure, $\mathbf{P_I}$ is the influent pressure, $\mathbf{P_C}$ is the concentrate pressure and $\mathbf{P_p}$ is the permeate pressure.

For this example, the pressures for stage one are P_I = 154 psi, P_C = 100 psi and P_p = 90 psi, and the pressures for stage two are P_I = 100 psi, P_C = 54 psi and P_p = 30 psi.

The NDP for stage one is:

$$NDP = [(154\ psi + 100\ psi) / 2] - 90\ psi - 3.5\ psi = 33.5\ psi$$

The NDP for stage two is:

$$NDP = [(100\ psi + 54\ psi) / 2] - 30\ psi - 5.0\ psi = 42\ psi$$

Using these results, the MTC_W can be calculated from Equation 6.20 as:

The MTC_W for stage one is:

$$MTC_{W(1)} = F_{W(1)} / NDP_{(1)} = 13.4\ gfd / 33.5\ psi = 0.40\ gfd/psi$$

The MTC_W for stage two is:

$$MTC_{W(2)} = F_{W(2)} / NDP_{(2)} = 13.4\ gfd / 42\ psi = 0.32\ gfd/psi$$

The MTC_W for the system is calculated by flow weighting the MTC_W for each stage using the respective permeate flow of each stage:

$$MTC_{W\text{-}sys} = [(MTC_{W(1)} \times Q_{p\text{-}s\ (1)}) + (MTC_{W(2)} \times Q_{p\text{-}s\ (2)})] / (Q_{p\text{-}s\ (1)} + Q_{p\text{-}s\ (2)})$$

Using the preceding results:

$$MTC_{W\text{-}sys} = [(0.40gfd/psi \times 5628gpd) + (0.32gfd/psi \times 2814gpd)]/(5628gpd + 2814gpd)$$

$$MTC_{W\text{-}sys} = 0.37\ gfd/psi$$

The MTC_W for each stage and for the system is calculated for each set of operational data and plotted as a function of cumulative operating time. A spreadsheet incorporating these equations can be used to calculate the net driving pressure, the normalized flux and the MTC_W from the data recorded in the daily operations log, Table 6-3. For the preceding example the system recovery, flux, MTC_W, NDP, and run time are summarized in Table 6-8 for each set of operational data collected during the operation of a two-stage pilot system.

The data summarized in Table 6-8 is presented graphically in Figure 6-2. The slope of a linear least squares fit of the plotted data is the change in the MTC_W with time for each stage and the system. The slope of these lines is used to predict the rate of fouling and the required cleaning frequency. The linear regression lines for stage one, stage two and the system were calculated from the data plotted in Figure 6-2.

Linear regression for the stage one flux data:

$$MTC_W = -0.0004 \times time + 0.379$$

Linear regression for the stage two flux data:

$$MTC_W = 0.00002 \times \text{time} + 0.312$$

Linear regression for the system flux data:

$$MTC_W = -0.0003 \times \text{time} + 0.357$$

The slope of the flux curve for stage one is negative indicating a decline in the flux during operation, while the slope of the flux curve for stage two is positive indicating no decline over the course of this study. One possible explanation is that colloidal fouling occurred in the first stage.

Equation 6.23 can be used to estimate the cleaning frequency from the rate of MTC_W decline and the acceptable loss in the MTC_W.

$$\mathbf{CF} = \frac{\Omega \times \mathbf{MTC}_{W(o)}}{\mathbf{dMTC}_W / \mathbf{dt}} \qquad \textbf{(6.23)}$$

where **CF** is the cleaning frequency, Ω is the acceptable fractional loss in the MTC_W prior to cleaning (e.g., 0.15), $\mathbf{MTC}_{W(o)}$ is the design MTC_W during operation with the source water, and $\mathbf{dMTC}_W/\mathbf{dt}$ is the rate of MTC_W decline determined from a linear regression of the flux data.

A linear model was used to estimate the rate of MTC_W decline in this example. The best model to fit the data generated during the membrane studies should be used to estimate MTC_W decline, and this model may or may not be linear. In some situations, a linear regression for a plot of the log of time versus the log of the MTC_W may be used to predict the rate of MTC_W decline.

Using equation 6.23 with a baseline MTC_W of 0.35 gfd/psi and a 15% decline before cleaning, the following cleaning frequencies are calculated:

The cleaning frequency for stage one:

$$CF = (0.15 \times 0.35 \text{ gfd/psi}) / 0.0004 \text{ gfd/psi/day} = 131 \text{ days}$$

The cleaning frequency for stage two:

$$CF = (0.15 \times 0.35 \text{ gfd/psi}) / -0.00002 \text{ gfd/psi/day} = \text{not defined}$$

The cleaning frequency for stage two is not defined since the rate of MTC_W decline was negative (i.e., the MTC_W was increasing with time).

The cleaning frequency for the system:

$$CF = (0.15 \times 0.35 \text{ gfd/psi}) / 0.0003 \text{ gfd/psi/day} = 175 \text{ days}$$

These results indicate that the system will need to be cleaned approximately every 175 days or 6 months when the system MTC_W has declined by 15%. This is not an excessive cleaning frequency and this study, conducted on a ground water with a high TOC concentration, shows that membrane processes are a viable option for the control of DBP formation.

The cleaning frequency in this example is based on a linear model of the system MTC_W decline. The linear least fit equation was chosen to model this data because it followed a linear trend which is similar to information published in reports of long-term (greater than one year) studies which used linear least squares models of MTC_W decline to estimate cleaning frequencies (Taylor et al., 1986, 1990, 1992). However, the model which best fits the data should be used to predict cleaning frequencies. The decision to use the system MTC_W decline instead of the second stage MTC_W decline was made in this case, because over-all water production was deemed most important. There may be cases were the decline of an individual stage may determine the time to stop production for cleaning.

6.3 Sampling Requirements

The following section describes the monitoring and sampling requirements for the pilot membrane studies, and data sheets that present the reporting requirements are described in Section 6.3.5. Unless explicitly stated otherwise, the monitoring and sampling requirements listed in this section are requirements of the ICR.

6.3.1 Daily System Monitoring

The system must be monitored at least once each shift during each day of operation to insure that it is functioning properly. The operating parameters that must be monitored during each shift are summarized in Table 6-2 and include flow rates, direct flow measurements, pressures, temperatures, pH and TDS concentrations. These monitoring requirements are specific to a two-stage, 2-1 system. If a different configuration is used, monitoring should be conducted at the following points.

- The flow rate must be monitored for the permeate stream from each stage, the permeate stream from the system, the concentrate waste stream from the system and the concentrate recycle stream.

- The flow must be directly measured for the system permeate stream and the system concentrate waste stream.

- The pressure must be measured for the influent to the cartridge filters, the effluent from the cartridge filters, the influent stream to each stage, the permeate flow from each stage, the permeate flow from the system, the concentrate waste stream from the system, and before and after any inter-stage pumps used in the system.

- The temperature must be measured for the system influent stream and after any inter-stage pumps used in the system.

- The pH must be measured for the feed water prior to acid addition, the feed water after mixing with the pretreatment chemicals, the influent stream to the system, and the concentrate waste stream from the system.

- The TDS concentration must be measured for the feed water prior to acid addition, the feed water after mixing with the pretreatment chemicals, the influent to each stage, the permeate flow from each stage, the permeate flow from the system, and the concentrate waste stream from the system.

Table 6-2 only lists the required monitoring points. Monitoring at additional points may be appropriate in some situations. It may also be appropriate to monitor additional water quality parameters specific to the source water or treatment objectives.

An example of a daily operations log that can be used to record this data is shown in Table 6-3, but this data should be summarized in a data sheet similar to Table 6-11.

6.3.2 Biweekly System Monitoring

Biweekly system monitoring must include analysis of the following parameters: TOC, UV_{254}, pH, alkalinity, total hardness, calcium hardness and turbidity. Each of these analyses will be conducted on the feed to the system (after cartridge filtration but prior to joining with the concentrate recycle stream), the influent to each stage, the permeate from each stage, the system permeate and the concentrate waste from the system.

Biweekly sampling must also include collection of samples for the following analyses: bromide and SDS for THM4, HAA6, TOX and chlorine demand. Each of these analyses must be conducted on the feed to the system (after cartridge filtration but prior to joining with the concentrate recycle stream) and the system permeate.

The results from these biweekly analyses can be summarized in data sheets similar to those shown in Tables 6-12 through 6-15. A total of at least twenty (20), but no more than twenty-six (26), biweekly sample sets will be collected over the course of a yearlong pilot-scale study. The analyses on every fifth set of biweekly samples should be duplicated, resulting in four to five sets of duplicate analyses over the course of the yearlong study. The results from the duplicate analyses can be reported on data sheets similar to Tables 6-16 through 6-18.

6.3.3 Additional Monitoring And Reporting

In addition to the above monitoring and reporting requirements, any additional information that would help to assess membrane performance should be summarized and included in the ICR report. Some examples include:

- The date and time of membrane cleaning and a brief description of the cleaning procedure (i.e., cleaning agent, volume of cleaning solution, duration of cleaning, etc.).

- Process upsets that could affect performance (e.g., pretreatment failure, a major change in water quality, operator error, etc.).

- Replacement of a membrane element or any other system component.

- Any change in the system operating parameters.

- Any time that the system is off for more than two hours.

6.3.4 Pressure Vessel Or Element Monitoring (Optional)

Single pressure vessels or elements do not need to be monitored for the ICR as this level of analysis would be cumbersome. However, when there is a deterioration in permeate quality or productivity within a stage, it may be advantageous to isolate a single pressure vessel or element. In this manner, failed elements can be identified and replaced. The flexibility to isolate single pressure vessels can be realized by adding flow meters, pressure gauges and sample ports to each pressure vessel. Single elements may need to be evaluated in a single module apparatus, such as the system described in Section 5.0.

6.3.5 Data Sheets

This section includes data sheets that can be used to record the appropriate data from the pilot-scale studies for the ICR. Corresponding data collection software will be sent to utilities electing to conduct pilot-scale experiments after the plant submits a study concept form to EPA.

The data sheet in Table 6-9 is used to report the characteristics of the membrane used during the ICR treatment studies. These are the membrane characteristics as reported by the manufacturer, and although some of this information may not be available, the data sheet should be filled out as completely as possible. The area and cost of an 8" x 40" element are requested for use in the cost analysis.

The data sheet in Table 6-10 requests information on the foulants in the feed water and the pretreatment processes used to control fouling. The first section of this table requests concentrations of foulants and fouling indices for the feed water. Only the foulants and indices relevant to the water being investigated need to be measured and reported. The blank rows should be used to report additional foulants that were measured but not listed in this table. This information should be used as a guide to selecting appropriate pretreatment processes. During the run, the relevant fouling indices and water quality parameters should be periodically measured to insure that pretreatment processes are performing properly and that the proper chemical doses are being applied to the feed water.

The second half of this table requests information about the pretreatment processes used prior to NF or RO. All pretreatment processes used should be reported here including

processes in the existing full-scale treatment train, upstream of the point where the feed to the pilot-scale system is tapped; and processes that were added specifically for membrane pretreatment. Existing full-scale treatment processes used as membrane pretreatment should be marked with an "E", modifications to processes in the existing plant treatment train (e.g., an increase in the coagulant dose) should be indicated by an "M" and pretreatment processes used in addition to the existing treatment train (e.g., acid or antiscalant addition) should be indicated with an "A". This table can be used to provide some of the pretreatment information required in the final treatment study report.

Table 6-11 can be used to summarize the daily operating parameters that are recorded in the daily operations log, Table 6-3. Temperature normalized fluxes, the MTC_W, and both feed and bulk rejections will be calculated by the data collection software. The feed rejection is calculated from the feed and permeate concentrations. To calculate the bulk rejection, the permeate and feed concentrations and the recovery are used to estimate the bulk concentration which is then used to calculate the bulk rejection. The cumulative time in this data sheet should be set at 0:00 at the start of the study and continued over the yearlong study. Down-time for the system must be subtracted from the cumulative time (i.e., by stopping the timer when the system is turned off).

Results from the analyses of biweekly water quality samples should be reported on data sheets similar to Tables 6-12 through 6-15. The date on which the samples were collected should be listed at the top of the data sheet along with the week of the run (e.g., week 2, week 4, week 6, ... week 52). At least twenty (20), but no more than twenty-six (26), biweekly sample sets will be collected over the course of a yearlong pilot-scale study. The analyses on every fifth set of biweekly samples should be duplicated, resulting in four to five sets of duplicate analyses over the course of the yearlong study. The results from duplicate analyses can be reported on data sheets similar to Tables 6-16 through 6-18.

The analyses for alkalinity, TDS, total hardness, calcium hardness, turbidity, TOC, and UV_{254} are conducted on the cartridge filtered feed water, the system permeate and the system concentrate waste; thus mass balance closure errors can be calculated for these parameters. Mass balance closure errors for these analytes are typically less than a few percent.

The mass balance closure error is calculated in two steps. First the concentrate concentration is calculated from the prefiltered feed and system permeate concentrations and the fractional system recovery using Equation 6.24.

$$C_{C(calc)} = \frac{C_F - (C_p \times R)}{(1 - R)} \qquad (6.24)$$

where $C_{C(calc)}$ is the calculated concentrate concentration. Next the mass balance closure error is determined by comparing calculated and measured concentrate values:

$$\mathbf{Error_{MB}} = \frac{\mathbf{C_{C(meas)} - C_{C(calc)}}}{\mathbf{C_{C(meas)}}} \times \mathbf{100\%} \qquad \mathbf{(6.25)}$$

where $\mathbf{Error_{MB}}$ is the mass balance closure error expressed as a percentage and $\mathbf{C_{C(meas)}}$ is the measured concentrate concentration.

Since permeate quality often exceeds the treatment objectives, the system permeate can be blended with by-passed feed water. This can substantially reduce the required membrane area and post-treatment requirements, and thus the cost. However, any removal of pathogens that the membrane is capable of will be negated by blending permeate and by-passed feed water, unless the pathogens were removed or inactivated by a process upstream of the membrane process. By calculating the water quality for different blending ratios, costs for different levels of treatment can be estimated. Tables 6-19 (a and b) use the average prefiltered feed and system permeate water quality parameters to calculate the amount of flow that must be treated by membranes to achieve the Stage 1 MCLs (Table 6-19a) and the proposed Stage 2 MCLs (Table 6-19b). Water quality parameters that impact post-treatment requirements are also calculated for the blended waters. In these two tables, Q_T is the total blended flow, and the ratio Q_p/Q_T is the fraction of flow that must be treated by membranes to meet the treatment objectives. This ratio is calculated for both the THM4 and HAA5 MCLs as either can control the blend ratio. The subscript **b** in these tables denotes blended water quality.

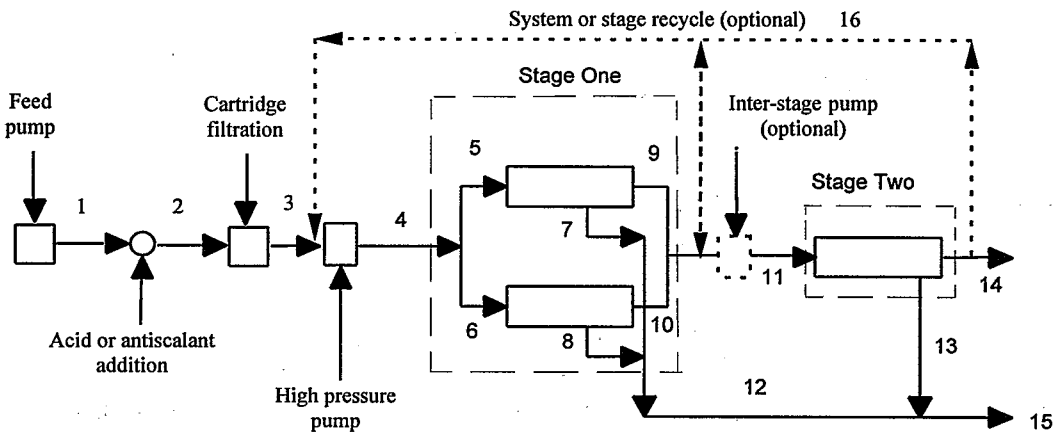

Figure 6-1 Flow Diagram Of A Two-Stage Pilot Plant Showing Sampling And Monitoring Locations By Number

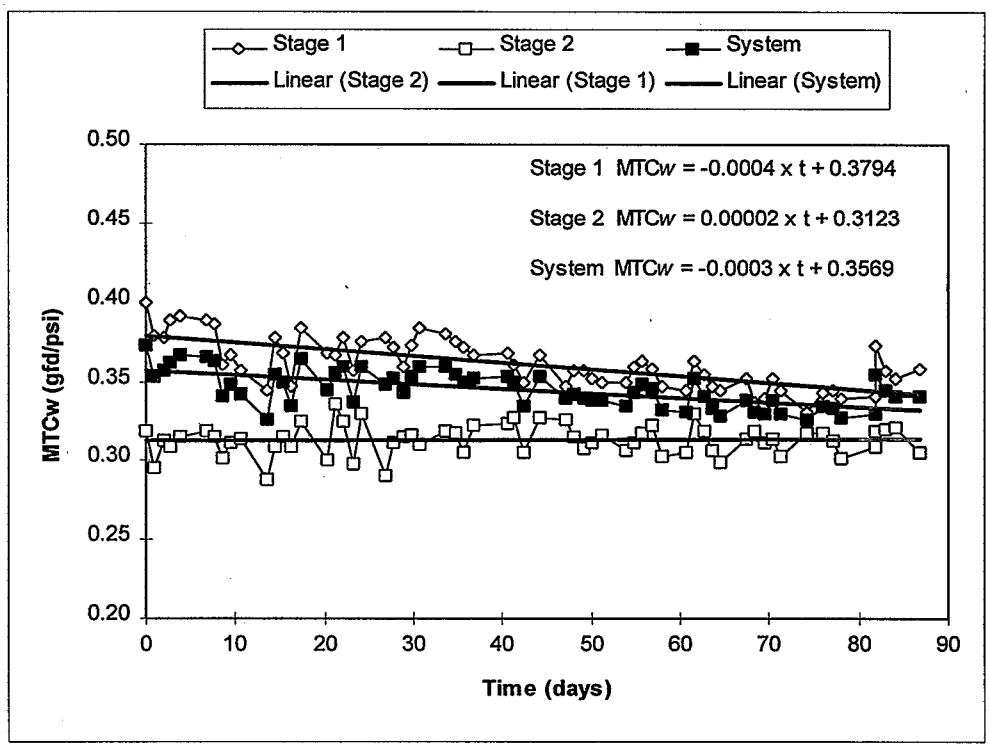

Figure 6-2 Two-Stage Pilot Plant Membrane Productivity

Table 6-1 Two-Stage Membrane Pilot Plant Numerical Identification Code

Number	Description
1	Feed water
2	Acidified feed water
3	Cartridge-filtered feed water
4	Influent to stage 1
5	Influent to pressure vessel 1, stage 1
6	Influent to pressure vessel 2, stage 1
7	Permeate from pressure vessel 1, stage 1
8	Permeate from pressure vessel 2, stage 1
9	Concentrate from pressure vessel 1, stage 1
10	Concentrate from pressure vessel 2, stage 1
11	Influent to stage 2
12	Permeate from stage 1
13	Permeate from stage 2
14	System concentrate waste
15	System permeate
16	Concentrate recycle

Table 6-2 Minimum Monitoring Matrix For A Two-Stage Pilot Plant

Parameter	Location Number															
	1	2	3	4*	5	6	7	8	9	10	11	12	13	14	15	16
Flow rate												D	D	D	D	D
Pressure		D	D	D							D	D	D	D	D	
Temperature				D												
Direct flow measurement														D	D	
TDS	D		D	D							D	D	D	D	D	
pH	D		D	D							B	B	B	D	B	
Total Hardness			B	B							B	B	B	B	B	
Calcium Hardness			B	B							B	B	B	B	B	
Alkalinity			B	B							B	B	B	B	B	
Turbidity			B	B							B	B	B	B	B	
UV_{254}			B	B							B	B	B	B	B	
TOC			B	B							B	B	B	B	B	
Bromide			B												B	
SDS - THM4			B												B	
SDS - HAA6			B												B	
SDS - TOX			B												B	
SDS - Chlorine demand			B												B	

D - daily (once per shift)
B - biweekly
*: The water quality parameters at location 4 only need to be monitored if concentrate recycle is used.

Table 6-3 Daily Operations Log Sheet For A Two-Stage Membrane Pilot Plant

Operators initials _____ Clock Counter _____

Date _____ Time on _____ _____ _____

Time _____ Time off _____ _____ _____

Pressure Measurements (psi)

2	Acidified feed water	_____
3	Cartridge-filtered feed	_____
4	Influent to stage 1	_____
11	Influent to stage 2	_____
12	Permeate stage 1	_____
13	Permeate stage 2	_____
14	Concentrate stage 2	_____
15	System permeate	_____

Flow Rate Measurements (gpm)

12	Permeate stage 1	_____
13	Permeate stage 2	_____
14	System waste	_____
15	System permeate	_____
16	Concentrate recycle	_____

Directly Measured Flows (gpm)

14	System concentrate waste	_____
15	System permeate	_____

Temperature Measurements (°C)

4	Influent to stage 1	_____
11	Influent to stage 2	_____

TDS Measurements (mg/L)

1	Feed water	_____
3	Cartridge-filtered feed	_____
4	System influent	_____
11	Influent to stage 2	_____
12	Permeate stage 1	_____
13	Permeate stage 2	_____
14	System waste	_____
15	System permeate	_____

pH Measurements

1	Feed water	_____
3	Cartridge-filtered feed	_____
4	Influent to stage 1	_____
14	System waste	_____

Reasons For Down Time:

_____

_____

_____

Notes:

_____

_____

_____

_____

Time To Complete Maintenance:

_____

_____

Table 6-4 RO And NF Membrane Pilot Plant Design Criteria

Parameter	Design Criteria
Number of stages	At least 2 stages are required for the ICR, but 1 or 3 is not unusual in pilot plants.
Number of pressure vessels per stage	At least a 2-1 array is required for ICR pilot plants.
Number of elements per pressure vessel	At least 3 elements per pressure vessel are required for the ICR but 1 to 6 is possible.
Recovery per stage, %	Restricted by minimum flow into element, typically 30% to 50% for a two-stage pilot plant.
Recovery for system, %	At least 75% for the ICR pilot studies, but may be restricted by a limiting salt.
Design flux, gfd	Typically 15 gfd for RO/NF ground water systems but can range from 10 to 20 gfd.
Surface area per element, ft^2	Restricted by element diameter, typically 20 ft^2 for a 2.5" element diameter and 80 ft^2 for a 4.0" element diameter.
MTC_W, gfd/psi	Restricted by membrane resistance, typically 0.20 to 0.50 gfd/psi for a NF element, and 0.10 to 0.25 gfd/psi for a RO element.
Acceptable range of feed flow rates through an element, gpm	Specified by the manufacturer, typically 0.5 to 4 gpm for a 2.5" element and 3 to 16 gpm for a 4" element.
Pressure loss per element, psi	Hydraulic losses due to flow across the element surface and through the feed spacer, estimated at 3 psi per element.
Pressure loss in stage entrance and exit, psi	Hydraulic losses due to flow in and out of the inter-stage piping, estimated at 5 psi per stage.
Feed stream TDS, mg/L	Typically a function of the raw water source.
TDS rejection, %	Provided by manufacturer or testing, typically 30 to 90% for NF and 95 to 99% for RO.

Table 6-5 Osmotic Pressure Estimates For Stages 1 And 2 Of A 2-1 Membrane System With Three Elements Per Pressure Vessel, Operated At 75% Recovery

Stage 1						Stage 2					
TDS_F = 1000 mg/L (R_{sys} = 75%)						TDS_F = 1000 mg/L (R_{sys} = 75%)					
Rej_{TDS}	r = 0 Δπ (psi)	r = 1 Δπ (psi)	r = 2 Δπ (psi)	r = 3 Δπ (psi)	r = 5 Δπ (psi)	Rej_{TDS}	r = 0 Δπ (psi)	r = 1 Δπ (psi)	r = 2 Δπ (psi)	r = 3 Δπ (psi)	r = 5 Δπ (psi)
0.5	6.7	7.6	7.8	7.8	7.9	0.5	9.6	8.5	8.3	8.2	8.1
0.6	8.2	10.1	10.4	10.5	10.7	0.6	12.6	11.5	11.3	11.2	11.1
0.7	9.8	13.1	13.7	14.0	14.3	0.7	16.2	15.3	15.1	15.0	14.9
0.8	11.4	17.0	18.1	18.6	19.1	0.8	20.2	20.3	20.3	20.2	20.1
0.9	13.2	22.1	24.2	25.1	26.0	0.9	24.8	27.1	27.4	27.5	27.6
0.95	14.1	25.3	28.1	29.4	30.7	0.95	27.3	31.4	32.1	32.4	32.7
0.98	14.6	27.5	30.9	32.5	34.0	0.98	28.9	34.5	35.5	35.9	36.3
TDS_F = 500 mg/L (R_{sys} = 75%)						TDS_F = 500 mg/L (R_{sys} = 75%)					
Rej_{TDS}	r = 0 Δπ (psi)	r = 1 Δπ (psi)	r = 2 Δπ (psi)	r = 3 Δπ (psi)	r = 5 Δπ (psi)	Rej_{TDS}	r = 0 Δπ (psi)	r = 1 Δπ (psi)	r = 2 Δπ (psi)	r = 3 Δπ (psi)	r = 5 Δπ (psi)
0.5	3.3	3.8	3.9	3.9	3.9	0.5	4.8	4.2	4.1	4.1	4.1
0.6	4.1	5.0	5.2	5.3	5.3	0.6	6.3	5.7	5.6	5.6	5.5
0.7	4.9	6.6	6.9	7.0	7.1	0.7	8.1	7.7	7.6	7.5	7.5
0.8	5.7	8.5	9.1	9.3	9.6	0.8	10.1	10.2	10.1	10.1	10.1
0.9	6.6	11.0	12.1	12.6	13.0	0.9	12.4	13.6	13.7	13.8	13.8
0.95	7.0	12.7	14.1	14.7	15.3	0.95	13.7	15.7	16.1	16.2	16.3
0.98	7.3	13.8	15.5	16.3	17.0	0.98	14.5	17.2	17.7	18.0	18.2
TDS_F = 300 mg/L (R_{sys} = 75%)						TDS_F = 300 mg/L (R_{sys} = 75%)					
Rej_{TDS}	r = 0 Δπ (psi)	r = 1 Δπ (psi)	r = 2 Δπ (psi)	r = 3 Δπ (psi)	r = 5 Δπ (psi)	Rej_{TDS}	r = 0 Δπ (psi)	r = 1 Δπ (psi)	r = 2 Δπ (psi)	r = 3 Δπ (psi)	r = 5 Δπ (psi)
0.5	2.0	2.3	2.3	2.4	2.4	0.5	2.9	2.5	2.5	2.5	2.4
0.6	2.5	3.0	3.1	3.2	3.2	0.6	3.8	3.4	3.4	3.4	3.3
0.7	2.9	3.9	4.1	4.2	4.3	0.7	4.8	4.6	4.5	4.5	4.5
0.8	3.4	5.1	5.4	5.6	5.7	0.8	6.1	6.1	6.1	6.1	6.0
0.9	4.0	6.6	7.2	7.5	7.8	0.9	7.4	8.1	8.2	8.3	8.3
0.95	4.2	7.6	8.4	8.8	9.2	0.95	8.2	9.4	9.6	9.7	9.8
0.98	4.4	8.3	9.3	9.8	10.2	0.98	8.7	10.3	10.6	10.8	10.9
TDS_F = 200 mg/L (R_{sys} = 75%)						TDS_F = 200 mg/L (R_{sys} = 75%)					
Rej_{TDS}	r = 0 Δπ (psi)	r = 1 Δπ (psi)	r = 2 Δπ (psi)	r = 3 Δπ (psi)	r = 5 Δπ (psi)	Rej_{TDS}	r = 0 Δπ (psi)	r = 1 Δπ (psi)	r = 2 Δπ (psi)	r = 3 Δπ (psi)	r = 5 Δπ (psi)
0.5	1.3	1.5	1.6	1.6	1.6	0.5	1.9	1.7	1.7	1.6	1.6
0.6	1.6	2.0	2.1	2.1	2.1	0.6	2.5	2.3	2.3	2.2	2.2
0.7	2.0	2.6	2.7	2.8	2.9	0.7	3.2	3.1	3.0	3.0	3.0
0.8	2.3	3.4	3.6	3.7	3.8	0.8	4.0	4.1	4.1	4.0	4.0
0.9	2.6	4.4	4.8	5.0	5.2	0.9	5.0	5.4	5.5	5.5	5.5
0.95	2.8	5.1	5.6	5.9	6.1	0.95	5.5	6.3	6.4	6.5	6.5
0.98	2.9	5.5	6.2	6.5	6.8	0.98	5.8	6.9	7.1	7.2	7.3

TDS_F = the TDS concentration in the feed water.

Rej_{TDS} = the manufacturer reported TDS rejection, expressed as a decimal fraction.

r = the recycle ratio (Q_R/Q_F)

Table 6-6 Example Design Criteria For A Nanofiltration Pilot Plant

Parameter	Value
Number of stages	2
Number of pressure vessels in stage 1	2
Number of pressure vessels in stage 2	1
Number of elements per pressure vessel	3
Recovery per stage, %	50
Recovery for system, %	75
Design flux, gfd	15
Surface area per 4" x 40" element, ft^2	70
MTC_W, gfd/psi	0.30
Maximum flow rate to an element, gpm	16
Minimum flow rate to an element, gpm	4
Pressure loss per element, psi	3
Pressure loss in stage entrance and exit, psi	5
Feed stream TDS, mg/L	300
TDS rejection, %	70

Table 6-7 Pilot Plant Design Parameters For The Example Problem

Location #[1]	Description	Flow rate* (gpm)	Pressure (psi)
3	Cartridge-filtered feed water	8.8	20 to 30
4	Influent to system / stage 1	10.9 to 20.4	95
5	Influent to pressure vessel 1, stage 1	5.4 to 10.2	95
6	Influent to pressure vessel 2, stage 1	5.4 to 10.2	95
7	Permeate from pressure vessel 1, stage 1	2.2	30
8	Permeate from pressure vessel 2, stage 1	2.2	30
9	Concentrate from pressure vessel 1, stage 1	3.2 to 8.0	81
10	Concentrate from pressure vessel 2, stage 1	3.2 to 8.0	81
11	Influent to stage 2	6.4 to 16.0	81
12	Permeate from stage 1	4.4	30
13	Permeate from stage 2	2.2	30
14**	Concentrate from stage 2	4.2 to 13.8	67
14	System concentrate waste	2.2	0
15	System permeate	6.6	30
16	System concentrate recycle	2.2 to 11.6	67

1: Refer to Table 6-1 and Figure 6-1 for an explanation of the location numbers.

*: A range of flow rates is provided to account for different recycle flow rates.

**: This location represents the total concentrate flow leaving stage 2 (i.e., recycle plus waste)

Table 6-8 Example Of Time-Dependent Membrane Productivity For A Two-Stage Pilot Plant

Runtime (days)	System Recovery (%)	NDP Stage 1 (psi)	NDP Stage 2 (psi)	NPD System (psi)	Flux Stage 1 (gfd)	Flux Stage 2 (gfd)	Flux System (gfd)	MTC_W Stage 1 (gfd/psi)	MTC_W Stage 2 (gfd/psi)	MTC_W System (gfd/psi)
0.0	75	34	42	36	13.4	13.4	13.4	0.40	0.32	0.37
1.0	74	37	43	38	13.8	12.6	13.4	0.38	0.30	0.35
2.0	75	36	42	38	13.6	13.0	13.4	0.38	0.31	0.36
2.8	76	35	44	38	13.6	13.6	13.6	0.39	0.31	0.36
3.8	77	36	45	39	14.2	14.2	14.2	0.39	0.32	0.37
6.7	76	37	45	39	14.2	14.2	14.2	0.39	0.32	0.37
7.7	76	38	45	40	14.5	14.2	14.4	0.39	0.32	0.36
8.7	76	38	45	40	13.6	13.6	13.6	0.36	0.30	0.34
9.6	76	37	45	39	13.4	14.0	13.6	0.37	0.31	0.35
13.6	75	38	45	40	13.0	13.0	13.0	0.34	0.29	0.33
14.4	76	36	45	39	13.6	13.9	13.7	0.38	0.31	0.35
15.4	76	37	45	39	13.6	14.2	13.8	0.37	0.32	0.35
16.3	74	38	42	39	13.0	13.0	13.0	0.35	0.31	0.33
17.4	76	37	43	38	14.0	14.0	14.0	0.38	0.33	0.36
20.2	76	38	48	41	13.8	14.4	14.0	0.37	0.30	0.34
22.2	77	37	45	39	14.0	14.6	14.2	0.38	0.32	0.36
23.2	75	38	47	40	13.4	14.0	13.6	0.36	0.30	0.34
24.1	76	36	45	39	13.6	14.8	14.0	0.37	0.33	0.36
27.0	76	37	50	40	13.8	14.4	14.0	0.38	0.29	0.35
27.8	76	37	45	39	13.6	13.9	13.7	0.37	0.31	0.35
28.8	75	37	47	40	13.3	14.8	13.8	0.36	0.32	0.34
30.8	76	37	45	39	14.1	13.8	14.0	0.38	0.31	0.36
33.7	76	37	47	40	13.9	14.8	14.2	0.38	0.32	0.36
34.7	76	37	46	39	13.7	14.6	14.0	0.37	0.32	0.35
35.6	76	37	47	40	13.6	14.2	13.8	0.37	0.31	0.35
36.7	76	37	44	39	13.4	14.0	13.6	0.37	0.32	0.35
40.5	76	38	45	40	13.8	14.4	14.0	0.37	0.32	0.35
42.4	76	38	47	41	13.3	14.2	13.6	0.35	0.31	0.33
44.2	76	37	44	39	13.6	14.2	13.8	0.37	0.33	0.35
47.2	75	39	43	40	13.4	14.0	13.6	0.35	0.33	0.34
48.1	75	38	45	40	13.4	14.0	13.6	0.36	0.31	0.34
49.1	75	38	46	40	13.4	14.0	13.6	0.36	0.31	0.34
50.1	76	38	45	40	13.4	14.0	13.6	0.35	0.31	0.34
51.1	75	38	45	40	13.3	14.2	13.6	0.35	0.32	0.34
54.0	75	38	45	40	13.2	13.8	13.4	0.35	0.31	0.33
54.9	75	37	45	40	13.4	14.0	13.6	0.36	0.31	0.34
56.9	76	38	44	40	13.6	14.2	13.8	0.36	0.32	0.35
57.9	75	38	46	40	13.2	13.8	13.4	0.35	0.30	0.33
60.8	73	38	45	40	13.0	13.6	13.2	0.34	0.31	0.33
61.5	76	38	43	39	13.7	14.0	13.8	0.36	0.33	0.35
62.7	75	37	44	39	13.1	14.0	13.4	0.35	0.32	0.34
63.5	75	38	45	40	13.2	13.8	13.4	0.35	0.31	0.33
64.6	75	38	46	40	13.0	13.6	13.2	0.34	0.30	0.33
67.4	75	38	44	40	13.2	13.8	13.4	0.35	0.31	0.34
68.4	75	39	44	40	13.1	14.0	13.4	0.34	0.32	0.33
70.4	75	38	44	40	13.2	13.8	13.4	0.35	0.31	0.34
71.3	75	38	45	40	13.0	13.6	13.2	0.34	0.30	0.33
74.1	75	38	44	40	12.6	13.8	13.0	0.33	0.32	0.33
76.1	74	38	44	39	12.9	13.8	13.2	0.34	0.32	0.33
77.2	75	38	44	40	13.0	13.6	13.2	0.34	0.31	0.33
78.1	74	38	45	40	13.0	13.6	13.2	0.34	0.30	0.33
82.0	74	39	44	41	13.3	13.6	13.4	0.34	0.31	0.33
82.0	76	38	44	40	14.1	14.1	14.1	0.37	0.32	0.35
83.1	76	38	45	40	13.5	14.4	13.8	0.36	0.32	0.34
84.0	75	38	44	40	13.2	14.1	13.5	0.35	0.32	0.34
86.9	75	38	46	40	13.6	13.9	13.7	0.36	0.31	0.34

Table 6-9 Membrane Characteristics As Reported By The Manufacturer

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Characteristics of the membrane elements used in the study

Membrane manufacturer	
Membrane module model number	
Size of element used in study (e.g. 4" x 40")	
Active membrane area of element used in study	
Active membrane area of an equivalent 8" x 40" element	
Purchase price for an equivalent 8" x 40 " element ($)	
Molecular weight cutoff (Daltons)	
Membrane material / construction	
Membrane hydrophobicity (circle one)	Hydrophilic Hydrophobic
Membrane charge (circle one)	Negative Neutral Positive
Design pressure (psi)	
Design flux at the design pressure (gfd)	
Variability of design flux (%)	
MTC_W (gfd/psi)	
Standard testing recovery (%)	
Standard testing pH	
Standard testing temperature (°C)	
Design cross-flow velocity (fps)	
Maximum flow rate to the element (gpm)	
Minimum flow rate to the element (gpm)	
Required feed flow to permeate flow rate ratio	
Maximum element recovery (%)	
Rejection of reference solute and conditions of test (e.g. solute type and concentration)	
Variability of rejection of reference solute (%)	
Spacer thickness (ft)	
Scroll width (ft)	
Acceptable range of operating pressures	
Acceptable range of operating pH values	
Typical pressure drop across a single element	
Maximum permissible SDI	
Maximum permissible turbidity (ntu)	
Chlorine/oxidant tolerance	
Suggested cleaning procedures	

Note: Some of this information may not be available, but this table should be filled out as completely as possible for each membrane tested.

Table 6-10 Membrane Pretreatment Data

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Foulants and fouling indices of the feed water prior to pretreatment[1]

Alkalinity (mg $CaCO_3$/L)	
Ca Hardness (mg $CaCO_3$/L)	
LSI	
Dissolved iron (mg/L)	
Total iron (mg/L)	
Dissolved aluminum (mg/L)	
Total aluminum (mg/L)	
Fluoride (mg/L)	
Phosphate (mg/L)	
Sulfate (mg/L)	
Calcium (mg/L)	
Barium (mg/L)	
Strontium (mg/L)	
Reactive silica (mg/L as SiO_2)	
Turbidity (ntu)	
SDI	
MFI	
MPFI	

1: Only those foulants and fouling indices relevant to the water being tested need to be evaluated. Additional foulants and indices can be listed in the blank rows or on an attached sheet.

Pretreatment processes used prior to nanofiltration or reverse osmosis[2]

Pre-filter exclusion size (μm)	
Type of acid used	
Acid concentration (units)	
mL of acid per L of feed	
Type of antiscalant used	
Antiscalant concentration (units)	
mL of antiscalant per L of feed	
Type of coagulant used	
Coagulant dose (mg/L)	
Type of polymer used during coag.	
Polymer dose (mg/L)	

2: Use an "E" to indicate a pretreatment process that is currently part of the plant treatment train, an "M" to indicate a modification to a process that is currently part of the plant treatment train, and an "A" to indicate an addition to the current treatment train.

Additional pretreatment processes, such as MF, can be listed in the blank rows or on an attached sheet.

Table 6-11 Membrane Operational And Performance Data Monitoring With Time (Page 1 of 3)

Utility name and address ______________________________ Phone number ______________

______________________________ FAX number ______________

ICR plant number ________________ Contact person ____________________

Membrane trade name ______________________________

System parameters monitored with time

Date	Time (hr)	Cumulative time (hr)	SYSTEM								
			Q_W (gpm)	Q_p (gpm)	Q_R (gpm)	R_{sys} (%)	pH_F before acid	pH_F after acid	TDS_F before acid	TDS_F after acid	TDS_p (mg/L)

Table 6-11 Membrane Operational And Performance Data Monitoring With Time (Page 2 of 3)

Utility name and address ______________________________ Phone number ______________

______________________________ FAX number ______________

ICR plant number ____________________ Contact person ____________________

Membrane trade name ______________________________

Stage 1 parameters monitored with time

Date	Time	Cumulative	STAGE ONE									
		time	Q_I	Q_p	$Temp_I$	P_I	P_C	P_P	pH_I	TDS_I	TDS_p	TDS_C
	(hr)	(hr)	(gpm)	(gpm)	(°C)	(psi)	(psi)	(psi)		(mg/L)	(mg/L)	(mg/L)

Table 6-11 Membrane Operational And Performance Data Monitoring With Time (Page 3 of 3)

Utility name and address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____

Stage 2 parameters monitored with time

Date	Time (hr)	Cumulative time (hr)	STAGE TWO									
			Q_I (gpm)	Q_p (gpm)	$Temp_I$ (°C)	P_I (psi)	P_C (psi)	P_P (psi)	pH_I	TDS_I (mg/L)	TDS_p (mg/L)	TDS_C (mg/L)

Table 6-12 Membrane Pilot System Biweekly Water Quality Parameters For Week Two

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Parameter	Units	$C_{F\text{-}sys}$	$C_{p\text{-}sys}$	$C_{W\text{-}sys}$	$C_{I\text{-}s\ (1)}$	$C_{I\text{-}s\ (2)}$	$C_{p\text{-}s\ (1)}$	$C_{p\text{-}s\ (2)}$
Sampling date	MM/DD/YY							
Sampling time	hh:mm							
Alkalinity	mg $CaCO_3$ / L							
TDS	mg/L							
Total hardness	mg $CaCO_3$ / L							
Calcium hardness	mg $CaCO_3$ / L							
Bromide	µg/L			---	---	---	---	---
pH	---							
Turbidity	ntu							
Temperature	°C							
TOC	mg/L							
UV_{254}	cm^{-1}							
SDS samples				---	---	---	---	---
Chlorine dose	mg/L			---	---	---	---	---
Chlorine residual	mg/L			---	---	---	---	---
Chlorine demand	mg/L			---	---	---	---	---
Chlorination temp.	°C			---	---	---	---	---
Chlorination pH	---			---	---	---	---	---
Incubation time	hours			---	---	---	---	---
TOX	µg/L			---	---	---	---	---
$CHCl_3$	µg/L			---	---	---	---	---
$CHBrCl_2$	µg/L			---	---	---	---	---
$CHBr_2Cl$	µg/L			---	---	---	---	---
$CHBr_3$	µg/L			---	---	---	---	---
THM4	µg/L			---	---	---	---	---
*MCAA**	µg/L			---	---	---	---	---
*DCAA**	µg/L			---	---	---	---	---
*TCAA**	µg/L			---	---	---	---	---
*MBAA**	µg/L			---	---	---	---	---
*DBAA**	µg/L			---	---	---	---	---
*BCAA**	µg/L			---	---	---	---	---
TBAA	µg/L			---	---	---	---	---
CDBAA	µg/L			---	---	---	---	---
DCBAA	µg/L			---	---	---	---	---
HAA6	µg/L			---	---	---	---	---

* These six species make up HAA6. The other three HAA species should be reported if measured.

Sampling points are defined in Figure 6-1 and Table 6-2: $C_{F\text{-}sys}$ = system feed after prefiltration, $C_{p\text{-}sys}$ = system permeate, $C_{W\text{-}sys}$ = system waste, $C_{I\text{-}s(i)}$ = influent to stage i, and $C_{p\text{-}sys}$ = permeate from stage i

Table 6-13 Membrane Pilot System Biweekly Water Quality Parameters For Week Four

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Parameter	Units	$C_{F\text{-}sys}$	$C_{p\text{-}sys}$	$C_{W\text{-}sys}$	$C_{I\text{-}s\ (1)}$	$C_{I\text{-}s\ (2)}$	$C_{p\text{-}s\ (1)}$	$C_{p\text{-}s\ (2)}$
Sampling date	MM/DD/YY							
Sampling time	hh:mm							
Alkalinity	mg $CaCO_3$ / L							
TDS	mg/L							
Total hardness	mg $CaCO_3$ / L							
Calcium hardness	mg $CaCO_3$ / L							
Bromide	µg/L			---	---	---	---	---
pH	---							
Turbidity	ntu							
Temperature	°C							
TOC	mg/L							
UV_{254}	cm^{-1}							
SDS samples				---	---	---	---	---
Chlorine dose	mg/L			---	---	---	---	---
Chlorine residual	mg/L			---	---	---	---	---
Chlorine demand	mg/L			---	---	---	---	---
Chlorination temp.	°C			---	---	---	---	---
Chlorination pH	---			---	---	---	---	---
Incubation time	hours			---	---	---	---	---
TOX	µg/L			---	---	---	---	---
$CHCl_3$	µg/L			---	---	---	---	---
$CHBrCl_2$	µg/L			---	---	---	---	---
$CHBr_2Cl$	µg/L			---	---	---	---	---
$CHBr_3$	µg/L			---	---	---	---	---
THM4	µg/L			---	---	---	---	---
*MCAA**	µg/L			---	---	---	---	---
*DCAA**	µg/L			---	---	---	---	---
*TCAA**	µg/L			---	---	---	---	---
*MBAA**	µg/L			---	---	---	---	---
*DBAA**	µg/L			---	---	---	---	---
*BCAA**	µg/L			---	---	---	---	---
TBAA	µg/L			---	---	---	---	---
CDBAA	µg/L			---	---	---	---	---
DCBAA	µg/L			---	---	---	---	---
HAA6	µg/L			---	---	---	---	---

* These six species make up HAA6. The other three HAA species should be reported if measured.

Sampling points are defined in Figure 6-1 and Table 6-2: $C_{F\text{-}sys}$ = system feed after prefiltration, $C_{p\text{-}sys}$ = system permeate, $C_{W\text{-}sys}$ = system waste, $C_{I\text{-}s(i)}$ = influent to stage i, and $C_{p\text{-}sys}$ = permeate from stage i

Table 6-14 Membrane Pilot System Biweekly Water Quality Parameters For Week Six

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Parameter	Units	$C_{F\text{-}sys}$	$C_{p\text{-}sys}$	$C_{W\text{-}sys}$	$C_{I\text{-}s\ (1)}$	$C_{I\text{-}s\ (2)}$	$C_{p\text{-}s\ (1)}$	$C_{p\text{-}s\ (2)}$
Sampling date	MM/DD/YY							
Sampling time	hh:mm							
Alkalinity	mg $CaCO_3$ / L							
TDS	mg/L							
Total hardness	mg $CaCO_3$ / L							
Calcium hardness	mg $CaCO_3$ / L							
Bromide	µg/L			---	---	---	---	---
pH	---							
Turbidity	ntu							
Temperature	°C							
TOC	mg/L							
UV_{254}	cm^{-1}							
SDS samples				---	---	---	---	---
Chlorine dose	mg/L			---	---	---	---	---
Chlorine residual	mg/L			---	---	---	---	---
Chlorine demand	mg/L			---	---	---	---	---
Chlorination temp.	°C			---	---	---	---	---
Chlorination pH	---			---	---	---	---	---
Incubation time	hours			---	---	---	---	---
TOX	µg/L			---	---	---	---	---
$CHCl_3$	µg/L			---	---	---	---	---
$CHBrCl_2$	µg/L			---	---	---	---	---
$CHBr_2Cl$	µg/L			---	---	---	---	---
$CHBr_3$	µg/L			---	---	---	---	---
THM4	µg/L			---	---	---	---	---
*MCAA**	µg/L			---	---	---	---	---
*DCAA**	µg/L			---	---	---	---	---
*TCAA**	µg/L			---	---	---	---	---
*MBAA**	µg/L			---	---	---	---	---
*DBAA**	µg/L			---	---	---	---	---
*BCAA**	µg/L			---	---	---	---	---
TBAA	µg/L			---	---	---	---	---
CDBAA	µg/L			---	---	---	---	---
DCBAA	µg/L			---	---	---	---	---
HAA6	µg/L			---	---	---	---	---

* These six species make up HAA6. The other three HAA species should be reported if measured.

Sampling points are defined in Figure 6-1 and Table 6-2: $C_{F\text{-}sys}$ = system feed after prefiltration, $C_{p\text{-}sys}$ = system permeate, $C_{W\text{-}sys}$ = system waste, $C_{I\text{-}s(i)}$ = influent to stage i, and $C_{p\text{-}sys}$ = permeate from stage i

Table 6-15 Membrane Pilot System Biweekly Water Quality Parameters For Week _____

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Parameter	Units	$C_{F\text{-}sys}$	$C_{p\text{-}sys}$	$C_{W\text{-}sys}$	$C_{I\text{-}s\ (1)}$	$C_{I\text{-}s\ (2)}$	$C_{p\text{-}s\ (1)}$	$C_{p\text{-}s\ (2)}$
Sampling date	MM/DD/YY							
Sampling time	hh:mm							
Alkalinity	mg $CaCO_3$ / L							
TDS	mg/L							
Total hardness	mg $CaCO_3$ / L							
Calcium hardness	mg $CaCO_3$ / L							
Bromide	µg/L			---	---	---	---	---
pH	---							
Turbidity	ntu							
Temperature	°C							
TOC	mg/L							
UV_{254}	cm^{-1}							
SDS samples				---	---	---	---	---
Chlorine dose	mg/L			---	---	---	---	---
Chlorine residual	mg/L			---	---	---	---	---
Chlorine demand	mg/L			---	---	---	---	---
Chlorination temp.	°C			---	---	---	---	---
Chlorination pH	---			---	---	---	---	---
Incubation time	hours			---	---	---	---	---
TOX	µg/L			---	---	---	---	---
$CHCl_3$	µg/L			---	---	---	---	---
$CHBrCl_2$	µg/L			---	---	---	---	---
$CHBr_2Cl$	µg/L			---	---	---	---	---
$CHBr_3$	µg/L			---	---	---	---	---
THM4	µg/L			---	---	---	---	---
*MCAA**	µg/L			---	---	---	---	---
*DCAA**	µg/L			---	---	---	---	---
*TCAA**	µg/L			---	---	---	---	---
*MBAA**	µg/L			---	---	---	---	---
*DBAA**	µg/L			---	---	---	---	---
*BCAA**	µg/L			---	---	---	---	---
TBAA	µg/L			---	---	---	---	---
CDBAA	µg/L			---	---	---	---	---
DCBAA	µg/L			---	---	---	---	---
HAA6	µg/L			---	---	---	---	---

* These six species make up HAA6. The other three HAA species should be reported if measured.

Sampling points are defined in Figure 6-1 and Table 6-2: $C_{F\text{-}sys}$ = system feed after prefiltration, $C_{p\text{-}sys}$ = system permeate, $C_{W\text{-}sys}$ = system waste, $C_{I\text{-}s(i)}$ = influent to stage i, and $C_{p\text{-}sys}$ = permeate from stage i

Table 6-16 Duplicate Analysis Of Membrane Pilot System Biweekly Water Quality Parameters For Week Ten

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Parameter	Units	$C_{F\text{-}sys}$	$C_{p\text{-}sys}$	$C_{W\text{-}sys}$	$C_{I\text{-}s\,(1)}$	$C_{I\text{-}s\,(2)}$	$C_{p\text{-}s\,(1)}$	$C_{p\text{-}s\,(2)}$
Sampling date	MM/DD/YY							
Sampling time	hh:mm							
Alkalinity	mg $CaCO_3$ / L							
TDS	mg/L							
Total hardness	mg $CaCO_3$ / L							
Calcium hardness	mg $CaCO_3$ / L							
Bromide	µg/L			---	---	---	---	---
pH	---							
Turbidity	ntu							
Temperature	°C							
TOC	mg/L							
UV_{254}	cm^{-1}							
SDS samples				---	---	---	---	---
Chlorine dose	mg/L			---	---	---	---	---
Chlorine residual	mg/L			---	---	---	---	---
Chlorine demand	mg/L			---	---	---	---	---
Chlorination temp.	°C			---	---	---	---	---
Chlorination pH	---			---	---	---	---	---
Incubation time	hours			---	---	---	---	---
TOX	µg/L			---	---	---	---	---
$CHCl_3$	µg/L			---	---	---	---	---
$CHBrCl_2$	µg/L			---	---	---	---	---
$CHBr_2Cl$	µg/L			---	---	---	---	---
$CHBr_3$	µg/L			---	---	---	---	---
THM4	µg/L			---	---	---	---	---
*MCAA**	µg/L			---	---	---	---	---
*DCAA**	µg/L			---	---	---	---	---
*TCAA**	µg/L			---	---	---	---	---
*MBAA**	µg/L			---	---	---	---	---
*DBAA**	µg/L			---	---	---	---	---
*BCAA**	µg/L			---	---	---	---	---
TBAA	µg/L			---	---	---	---	---
CDBAA	µg/L			---	---	---	---	---
DCBAA	µg/L			---	---	---	---	---
HAA6	µg/L			---	---	---	---	---

* These six species make up HAA6. The other three HAA species should be reported if measured.

Sampling points are defined in Figure 6-1 and Table 6-2: $C_{F\text{-}sys}$ = system feed after prefiltration, $C_{p\text{-}sys}$ = system permeate, $C_{W\text{-}sys}$ = system waste, $C_{I\text{-}s(i)}$ = influent to stage i, and $C_{p\text{-}sys}$ = permeate from stage i

Table 6-17 Duplicate Analysis Of Membrane Pilot System Biweekly Water Quality Parameters For Week Twenty

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Parameter	Units	$C_{F\text{-}sys}$	$C_{p\text{-}sys}$	$C_{W\text{-}sys}$	$C_{I\text{-}s\ (1)}$	$C_{I\text{-}s\ (2)}$	$C_{p\text{-}s\ (1)}$	$C_{p\text{-}s\ (2)}$
Sampling date	MM/DD/YY							
Sampling time	hh:mm							
Alkalinity	mg $CaCO_3$ / L							
TDS	mg/L							
Total hardness	mg $CaCO_3$ / L							
Calcium hardness	mg $CaCO_3$ / L							
Bromide	µg/L			---	---	---	---	---
pH	---							
Turbidity	ntu							
Temperature	°C							
TOC	mg/L							
UV_{254}	cm^{-1}							
SDS samples				---	---	---	---	---
Chlorine dose	mg/L			---	---	---	---	---
Chlorine residual	mg/L			---	---	---	---	---
Chlorine demand	mg/L			---	---	---	---	---
Chlorination temp.	°C			---	---	---	---	---
Chlorination pH	---			---	---	---	---	---
Incubation time	hours			---	---	---	---	---
TOX	µg/L			---	---	---	---	---
$CHCl_3$	µg/L			---	---	---	---	---
$CHBrCl_2$	µg/L			---	---	---	---	---
$CHBr_2Cl$	µg/L			---	---	---	---	---
$CHBr_3$	µg/L			---	---	---	---	---
THM4	µg/L			---	---	---	---	---
*MCAA**	µg/L			---	---	---	---	---
*DCAA**	µg/L			---	---	---	---	---
*TCAA**	µg/L			---	---	---	---	---
*MBAA**	µg/L			---	---	---	---	---
*DBAA**	µg/L			---	---	---	---	---
*BCAA**	µg/L			---	---	---	---	---
TBAA	µg/L			---	---	---	---	---
CDBAA	µg/L			---	---	---	---	---
DCBAA	µg/L			---	---	---	---	---
HAA6	µg/L			---	---	---	---	---

* These six species make up HAA6. The other three HAA species should be reported if measured.

Sampling points are defined in Figure 6-1 and Table 6-2: $C_{F\text{-}sys}$ = system feed after prefiltration, $C_{p\text{-}sys}$ = system permeate, $C_{W\text{-}sys}$ = system waste, $C_{I\text{-}s(i)}$ = influent to stage i, and $C_{p\text{-}sys}$ = permeate from stage i

Table 6-18 Duplicate Analysis Of Membrane Pilot System Biweekly Water Quality Parameters For Week _____

Utility name and address _____

_____

ICR plant number _____ Phone # _____

Contact person _____ FAX # _____

Membrane trade name _____

Parameter	Units	$C_{F\text{-}sys}$	$C_{p\text{-}sys}$	$C_{W\text{-}sys}$	$C_{I\text{-}s\ (1)}$	$C_{I\text{-}s\ (2)}$	$C_{p\text{-}s\ (1)}$	$C_{p\text{-}s\ (2)}$
Sampling date	MM/DD/YY							
Sampling time	hh:mm							
Alkalinity	mg $CaCO_3$ / L							
TDS	mg/L							
Total hardness	mg $CaCO_3$ / L							
Calcium hardness	mg $CaCO_3$ / L							
Bromide	µg/L			---	---	---	---	---
pH	---							
Turbidity	ntu							
Temperature	°C							
TOC	mg/L							
UV_{254}	cm^{-1}							
SDS samples				---	---	---	---	---
Chlorine dose	mg/L			---	---	---	---	---
Chlorine residual	mg/L			---	---	---	---	---
Chlorine demand	mg/L			---	---	---	---	---
Chlorination temp.	°C			---	---	---	---	---
Chlorination pH	---			---	---	---	---	---
Incubation time	hours			---	---	---	---	---
TOX	µg/L			---	---	---	---	---
$CHCl_3$	µg/L			---	---	---	---	---
$CHBrCl_2$	µg/L			---	---	---	---	---
$CHBr_2Cl$	µg/L			---	---	---	---	---
$CHBr_3$	µg/L			---	---	---	---	---
THM4	µg/L			---	---	---	---	---
*MCAA**	µg/L			---	---	---	---	---
*DCAA**	µg/L			---	---	---	---	---
*TCAA**	µg/L			---	---	---	---	---
*MBAA**	µg/L			---	---	---	---	---
*DBAA**	µg/L			---	---	---	---	---
*BCAA**	µg/L			---	---	---	---	---
TBAA	µg/L			---	---	---	---	---
CDBAA	µg/L			---	---	---	---	---
DCBAA	µg/L			---	---	---	---	---
HAA6	µg/L			---	---	---	---	---

* These six species make up HAA6. The other three HAA species should be reported if measured.

Sampling points are defined in Figure 6-1 and Table 6-2: $C_{F\text{-}sys}$ = system feed after prefiltration, $C_{p\text{-}sys}$ = system permeate, $C_{W\text{-}sys}$ = system waste, $C_{I\text{-}s(i)}$ = influent to stage i, and $C_{p\text{-}sys}$ = permeate from stage i

Table 6-19a Blending Calculations To Determine The Fraction Of Flow That Requires NF Treatment To Meet The Stage I DBP Regulations

Utility name and address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____

	WEEK #				
Parameter	**2**	**4**	**6**	**8**	**...**
$THM4_F$, µg/L					
$THM4_p$, µg/L					
$HAA5_F$, µg/L					
$HAA5_p$, µg/L					
Alk_F, mg/L $CaCO_3$					
Alk_p, mg/L $CaCO_3$					
T-Hd_F, mg/L $CaCO_3$					
T-Hd_p, mg/L $CaCO_3$					
Ca-Hd_F, mg/L $CaCO_3$					
Ca-Hd_p, mg/L $CaCO_3$					

THM4 Controls

Q_p/Q_T (THM4), %					
Alk_b, mg/L $CaCO_3$					
T-Hd_b, mg/L $CaCO_3$					
Ca-Hd_b, mg/L CaCO3					
$THM4_b$, µg/L					
$HAA5_b$, µg/L					

HAA5 Controls

Q_p/Q_T (HAA5), %					
Alk_b, mg/L $CaCO_3$					
T-Hd_b, mg/L $CaCO_3$					
Ca-Hd_b, mg/L CaCO3					
$THM4_b$, µg/L					
$HAA5_b$, µg/L					

Notes: In the first section of this table, the feed and permeate concentrations are entered for each run. The spreadsheet uses these values to calculate the flow that must be treated to meet the stage I DBP MCLs with a 10% factor of safety (i.e.72/54 µg/L - THM4/HAA5). The higher of the two Q_p/Q_I flow ratios (i.e. permeate flow to total flow) based on either THM4 or HAA5 controls the design. The blended water quality parameters are also calculated for the feed / permeate blends. If the permeate quality does not meet the MCLs prior to blending, then these calculations are meaningless.

Table 6-19b Blending Calculations To Determine The Fraction Of Flow That Requires NF Treatment To Meet The Stage II DBP Regulations

Utility name and address _____ Phone number _____

_____ FAX number _____

ICR plant number _____ Contact person _____

Membrane trade name _____

	WEEK #				
Parameter	**2**	**4**	**6**	**8**	**...**
$THM4_F$, µg/L					
$THM4_p$, µg/L					
$HAA5_F$, µg/L					
$HAA5_p$, µg/L					
Alk_F, mg/L $CaCO_3$					
Alk_p, mg/L $CaCO_3$					
$T\text{-}Hd_F$, mg/L $CaCO_3$					
$T\text{-}Hd_p$, mg/L $CaCO_3$					
$Ca\text{-}Hd_F$, mg/L $CaCO_3$					
$Ca\text{-}Hd_p$, mg/L $CaCO_3$					

THM4 Controls

Q_p/Q_T (THM4), %					
Alk_b, mg/L $CaCO_3$					
$T\text{-}Hd_b$, mg/L $CaCO_3$					
$Ca\text{-}Hd_b$, mg/L CaCO3					
$THM4_b$, µg/L					
$HAA5_b$, µg/L					

HAA5 Controls

Q_p/Q_T (HAA5), %					
Alk_b, mg/L $CaCO_3$					
$T\text{-}Hd_b$, mg/L $CaCO_3$					
$Ca\text{-}Hd_b$, mg/L CaCO3					
$THM4_b$, µg/L					
$HAA5_b$, µg/L					

Notes: In the first section of this table, the feed and permeate concentrations are entered for each run. The spreadsheet uses these values to calculate the flow that must be treated to meet the stage II DBP MCLs with a 10% factor of safety (i.e.36/27 µg/L - THM4/HAA5). The higher of the two Q_p/Q_I flow ratios (i.e. permeate flow to total flow) based on either THM4 or HAA5 controls the design. The blended water quality parameters are also calculated for the feed / permeate blends. If the permeate quality does not meet the MCLs prior to blending, then these calculations are meaningless.

7.0 Cost Survey

The cost of a membrane system is generally divided into construction costs and operating and maintenance costs. The largest components of construction costs are the membranes, membrane skids and the building; and the largest components of O&M costs include electricity, labor, membrane replacement and chemical costs (Suratt, 1991). However, the cost of pretreatment and concentrate disposal can be significant components of both construction and O&M costs.

In order to develop an estimate of the cost of membrane treatment for the control of DBPs, the ICR requires the utility to provide estimates of several cost parameters. These parameters include design information such as the MTC_W, cleaning frequency and the permeate quality, and site-specific parameters such as the local cost of electricity and labor. Cost parameters must be provided for each membrane tested.

An assumption in this cost analysis is that a membrane process is being added to an existing treatment facility. Therefore, some of the cost parameters requested in this section may not be applicable. For example, some utilities may need to acquire additional land to construct a membrane facility, while others may be in possession of the required land. If a cost is not incurred, then zero (0) should be entered for that cost in the tables described in this section.

The design parameters necessary for the cost analysis will be obtained from bench- or pilot-scale membrane studies, and Table 7-1 lists these parameters along with example values. The "total required plant production" is the demand that must be met by the treatment plant. In a nanofiltration plant, the total production consist of the membrane train capacity and the flow that by-passes the membrane train. If by-pass is not used, then the total required plant capacity is equivalent to the membrane train capacity. It should be noted that the required feed flow rate to a membrane system is significantly higher than the membrane train capacity and can be calculated by dividing the membrane train capacity by the fractional recovery. The average THM4 and HAA5 permeate concentrations requested in Table 7-1 should be averaged over all of the data collected during the study for a specific membrane. The average plant feed water temperature should reflect the yearly average water temperature experienced in the full-scale plant. This average temperature is used to normalize the MTC_W to a common temperature. The average temperature-normalized MTC_W over the course of the study should be reported along with minimum and maximum values. The range of acceptable operating pressures for a specific membrane is also requested and will typically range from zero to the maximum allowable pressure. The cleaning frequency must be obtained from an analysis of the flux data collected over the study. The feed TDS and TDS rejection should be averaged over all of the data collected during the study for a specific membrane.

Table 7-2 lists estimates of the building area requirements for a membrane facility. More accurate site-specific information can be used to estimate the building area requirements if available. The estimated building area will be used as one of the construction cost estimate parameters listed in Table 7-3. In Table 7-2, the area estimates for the "membrane process

equipment," "electrical room," and "chemical rooms" are based on the membrane train capacity. Thus, the total area for each of these three rooms is calculated by multiplying the area estimate by the membrane train capacity. For example, the building area for the membrane process equipment for a 10 mgd membrane train would be 9500 ft^2. The area estimates for the other five rooms are independent of the membrane train capacity, and the area for the generator room would be 400 ft^2 for either a 10 or a 20 mgd plant.

The information required to make a construction cost estimate is listed in Table 7-3, and the information required to make an O&M cost estimate is listed in Table 7-4. Example values are included in these tables and should only be used as default values if site-specific estimates are unavailable. As stated earlier, if a cost is not incurred then zero (0) should be entered for that cost. The last item in Table 7-3 asks if odor control would be required for the product water. In most cases, odor in membrane permeate is due to hydrogen sulfide which would need to be stripped from the product prior to distribution.

The costs associated with chemicals must be estimated to develop an accurate O&M cost projection. Table 7-5 requests information on chemicals used specifically for membrane processes and the associated costs and dosages. Chemicals used in membrane processes include pretreatment and post-treatment chemicals as well as cleaning agents. The cost of chlorine is also requested since the low chlorine demand of membrane permeate can result in a significantly lower dose.

The cost of membrane pretreatment and concentrate disposal can be substantial additions to the cost of a membrane plant. However, due to the variety of pretreatment and concentrate disposal processes, it is impossible to generate a set of standard cost parameters. For the purpose of the ICR, the plant is asked to report a pretreatment scheme and concentrate disposal method which could be used at the specific plant. An example of a pretreatment scheme and concentrate disposal method is shown in Table 7-6. In this example, pretreatment consists of enhanced coagulation with a 50 mg/L increase in the alum dose along with cartridge filtration and acid addition to a pH of 4.0, and the concentrate stream is assumed to have a low TDS concentration <1500 mg/L and can be discharged to the local sewer system at a cost of $0.50 per 1000 gallons. If more accurate cost data for pretreatment and concentrate disposal is available, then it should be provided to EPA.

Table 7-1 Design Parameters For Cost Analysis

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Membrane trade name _____ Manufacturer _____

Design Parameter	Example values	Specific utility values
Total required plant production (mgd)	10	
Permeate to total flow ratio	0.8	
By-pass flow rate (mgd)	2	
Required membrane train capacity (mgd)	8	
Average THM4 permeate concentration (µg/L)	21	
Average HAA5 permeate concentration (µg/L)	9	
Average THM4 feed concentration (µg/L)	102	
Average HAA5 feed concentration (µg/L)	90	
Average plant feed water temperature (°C)	18.3	
Average temperature-normalized MTC_W (gfd/psi)	0.18	
Maximum temperature-normalized MTC_W (gfd/psi)	0.25	
Minimum temperature-normalized MTC_W (gfd/psi)	0.16	
Range of acceptable operating pressures (psi)	0 to 225	
Average cleaning frequency (days)	60	
Average feed TDS (mg/L)	150	
Average TDS rejection (%)	30	

Table 7-2 Estimated Building Area Requirements

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Membrane trade name _____ Manufacturer _____

Building area	Area estimate	Total area
Membrane process equipment (ft^2 per mgd)	950	
Electrical room (ft^2 per mgd)	125	
Chemical rooms (ft^2 per mgd)	175	
Control room (ft^2)	350	
Generator (ft^2)	400	
Transformer vault (ft^2)	500	
Offices and reception (ft^2)	variable	
Bathrooms (ft^2)	250	

Table 7-3 Construction Cost Information

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Membrane trade name _____ Manufacturer _____

Cost Parameter	Example values	Specific utility values
Capital recovery interest rate (%)	10	
Capital recovery period (years)	20	
Overhead and profit factor (% of construction cost)	5	
Special site-work factor (% of construction cost)	5	
Construction contingencies (% of construction cost)	10	
Engineering fee factor (% of construction cost)	10	
Contract mobilization, insurance and bonds (% of construction costs)	5	
ENR construction cost index (CCI base year 1913) (date)	4965 (May 92)	
Producers price index (PPI base year 1967 = 100) (date)	326 (May 92)	
Building area requirements (ft^2), from Table 7-2	14,500	
Building costs ($/ft^2$)	100	
Land area requirements (ft^2)	20,000	
Land costs ($/ft^2$)	0	
Cost of a standard 8"x 40" membrane element ($)	1000	
Area of a standard 8"x 40" membrane element (ft^2)	400	
Would sulfide concentrations necessitate odor control (yes / no)	---	

Table 7-4 O&M Cost Information

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Membrane trade name _____ Manufacturer _____

Cost Parameter	Example values	Specific utility values
Labor rate + fringe ($/personnel-hour)	15	
Labor overhead factor (% of labor)	10	
Number of O&M personnel hours per week	80	
Electric rate ($/kWh)	0.086	
Membrane replacement frequency (%/year)	12	
SDS chlorine demand of membrane feed (mg/L)	8.0	
SDS chlorine demand of membrane permeate (mg/L)	1.5	

Table 7-5 Cost And Dose For Chemicals Required For Membrane Treatment

Utility name and address _____

_____

ICR plant number _____ Contact person _____

Phone number _____ FAX number _____

Membrane trade name _____ Manufacturer _____

Chemical[1]	Use for chemical	Chemical dose	Bulk chemical cost
Chlorine	Disinfectant		
Sulfuric acid	Pretreatment		
Alum	Pretreatment		
Hydrochloric acid	Pretreatment		
Antiscalant[2]	Pretreatment		
Caustic	Post-treatment		
Sodium Hydroxide	Membrane cleaning		
Phosphoric acid	Membrane cleaning		

1: Information for cleaning chemicals and pretreatment chemicals (such as alum) should also be provided in this table. For cleaning agents, the concentration of the cleaning solution used to clean the membranes should be reported as the chemical dose.

2: Report the product name and manufacturer of the specific antiscalant used.

Table 7-6 Example Pretreatment Scheme And Concentrate Disposal Method

Pretreatment scheme
Conventional treatment train in existing plant (process data supplied separately)
50 mg/L increase in the alum dose during coagulation
5 um cartridge filtration
5 mL/gal of concentrated sulfuric acid to adjust the pH of the feed stream to 4.0

Concentrate disposal method
Discharge low TDS concentrate to local sewer at a cost of $0.50 per 1000 gallons

8.0 References

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Appendix 3-A

Water Quality Prediction For Multi-Stage Systems

Define:

(1) Rej_{TDS} = TDS rejection per element.
(2) $TDS_P = TDS_I \times (1-Rej_{TDS})$
(3) R = System recovery = Q_P/Q_F
(4) r = Recycle ratio = Q_R/Q_F
(5) N_e = Number of elements per pressure vessel.
(6) $N_{v\text{-}s(i)}$ = Number of pressure vessels per stage (i through j), $N_{v\text{-}s(0)}=0$.
(7) R_e = recovery for each element $= \dfrac{R}{N_e \sum_{i=1}^{j} N_{v\text{-}s_i}}$
(8) $TDS_I = TDS_{w(0)}$ = Feed water quality into first stage.

(1) Final Concentration Quality

$$TDS_w = \frac{A}{1+r(1-A)} TDS_F \tag{1}$$

where,

$$A = \prod_{i=1}^{i=j} \prod_{k=1}^{k=Ne} \left[\frac{\left[\left(1 + r - N_e R_e \sum_{i=1}^{j} N_{v-s_{i-1}} \right) / N_{v-s_i} \right] - kR_e + R_e \times Re\, j_{TDS}}{\left[\left(1 + r - N_e R_e \sum_{i=1}^{j} N_{v-s_{i-1}} \right) / N_{v-s_i} \right] - kR_e} \right] \tag{2}$$

(2) Final Permeate Quality

$$TDS_p = \left[TDS_F - \left(1 - N_e R_e \sum_{i=1}^{j} N_{v-s_i} \right) TDS_w \right] / \left(N_e R_e \sum_{i=1}^{j} N_{v-s_i} \right) \tag{3}$$

or

$$TDS_p = \frac{TDS_F - (1-R)TDS_w}{R} \tag{4}$$

(3) Feed Water Quality

$$TDS_I = \frac{1}{1+r} TDS_F + \frac{r}{1+r} TDS_w \tag{5}$$

(4) Water Quality in each stage

(a) Concentration

$$TDS_{w(i)} = B \times TDS_{w(i-1)} \tag{6}$$

where,

$$B = \prod_{k=1}^{k=Nc} \left[\frac{\left[\left(1 + r - N_e R_e \sum_{i=1}^{j} N_{v-s_{i-1}} \right) / N_{v-s_i} \right] - kR_e + R_e \times Re\, j_{TDS}}{\left[\left(1 + r - N_e R_e \sum_{i=1}^{j} N_{v-s_{i-1}} \right) / N_{v-s_i} \right] - kR_e} \right] \tag{7}$$

(b) Permeate

$$TDS_{p(i)} = \frac{\left(\left(1 + r - N_e R_e \sum_{i=1}^{j} N_{v-s_{i-1}} \right) / N_{v-s_i} \right) TDS_{w(i-1)}}{N_e R_e} - \frac{\left(\left(1 + r - N_e R_e \sum_{i=1}^{j} N_{v-s_{i-1}} \right) / N_{v-s_i} - N_e R_e \right) TDS_{w(i)}}{N_e R_e} \tag{8}$$

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