INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

UNIVERSITY OF CALIFORNIA

Los Angeles

Biodegradable Dissolved Organic Carbon (BDOC) for Characterizing Reclaimed and Treated Wastewaters: Method Development and Applications

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Civil Engineering

by

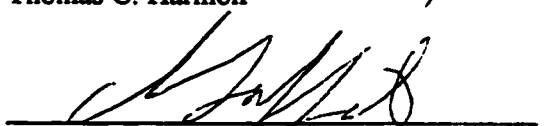
Eakalak Khan

1997

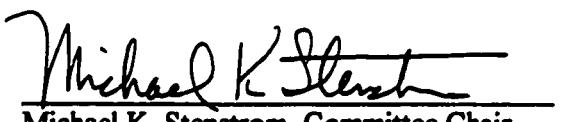
The dissertation of Eakalak Khan is approved.

Menachem Elimelech

Thomas C. Harmon



Irwin H. Suffet



Michael K. Stenstrom, Committee Chair

University of California, Los Angeles

1997

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Michael Stenstrom, for his guidance, advice, and support throughout my study at UCLA. Gratitude is also extended to Dr. Roger Babcock and the members of my committee, Dr. Menachem Elimelech, Dr. Thomas Harmon, and Dr. Mel Suffet, for their valuable comments and suggestions.

I wish to thank the Ahmanson Foundation for providing partial financial support of my research. Appreciation is also conveyed to Mrs. Parivash Dezham, Mr. John Major, Mr. Dan Fooley, Mr. Dan Pierce, Mrs. Jacky Gamble, Mrs. Debra Bolding, Mrs. Michelle Fitzgerald, Ms. Jinny McGeorge, Mr. Mark Pettit, Mrs. Mary Snyder, Mr. Matthew Grieger, and Mr. James Chen for helping me with the sample collection at their wastewater treatment plants. I wish to thank Dr. Kapal Madireddi and Mr. Bruno Levine for collecting and transporting the samples from the Lake Arrowhead pilot plant to UCLA, and Mr. Edward Ruth for his suggestions on some experimental problems I encountered.

I would like to express my deep appreciation to Sarunyu for his assistance on the secondary effluent experiment in Chapter 3, Van for his help during the ozonation experiment in Chapter 4, Farah and Golf for their patience, understanding, assistance on glassware cleaning, and especially dinner services whenever I worked late.

I am most grateful to the moral and occasional financial support of my parents, Jeff and Pia Khan, during my study at UCLA.

VITA

August 20, 1968	Born, Chiang Mai, Thailand
1990	B. Eng., Environmental Engineering Chiang Mai University Chiang Mai, Thailand
1990	Civil and Sanitary Engineer Envirtech Co. Ltd. Bangkok, Thailand
1991-1992	Research Assistant Department of Agricultural Engineering University of Hawaii Honolulu, Hawaii
1993	M.S., Agricultural Engineering University of Hawaii Honolulu, Hawaii
1993	Junior Specialist and Pilot Operator Department of Agricultural Engineering University of Hawaii Honolulu, Hawaii
1994	M.S., Civil Engineering University of California, Los Angeles
1994-1997	Research Assistant Department of Civil and Environmental Engineering University of California, Los Angeles

PUBLICATIONS AND PRESENTATIONS

Khan, E., Babcock, R. W., Suffet, I. H., and Stenstrom, M. K. Method Development for Measuring Biodegradable Organic Carbon in Reclaimed and Treated Wastewaters. *Accepted for publication in Water Environ. Res.*.

Khan, E., Babcock, R. W., Viriyavejakul, S., Suffet, I. H., and Stenstrom, M. K. Biodegradable Dissolved Organic Carbon (BDOC) for Indicating Wastewater Reclamation Plant Performance and Treated Wastewater Quality. *Accepted for publication in Water Environ. Res.*.

Khan, E., Stenstrom, M. K., Babcock, R. W., and Suffet, I. H. (1996) Biodegradable Organic Carbon for Characterizing Reclaimed and Treated Wastewaters. In *Proc. 69th Annual Water Environment Federation Conf. & Exp.*, Oct. 5-9, 1996, Dallas, TX. Water Environment Federation, Paper # 9668003, Vol. 4, pp. 617-628.

Khan, E., Stenstrom, M. K., Babcock, R. W., and Suffet, I. H. Biodegradable Organic Carbon for Characterizing Reclaimed and Treated Wastewaters, Presented at the *69th Annual Water Environment Federation Conf. & Exp.*, Oct. 5-9, 1996, Dallas, TX.

Khan, E., Stenstrom, M. K., and Suffet, I. H. (1996) Development of the Biodegradable Dissolved Organic Carbon Method for Characterizing Reclaimed Waters. In *Proc. 4th International Biodegradable Organic Matter Conf.*, June 19-21, 1996, Waterloo, Canada. International Working Group on Biodegradable Organic Matter in Drinking Water, pp. 37-40.

Khan, E., Stenstrom, M. K., and Suffet, I. H. Development of the Biodegradable Dissolved Organic Carbon Method for Characterizing Reclaimed Waters, Presented at the *4th International Biodegradable Organic Matter Conf.*, June 19-21, 1996, Waterloo, Canada. (read by I. H. Suffet)

Khan, E., Suffet, I. H., Levine, B. B., Madireddi, K., Babcock, R. W., and Stenstrom, M. K. Evaluation of Natural Organic Matter Removal at a Water Reuse Pilot Plant, Presented at the *University of California Water Reuse Research Program Conf.*, June 5-6, 1997, Monterey, CA.

Khan, E., Suffet, I. H., Levine, B. B., Madireddi, K., Babcock, R. W., and Stenstrom, M. K. (1996) Evaluation of Natural Organic Matter Removal by TOC, DOC, UV_{254}, BDOC, and Ultimate Soluble BOD at a Water Reuse Pilot Plant. In *Proc. Natural Organic Matter Workshop*, Sept. 18-19, 1996, Poitiers, France. International Water Supply Association (IWSA), Paper # 23, pp. 1-5.

Khan, E., Suffet, I. H., Levine, B. B., Madireddi, K., Babcock, R. W., and Stenstrom, M. K. Evaluation of Natural Organic Matter Removal by TOC, DOC, UV_{254}, BDOC, and Ultimate Soluble BOD at a Water Reuse Pilot Plant, Presented at the *Natural Organic Matter Workshop*, Sept. 18-19, 1996, Poitiers, France. (read by I. H. Suffet)

Khan, E., Yang, P. Y., and Kinoshita, C. M. (1994) Bioethanol Production from Dilute Feedstock. *Biores. Tech.*, **47**(1), pp. 29-36.

Levine, B. B., Madireddi, K., Khan, E., Stenstrom, M. K., Ye, Q. F., and Suffet, I. H. (1997) Treatment of Trace Organic Compounds by Ozone/BAC for Wastewater Reuse: The Lake Arrowhead Pilot Plant. In *Proc. Specialty Conference Series on Beneficial Reuse of Water and Solids*, April, 1997, Maebella, Malaga, Spain. Environmental Federation.

Levine, B. B., Madireddi, K., Khan, E., Stenstrom, M. K., Ye, Q. F., and Suffet, I. H. Treatment of Trace Organic Compounds by Ozone/BAC for Wastewater Reuse: The Lake Arrowhead Pilot Plant, Presented at the *Specialty Conference Series on Beneficial Reuse of Water and Solids*, April, 1997, Maebella, Malaga, Spain. (read by B. B. Levine)

Madireddi, K., Babcock, R. W., Levine, B. B., Huo, T. L., Khan, E., Ye, Q. F., Suffet, I. H., Neethling, J. B., and Stenstrom, M. K. (1997) Wastewater Reclamation at Lake Arrowhead, California: An Overview. *Water Environ. Res.*, **69**(3), pp. 350-362.

Yang, P. Y., Khan, E., Gan, C., Paquin, D. G., and Liang, T. (1997) A Prototype Small Swine Waste Treatment System for Land Limited and Tropical Application. *Water Sci. and Tech.*, **35**(6), pp. 145-152.

Yang, P. Y., Khan, E., Gan, C., Paquin, D. G., and Liang, T. (1994) A Prototype Animal Waste Treatment System in Hawaii. In *Proc. American Society of Agricultural Engineers International Summer Meeting*, June 19-22, 1994, Kansas City, MO. American Society of Agricultural Engineers (ASAE), St. Joseph, MI.

Yang, P. Y., Khan, E., Gan, C., Paquin, D. G., and Liang, T. A Prototype Animal Waste Treatment System in Hawaii, Presented at the *American Society of Agricultural Engineers International Summer Meeting*, June 19-22, 1994, Kansas City, MO. (read by P. Y. Yang)

ABSTRACT OF THE DISSERTATION

Biodegradable Dissolved Organic Carbon (BDOC)

for Characterizing Reclaimed and Treated Wastewaters:

Method Development and Applications

by

Eakalak Khan

Doctor of Philosophy in Civil Engineering

University of California, Los Angeles, 1997

Professor Michael K. Stenstrom, Chair

Analyses that measure oxygen demand, such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD), have long been used as indicators of contamination and wastewater treatment plant efficiency. They measure the tendency of pollutants to react with oxygen, which is usually a good indicator of water quality or level of treatment. Both parameters include reactions with organic as well as inorganic substances and suffer from a lack of precision and accuracy at low concentrations, which are becoming increasingly more important.

Biodegradable dissolved organic carbon (BDOC) is a relatively new procedure which has advantages over both BOD and COD analyses, including insensitivity to

inorganic oxidations. A modified BDOC procedure was developed to characterize the performance of advanced treatment methods, such as those used in municipal water reclamation, and secondary treated wastewaters, where moderately low dissolved organic carbon (DOC) concentrations (4 to 15 mg/L) are routinely encountered. The development of the modified BDOC procedure is based on a combination of a novel BDOC batch procedure utilized in drinking water treatment and the classical biochemical oxygen demand (BOD) technique used in wastewater treatment. The modified BDOC method was able to detect the increase in biodegradability of ozonated tertiary treated wastewater and to indicate secondary effluent quality. The procedure has reduced variability and increased precision as compared to BOD and COD. Employing a large volume of concentrated inoculum, such as mixed liquor suspended solids, the incubation time can be reduced from 28 days to 5 days and the simultaneous determinations of BDOC and soluble BOD_5 are possible. With adequate further studies, the BDOC procedure using the concentrated inoculum can be proposed as a standard method.

1.0 INTRODUCTION

1.1 Overview of the Problem

Removal of organic contaminants is a primary goal of both water and wastewater treatment. Traditional methods of evaluating treatment efficiency measure the tendency of the contaminants to react with oxygen. Biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total oxygen demand (TOD) have all been used. Organic carbon is frequently one of the main components of the contaminants, and for this reason total organic carbon (TOC) removal is sometimes used as a primary indicator of treatment plant efficiency.

All four measurements have advantages and disadvantages. BOD provides the best estimate of the reactivity of the contaminants in the natural environment, but is insensitive and imprecise at low concentrations. COD provides no indication of biodegradability, and has limited precision and accuracy below 5 mg/L (*Standard Methods*, 1989). The COD procedure also uses toxic reagents and produces hazardous wastes.

The presence of certain contaminants or conditions interfere with BOD, COD, and TOD analyses. The BOD test measures the presence of both carbonaceous and nitrogenous oxygen demands, which are becoming known as CBOD and NBOD.

Sometimes it is desirable to have one analysis measure both demands, but more often separate measurement of the demands is preferred (Albertson, 1995). The COD test does not completely oxidize some ring organics such as pyridine and related compounds, and is subject to interference at high chloride concentrations (*Standard Methods*, 1989). The TOD procedure is an instrumental method that combusts the sample and provides complete oxidation and very rapid response. Unfortunately, if nitrate is present in the sample it will produce a false reading when some is reduced to nitrite or other nitrous oxides. The indicated TOD is sometimes negative for samples with low oxygen demand and high nitrate concentrations. TOC is a very rapid procedure with low detection limits (between 0.05 to 0.10 mg/L) and excellent precision, and has fewer of the previously cited disadvantages. Therefore, it is frequently used as an indicator of contaminants in potable waters as well as reclaimed and treated wastewaters. Its primary disadvantage is that it provides no indication of the biodegradability of the contaminants.

1.2 Objectives

The first objective of this research is to develop a reliable and sensitive procedure for measuring biologically reactive organics in waters containing moderate dissolved organic carbon (DOC) concentrations such as reclaimed and secondary treated wastewaters (DOC = 4 to 15 mg/L). The second objective is to demonstrate the utility of the new procedure. A new procedure is needed for use in evaluating the performance of

biological activated carbon (ozone/granular activated carbon) systems in wastewater reclamation plants. A protocol is also needed to evaluate the performance of optimized secondary treatment plants. BOD is too insensitive and imprecise to indicate and/or differentiate the quality of effluents from these plants.

1.3 Dissertation Organization

This dissertation is divided into 5 chapters. Chapter 2 mainly describes how the new procedure was developed. It includes the protocol procedure and different aspects of the protocol such as filter type used, detection limit, precision, accuracy, inoculum origin and size, inoculum filtration, agitation of samples, incubation temperature, and kinetics. Chapter 3 presents the applications of the new procedure to reclaimed and secondary treated wastewaters. It demonstrates how the protocol can be used to evaluate the performance of a biological activated carbon system at a wastewater reuse pilot facility and the quality of secondary effluents. Portions of Chapter 2 and Chapter 3 have been accepted for publication as a two paper series in the *Water Environment Research Journal*. Chapter 4 discusses the use of a larger and more concentrated inoculum to remove the disadvantages of the new procedure so that it can be routinely used at wastewater treatment and reclamation facilities. Part of the material in Chapter 4 will be submitted for review and possible publication in the *Journal of Environmental Engineering (ASCE)*. Conclusions and recommendations for future work are presented in

Chapter 5. It should be noted that there is ongoing collaborative research with investigators at the University of Hawaii. The results from the collaboration are not presented in this dissertation but will be included in the manuscript which will be submitted for review and possible publication in the *Water Environment Research Journal*.

2.0 METHOD DEVELOPMENT

2.1 Background

In 1987, Servais *et al.* introduced a new parameter called biodegradable dissolved organic carbon (BDOC). Huck (1990) defined BDOC as the portion of organic carbon in water that can be metabolized by heterotrophic microorganisms. Besides causing taste, odor, and color in water, BDOC can react with some disinfectants to form undesirable products. BDOC can also be a problem in drinking water by inducing regrowth in the distribution system, which inhibits or defeats disinfection.

Servais *et al.* (1989) suggested a batch protocol for determining BDOC in drinking water. A schematic diagram of the protocol procedure is presented in Figure 1. They filtered 200 mL of the sample using a 0.22 μm membrane filter that had been previously conditioned by washing with distilled water and the sample, respectively. They used a 2 mL inoculum created by filtering a portion of the sample through a 2 μm filter to remove protozoans. This inoculum should be well acclimated to the organic compounds in the sample. They incubated the sample in the dark at 20°C for 28 days and calculated the BDOC from the difference between the initial and final DOCs.

Their BDOC protocol is a bioassay test similar to the BOD test. Biodegradation in the environment is simulated by using an inoculum collected from the same location as the

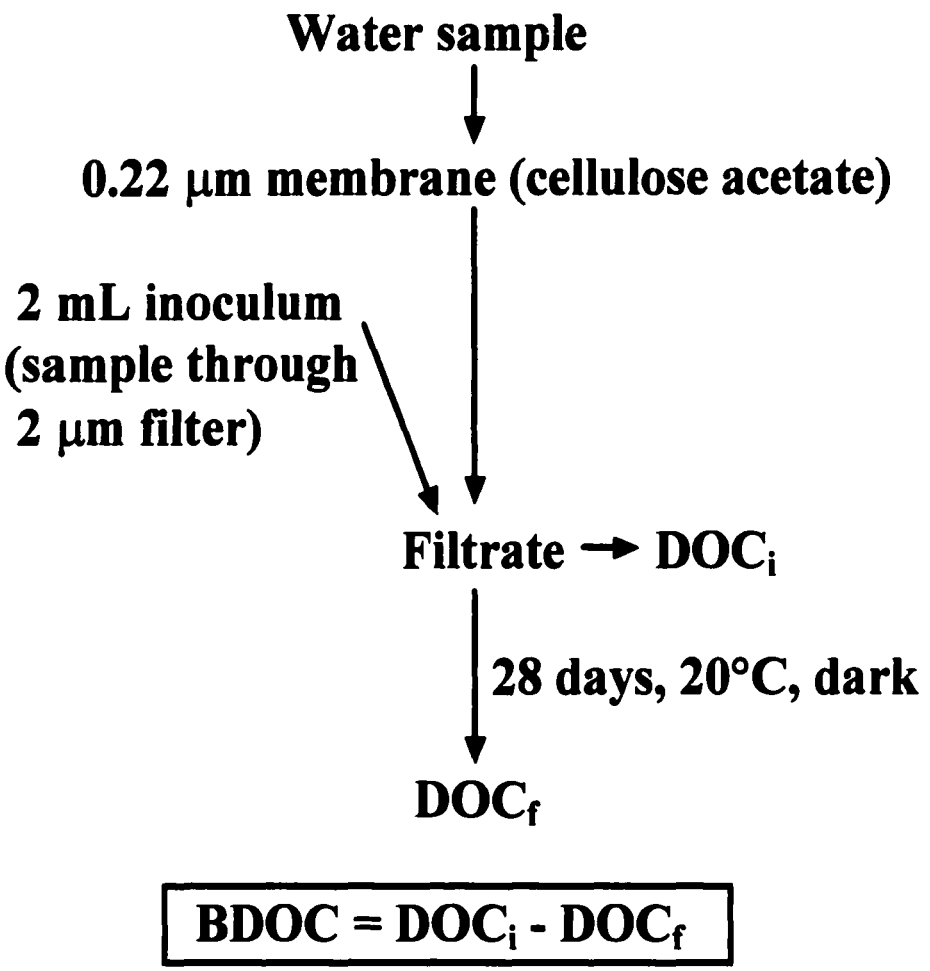


Figure 1 Schematic diagram of the original batch BDOC procedure by Servais *et al.* (1989).

sample. The method measures the amount of organic carbon used for both cell synthesis and respiration. Hence, BDOC could be suitable for monitoring the effectiveness of biological treatments. Servais *et al.* (1987) also proposed bacteria biomass and mortality measurements during the incubation for determination of BDOC (instead of DOC reduction). Although the biomass and mortality approach is more sensitive, it is not widely used because it is more time consuming and requires more complicated techniques.

An alternative to the BDOC procedure called assimilable organic carbon (AOC), was invented by van der Kooij *et al.* (1982). AOC is the portion of the organic carbon that can be synthesized to cellular material by a single bacterial strain. In the AOC determination method, a preheated water sample is seeded with a pure strain of *Pseudomonas fluorescens* P17. The sample is incubated at 15°C, and bacterial growth is monitored daily by colony counts (spread plate techniques) until the maximum growth is reached. The incubation period (the number of days to reach the maximum yield) can be from 3 to 30 days depending on the type of the water sample. By concurrently determining the growth yield of bacteria in solutions of known acetate concentration, the maximum growth can be converted into AOC and expressed as μg of acetate-C equivalents/L.

van der Kooij (1987) and van der Kooij *et al.* (1989) included a *Spirillum* strain, NOX, into the procedure as an alternative seed or a dual strain seed due to the inability of *Pseudomonas fluorescens* P17 to metabolize oxalic acid, which is one of the products frequently formed during ozonation. Kemmy *et al.* (1989) attempted to measure AOC

using an inoculum of four specially selected bacterial species: *Pseudomonas fluorescens*, a *Curtobacterium sp.*, a *Corynebacterium sp.*, and an unidentified corenyform. Unreliable and unexplainable results were occasionally obtained; AOC values were greater than DOC values, which is not possible. Thus, the method has not been frequently used.

Unlike BDOC, AOC only accounts for the organic carbon used for cell synthesis. Since the AOC test measures cell growth of a single or dual strain, the test does not guarantee that all the assimilable carbon is measured. The inoculum may not be capable of metabolizing all contaminants. Therefore, the reported AOC value is normally less than the reported BDOC value for the same sample. The AOC method has been widely adopted when the bacterial regrowth is a concern. For reclaimed and secondary treated wastewaters, where a large variety of compounds may be present, an acclimated, mixed culture inoculum should provide a better indication of the degradable organic carbon than any single or dual strains.

In order to shorten the BDOC determination period, Lucena *et al.* (1990), Mogren *et al.* (1990), Ribas *et al.* (1991), Frias *et al.* (1992), and Kaplan and Newbold (1995) introduced dynamic reactors for BDOC measurement. A glass column reactor was filled with an inert support media (filter sand or glass balls) where high concentrations of microorganisms responsible for DOC consumption are attached. When the amount of sample is limited, the discrete sample is pumped and recirculated across the column and the reduction of DOC in a period of 5 days is taken as BDOC (Mogren *et al.*, 1990 and Frias *et al.*, 1992). In the other methods which require a large amount of sample (Lucena

et al., 1990, Ribas *et al.*, 1991, and Kaplan and Newbold, 1995), the sample is continuously passed through the column (once through system) and the BDOC value can be calculated from the difference between the DOC of the inlet and outlet samples. This approach reduced the measurement time to about 2 to 3 hours. However, the major weaknesses of both approaches are the difficulty in standardizing the method and a long start-up period.

In the wastewater treatment field, Hiser and Busch (1964) introduced a test similar to BDOC for soluble wastes, called total biological oxygen demand (T_bOD). The test measures the reduction of chemical oxygen demand (ΔCOD) as a function of time in a batch system. Gaudy (1972) suggested that the concept of ΔCOD can be extended to continuous flow systems for biological treatment design and operation, and water quality assessment. Gaudy and Gaudy (1988) later stated that not only the ΔCOD but the reduction of total organic carbon (ΔTOC) can also be used as a tool in a bioassay to quantify the amount of the organic matter that can be metabolized by acclimated microorganisms; however, the concept did not receive wide spread acceptance.

As a consequence, the batch BDOC method is relatively unknown in the wastewater treatment field. Its application is limited to water samples with low dissolved organic carbon (DOC $<$ 4 mg/L) because of dissolved oxygen (DO) consumption limitation during the incubation (unless samples are diluted). The DO concentration at the end of the incubation period should be sufficiently high (generally $\geq$ 1.0 mg/L) so that it is never rate limiting.

2.2 Methodology

2.2.1 Protocol

A modified batch BDOC protocol was developed using a combination of the original batch BDOC protocol (Servais *et al.*, 1989) and BOD techniques. It was expected that the modified BDOC protocol can determine DOC, BDOC, and soluble BOD (SBOD), simultaneously. Figure 2 illustrates a diagram of the modified batch BDOC procedure. The water sample was filtered through a 0.7 μm glass fiber filter (GF/F, Whatman) previously rinsed with 300 mL of deionized (DI) water which had TOC less than 0.20 mg/L. The filtrate was analyzed for TOC, and reported as DOC. A dilution factor, F, was calculated to insure that adequate DO (DO ≥ 1.0 mg/L) remains at the end of the test. Several trials or multiple dilutions may be required for samples with unknown DOCs or BODs. The dilutions were made with DI water having a known TOC of less than 0.20 mg/L to produce at least 320 mL of combined volume, and placed in a washed container with at least 20% gas volume. The mixture was saturated with DO by shaking. After shaking, a 20 mL sample was collected, measured for TOC, and recorded as DOC_i. The mixture was next placed in a washed BOD bottle. The DO was measured with a washed probe (to prevent sample contamination), and recorded as DO_i. A 2 mL inoculum of unfiltered water sample was then added. The inoculum should contain microorganisms present in the environment where the sample was collected or other acclimated organisms. The bottle was water sealed and incubated in the dark without shaking at 20 ± 0.5°C for

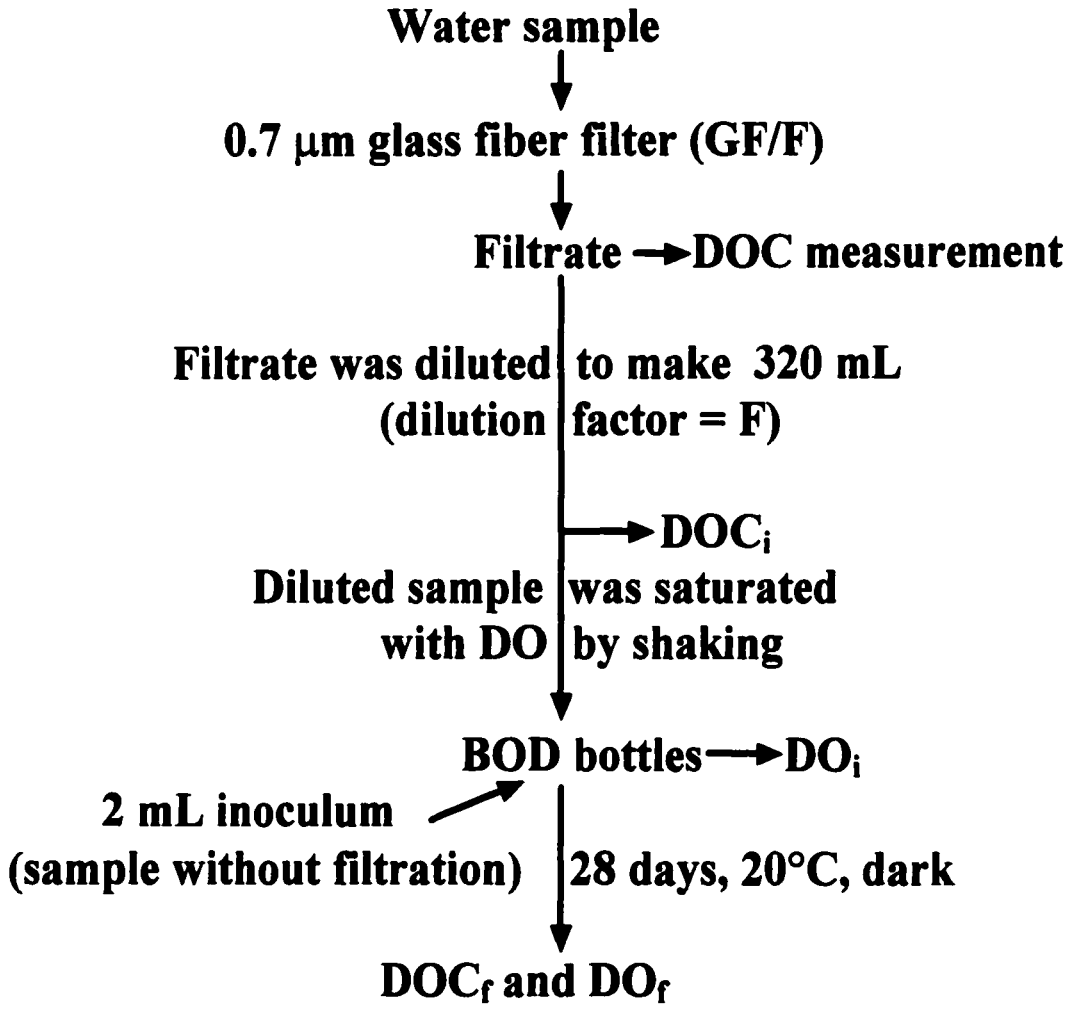


Figure 2 Schematic diagram of the modified batch BDOC procedure.

28 days. At the end of the incubation, the DO was measured and recorded as DO_f. Next, 20 mL of the supernatant were collected and measured for TOC directly without any filtration, and recorded as DOC_f. A seed control (sample b) was prepared in the same way except that the 2 mL seed was added to 300 mL of dilution water with no sample, and the values were recorded as DO_{bi}, DOC_{bi}, DO_{bf}, and DOC_{bf}, respectively. BDOC and ultimate SBOD ($SBOD_u$) were calculated using the following equations:

$$BDOC\ (mg/L) = \left[\left(DOC_i - DOC_f\right) - \left(DOC_{bi} - DOC_{bf}\right)\right]F \qquad (1)$$

$$SBOD_u\ (mg/L) = \left[\left(DO_i - DO_f\right) - \left(DO_{bi} - DO_{bf}\right)\right]F \qquad (2)$$

where $F = \dfrac{(mL\ of\ dilution\ water + mL\ of\ sample)}{mL\ of\ sample}$,

observing the criteria of (DO_i - DO_f) ≥ 2 mg/L and DO_f ≥ 1 mg/L (*Standard Methods*, 1989).

When the 5-day SBOD ($SBOD_5$) was of more interest than $SBOD_u$ such as in secondary effluent samples, the DOs of both sample and seed control were measured after 5 days of incubation and recorded as DO_5 and DO_{b5}. $SBOD_5$ was calculated by substituting DO_5 and DO_{b5} (instead of DO_f and DO_{bf}) in Equation (2). For BDOC determination, after the DO measurement, 100 mL of the mixture was discarded and the mixture was resaturated with DO by shaking. The incubation was continued for 23 days

(total incubation period of 28 days). During the second incubation period, the DO in the mixture was recharged by shaking the bottle daily. This insures adequate DO if nitrification occurs. The above procedure for simultaneous SBOD determination is general. Some other techniques such as dilution water check and preparation, sample storage, and sample dechlorination or deozonation, if required, should be incorporated and performed as described in *Standard Methods* (1989).

The modified BDOC protocol presented above is different from the original batch protocol in many aspects. It was eventually developed from the original procedure after several series of experiments to identify problems and sources of error. The type of filter used for DOC determination was changed from 0.22 μm cellulose acetate (CA) membrane filter to 0.7 μm glass fiber filter. It was found that the CA membrane releases a substantial amount of organic carbon. The leaching of organic carbon from the CA membrane was studied in detail and the results are described and discussed in the results and discussion section of this chapter. A BOD bottle was used for incubation. Both BOD bottles and glass fiber filters are standard equipment in water quality laboratories. The seed employed in the modified protocol was not filtered in order to maintain the similarities in microbial types and activities between the actual environment and the incubation. As a result, the seed should contain both heterotrophic bacteria and protozoans. DO was measured before and after the incubation to determine SBOD and to confirm its adequacy throughout the incubation period. The dilution and seed control were incorporated to

make the protocol workable with moderately high DOC waters and to produce more accurate results.

2.2.2 DOC and DO measurements.

DOC was measured with a Dohrmann Total Organic Carbon Analyzer model DC-80 (Xertex Corporation, Santa Clara, CA) using ultraviolet promoted persulfate oxidation and infrared spectrometry. The analyzer was calibrated daily using 10 mg TOC/L potassium hydrogen phthalate (KHP) standard solution and the multiple point calibration procedure recommended by the manufacturer. The analyzer has a useful range of 0.10 to 20.00 mg/L (limit of quantitation to limit of linearity) and a detection limit of 0.04 mg/L for a sample size of 1 mL. The mean value of three DOC measurements was reported. DO was measured using a YSI 58 DO Meter and a YSI 5720 DO Probe (Yellow Springs Instrument Co., Inc., Yellow Springs, OH).

2.3 Results and Discussion

The original BDOC procedure (Servais *et al.*, 1989) was first used to measure BDOC of the effluent samples from the sand filter, the primary ozonation columns (5 columns), and the biological activated carbon (BAC) filter of the Lake Arrowhead wastewater reclamation pilot plant (Madireddi *et al.*, 1997). A schematic diagram of the pilot plant is shown in Figure 3. Problems and inconsistent BDOC results were obtained

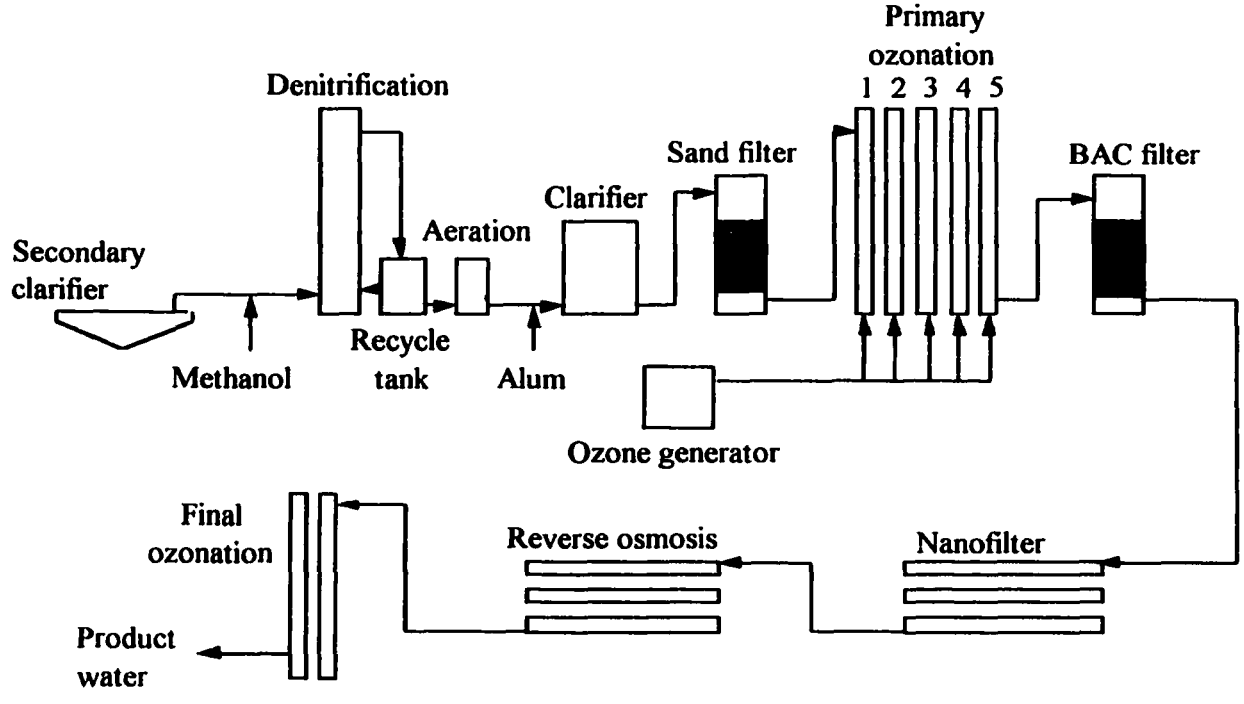


Figure 3 Lake Arrowhead reclamation pilot plant schematic.

using the original procedure. To identify the problems and sources of error, various aspects of the original protocol were evaluated and modified. The main modification is the inclusion of the dilution and/or DO recharge (shaking) techniques to avoid oxygen depletion during the incubation. The filter type, inoculum origin and size, and inoculum filtration (after incubation) were all investigated. Control experiments using prepared samples containing known compounds (dextrose and sodium acetate) were also conducted. After the complete development, the modified protocol was employed to determine BDOC of secondary effluents. Reduction of the incubation period was attempted by agitating the sample, increasing the incubation temperature, and studying the protocol kinetics.

2.3.1 Filter type

The initial BDOC analysis using 0.22 μm cellulose acetate (CA) membrane filters provided inconsistent results. It was suspected that the membrane releases organic carbon even after being rinsed with 300 mL of DI water and 300 mL of sample. A soak test was performed to determine the amount of organic carbon released from the CA membrane filters. The test was divided into two series. In each series, two 0.22 μm CA membrane filters were placed separately into two BOD bottles. Each bottle was filled with DI water that had extremely low TOC as shown in the second column of Table 1. The bottles were shaken at 100 rpm at 20°C. Water samples were taken for TOC measurements after specific times as indicated in Table 1 (columns 3 to 5). The results show that without pre-

rinsing, 0.22 μm CA membrane filter can release about 0.40 to 0.50 mg of TOC (1.40 to 1.70 mg TOC/L in 300 mL BOD bottle) in 24 hours.

Table 1 Release of organic carbon from 0.22 μm CA membrane filters and the biodegradability of leached organic carbon.

Series	TOC (mg/L)						BDOC	BDOC/TOC
no.	0 min	15 min	30 min	24 hr	0 min	24 hr	(mg/L)	(%)
1A	0.07	-	1.33	1.63	-	-	1.14	69.9
1B	0.07	-	1.22	1.72	-	-	0.90	52.3
2A	0.14	1.18	-	1.40	0.05	0.14	1.11	79.3
2B	0.14	1.17	-	1.42	0.05	0.14	1.17	82.4

After 24 hours, the filters used in series 2 were rinsed and placed in bottles containing fresh DI water with the TOC's indicated in column 6. In the second 24 hour period, organic carbon still leached from the filters. The leached DOC was sometimes more than the DOC reacting during the BDOC analysis. The leached organic carbon after the first 24 hours was not analyzed but its biodegradability was evaluated (measured for BDOC) and the results are shown in column 8. Approximately 50 to 80% of the leached organic carbon degraded during the 28 day period, which further complicates the use of CA membrane filters. It is possible that the filters were hydrolyzing and releasing TOC. The 0.22 μm CA membrane filters were abandoned. No leaching or adsorption problems were detected with glass fiber filters (GF/F), which were used for all subsequent analysis.

2.3.2 Detection limit, precision, and accuracy of the modified BDOC protocol

The modified BDOC protocol was evaluated following the procedure for determining method detection limit (MDL) in *Standard Methods* (1989) using 5 blank samples spiked with sodium acetate (0.40 to 0.50 mg DOC/L). The results indicate a method detection limit (MDL) of 0.10 to 0.15 mg/L (Table A-1, Appendix A) which is lower than the MDLs for the COD and BOD_5 tests that are 5 mg/L and 2.0 mg/L, respectively. Even though the detection limit of the BDOC test is much lower than those for the COD and BOD_5 tests, it alone is not sufficient to conclude that the BDOC test is better than the other two tests. As a consequence, the modified BDOC protocol was further investigated for precision.

To determine precision, the modified BDOC protocol was used on 29 reclaimed wastewater samples and 43 secondary effluent samples. DOC concentrations of these 72 samples ranged from 4.50 to 15.50 mg/L. Each sample was run in triplicate. The mean BDOC concentration and standard deviation (SD) of each sample were calculated (Table B-1, Appendix B). Assuming a linear relationship between BDOC concentration and the precision of the method, a linear regression between 72 mean BDOC concentrations and their SDs (Figure B-1, Appendix B) yields the following statistically significant relationship ($p < 0.0005$):

$$SD\ (mg/L) = 0.03(BDOC) + 0.03,\ r = 0.55 \qquad (3)$$

or

$$Coefficient\ of\ variation\ (\%) = 100\left(\frac{SD}{BDOC}\right) = 3.0 + \left(\frac{3.0}{BDOC}\right) \qquad (4)$$

BDOC concentrations were measured in 72 samples and ranged from 0.50 to 5.00 mg/L. The SD was 0.05 to 0.18 mg/L which corresponds to a range of coefficient of variation (CV) of 3.6 to 9.0%. According to a series of interlaboratory studies on BOD_5 measurements using synthetic water samples (1:1 mixture of glucose and glutamic) as described in *Standard Methods* (1989), the predicted BOD_5 CV for samples with a range of BOD_5 from 2 to 30 mg/L (a typical range of BOD_5 for reclaimed and secondary treated wastewaters) are from 16.9 to 40.4%. The CV of the COD procedure is not defined for concentrations in this low range; however, the CV of samples with a COD concentration of 200 mg/L and 0 to 100 mg/L chloride concentration, ranges from 4.8 to 10.8%. At lower COD concentrations as found in reclaimed and secondary treated wastewaters (5 mg/L $\leq$ COD $\leq$ 80 mg/L) and greater chloride concentrations, the CV should be higher. It can be concluded that the BDOC procedure is more precise than the BOD_5 and COD procedures.

The variability of the BDOC procedure described above can arise from three sources: instrumental; personal; and method. The last two sources of variability are very difficult to identify. To estimate the variability due to the instrument, a review of the long term performance of the TOC analyzer was made. During a span of two years before this study, the same TOC analyzer was used for DOC measurement of various samples

including reclaimed and secondary treated wastewaters. A review of approximately 2500 triplicate analyses (DOC ≤ 15.00 mg/L) showed a CV of 1.0%. If DOC concentrations of the dilution water used for seed control are low (≤ 0.20 mg/L), the pooled SD of the initial and final DOC measurements of a sample can be used to estimate the variability caused by the instrument. Based on the CV of 1.0% and the actual DOC data before and after incubation of 72 samples used in the precision study, the range of pooled SD caused by the DOC measurements is from 0.05 to 0.19 mg/L, which agrees with the range provided by Equation (3). Accordingly, it appears that the variability in BDOC analysis caused by person and method are small, and the precision of the modified BDOC protocol is primarily dependent upon the precision of the DOC measurements.

It is very difficult to determine the accuracy of the modified BDOC protocol because it is a bioassay method and the true value can never be known. Two biodegradable compounds, dextrose and sodium acetate, were used to prepare standard solutions that have DOC concentrations of 1.40 mg/L and 0.80 mg/L, respectively. The BDOC results in Table 2 show that the predictions are very accurate. Recovery ranges are from 94.3 to 101.4% for dextrose standard solution and from 96.4 to 101.2% for sodium acetate standard solution. The protocol should provide even more accuracy with standards that have higher DOC concentrations. Response of the modified BDOC protocol to samples containing standard compounds with higher DOC concentrations was subsequently studied and the results are presented in Chapter 4.

Table 2 Accuracy of the modified BDOC protocol.

Standard solution	Actual DOC (mg/L)	BDOC (mg/L)	Recovery (%)
Dextrose	1.41	1.39	97.9
		1.33	94.3
		1.33	94.3
		1.29	101.4
Sodium acetate	0.83	0.81	97.6
		0.81	97.6
		0.80	96.4
		0.84	101.2

2.3.3 Inoculum origin and size

Table 3 shows a comparison of the BDOC values determined using inoculum from two different sources: BAC filter effluent and sand filter effluent. The results for this case show that the BDOC measurement is not a function of the inoculum origin. Most of the difference between the two inocula are within the method's precision range and their significance levels (*t*-test) are ≥ 0.05 (Appendix C describes in details on how significance level (*t*-test) of the BDOC difference was performed). For the later procedure, it was decided to inoculate the sample with the unfiltered sample. For samples that might not contain sufficient microorganisms to serve as an inoculum such as ozonated samples, the BAC filter inoculum was used.

Three inoculum sizes were investigated and the results are shown in Table 4. The inoculum size does not significantly affect the BDOC determination for these conditions. The differences between the BDOC values using different inoculum sizes (2 mL vs. 4 mL and 2 mL vs. 1 mL) fall within the method's precision and are insignificant (*t*-test, $p > 0.05$). An inoculum size of 2 mL was chosen for the remainder of the study.

Table 3 Inoculum origin effect on BDOC determination.

Sampling date	Treatment unit	DOC (mg/L)	BDOC (mg/L)		BDOC difference (mg/L)	Significance level of the difference, (t-test)
			2 mL BAC fil. inoculum	2 mL sand fil. inoculum		
10/13/94	Sand filter	8.49	1.61	1.28	0.33	0.07
	Ozonation column 5	5.89	1.85	1.91	0.06	0.31
	BAC filter	4.71	0.67	0.40	0.27	0.05
10/25/94	Sand filter	8.67	2.26	2.02	0.24	0.12
	Ozonation column 5	8.36	2.95	3.34	0.39	0.10
	BAC filter	6.40	1.56	1.56	0.00	0.50
11/01/94	Sand filter	7.45	0.98	1.23	0.25	0.08
	Ozonation column 5	6.99	2.18	2.10	0.08	0.28
	BAC filter	5.05	0.85	0.80	0.05	0.26

Table 4 Inoculum size effect on BDOC determination.

Sampling date	Treatment unit	DOC (mg/L)	BDOC (mg/L)			BDOC difference (mg/L)	Significance level of the difference, (t-test)
			1 mL BAC fil. inoculum	2 mL BAC fil. inoculum	4 mL BAC fil. inoculum		
08/13/94	Sand filter	9.66	-	2.87	2.98	0.11	0.26
	Ozonation column 5	8.04	-	2.57	2.68	0.11	0.25
	BAC filter	6.06	-	1.88	1.85	0.03	0.41
09/09/94	Sand filter	7.12	-	1.71	1.98	0.27	0.10
	Ozonation column 5	6.84	-	2.04	2.04	0.00	0.50
	BAC filter	5.32	-	0.90	0.83	0.07	0.26
10/06/94	Sand filter	7.26	1.12	1.16	-	0.04	0.31
	Ozonation column 5	9.44	4.57	4.58	-	0.01	0.48
	BAC filter	5.29	1.51	1.61	-	0.10	0.21

2.3.4 Filtration after incubation

Microbial growth occurs during the BDOC procedure. To determine if the cells interfere with the procedure or if there is a significant TOC associated with cell mass, a series of experiments was performed with and without glass fiber filtration prior to final TOC analysis. Table 5 shows the results, which indicate that filtration had no significant effect. For simplicity and convenience, the modified BDOC procedure therefore does not require filtration of the sample after the incubation.

2.3.5 Agitation of samples, temperature of incubation, and kinetics of the protocol

It was expected that agitating samples or incubating at a higher temperature would reduce the incubation period. Fourteen reclaimed wastewater samples and thirty-nine secondary effluent samples were used to study the effects of agitation and incubation temperature on protocol kinetics. Agitation was provided by leaving 30% headspace in the incubation bottle and shaking at 100 rpm throughout the incubation. Simultaneous determination of SBOD could not be performed with this procedure. The temperature of 37°C was chosen since it is the upper limit of the mesophillic range. Four different incubation conditions (agitation at 20°C, no agitation at 20°C, agitation at 37°C, and no agitation at 37°C) were studied. Duplicates were run for all conditions. Kinetics were investigated by collecting samples for TOC analysis at 5, 10, 15, and 20 days in addition to the final determination at 28 days. The BDOC results (mean values of duplicates) for different conditions were compared.

Table 5 Effect of inoculum filtration on BDOC determination.

Sampling date	Treatment unit	DOC (mg/L)	BDOC (mg/L)		BDOC difference (mg/L)	Significance level of the difference, (t-test)
			With filtration	Without filtration		
08/13/94	Sand filter	9.66	2.87	3.03	0.16	0.20
	Ozonation column 1	8.63	2.44	2.20	0.24	0.13
	Ozonation column 2	8.66	2.59	2.79	0.20	0.16
	Ozonation column 3	8.35	2.84	2.68	0.16	0.20
	Ozonation column 4	8.24	2.77	2.53	0.24	0.14
	Ozonation column 5	8.04	2.57	2.73	0.16	0.19
	BAC filter	6.06	1.88	1.85	0.03	0.39

Figure 4(a and b) illustrates the significance levels (t-test) of the differences in BDOC concentrations measured for agitated and non-agitated reclaimed wastewater samples. Points falling below the horizontal line at 0.05 are significant at significance level of 0.05 using one-tailed t-test. At each temperature, only 1 out of 70 observations has a significance level below 0.05. The significance levels of the differences are all above 0.05 at 15, 20, and 28 days of incubation. Thus, at both incubation temperatures, agitation had no effect on the protocol kinetics.

Figure 5 shows the significance levels of the differences in BDOC concentrations of reclaimed wastewater samples when incubated at 20°C and 37°C (regardless of agitation condition since it has no effect on BDOC determination). All 28 observations have significance levels below 0.05 at 5 and 10 days (14 observations for each incubation time). Only 2 and 4 observations have significance levels above 0.05 at 15 and 20 days, respectively. At 28 days, all 14 observations have significance levels above 0.05. This indicates that incubating reclaimed wastewater samples at the two temperatures resulted in significantly different BDOC concentrations at 5, 10, 15, and 20 days of incubation. However, the final BDOCs or BDOCs at 28 days of incubation at the two temperatures are not significantly different.

The effect of incubation temperature on protocol kinetics is further shown in Figure 6 which is a plot of normalized mean BDOC (mean of BDOCs exerted at time t regardless of agitation condition divided by mean of BDOCs exerted after 28 days of incubation at the same temperature regardless of agitation condition) versus incubation

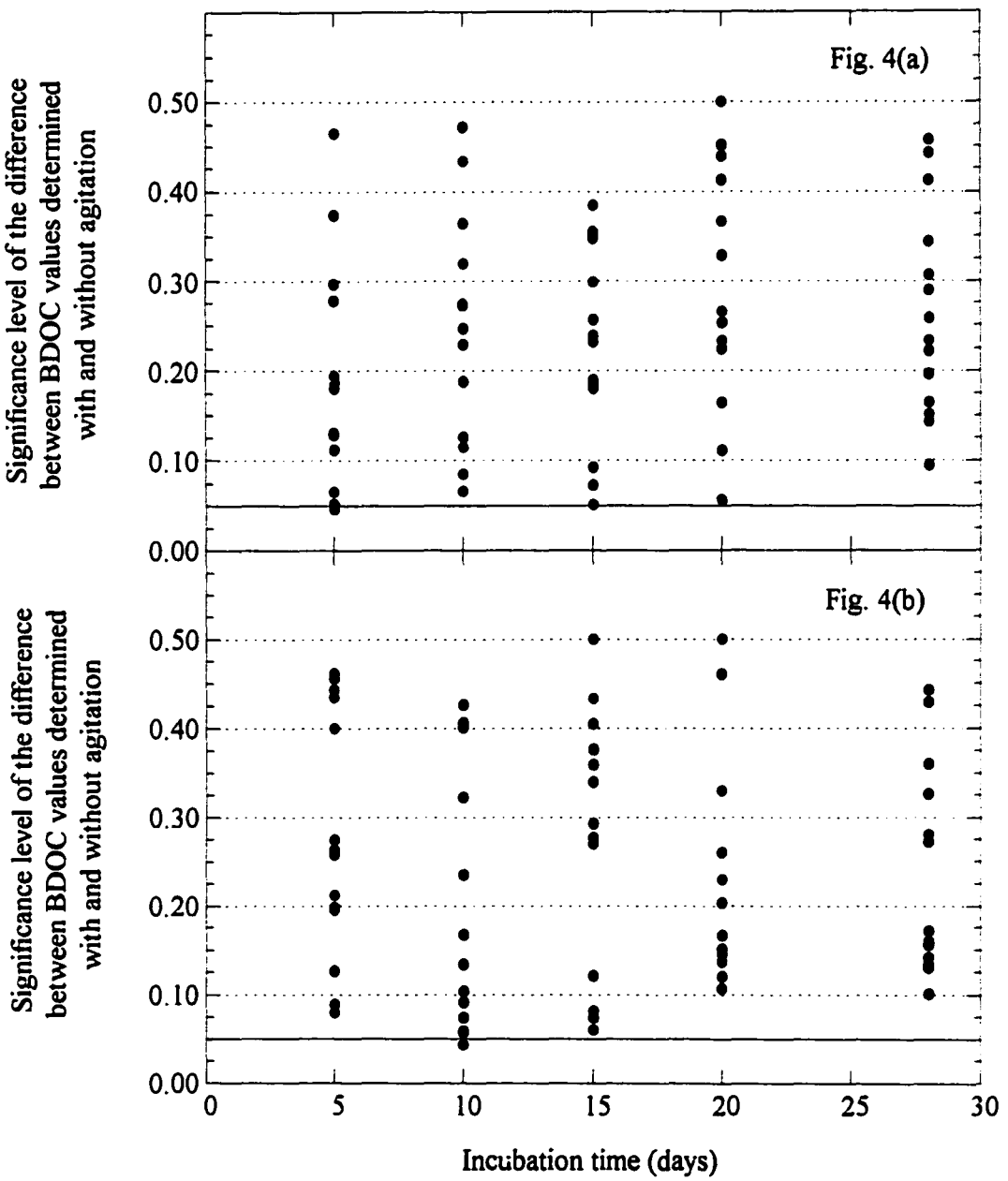


Figure 4 Agitation effect on determination of BDOC in reclaimed wastewater samples at a) 20°C and b) 37°C.

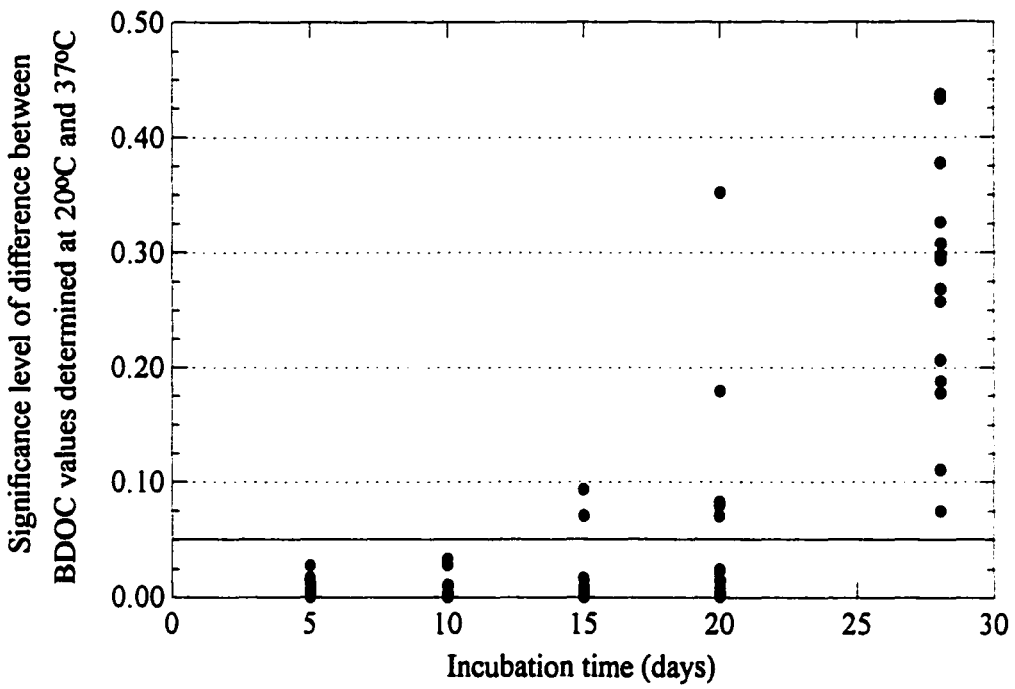


Figure 5 Incubation temperature effect on determination of BDOC in reclaimed wastewater samples.

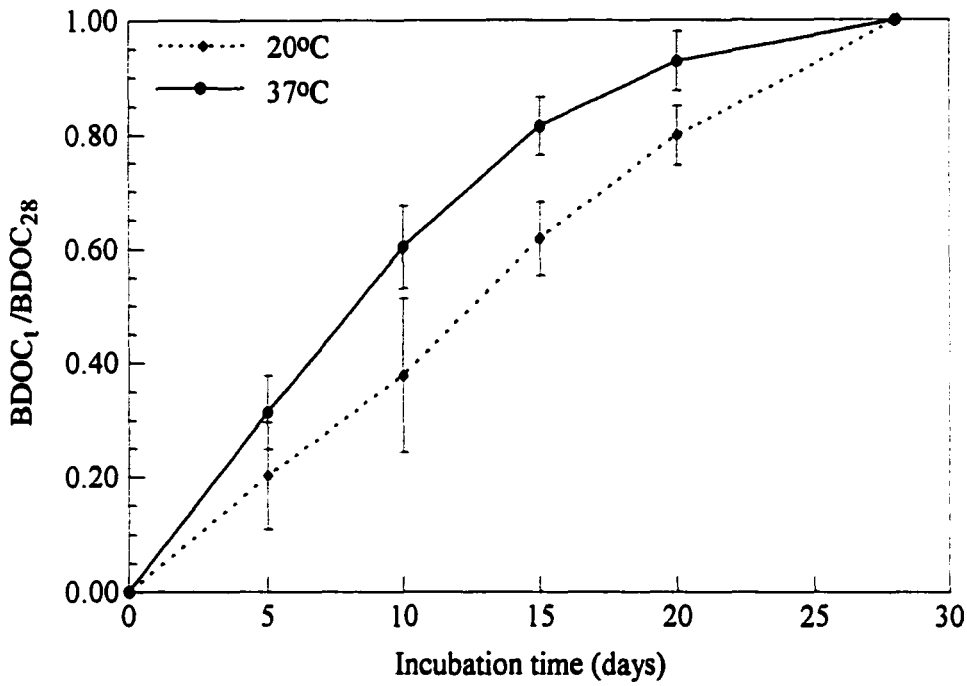


Figure 6 Incubation temperature effect on the protocol kinetics of reclaimed wastewater samples.

time. The error bars represent standard deviations generated from normalized mean BDOC values of 14 samples. Figure 6 relies on the assumption that BDOC exerted after 28 days of incubation ($BDOC_{28}$) is approximately equal to ultimate BDOC ($BDOC_u$). It was speculated that BDOC exertion or DOC decrease during the incubation follows first-order kinetics. Relying on the same assumption ($BDOC_{28} \approx BDOC_u$), logarithmic transformations of the remaining fractions of BDOC (1 - mean value in Figure 6) were performed. The slope of a linear regression between the transformed values and incubation time, multiplied by -1, is an initial estimate of the first-order rate constant (k). This initial value was used to calculate $BDOC_{28}/BDOC_u$. Next, $BDOC_t/BDOC_u$ values were estimated (mean value in Figure 6 times $BDOC_{28}/BDOC_u$). A new k value was obtained from a new linear regression between $Ln[1-(BDOC_t/BDOC_u)]$, including $Ln[1-(BDOC_{28}/BDOC_u)]$, and incubation time. The iteration was performed until there was no change in the k value. Appendix D shows an example on how the fit of the first-order kinetic model of BDOC exertion data was investigated.

Figure 7 shows the final results of the iterations and the k values are 0.024 and 0.095 day^{-1} for 20°C and 37°C, respectively. These rate constants were used to calculate $BDOC_t/BDOC_u$ values and the results were compared to the actual values (mean value in Figure 6 times $BDOC_{28}/BDOC_u$). $BDOC_{28}/BDOC_u$ values are 0.49 and 0.93 for 20°C and 37°C, respectively. According to the comparisons (residuals) and $BDOC_{28}/BDOC_u$ values, only the BDOC exertion at 37°C follows first-order kinetics. This may be because the inoculum size is small and therefore the incubation at 20°C has a lag period.

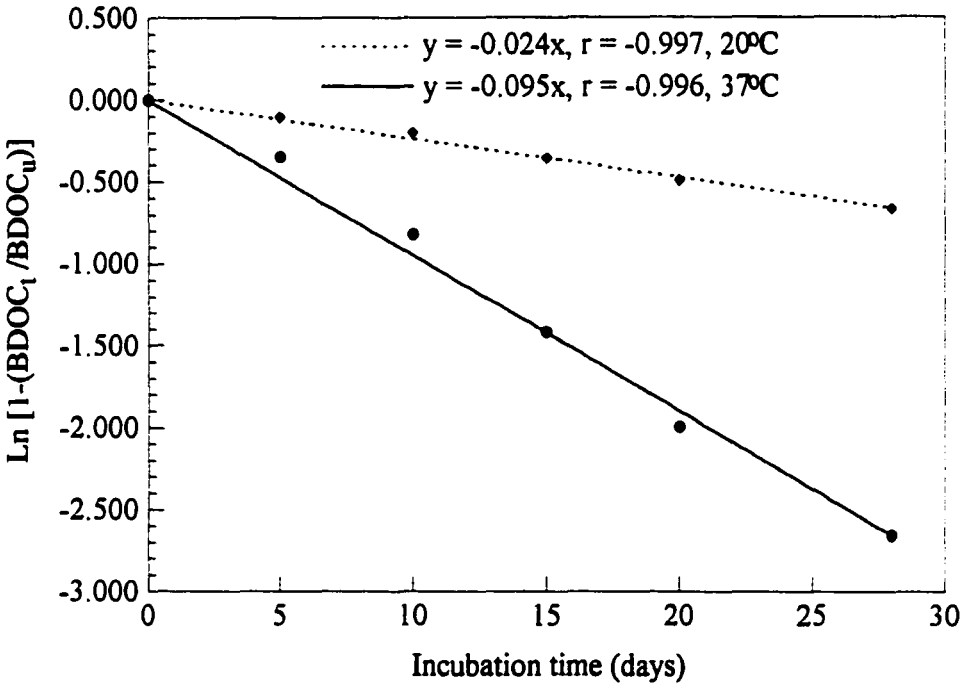


Figure 7 Determination of BDOC exertion rate constants of reclaimed wastewater samples by the first-order model.

As illustrated in Figure 8(a and b), similar results were obtained when secondary effluent samples were used to study the agitation effect on the BDOC exertion rate. Agitation did not accelerate the exertion of BDOC. Figure 9 shows that incubation temperature had a pronounced effect on the BDOCs of secondary effluent samples during the incubation. Unlike the results shown in Figure 6, the differences are very significant (< 0.05, *t*-test) even at the end of the incubation (only 4 out of 39 cases are not significant). Figure 10 which is a plot of normalized mean BDOC (mean of BDOCs at time t regardless of agitation condition divided by mean of $BDOC_{28}$ exerted at 37°C regardless of agitation condition) illustrates the differences. At 28 days, the BDOC exerted at 20°C is only 75% (± 12%) of the BDOC exerted at 37°C. The assumption that $BDOC_{28}$ is approximately equal to $BDOC_u$, is not true for this case. This difference may have occurred because secondary effluent samples are more recalcitrant than ozonated, reclaimed wastewater samples. The modified BDOC protocol was subsequently investigated to detect the biodegradability of ozonated secondary effluents. The results are reported in Chapter 4.

Investigation on the BDOC exertion rate constants for secondary effluent samples followed the same process described above for reclaimed wastewater samples and the results are also similar. Only the BDOC exertion at 37°C agrees with the first-order model and $BDOC_{28}/BDOC_u$ value is 0.85. As shown in Figure 11, the k value of 0.068 day^{-1} for 37°C indicates that the BDOC exertion of secondary effluent samples is much slower than the BDOC exertion of the ozonated, reclaimed wastewater samples (k value of 0.095 day^{-1}). The incubation temperature of 20°C was still chosen for the modified

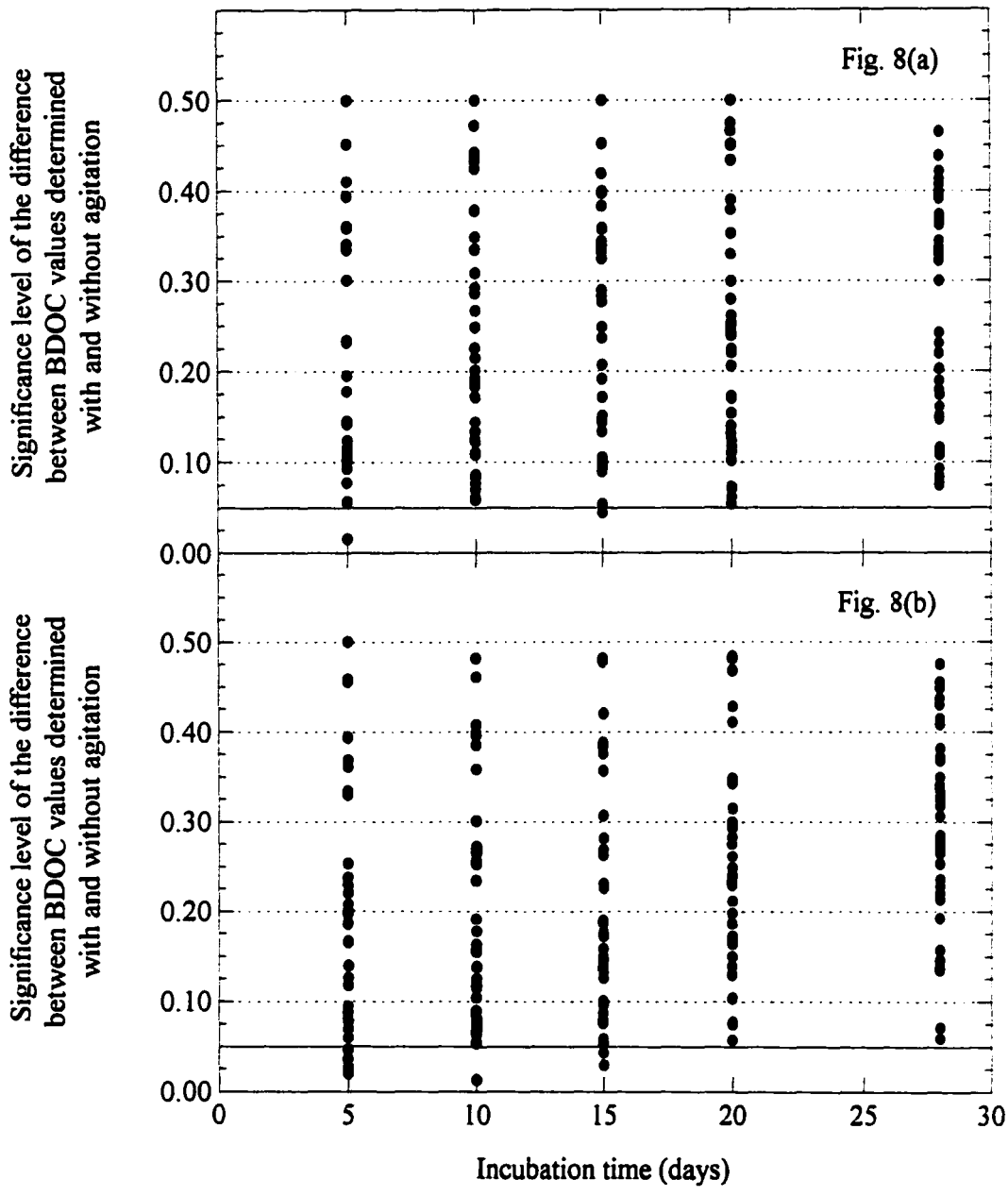


Figure 8 Agitation effect on determination of BDOC in secondary effluent samples at a) 20°C and b) 37°C.

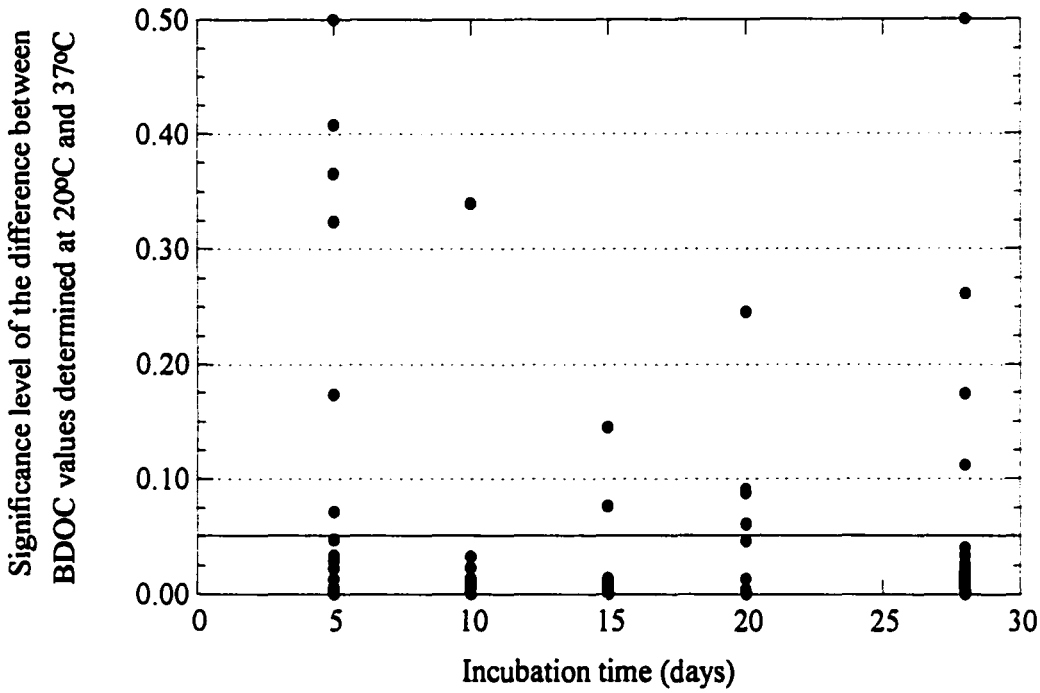


Figure 9 Incubation temperature effect on determination of BDOC in secondary effluent samples.

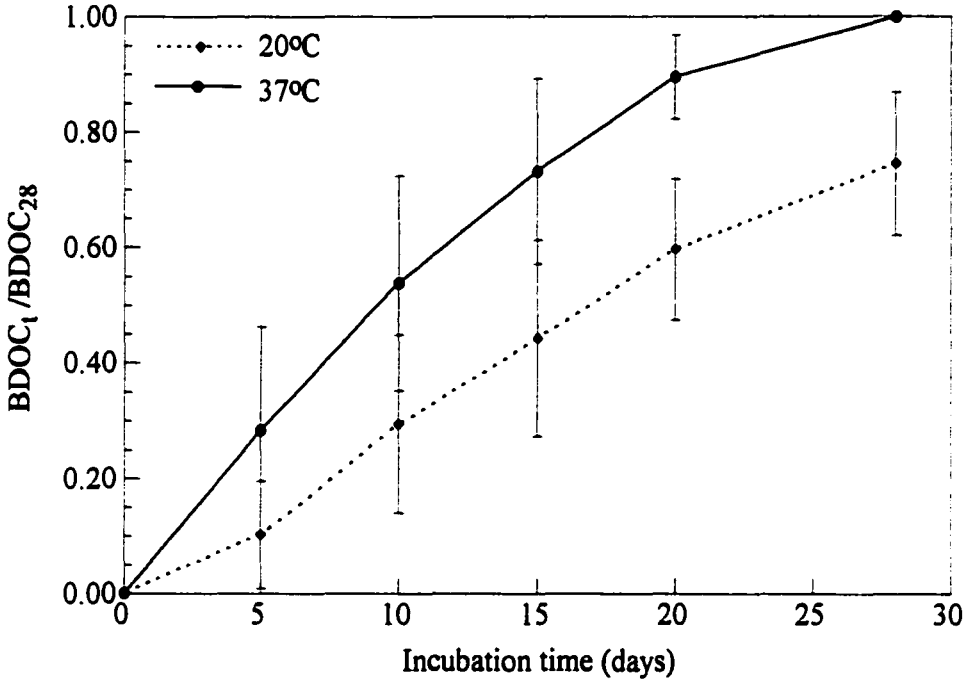


Figure 10 Incubation temperature effect on the protocol kinetics of secondary effluent samples.

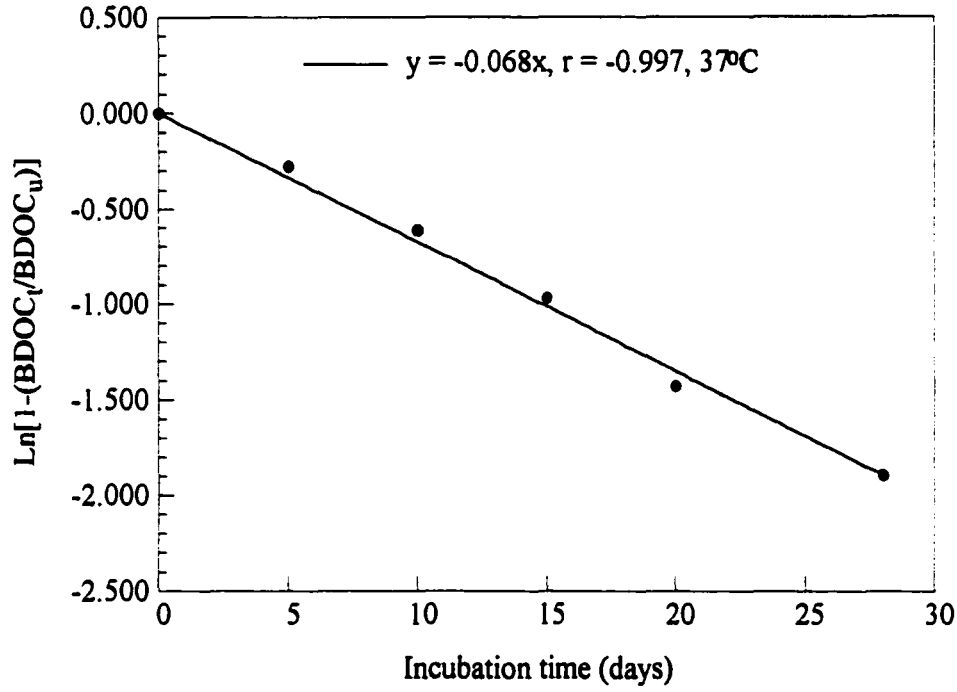


Figure 11 Determination of BDOC exertion rate constants of secondary effluent samples by the first-order model.

protocol because it is the standard temperature that has been used in most of the analytical procedures including the BOD test. In addition, considering BOD_5 which is only 68% of BOD_u, it is believed that BDOC exerted after 28 days of incubation ($\approx$ 64% of $BDOC_u$) is sufficient to indicate secondary effluent quality.

2.3.6 Simultaneous determinations of BDOC and SBOD

The protocol was used successfully for simultaneous determinations of BDOC and $SBOD_u$ of reclaimed wastewater samples. Nitrification does not affect BDOC determination but nitrification inhibitors such as 2-chloro-6-(trichloromethyl) pyridine and allylthiourea, will interfere with the BDOC exerted during the procedure. BDOC and $SBOD_5$ of secondary effluent samples could not be determined simultaneously because oxygen consumption in these samples after 5 days of incubation did not meet the depletion criteria ($\geq$ 2 mg/L). Inoculating the sample with 2 mL of the unfiltered sample might not have provided an adequate seed for $SBOD_5$ measurement. The problem can be solved by increasing the inoculum size and/or using a more concentrated inoculum; however, for simultaneous determinations of BDOC and $SBOD_5$, separation of microorganisms after the incubation will be required. It is also expected that increasing the inoculum size and/or using a more concentrated inoculum, will eliminate the lag phase and reduce the incubation period.

2.4 Conclusions

A modified bioassay protocol for measuring BDOC in water samples with moderately low DOC, such as reclaimed and secondary treated wastewaters (4 to 15 mg of DOC/L), was introduced. The modified BDOC protocol was developed from the existing batch BDOC protocol and BOD techniques. The development of the modified procedure was focused on adequacy of DO throughout the incubation period and simultaneous determinations of DOC, BDOC, and SBOD. The primary advantages of the modified BDOC protocol over BOD and COD tests are higher precision and higher sensitivity.

Glass fiber filters (GF/F) were used in the modified protocol instead of 0.22 μm CA membrane filters because the membrane filter releases a substantial amount of organic carbon which interferes with the procedure. The modified protocol provides good reproducibility. The precision of the protocol ranges from 0.05 to 0.18 mg/L while the method detection limit is approximately 0.15 mg/L. The precision of the new BDOC method is much better than those of BOD and COD methods. BDOC measurement is not sensitive to inoculum origin and size. Glass fiber filtration of sample at the end of the incubation has an insignificant effect on the BDOC determination.

Shaking the incubation bottle with 30% gas volume at 100 rpm does not accelerate the kinetics of the exertion. The final BDOC concentrations ($BDOC_{28}$) of reclaimed wastewater samples provided by incubation temperatures of 20°C and 37°C are not

different. For secondary effluent samples, $BDOC_{28}$ exerted at 20°C is only 75% of $BDOC_{28}$ exerted at 37°C and 64% of $BDOC_u$. This may be due to the nature of secondary effluents which are more bio-refractory than reclaimed wastewaters investigated in this research. It was decided to adopt the incubation temperature of 20°C for the modified BDOC procedure since it is the laboratory reference temperature used for the BOD test and most of the water quality analyses. The first-order model can be used to describe the BDOC exertion kinetics only for the incubation at 37°C.

Using the modified BDOC protocol, simultaneous determinations of DOC, BDOC, and $SBOD_u$ of reclaimed wastewaters can be achieved. Unfortunately, $SBOD_5$ cannot be determined simultaneously with DOC and BDOC of secondary effluents because of inadequate inoculum. The protocol may be refined by increasing the inoculum size and/or using a more concentrated inoculum and adding a cell separation step. This may also reduce the incubation time.

3.0 APPLICATIONS OF THE MODIFIED BDOC PROCEDURE

Within the last few years, there has been an increasing interest in assessing the biodegradability of dissolved aquatic organic matter. DOC is the main parameter most commonly used to represent the amount of dissolved organic matter in waters. As a result, several methods for determining BDOC have been proposed since 1985.

BDOC methods can be categorized into two major groups: batch (Joret and Levi, 1986, Servais *et al.*, 1987, 1989, and Joret *et al.*, 1988) and biofilm reactor (Lucena *et al.*, 1990, Mogren *et al.*, 1990, Ribas *et al.*, 1991, Frias *et al.*, 1992, Kaplan and Newbold, 1995), which are sometimes referred to as static methods and dynamic methods, respectively. Most of the batch methods and all of the biofilm reactor methods share the same concept which involves the measurement of DOC concentrations before and after a period of controlled biochemical reaction. All BDOC methods have provided good and statistically identical results for all types of drinking water samples (Frias *et al.*, 1995). Major applications of BDOC methods have been examinations of raw and finished waters and evaluation of BAC system performance.

BDOC methods have been widely accepted in the drinking water industry, but none of the methods has been proven to be applicable to reclaimed and secondary treated wastewaters. This is because the characteristics of reclaimed and secondary treated wastewaters are very different from drinking water. DOC in reclaimed and secondary

treated wastewaters usually are of higher concentration and are more recalcitrant than that in drinking water. Several techniques must be added to the batch methods. Biofilm BDOC methods resemble the trickling filter process in wastewater treatment. The methods may perform well with reclaimed wastewater containing more readily degradable BDOC such as ozonated wastewater. Although it has never been tested, applying the methods to secondary effluents might result in insignificant DOC reduction or no BDOC detection.

In Chapter 2, a batch BDOC protocol was specifically developed for characterizing reclaimed and secondary treated wastewaters by combining an existing batch protocol (Servais *et al.*, 1989) and the BOD test. Dilution and seed control techniques are included in the protocol to avoid DO depletion and to produce more accurate results. The protocol is capable of determining DOC, BDOC, and $SBOD_u$ of reclaimed wastewater samples simultaneously. It employs a 2 mL acclimated inoculum (unfiltered sample) and follows both the DOC and DO decreases in reclaimed wastewater samples during an incubation period of 28 days in the dark at 20°C. BDOC is estimated by multiplying the difference between DOC reductions in the sample and in the seed control by the dilution factor. SBOD is calculated in the same way using DO reduction instead of DOC reduction. For secondary effluent samples, the procedure is the same except that the incubation period for SBOD is 5 days. However, the protocol cannot determine $SBOD_5$ of secondary effluents simultaneously along with DOC and BDOC because the inoculum is inadequate.

In this chapter, the modified BDOC protocol is tested to show that it can be useful to the wastewater treatment and reclamation industries. The utility of this new method is

shown by an evaluation of the performance of a BAC system at a wastewater reuse facility. The utility of the method is further demonstrated by showing how it can be used to characterize secondary treatment plant effluents.

3.1 Background

The first BDOC method (Servais *et al.*, 1987) was developed specifically for testing raw water quality and designing, monitoring, and optimizing operating conditions of BAC systems. Occasionally, BDOC has been utilized for measuring the effects of other treatment processes. Considerable interest in BDOC of finished water occurred after BDOC was linked to chlorine demand and microbial regrowth in distribution systems.

3.1.1 BDOC for indicating raw water quality

Hascoet *et al.* (1986) applied a batch BDOC method (Servais *et al.*, 1987) to test a river water in France and presented the idea of using BDOC as another parameter for examining raw water. Servais *et al.* (1989) measured BDOC in three Belgian rivers using a revised batch protocol. Two of the three rivers are more contaminated by domestic and industrial sewage than the other. BDOC concentrations in the more contaminated rivers (2.0 to 6.1 mg/L) were approximately two to nine times higher than that of the less contaminated river (0.7 to 1.2 mg/L). The BDOC/DOC ratio ranged from 0.26 to 0.54 for the more contaminated rivers and 0.19 to 0.34 for the less contaminated river.

Mogren *et al.* (1990) applied a dynamic biofilter BDOC method on three raw water sources in the United States: Ohio River water, Florida ground water, and Delaware River water. Based on the results from single bioreactor analyses, water from all three sources had low BDOC and low BDOC/DOC ratio. BDOC and BDOC/DOC ratio values were 0.32 mg/L and 0.12 for Ohio River water, 0.75 mg/L and 0.07 for Florida ground water, and 0.45 mg/L and 0.15 for Delaware River water.

Ribas *et al.* (1992) employed their dynamic bioreactor method (Ribas *et al.*, 1991) to monitor BDOC in a Spanish river which served as a water supply for Barcelona city. BDOC and DOC concentrations were influenced by the flow of the river. Two separate monitoring events were performed in January 1992 and October 1992. BDOC and DOC concentrations during the first monitoring period were 1.35 ± 0.87 mg/L and 6.80 ± 0.59 mg/L, respectively. The flow of the river during the second monitoring period was 1.5 to 2 times higher and BDOC and DOC values decreased to 0.48 ± 0.31 mg/L and 4.39 ± 0.62 mg/L, respectively.

3.1.2 BDOC for designing, monitoring, and optimizing operating conditions of BAC systems

Several authors (Hascoet *et al.*, 1986, Servais *et al.*, 1987, Mogren *et al.*, 1990, and Ribas *et al.*, 1992) detected a BDOC increase after ozonating sand filter effluent. Optimum ozone dosage varies with water characteristics and batch studies are often required (Malley *et al.*, 1993 and Volk *et al.*, 1993). In both pilot and full scale BAC

systems, the most cost-effective ozone dosages that significantly increase BDOC, are chosen (Malley *et al.*, 1993). In order to reach the optimum BDOC formation, a short contact time and a high ozone dose are usually preferable over a long contact time and a low ozone dose (Volk *et al.*, 1993).

Ribas *et al.* (1992) also monitored the evolution of BDOC through a water treatment plant during the periods that they measured BDOC in the Spanish river. The processes included prechlorination, flocculation/sedimentation, sand filtration, granular activated carbon (GAC) filtration, and postchlorination. In the second monitoring period, an ozonation step was added in between sand filtration and GAC filtration. In both periods, the sand filtration removed significant DOC and had no effect on BDOC. The GAC filtration reduced DOC in both periods but eliminated BDOC only when the water was preozonated. They anticipated examination of the ozonation on the performance of the plant. Results from the two periods could not be compared because of the fluctuation in source water quality.

Hascoet *et al.* (1986) studied a BAC system. They did not specify a backwashing procedure but reported that backwashing had an adverse impact on the biomass in the biological activated carbon filter (BAF). BDOC reductions in the filter were between 55 to 60% during normal operation. After backwashing and immediately followed by 30 minutes of filtration, only 25% of BDOC was removed in the filter. Nevertheless, Servais *et al.* (1991) monitored bacteria populations in the outlet water from one of the BAFs used in a full scale drinking water plant in Paris before and after backwashing and learned

that only 4 to 8% of the bacterial biomass attached on GAC was released during washing. They later concluded that backwashing the filters has an insignificant impact on microbiological function.

Hascoet *et al.* (1986) and Servais *et al.* (1991) observed BDOC removal only in the first 20 to 40 cm of 100-cm-depth BAFs. The impact of filtration velocity on BDOC removal was briefly studied by Servais *et al.* (1989). A 100-cm-depth BAF was operated with filtration velocities of 6, 12, and 18 m/h. BDOC removal of approximately 70% was achieved at the filtration velocity of 6 m/h. Dramatic decreases in BDOC removal to approximately 30% and 20% were observed with the filtration velocities of 12 and 18 m/h, respectively. Merlet *et al.* (1991) obtained similar results by studying the relationship between BDOC removal in a BAF and empty bed contact time (EBCT) and concluded that removal of BDOC in a BAF is a function of EBCT. BDOC reduction in a BAF increases with increasing EBCT and thus decreasing filtration velocity.

3.1.3 BDOC for measuring the effects of water treatment processes other than BAC

Mogren *et al.* (1990) used their dynamic biofilter BDOC method to evaluate the impact of different drinking water treatment processes on BDOC. Samples from three treatment plants were collected. The first treatment plant drew its raw water from the Ohio River. The effect of chlorination located between coagulation/flocculation/ sedimentation and parallel dual media (anthracite/sand) filtration was examined. Chlorination resulted in a BDOC increase from 0.23 mg/L in the influent to 0.37 mg/L in

the effluent and no DOC reduction (2.24 mg/L in the influent and 2.22 mg/L in the effluent). Both BDOC and DOC decreased to < 0.10 mg/L and 2.06 mg/L when the same influent was fed to the filters without prechlorination. The filter could have been a biologically active filter and therefore biodegradation occurred. The impact of ozonation between lime softening and parallel dual media (anthracite/sand) filtration was studied for the second plant. The raw water was Florida ground water. Without preozonation, there was no significant DOC removal in the filter (7.94 to 7.91 mg/L) and BDOC increased from less than 0.10 mg/L to 0.21 mg/L. When the lime softened water was ozonated, BDOC increased to 0.52 mg/L, DOC remained constant (7.85 mg/L). Then, the filter reduced BDOC and DOC to 0.26 mg/L and 7.67 mg/L, respectively. Samples were collected from the following treatment processes of the third plant: ozonation, super-pulsator, parallel dual media filters. Raw water for the plant was supplied by the Delaware River. The filters were packed with different combinations of media, anthracite/sand or GAC/sand, and performance was compared. Unfortunately, the super-pulsator was very effective in removing BDOC (1.16 to 0.10 mg/L) and DOC (3.09 to 1.73 mg/L). The comparison could not be made. The two filters with different combinations of media produced effluents with the similar BDOC and DOC levels to those found in effluent of the super-pulsator.

3.1.4 Removal of BDOC for reducing chlorine demand

Significant chlorine demand and formation of organochlorine compounds can be reduced by effective removal of BDOC. The link between BDOC and chlorine demand was investigated by Merlet *et al.* (1991). In their study, a full scale BAF was operated with different EBCTs. Chlorine demand, BDOC, and DOC in the influent and effluent were measured. The BAF removed a large amount of chlorine demand (26 to 30%) and a small amount of DOC (17%). Strong linear relationships ($r \geq 0.80$) were found between BDOC and chlorine demand. Samples with higher BDOC concentrations tend to have higher values of chlorine demand. BDOC was much more reactive to chlorine than refractory organic carbon. The reactivity of BDOC was between 1.02 and 3.95 mg Cl_2/mg BDOC while refractory organic carbon had a lower reactivity of 0.52 to 1.45 mg Cl_2/mg DOC.

3.1.5 BDOC for indicating finished water quality and controlling microbial regrowth

BDOC has been related to regrowth of microorganisms. High BDOC in finished water indicates poor quality and a potential of microbial multiplication. Maintaining a free chlorine residual to prevent the regrowth along the distribution system is a common solution; however, a large amount of chlorine is required. Also, chlorine residual cannot completely inactivate fixed bacteria (Le Chevallier *et al.*, 1988). Controlling microbial dynamics by limiting available substrate (BDOC) is a new and interesting approach (Rittmann and Snoeyink, 1984, Kemmy *et al.*, 1989, Huck, 1990, and Servais *et al.*,

1993). Removal of BDOC to a level that limits microbial growth, provides not only a direct control of bacteria population but also an indirect control of protozoa population through a trophic food web (Servais *et al.*, 1993).

Servais *et al.* (1993) collected water and fixed bacteria (on the inner surface of the pipes) samples from five French distribution networks in four different cities. Analyses for BDOC and chlorine residual, enumeration of suspended bacteria, fixed bacteria, and protozoa were performed. Only samples with chlorine residual less than 0.03 mg Cl_2/L were taken into consideration. BDOC reduction in the networks and production of suspended and fixed bacteria were quantified. Strong positive linear correlations were obtained between BDOC in finished water and the following parameters: BDOC reduction in the networks ($r = 0.93$), abundance of suspended bacteria ($r = 0.66$), abundance of fixed bacteria ($r = 0.80$), logarithm of suspended bacteria production ($r = 0.76$), and logarithm of fixed bacteria production ($r = 0.77$). A positive linear relationship was also found between abundance of protozoa and abundance of bacteria (r not specified). Servais *et al.* (1993) finally stated that biologically stable waters should contain less than 0.15 mg of BDOC/L. At this threshold level, microbial growth is very limited.

3.2 Methodology

3.2.1 Reclaimed wastewater samples

Eight reclaimed wastewater samples were collected weekly from the Lake Arrowhead wastewater reclamation pilot plant, Lake Arrowhead, CA. The pilot plant had a capacity of 20 LPM (liter/min) and was operated by the University of California, Los Angeles (UCLA) and the Lake Arrowhead Community Services District (LACSD) (Madireddi *et al.*, 1997). It was designed to repurify secondary unchlorinated effluent from the Grass Valley trickling filter municipal wastewater treatment plant (WWTP) and to use the product water to replenish Lake Arrowhead during drought periods. According to the plan, the product water would be stored for one year in a small lake adjoining Lake Arrowhead, and then allowed to overflow into Lake Arrowhead, the sole drinking water source in the community. The treatment scheme of the pilot plant included denitrification, alum coagulation/flocculation/sedimentation, sand filtration, primary ozonation (5 columns), BAF, nanofiltration, reverse osmosis, and final ozone disinfection. The samples were taken from the effluent of the sand filter, each of the primary ozonation columns, the BAF, and the nanofilter.

3.2.2 Secondary effluent samples

Unchlorinated secondary effluent samples were collected daily for 10 consecutive working days from each of thirteen municipal WWTPs listed as follows:

- RP 1 WWTP, Ontario, CA, 36 MGD, operated by the Chino Basin Municipal Water District (CBMWD),
- RP 2 WWTP, Chino, CA, 5 MGD, operated by the CBMWD,
- Carbon Canyon WWTP, Chino, CA, 7 MGD, operated by the CBMWD,
- Tapia WWTP, Calabasas, CA, 9 MGD, operated by the Las Virgenes Municipal Water District,
- Glendale WWTP, Glendale, CA, 20 MGD, operated by the Los Angeles Bureau of Sanitation (LABS),
- Tillman WWTP, Van Nuys, CA, 65 MGD, operated by the LABS,
- Orange County WWTP no. 1, Fountain Valley, CA, 40 MGD, operated by the County Sanitation Districts of Orange County (CSDOC),
- Union Sanitary District (USD) WWTP, Union City, CA, 30 MGD, operated by the USD,
- Las Vegas WWTP, Las Vegas, NV, 50 MGD, operated by the City of Las Vegas,
- Orange County WWTP no. 2, Huntington Beach, CA, 60 MGD, operated by the CSDOC,
- Hyperion WWTP, Playa del Rey, CA, 200 MGD, operated by the LABS,
- Joint Water Pollution Control Plant (JWPCP), Carson, CA, 200 MGD, operated by the Sanitation Districts of Los Angeles County, and

- Sacramento Regional WWTP, Elk Grove, CA, 170 MGD, operated by the Sacramento Regional County Sanitation District.

All of the plants are conventional activated sludge (AS) plants except the last four plants (Orange County no. 2, Hyperion, JWPCP, and Sacramento) which are high purity oxygen (HPO) AS plants. The flow rates listed above are approximate actual flow rates and only the secondary portions of the Orange County no. 1 (only AS), Orange County no. 2, Hyperion, and JWPCP are reported.

3.2.3 Analyses and measurements

BDOC was determined by the modified protocol according to the procedure described in Chapter 2. In addition to applying the modified BDOC protocol on both reclaimed and secondary treated wastewaters, UV absorbance at 254 nm (UV_{254}) was measured for reclaimed wastewater samples and soluble COD (SCOD) was analyzed for secondary effluent samples. A Hewlett-Packard Diode Array Spectrophotometer model 8452A (Hewlett-Packard Company, Palo Alto, CA) and a 1-cm quartz cell were used to determine UV_{254}. The spectrophotometer was first adjusted to read zero absorbance with water blank (deionized water containing less than 0.20 mg DOC/L). Each sample was then analyzed three times (three portions) and the mean value was taken as the UV_{254}. SCOD was analyzed using the Open Reflux Method as specified in *Standard Methods* (1989).

3.3 Results and Discussion

3.3.1 BDOC as an indicator of reclamation plant performance

The modified BDOC procedure was used to quantify the performance of the Lake Arrowhead reclamation pilot plant. This was the original motivation for its development. Although the modified BDOC protocol was developed for samples with 4 to 15 mg of DOC/L, it was also tested with the nanofilter effluent which had only 0.25 to 2.0 mg/L of DOC/L. Figures 12(a) and 12(b) show DOC, UV_{254}, $SBOD_u$, and BDOC profiles of the Lake Arrowhead reclamation pilot plant from the sand filter to nanofilter. UV_{254} was measured to indicate the relative concentration of organic compounds that are aromatic in structure or that have conjugated double bonds. Each value is an average of the weekly data collected for 11 consecutive weeks. The error bars represent the standard deviations. DOC remains fairly constant from the sand filter through ozonation columns (7.29 to 7.66 mg/L), and drops dramatically after the BAC and nanofilter. This indicates that DOC is not a good parameter for monitoring the efficiency (biodegradability increase) of the ozonation. An increase of BDOC can be observed after each ozonation column (1.46 to 2.52 mg/L). The BAC filter removes approximately 50% of the BDOC. Eventually, most of the BDOC is removed by the nanofilter. The BDOC data show that the biodegradability is gradually enhanced by the ozonation and the BDOC increase by ozonation is subsequently removed by the BAC filter. $SBOD_u$ of nanofilter effluent was too low to measure. The same problem occurred occasionally with BDOC. Therefore, at

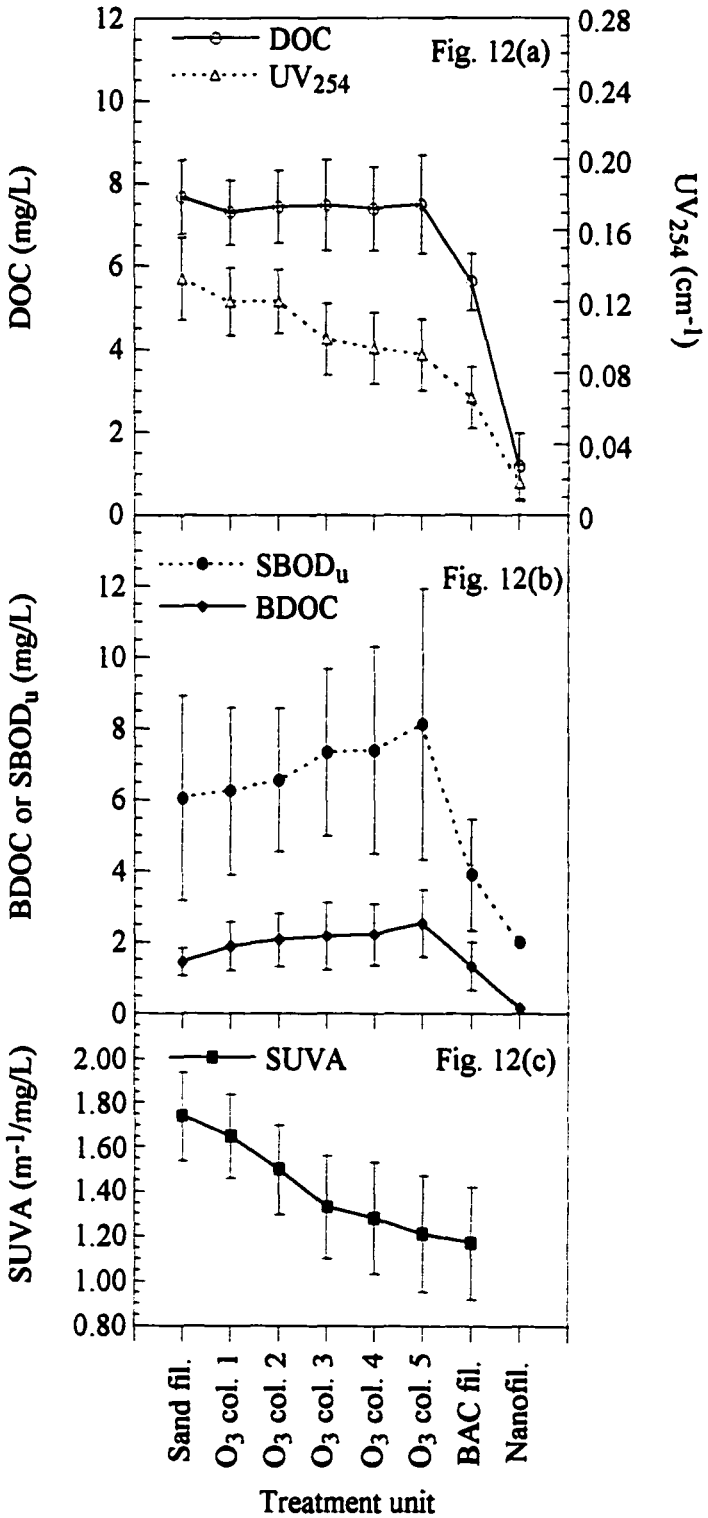


Figure 12 a) DOC and UV_{254}, b) $SBOD_u$ and BDOC, and c) SUVA profiles of the pilot plant.

the position of nanofilter in Figure 12(b), the detection limits of BDOC and $SBOD_u$ (0.15 and 2.0 mg/L) were plotted without error bars.

The detection of BDOC increase during ozonation agrees with a specific UV absorbance (UV_{254}/DOC expressed in m^{-1}/mg/L) profile of the pilot plant shown in Figure 12(c). In the drinking water field, specific UV absorbance (SUVA) value has been used to characterize the DOC of raw waters (Edzwald and Van Benschoten, 1990). SUVA values of reclaimed wastewater samples (excluding nanofilter effluent) were between 0.80 to 2.00 m^{-1}/mg/L. SUVA decreases after each ozone column (constant DOC and reduction in UV_{254}). Substantial reduction in SUVA was found after each of the first three ozone columns. According to Edzwald and Van Benschoten (1990), this suggests that the DOC of the reclaimed wastewaters is composed largely of non-humic materials and is very hydrophillic, less aromatic and of low molecular weight. Also, high molecular weight and aromatic compounds presented in the sand filter effluent were transformed to lower molecular weight and aliphatic compounds by the ozonation (Hascoet *et al.*, 1986, Servais *et al.*, 1987, Mogren *et al.*, 1990, Ribas *et al.*, 1992, Malley *et al.*, 1993, and Volk *et al.*, 1993). The transformation occurred predominantly in the first three ozone columns. As shown in Figure 13, a significant but not strongly negative linear relationship ($p < 0.0005$ and $r = -0.59$) was observed between biodegradability ratio (BDOC/DOC) and normalized UV_{254} (UV_{254}/initial UV_{254}) for ozonated, reclaimed wastewater (all 5 columns). This also shows that relative BDOC increase is associated with relative UV_{254} decrease.

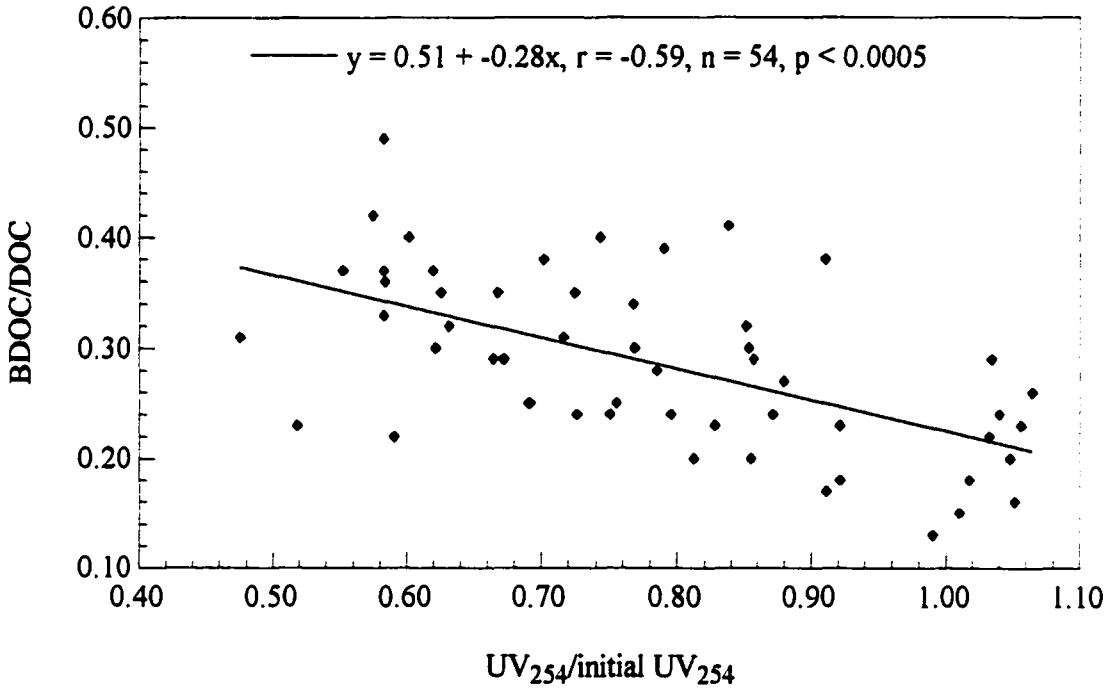


Figure 13 Relationship between biodegradability ratio (BDOC/DOC) and normalized UV_{254} (UV_{254}/ initial UV_{254}) for ozonated, reclaimed wastewater.

It was not expected that the $SBOD_u$ profile would show the same trend as the BDOC profile. This might be because $SBOD_u$ is more sensitive than $SBOD_5$. Also, all of the samples were well nitrified; the oxygen demand was therefore exerted only from the organic carbon biodegradation ($SBOD_u \approx SCBOD_u$). However, some of the weekly profiles shown in Figures 14(a) and 14(b) indicate that BDOC is a better parameter especially when long term monitoring cannot be performed.

The correlations among DOC, BDOC, and $SBOD_u$ for the sand filter, ozonation columns (regardless of the column) and BAC filter effluents are illustrated in Figures 15, 16, and 17. Since the BDOC and $SBOD_u$ of the nanofilter effluent were often less than the detection limits, they were not included. All of the correlations are significant ($p < 0.05$). Strong linear relationships were found between DOC and BDOC, and BDOC and $SBOD_u$ ($r = 0.70$ to 0.88 and 0.70 to 0.85). The linear regressions on the DOC and $SBOD_u$ data show weaker relationships ($r = 0.52$ to 0.74). This indicates that BDOC is a more appropriate parameter than $SBOD_u$ for this case. However, all of the correlations support the earlier discussion. They all show that the effluents from the ozonation columns were more biodegradable than those from the sand filter and BAC filter.

Figures 18 and 19 illustrate the correlations between DOC and UV_{254}, and BDOC and UV_{254}, respectively. For the sand filter effluent, DOC and BDOC have strong and significant positive relationships with UV_{254} ($r = 0.73$ and 0.81, $p < 0.01$ and 0.0025). As expected, DOC and BDOC correlate weakly with UV_{254} for the effluent samples from the ozonation columns ($r = 0.40$ and 0.12) and BAC filter ($r = 0.50$ and 0.17). The poor

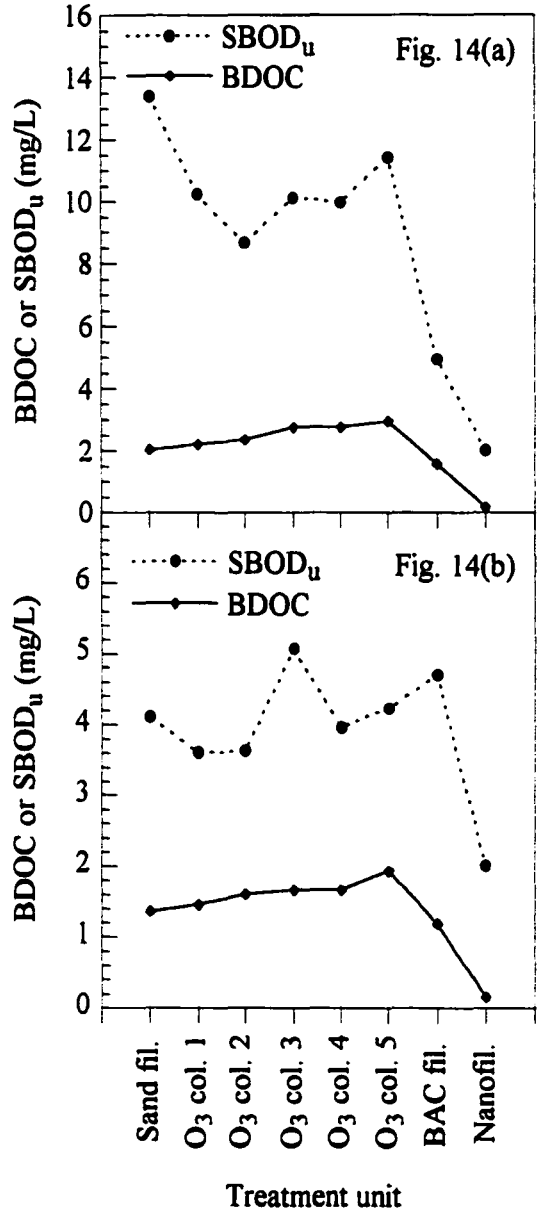


Figure 14 SBOD$_u$ and BDOC weekly profiles, sampling date: a) 10/25/94 and b) 11/22/94.

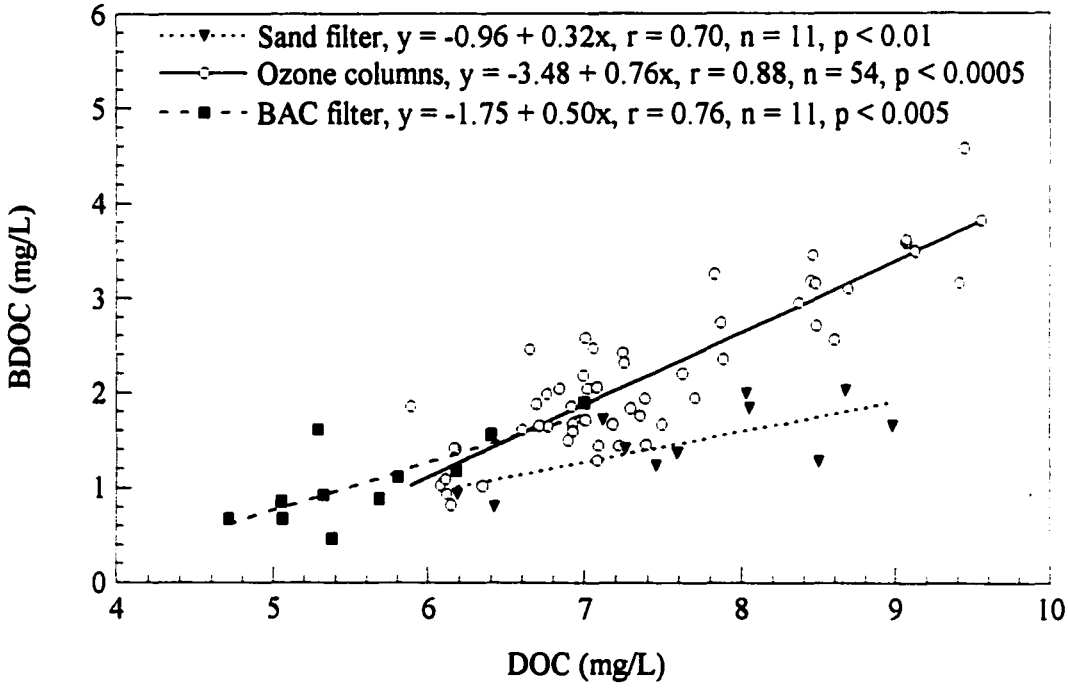


Figure 15 Correlations of DOC and BDOC for reclaimed wastewaters.

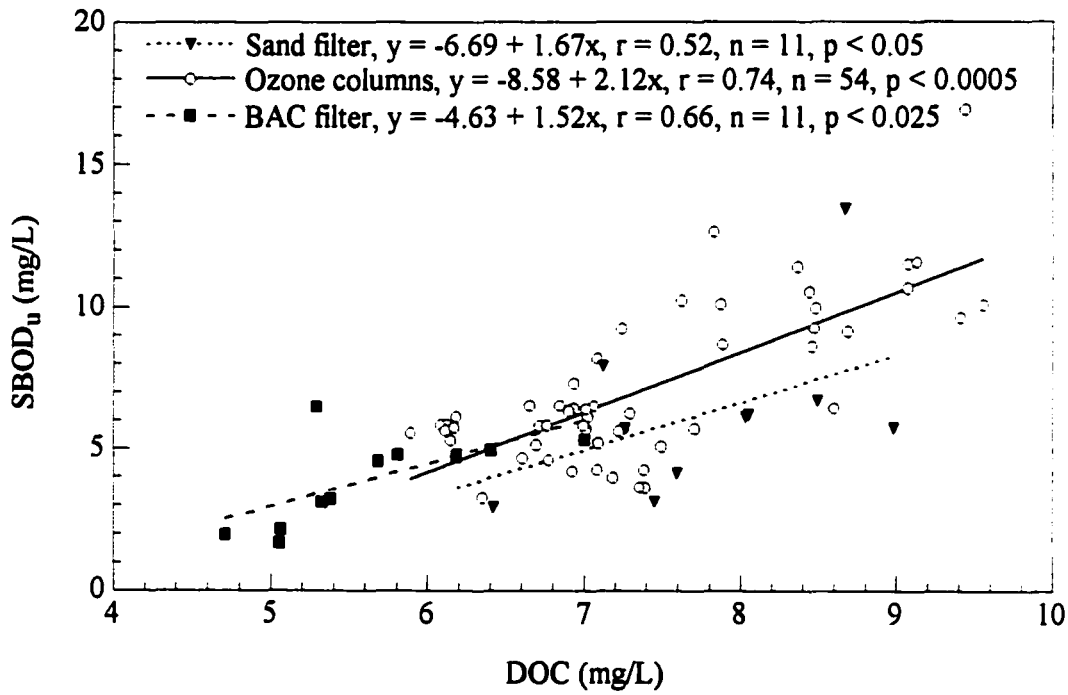


Figure 16 Correlations of DOC and $SBOD_u$ for reclaimed wastewaters.

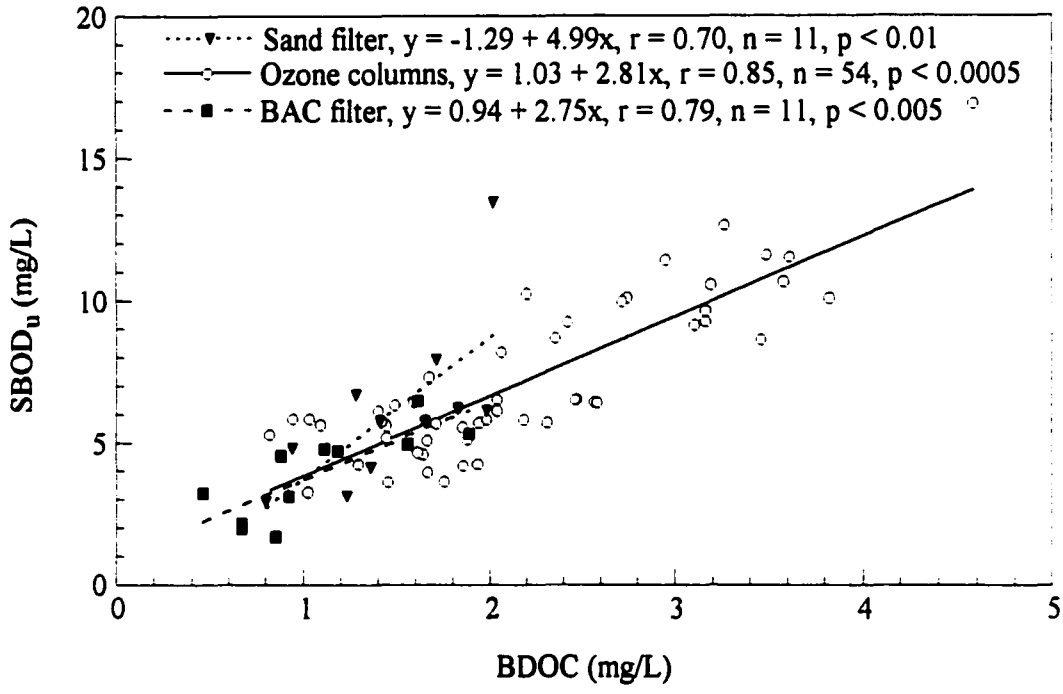


Figure 17 Correlations of BDOC and SBOD$_u$ for reclaimed wastewaters.

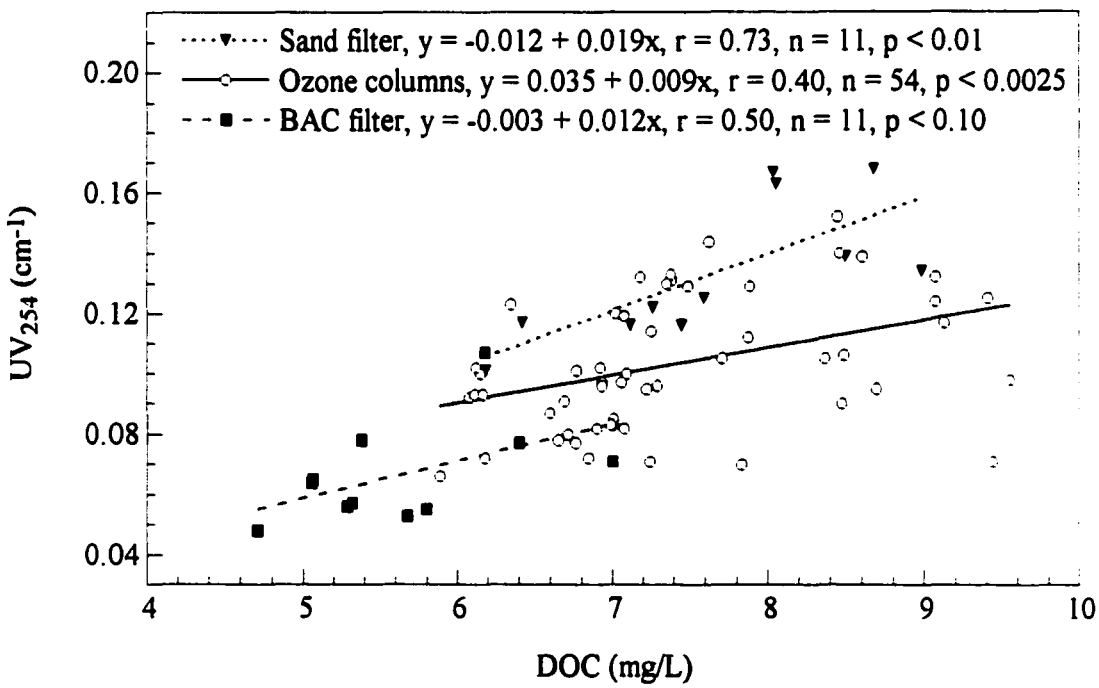


Figure 18 Correlations of DOC and UV_{254} for reclaimed wastewaters.

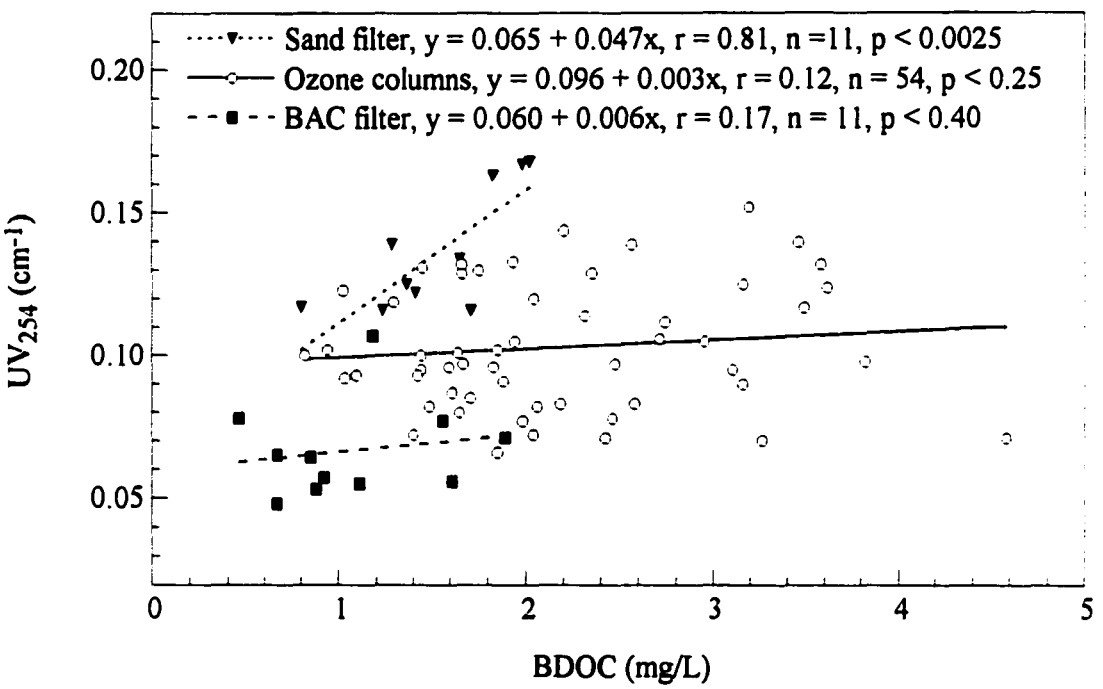


Figure 19 Correlations of BDOC and UV_{254} for reclaimed wastewaters.

relationships may be attributed to the highly varying and stochastic nature of reclaimed wastewater composition and reaction with ozone. The trickling filter performance varies considerably during the course of normal operation. As shown in Figure 20, very poor correlation was also found between BDOC increase and UV_{254} decrease after each ozone column ($r = 0.17$). UV_{254} declines dramatically across the ozonation columns but is not well connected to DOC and BDOC.

3.3.2 BDOC as an indicator of secondary effluent quality

Average DOC, BDOC, and SCOD concentrations and standard deviations of secondary effluents are listed in Table 6. The plants were selected to cover a wide range of solids retention time (SRT). Usually most of the plants are operated at either low or high SRTs (SRT $\leq$ 4 days or SRT $\geq$ 10 days). As a result, the secondary effluents of these plants are either non- or fully nitrified. In some of the high SRT plants (RP1, RP2, and Carbon Canyon), BOD_5 concentrations of secondary effluents are frequently below the detection limit. TOC has been used as an indicator for secondary effluent quality as well as a process controlling parameter.

The relationships between the three parameters and SRT have very similar trends. The AS plants operated at higher SRTs tend to produce the secondary effluents with much less DOC, BDOC, and SCOD. BDOC concentrations range from 0.47 ± 0.12 to 0.77 ± 0.14 mg/L for the effluent samples from high SRT plants and from 1.64 ± 0.29 to as high as 3.91 ± 0.52 mg/L for the effluent samples from low SRT plants. The BDOC

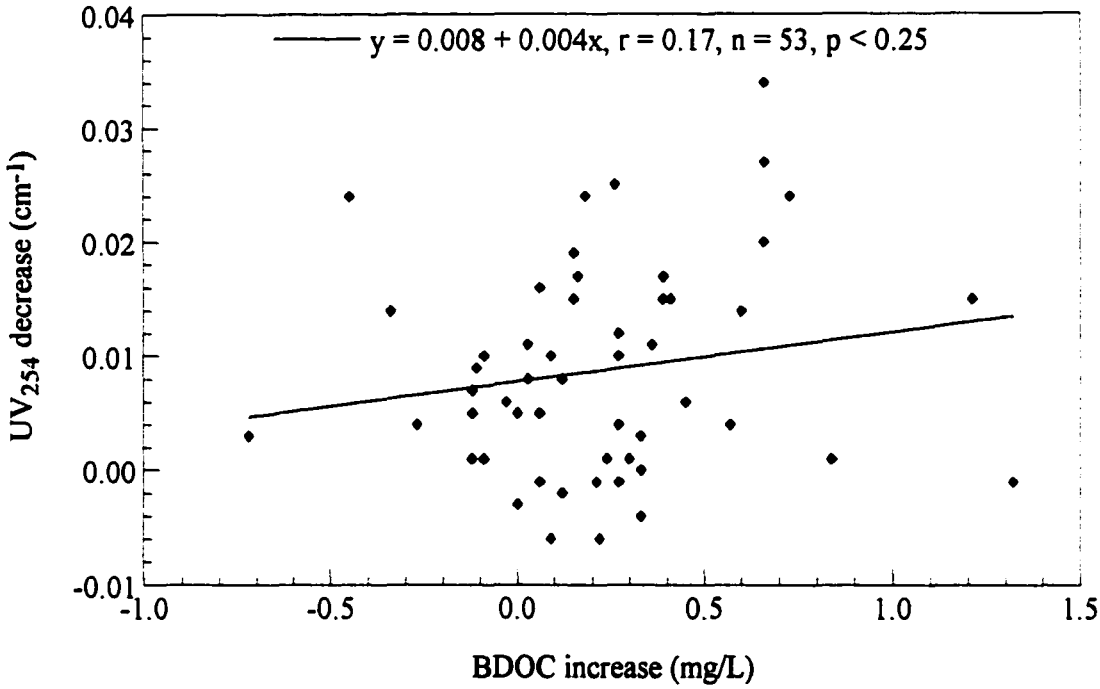


Figure 20 Correlation of BDOC increase and UV_{254} decrease for ozonated, reclaimed wastewater.

Table 6 DOC, BDOC, SCOD, and RDOC concentrations and BDOC/DOC of secondary effluents.

WWTP	Approx. SRT* (days)	Average DOC ± S. D. (mg/L) & (% daily variation)	Average BDOC ± S. D. (mg/L) & (% daily variation)	Average SCOD ± S. D. (mg/L) & (% daily variation)	Average RDOC ± S. D. (mg/L)	Average BDOC/DOC ± S. D. (%)
Orange no. 2#	0.7	11.00 ± 0.63 (6)	3.10 ± 0.42 (13)	34.6 ± 2.0 (6)	7.90 ± 0.57	28.20 ± 3.29
Hyperion#	1.4	10.96 ± 0.86 (8)	3.47 ± 0.60 (17)	33.5 ± 2.1 (6)	7.49 ± 0.50	31.50 ± 3.83
Sacramento#	2.0	8.58 ± 0.50 (6)	2.82 ± 0.38 (13)	24.1 ± 0.9 (4)	5.76 ± 0.20	32.73 ± 2.79
Union°	2.0	13.72 ± 0.98 (7)	3.90 ± 0.50 (13)	38.7 ± 1.7 (4)	9.82 ± 0.79	28.43 ± 2.89
Glendale°	2.0	9.21 ± 0.43 (5)	1.64 ± 0.29 (18)	28.0 ± 2.1 (8)	7.57 ± 0.20	17.78 ± 2.38
JWPCP#	2.4	12.35 ± 0.57 (5)	2.61 ± 0.48 (18)	38.1 ± 1.3 (3)	9.74 ± 0.31	21.04 ± 3.18
Orange no. 1°	2.5	8.72 ± 0.43 (5)	1.79 ± 0.39 (22)	28.1 ± 1.8 (6)	6.93 ± 0.39	20.43 ± 3.91
Tillman°	4.0	8.74 ± 0.27 (3)	1.72 ± 0.35 (20)	28.0 ± 0.8 (3)	7.01 ± 0.27	19.67 ± 3.60
Tapia+	10.0	7.66 ± 0.16 (2)	0.77 ± 0.14 (18)	21.0 ± 0.3 (1)	6.89 ± 0.12	10.03 ± 1.68
RP1+	10.0	4.96 ± 0.26 (9)	0.45 ± 0.12 (26)	14.4 ± 2.0 (14)	4.50 ± 0.23	9.07 ± 2.16
RP2+	10.0	5.72 ± 0.08 (1)	0.72 ± 0.11 (15)	16.6 ± 0.8 (5)	5.00 ± 0.13	12.60 ± 1.91
Las Vegas×	13.6	6.30 ± 0.37 (6)	0.67 ± 0.09 (13)	17.9 ± 0.8 (4)	5.64 ± 0.30	10.52 ± 1.12
Carbon Canyon+	80	4.91 ± 0.26 (5)	0.68 ± 0.17 (25)	11.0 ± 1.6 (15)	4.24 ± 0.15	13.66 ± 2.70

* Based on aeration tank volume
# HPO AS
o Conventional AS
\+ Conventional AS with nutrient removal
× Trickling filter followed by conventional AS with nutrient removal

concentrations in every plant have much more daily variation than the other two parameters. This shows higher sensitivity provided by the modified BDOC method. As illustrated in Figure 21, the relationship between BDOC and SRT is non-linear. BDOC sharply decreases with increasing SRT in the lower SRT range (0 - 4 days) and is stable in the higher SRT range (≥ 10 days). The plot in Figure 21 agrees with the effluent substrate concentration-SRT relationship shown in Figure 22 which was theoretically proposed by Lawrence and McCarty (1970) . Even though the relationship is routinely predicted by models, experimental verification using BOD or COD has not been very successful. This is probably because of the variability of the BOD and COD procedures. The relationship can be clearly seen using BDOC.

The type of plant has an impact on the effluent BDOC. High BDOC was observed in the effluents of the HPO AS plants (SRT = 0.7 to 2.5 days). Medium BDOC was detected in the effluents of conventional AS (CAS) plants (SRT = 2.0 to 4.0 days). The effluents of CAS plants with nutrient removal (SRT ≥ 10 days) have least BDOC. However, the effluent of one of the CAS plants (Union) has higher BDOC, DOC, and SCOD than the effluents of the HPO AS plants and therefore does not follow the trend. The reason for this difference was not investigated.

Average refractory DOC (RDOC = DOC - BDOC) concentrations and BDOC/ DOC values of secondary effluents are also shown in Table 6. Like the first three parameters, RDOC concentrations are lower in high SRT plants. However, RDOC does not abruptly decrease with increasing SRT in the lower SRT range. BDOC/DOC could be

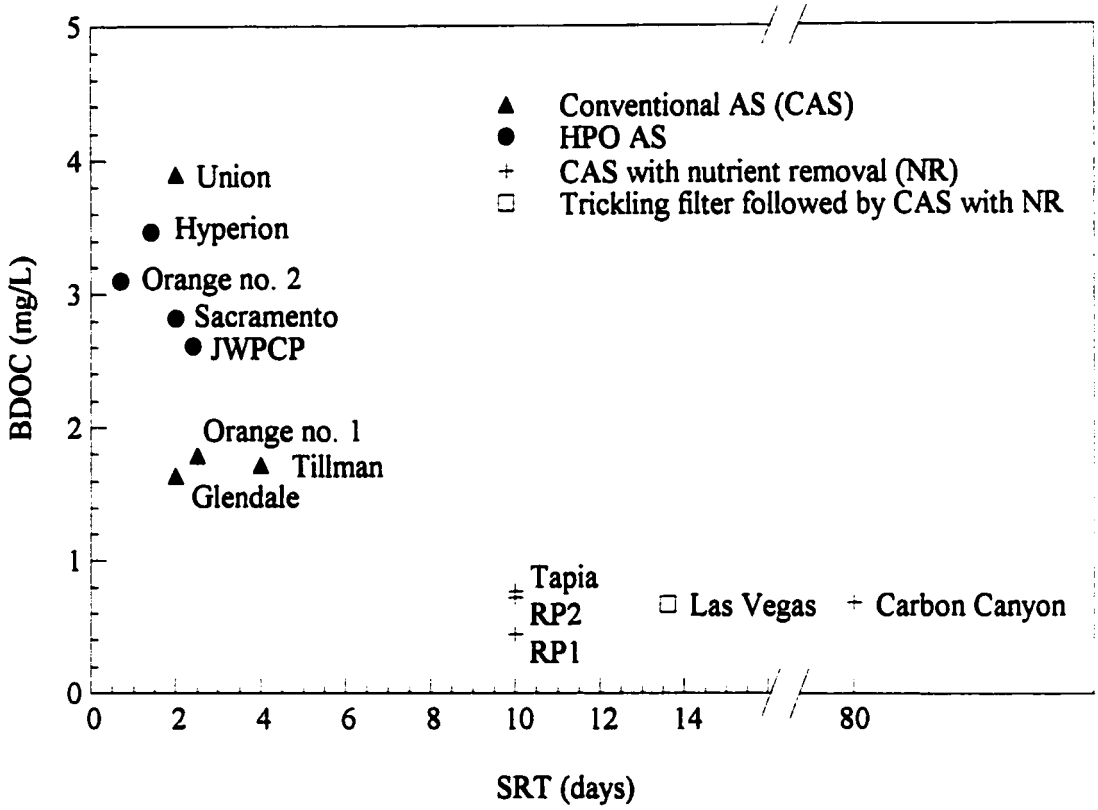


Figure 21 BDOC concentrations of secondary effluents versus SRTs of treatment plants.

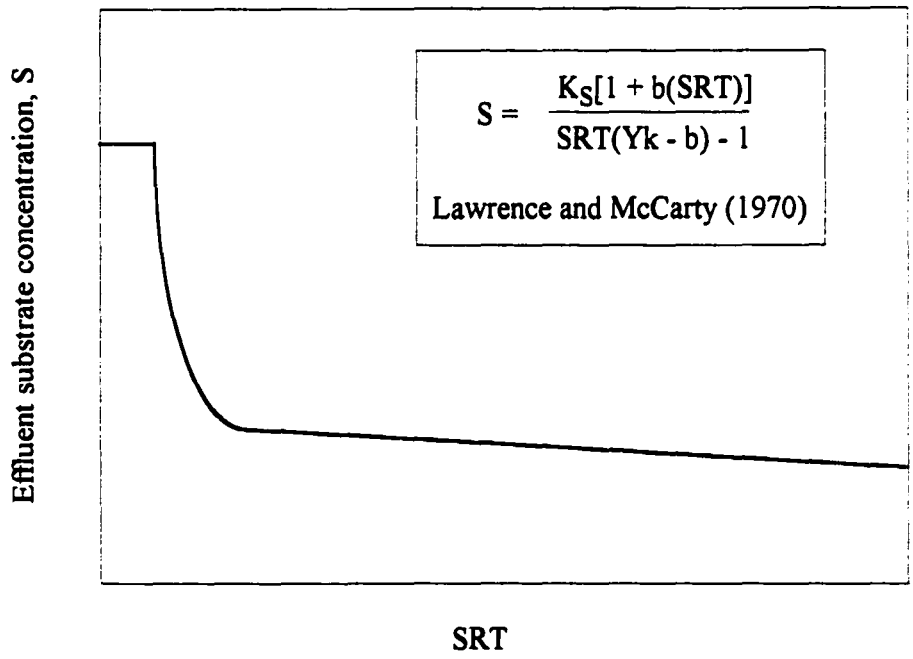


Figure 22 Steady-State relationship between SRT and effluent substrate concentration for completely mixed, continuous flow biological treatment processes (Lawrence and McCarty, 1970).

used to indicate biodegradability. Regardless of the absolute BDOC concentration, samples with higher BDOC/DOC values are more biodegradable than samples with lower BDOC values. As shown in Table 6, DOCs of secondary effluents from low SRT plants are more biodegradable or have greater BDOC per unit DOC than effluents from high SRT plants.

Figures 23, 24, and 25 illustrate extremely strong and significant relationships ($r > 0.85$ and $p < 0.0005$) among DOC, BDOC, and SCOD of the secondary effluents. This suggests that BDOC can be used for indicating the effluent quality as well as or better than DOC and SCOD. SCOD is less precise and both DOC and SCOD are unable to indicate the biodegradability.

3.4 Conclusions

This chapter presents two applications of a modified BDOC protocol exclusively designed for examining reclaimed and secondary treated wastewaters. The protocol was used to evaluate the performance of a wastewater reclamation system and secondary effluent quality.

The modified BDOC protocol was utilized to successfully evaluate the performance of an ozone/granular activated carbon system during a municipal wastewater reclamation project at Lake Arrowhead, California. The biodegradability increase during ozonation can be detected using the modified BDOC protocol. BDOC is a more

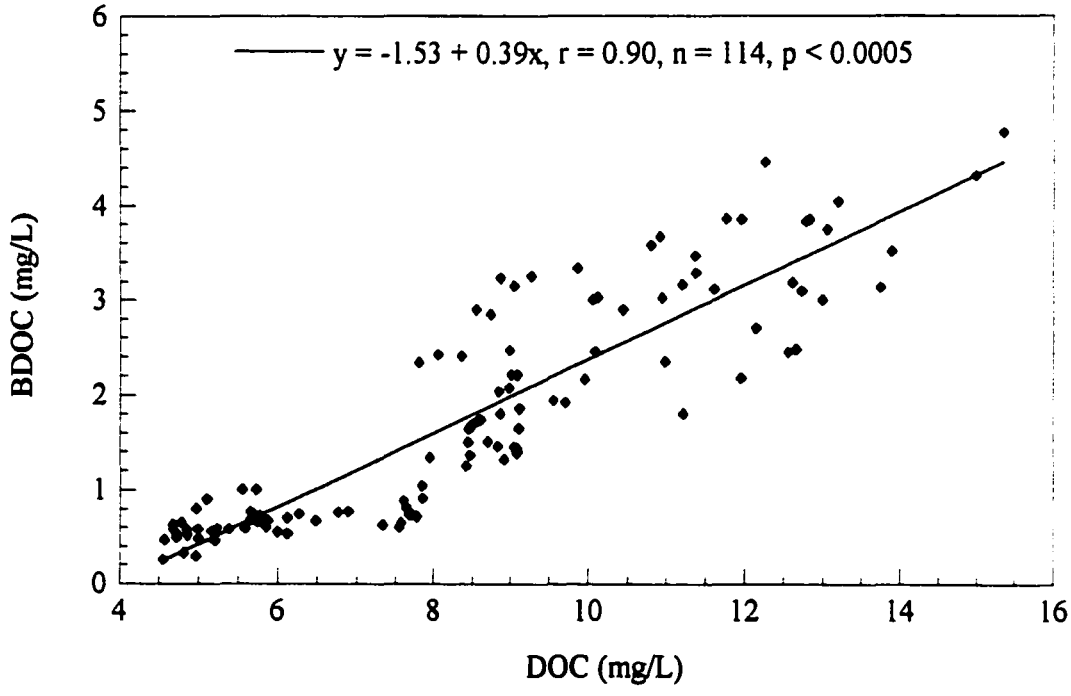


Figure 23 Correlation of DOC and BDOC for secondary effluents.

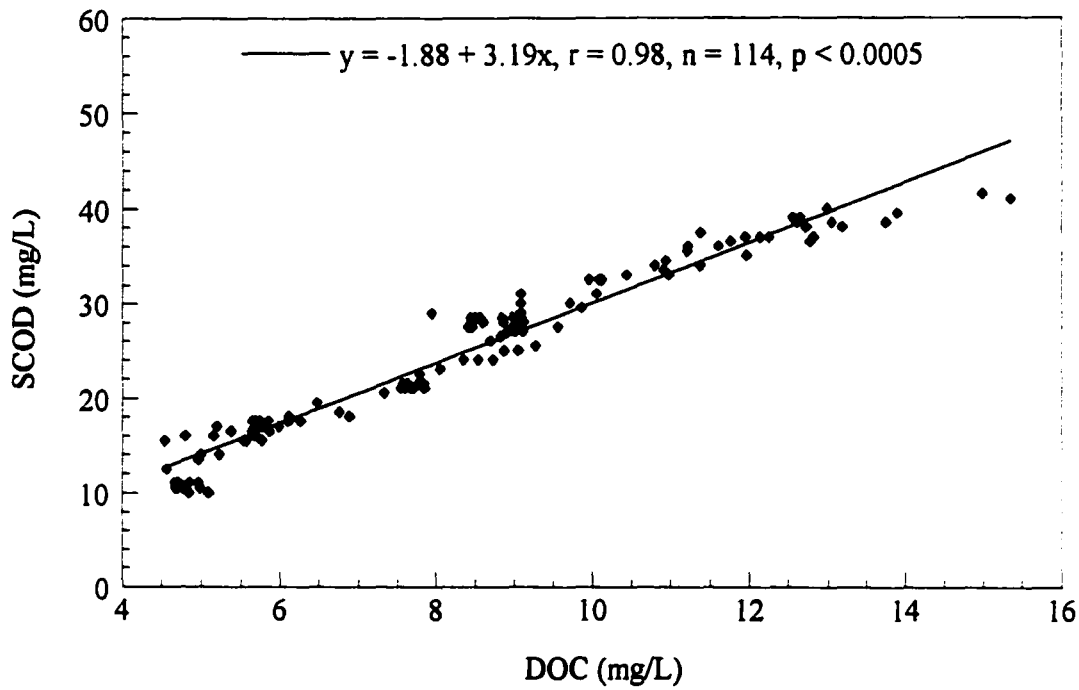


Figure 24 Correlation of DOC and SCOD for secondary effluents.

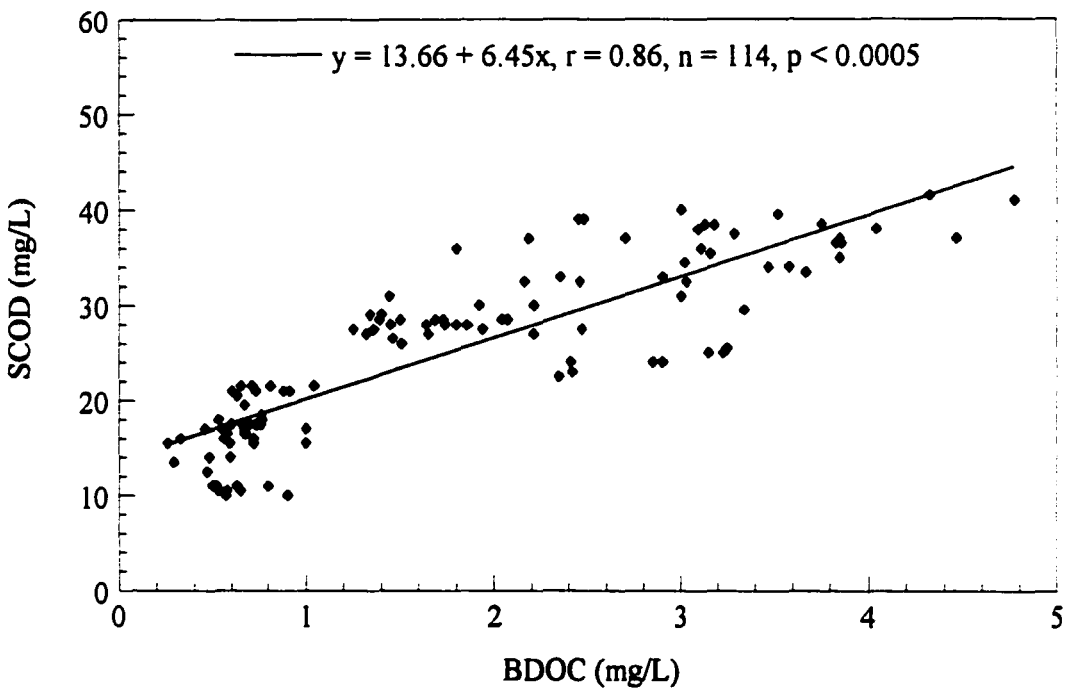


Figure 25 Correlation of BDOC and SCOD for secondary effluents.

appropriate parameter than DOC and $SBOD_u$ for indicating the plant performance, when removal of degradable organic carbon is an objective. DOC measurements could not distinguish the biodegradability in water samples from primary ozone columns. Although $SBOD_u$ and BDOC measurements along the reclamation pilot plant for 11 consecutive weeks provide similar profiles, $SBOD_u$ is less accurate and less precise. Significant and strong positive linear correlations among DOC, BDOC, and $SBOD_u$ were obtained.

BDOC can indicate secondary effluent quality. It provides more sensitivity than DOC and SCOD. The relationship between BDOC and SRT is non-linear. The effluents of low SRT treatment plants have higher BDOC concentrations than the effluents of high SRT treatment plants. The least BDOC was detected in the effluents of high SRT plants with nutrient removal. Excellent correlations were found among DOC, BDOC, and SCOD of secondary effluent samples. This confirms that BDOC can be used as a water quality parameter for secondary effluents as well as or better than currently existing parameters.

4.0 IMPROVEMENTS OF THE MODIFIED BDOC PROCEDURE

In Chapter 2, the modified BDOC batch protocol was developed for characterizing waters with moderate DOC (4 to 15 mg/L) such as reclaimed and secondary treated wastewaters. The development was performed by adapting a BDOC batch procedure (Servais *et al.*, 1989) used in the drinking water industry. By following the modified procedure, concurrent determinations of three water quality parameters, which are DOC, SBOD, and BDOC, are possible. It was also shown that BDOC is a more sensitive (lower detection limit) and more precise parameter than BOD and COD. The results in Chapter 3 show that BDOC can be useful to the wastewater treatment and reclamation fields, although there may be some drawbacks associated with the use of the protocol.

This chapter presents research that attempts to remove the technical barriers associated with the modified BDOC protocol so that BDOC can be used as a routine parameter for wastewater treatment and reclamation plants. The research focuses on the use of different inoculum types and sizes for a more rapid BDOC determination and simultaneous determinations of BDOC and $SBOD_5$. Three types of samples, which are standard solutions (specific compounds), secondary effluents, and ozonated secondary effluents, were used in this study. BDOC concentrations and the kinetics of BDOC exertion resulting from different inoculum types and sizes were compared.

4.1 Background

Although it has been shown in Chapter 3 that BDOC can successfully indicate the performance of wastewater reclamation plant and secondary effluent quality, the modified BDOC batch protocol still suffers from the following limitations and disadvantages.

4.1.1 Long incubation time

The modified BDOC protocol procedure requires an incubation time of 28 days. This long incubation time was designed to allow the maximum exertion of BDOC while minimizing the size and the concentration of the inoculum served during the incubation. The minimization of the inoculum size and concentration was intended to limit the release of organic carbon (soluble microbial products) which may cause the underestimation of BDOC.

4.1.2 Lag period

A kinetic study of the BDOC exertion during the procedure shows that, at the incubation temperature of 20 °C, the exertion does not agree with the first-order model. A lag period may have occurred during the incubation and caused the disagreement. Since the procedure requires an acclimated inoculum, the lag was likely generated by an inadequate number of viable cells provided at the beginning of the incubation.

4.1.3 Inability to determine BDOC and $SBOD_5$ of secondary effluents simultaneously

Although BOD is not as precise or sensitive as BDOC, it is advantageous to have a BDOC procedure that can concurrently provide BOD information. When the modified BDOC procedure was applied to secondary effluents, the dissolved oxygen (DO) consumptions after 5 days of incubation were always less than the criteria of 2.0 mg/L specified by *Standard Methods* (1989). When applying the procedure to reclaimed wastewaters, the final DO was measured after 28 days and the problem was not observed. The kinetic study during the incubation also suggested that the amount of BDOC exerted during the first 5 days of the incubation is very small (10.3 ± 9.5% of the final BDOC). This supports the speculation regarding the lag period and insufficient inoculum.

4.1.4 Difference between the final BDOC ($BDOC_{28}$) of secondary effluents incubated at 20°C and 37°C

Statistically significant differences (one-tailed *t*-test, $p < 0.05$) in $BDOC_{28}$ of secondary effluents incubated at 20°C and 37°C, were observed. Similar results were not found for reclaimed wastewaters; the differences in $BDOC_{28}$ incubated at 20°C and 37°C, were statistically insignificant (one-tailed *t*-test, $p > 0.05$). $BDOC_{28}$ of the secondary effluents at 20°C was only 75 ± 12% of that exerted at 37°C. This suggests that the rate of reaction is controlling the $BDOC_{28}$, and not the ultimate BDOC. Increasing initial inoculum volume or mass is one way to increase the rate of reaction.

It can be seen that all of the above limitations and disadvantages may be attributed to the small-size inoculum (2 mL of unfiltered effluent). Employing a larger inoculum size and/or a more concentrated inoculum should mitigate the limitations and disadvantages; however, separation of microorganisms after the incubation will be required as another step in the procedure.

By increasing the cell mass used during the incubation, Joret *et al.* (1988) successfully developed a more rapid assay for measuring BDOC in drinking water. In their procedure, a 300 mL water sample was inoculated with 100 g of prewashed biologically active sand collected from a water treatment plant that does not have prechlorination. The prewashing of the sand is required to reduce the possibility of sample contamination. During incubation at 20°C, the sample was aerated and DOC was measured daily until there was either no change or an increase in DOC, which usually occurred after 3 to 5 days. The difference between initial DOC and minimum DOC was taken as BDOC.

The procedure by Joret *et al.* (1988) greatly reduces the time of the test because a large amount of biomass is used (biofilm on the surface of the sand). Nevertheless, the procedure is still subject to several weaknesses. First, daily monitoring of DOC is labor and time consuming. Moreover, although the use of sand as a support medium may not release organic carbon (because of the prewashing), the adsorption of organics (instead of biodegradation) may occur. Finally, the aeration during incubation can strip volatile organic carbon (VOC) which may be biodegradable.

4.2 Methodology

A glass fiber filtration (GF/F, Whatman) step after the incubation was inserted into the modified BDOC batch procedure. Larger volume and/or more concentrated inocula, such as commercial BOD seed (Polyseed®, Polybac Corporation, Bethlehem, PA) and mixed liquor suspended solids (MLSS), were explored in addition to the 2 mL unfiltered effluent inoculum. All four inocula were used to determine BDOC in standard solutions, secondary effluents, and ozonated secondary effluents. The MLSS inoculum was collected from the same treatment facility as the sample on the last day of sampling period and used within 24 hours without any pre-rinsing. After the inoculum was brought back to the laboratory, it was continuously aerated to maintain aerobic condition. The well mixed inoculum was introduced to the sample using a wide-tip pipette. For standard solutions, the effluent and MLSS inocula were collected from the Chevron refinery wastewater treatment facility, El Segundo, CA. The kinetics of BDOC exertion for all four inocula were also observed.

4.2.1 Standard solution experiment

Sodium acetate and phenol standard solutions were studied. Each compound was used to prepare three solutions that have approximate DOC concentrations of 2, 5, and 10 mg/L (a total of 6 standard solutions), respectively. Four inocula, which were 2 mL of unfiltered effluent, 10 mL of unfiltered effluent, 2 mL (recommended by the manufacturer)

of commercial BOD seed, and 2 mL of MLSS, were tested. Using each of the four inocula, the BDOC test was performed without soluble BOD (SBOD) determination at two incubation temperatures: 20°C and 37°C (4 × 2 experimental design). To investigate the BDOC exertion kinetics, filtered samples were collected and measured for TOC at 1, 2, 3, 4, 5, 7, 10, 15, 20, and 28 days.

4.2.2 Secondary effluent experiment

Unchlorinated secondary effluent grab samples were collected daily for four consecutive days from each of the following three low solids retention time (SRT) high purity oxygen (HPO) activated sludge (AS) municipal wastewater treatment plants (WWTPs):

- Hyperion WWTP, Playa del Rey, CA, 200 MGD, SRT = 1.4 days, operated by the Los Angeles Bureau of Sanitation (LABS),
- Joint Water Pollution Control Plant (JWPCP), Carson, CA, 200 MGD, SRT = 2.4 days, operated by the Sanitation Districts of Los Angeles County, and
- Sacramento Regional WWTP, Elk Grove, CA, 170 MGD, SRT = 2.0 days, operated by the Sacramento Regional County Sanitation District.

The flow rates listed above are nominal flow rates and only the secondary portions of the Hyperion plant and JWPCP are reported. The experimental design for these sets of samples is similar to the design described for standard solution experiment with two exceptions. The first difference is that the 2 mL MLSS and 2 mL commercial BOD

inocula were tested in duplicate, and $SBOD_5$ measurement was simultaneously attempted on the duplicate. It was necessary to use a duplicate for the $SBOD_5$ measurement because the bottles for the BDOC measurement were opened daily to take samples. The second difference is that the TOC of filtered samples was measured only at 5, 10, 15, 20, and 28 days when the effluent inocula (2 mL and 10 mL) were used.

4.2.3 Non-ozonated versus ozonated secondary effluent experiment

Unchlorinated secondary effluent grab samples were collected daily for two consecutive days from each of the following three high SRT (fully nitrified) AS municipal WWTPs which are operated by the Chino Basin Municipal Water District (CBMWD):

- RP 1 WWTP, Ontario, CA, 36 MGD, SRT = 15 days,
- RP 2 WWTP, Chino, CA, 5 MGD, SRT = 15 days, and
- Carbon Canyon WWTP, Chino, CA, 7 MGD, SRT = 50 days.

These effluent samples are very recalcitrant (low DOC and low BDOC). The first half of each sample was filtered (GF/F, Whatman) and the second half was filtered and ozonated. The ozonation system consists of an Ozone Research and Equipment Corporation (OREC) Ozone Generator model 03V10, air feed (OREC, Phoenix, AZ) and a 2 L ozonation vessel (Pyrex separatory funnel). All components are resistant to ozone (Teflon tubing, Teflon and stainless steel fittings, stainless steel flow meter, glass gas sampling tube with Teflon septum and valves, and sintered-glass diffuser). Excessive ozone dose was provided. Samples from the first day were used to determine ozone contact time for

samples from the second day. UV absorbance at 254 nm (UV_{254}) was measured at different times to indicate relative biodegradability as the samples were ozonated. The ozone contact time was selected to minimize UV_{254}. Influent and effluent gas-phase ozone concentrations and liquid-phase ozone concentrations were monitored. Without concurrent $SBOD_5$ determination, the BDOC test was performed on samples from both days employing 4 different inocula, which were 2 mL of unfiltered sample, 2 mL of MLSS, 5 mL of MLSS, and 10 mL of MLSS, at two incubation temperatures (20°C and 37°C) on ozonated and non-ozonated samples (4 × 2 × 2 experimental design). The kinetics of BDOC exertion were observed for all cases following the same approach described in the above standard solution experiment section except that the 2 mL effluent inoculated samples were measured for TOC only at 5, 10, 15, 20, and 28 days.

4.2.4 Analyses and measurements

BDOC and $SBOD_5$ were determined by the modified BDOC batch protocol described in Chapter 2. The procedure and the instrument used for measuring UV_{254} are the same as described in Chapter 3. Gas-phase ozone was measured by following the procedure described in Collins *et al.* (1989). Liquid-phase ozone was determined using the Indigo Method as specified in *Standard Methods* (1989).

4.3 Results and Discussion

4.3.1 Standard solutions

Figure 26(a and b) shows the BDOC exertion and the reciprocal DOC reduction as a function of time when sodium acetate solution with a DOC concentration of 9.97 mg/L was examined. Complete BDOC exertion or DOC depletion occurred within 5 days for all four inocula at both temperatures. Regardless of the inoculum and the incubation temperature, the procedure was able to provide a precise prediction of BDOC at any time from 5 to 28 days. This would not be possible if the procedure did not include the seed control technique. Figure 26(c) shows the DOC concentrations created by the inocula. The initial DOC of the blank water before adding the inoculum was 0.12 mg/L. The plots suggest no evidence of continuing DOC release due to the endogenous respiration (soluble microbial products) at any incubation time and temperature for all four inocula; the DOC was relatively constant over the 28 day period. For five other standard solutions, the BDOC exertion and the DOC reduction curves are all similar to the curves shown in Figure 26(a and b) except for the standard solutions with lower DOC concentrations (2 and 5 mg DOC/L), the BDOC was fully exerted in a shorter time (1 to 3 days). BDOC exertion data for five other standard solutions are summarized in Appendix G.

The recoveries of acetate and phenol during the BDOC procedure at incubation times of 5 and 28 days are presented in Table 7(a) and Table 7(b), respectively. The recoveries at 5 days are specifically shown because it is expected to use the same

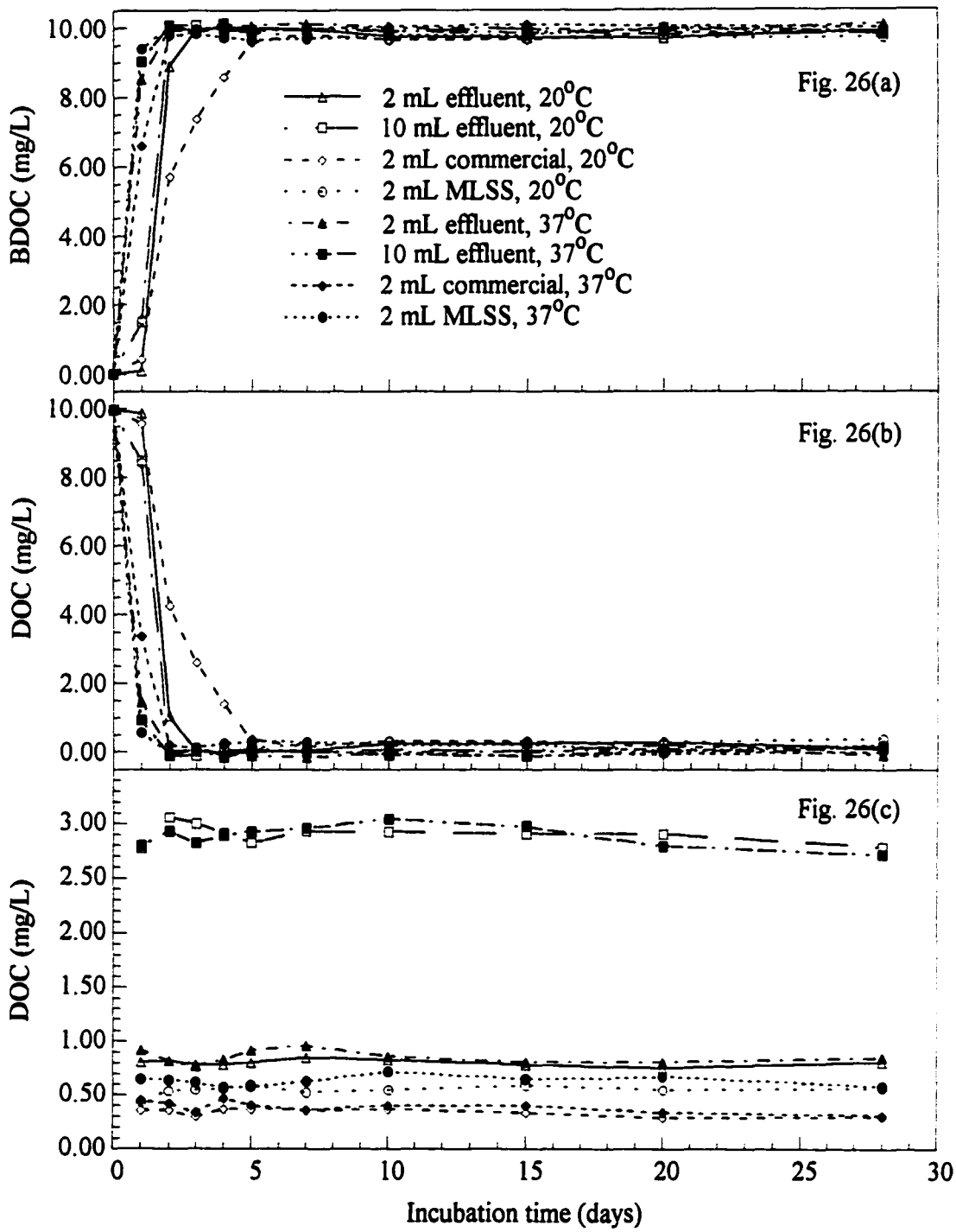


Figure 26 a) BDOC exertion, b) DOC reduction when the procedure was used to measure sodium acetate solution with a DOC of 9.97 mg/L, and c) DOC produced by adding the inoculum in the blank water (seed control) with an initial DOC of 0.12 mg/L.

Table 7(a) Recovery of acetate during the BDOC procedure.

Inoculum and incubation temp. (°C)	Recovery of acetate (%) = [(BDOC/DOC_0) × 100]						Average ± S. D.
	DOC_0 = 1.94 mg/L		DOC_0 = 4.89 mg/L		DOC_0 = 9.97 mg/L		
	5 days	28 days	5 days	28 days	5 days	28 days	
2 mL eff., 20	93.8	99.5	99.2	99.4	100.2	99.2	98.6 ± 2.4
10 mL eff., 20	92.8	96.9	96.5	98.2	99.3	98.4	97.0 ± 2.3
2 mL com., 20	99.5	98.5	100.0	100.0	96.3	99.1	98.9 ± 1.4
2 mL MLSS, 20	97.4	97.9	99.4	98.8	99.1	97.2	98.3 ± 0.9
2 mL eff., 37	101.5	101.0	102.7	101.4	100.9	101.1	101.4 ± 0.7
10 mL eff., 37	99.5	98.5	100.0	99.4	99.5	98.9	99.3 ± 0.5
2 mL com., 37	93.3	99.0	99.8	100.4	99.6	100.1	98.7 ± 2.7
2 mL MLSS, 37	86.6	95.4	93.3	97.8	96.8	98.0	94.7 ± 4.3
Average ± S. D.	95.6 ± 4.9	98.3 ± 1.7	98.9 ± 2.8	99.4 ± 1.2	99.0 ± 1.6	99.0 ± 1.2	98.4 ± 2.8

Table 7(b) Recovery of phenol during the BDOC procedure.

Inoculum and incubation temp. (°C)	Recovery of phenol (%) = [(BDOC/DOC_0) × 100]						Average ± S. D.
	DOC_0 = 1.87 mg/L		DOC_0 = 4.60 mg/L		DOC_0 = 9.81 mg/L		
	5 days	28 days	5 days	28 days	5 days	28 days	
2 mL eff., 20	93.6	98.4	101.3	98.7	95.3	97.8	97.5 ± 2.7
10 mL eff., 20	97.3	100.5	103.7	103.5	101.3	99.3	100.9 ± 2.5
2 mL com., 20	96.3	95.7	97.8	98.7	95.2	99.2	97.2 ± 1.7
2 mL MLSS, 20	100.0	94.7	99.8	97.2	98.9	98.9	98.3 ± 2.0
2 mL eff., 37	100.5	102.1	103.0	101.5	98.9	98.7	100.8 ± 1.7
10 mL eff., 37	111.8	107.0	104.8	102.8	101.3	101.6	104.9 ± 4.0
2 mL com., 37	98.4	97.3	100.4	98.7	97.2	99.1	98.5 ± 1.2
2 mL MLSS, 37	86.1	91.4	96.1	97.6	95.7	97.5	94.1 ± 4.5
Average ± S. D.	98.0 ± 7.2	98.4 ± 4.8	100.9 ± 3.0	99.8 ± 2.4	98.0 ± 2.5	99.0 ± 1.2	99.0 ± 4.0

incubation time as used in the BOD procedure. For standard solutions with DOC concentrations of approximately 5 and 10 mg/L, the procedure was able to estimate the BDOC precisely and accurately, assuming that the two compounds are 100% biodegradable. The standard deviations are less than or equal to 3.0% when different inocula and/or different temperatures were used for the same sample.

BDOC was underestimated when 2 mL of MLSS was employed as an inoculum at 37°C for the 1.94 mg DOC/L acetate and 1.87 mg DOC/L phenol standard solutions. A case of BDOC overestimation was found when the 1.87 mg DOC/L phenol standard solution was inoculated with 10 mL of unfiltered effluent and incubated at 37°C. These inaccuracies may be attributed to the unavoidable errors (personal and method) involved with the BDOC determination and the effect of the errors are more obvious as the initial DOC concentration of the sample decreases. The overall accuracy and precision of the procedure are high (98.4 ± 2.4% for acetate and 99.0 ± 4.0% for phenol).

Figure 27(a, b, and c) shows the effects of the inoculum and incubation temperature on the BDOC exertion for sodium acetate standard solutions incubated from 0 to 5 days. The DOC reduction is not shown since it is basically the reciprocal of the BDOC exertion. A lag period of about 1 day was observed for all cases at 20°C while the BDOC was either completely or almost completely exerted after 1 day at 37°C. Figure 27(c) indicates that the 2 mL commercial BOD seed was the least effective inoculum (slowest BDOC exertion) at both temperatures.

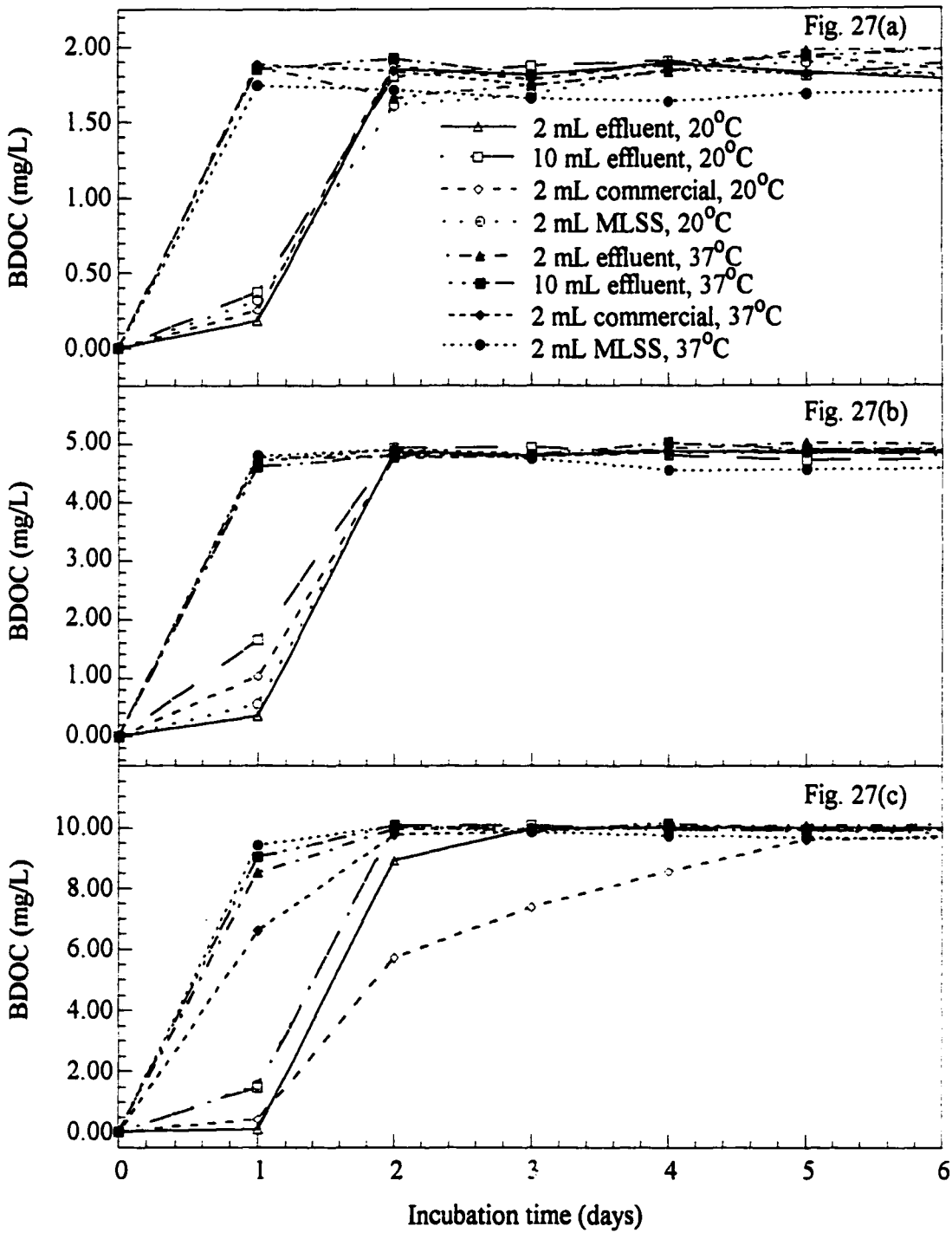


Figure 27 Effects of inoculum and incubation temperature on the exertion of BDOC for sodium acetate solutions with DOCs of a) 1.94 mg/L, b) 4.89 mg/L, and c) 9.97 mg/L.

Similar plots for phenol standard solutions are illustrated in Figure 28(a, b, and c). Longer lag periods up to 2 days were observed for some cases at 20°C. This is likely because acetate is a simpler substrate and is easier to biodegrade than phenol. Even at 37°C, the 2 mL effluent and 2 mL commercial BOD seed inocula also suffered from a lag period for most cases. Quantitative biodegradation kinetics could not be determined because of the limited data; however, it is apparent that the 2 mL commercial BOD seed inoculum provided the slowest degradation. Even though the BOD seed inoculum consists of a broad spectrum of specialized bacteria as specified by the manufacturer, the data seem to indicate that MLSS and secondary effluents are better inocula.

Applying any of the four inocula, the modified BDOC protocol responds to the standard solutions with high precision and accuracy after 1 to 5 days. The 10 mL effluent and 2 mL MLSS inocula react with the substrates (compounds) faster than the other two inocula and are good candidates for use in reducing the incubation time. The reaction of each inoculum to different types of samples (standard solutions versus actual treated wastewater) may not be the same. Therefore, a study on the response of all four inocula to secondary effluent samples was also conducted.

4.3.2 Secondary effluents

Concurrent determinations of $SBOD_5$ and BDOC were successful only when using the 2 mL MLSS inoculum. When inoculating the undiluted samples with the 2 mL BOD seed inoculum, the reductions of DO were less than the minimum criteria of 2.0 mg/L

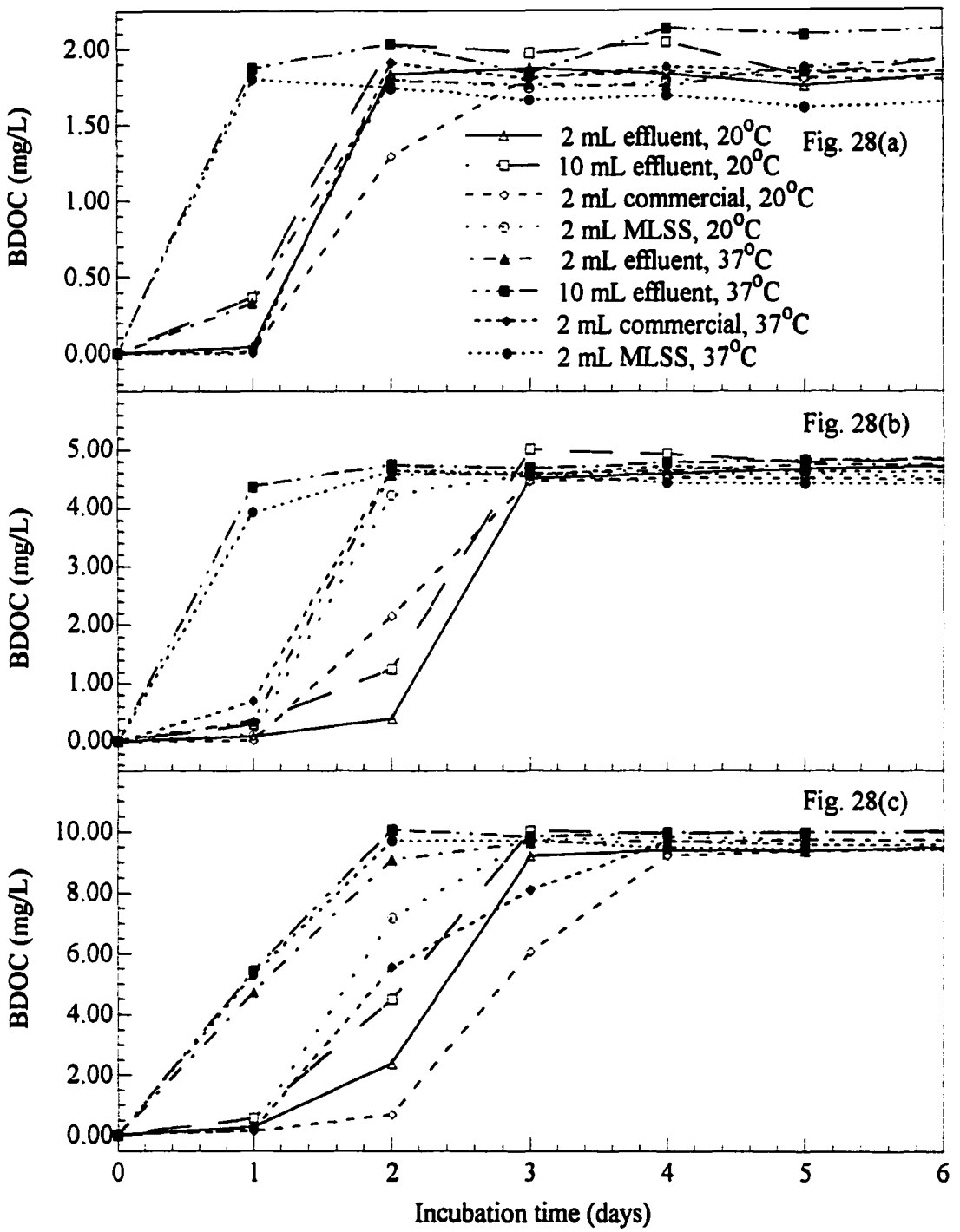


Figure 28 Effects of inoculum and incubation temperature on the exertion of BDOC for phenol solutions with DOCs of a) 1.87 mg/L, b) 4.60 mg/L, and c) 9.81 mg/L.

established by *Standard Methods* (1989). Four additional samples were collected daily for four consecutive days from each plant (listed in the methodology section on secondary effluent experiment) for the concurrent determinations. As illustrated in Figure 29, $SBOD_5$ and $BDOC_5$ (the same bottle) correlate fairly and significantly ($r = 0.61$ and $p < 0.001$). A weak but significant correlation ($r = 0.35$ and $p < 0.05$) between $SBOD_5$ and $BDOC_{28}$ was found. This is not surprising since there are many factors governing the rate of BOD exertion, and consequently the precision of BOD_5 is very poor. The correlation would be stronger if a longer incubation time for BOD measurement was allowed. This hypothesis is supported by the result presented in Chapter 3 (Figure 17) which shows fairly strong and significant correlations between ultimate SBOD ($SBOD_{28}$) and $BDOC_{28}$ of reclaimed wastewater samples ($r = 0.70$ to 0.85 and $p < 0.01$ to 0.0005).

Figure 30, which is a plot of normalized BDOC ($BDOC_t/BDOC_{28}$ using 2 mL MLSS at 37°C) versus incubation time (t), shows the effect of inoculum and temperature on BDOC exertion. Each value shown is an average normalized BDOC of 12 samples. Standard deviations of the normalized BDOCs are not shown in Figure 30 (as error bars) but in Table 8 because they visually interfere with the other information. After testing a few samples, it was discovered that the DOC reductions in the samples inoculated with 2 mL of commercial BOD seed were very small, and the daily DOC monitoring during the first four days was later canceled. The rate of BDOC exertion can be visually ranked from the fastest to the slowest as follows: 2 mL MLSS at 37°C, 10 mL effluent at 37°C, 2 mL effluent at 37°C, 2 mL MLSS at 20°C, 10 mL effluent at 20°C, 2 mL commercial BOD

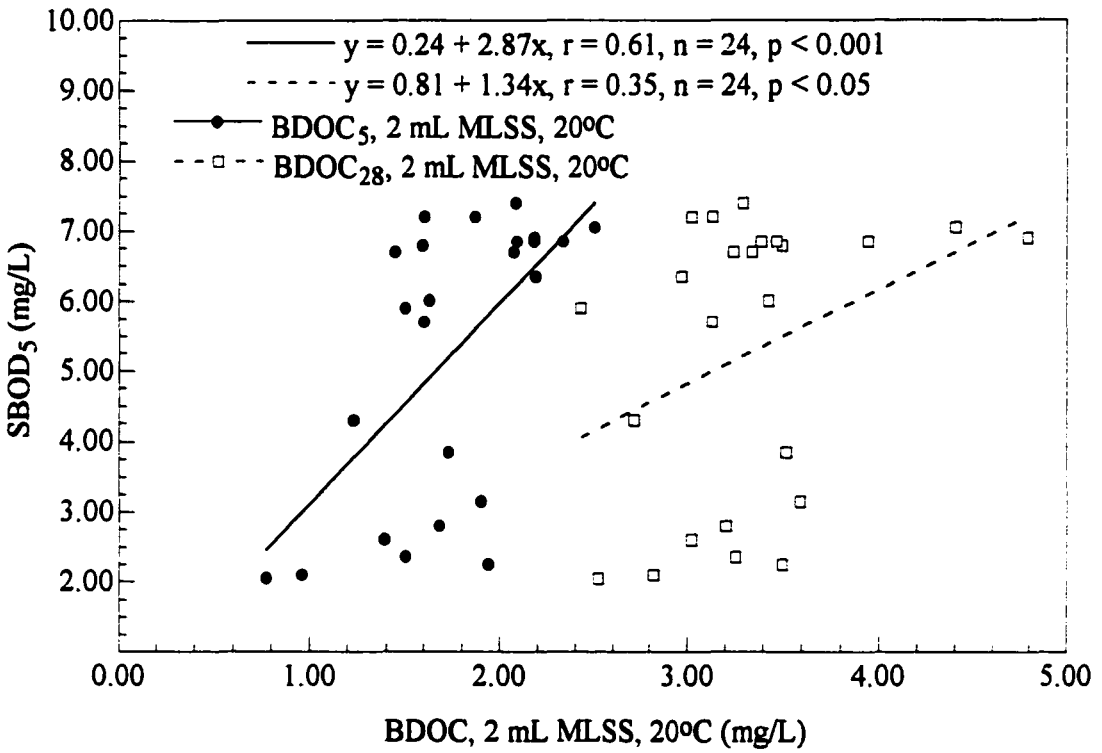


Figure 29 Correlations between BDOC, 2 mL MLSS, 20°C ($BDOC_5$ and $BDOC_{28}$) and $SBOD_5$ for secondary effluent samples from HPO plants.

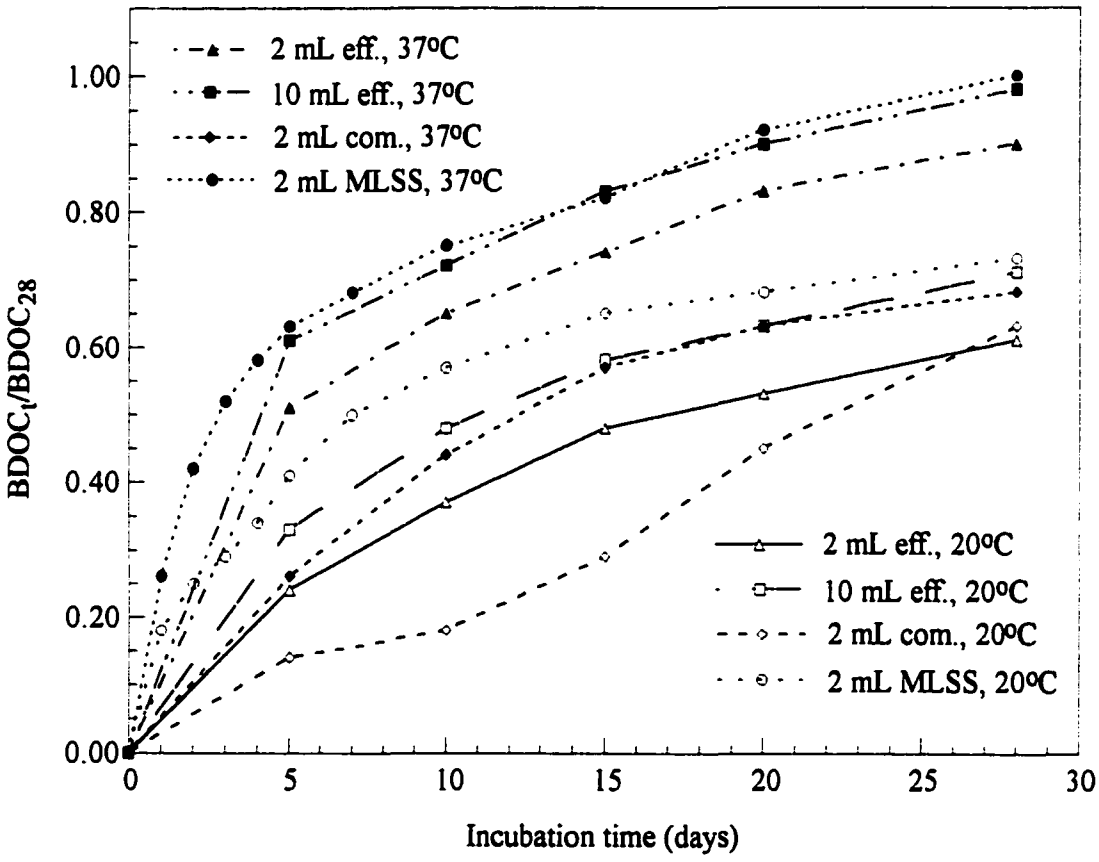


Figure 30 Effects of inoculum and incubation temperature on the exertion of BDOC for secondary effluent samples from HPO plants.

Table 8 Average normalized BDOC and standard deviation for secondary effluent samples from HPO plants.

Incubation time (days)	Average normalized BDOC ± standard deviation							
	20°C				37°C			
	2 mL eff.	10 mL eff.	2 mL com.	2 mL MLSS	2 mL eff.	10 mL eff.	2 mL com.	2 mL MLSS
1	-	-	-	0.18 ± 0.05	-	-	-	0.26 ± 0.04
2	-	-	-	0.25 ± 0.04	-	-	-	0.42 ± 0.04
3	-	-	-	0.29 ± 0.07	-	-	-	0.52 ± 0.06
4	-	-	-	0.34 ± 0.08	-	-	-	0.58 ± 0.05
5	0.24 ± 0.05	0.33 ± 0.05	0.14 ± 0.04	0.41 ± 0.08	0.51 ± 0.08	0.61 ± 0.06	0.26 ± 0.06	0.63 ± 0.05
7	-	-	-	0.50 ± 0.07	-	-	-	0.68 ± 0.05
10	0.37 ± 0.07	0.48 ± 0.06	0.18 ± 0.06	0.57 ± 0.07	0.65 ± 0.10	0.72 ± 0.09	0.44 ± 0.06	0.75 ± 0.05
15	0.48 ± 0.07	0.58 ± 0.05	0.29 ± 0.07	0.65 ± 0.03	0.74 ± 0.08	0.83 ± 0.06	0.57 ± 0.07	0.82 ± 0.04
20	0.53 ± 0.07	0.63 ± 0.05	0.45 ± 0.06	0.68 ± 0.05	0.83 ± 0.08	0.90 ± 0.09	0.63 ± 0.08	0.92 ± 0.02
28	0.61 ± 0.06	0.71 ± 0.06	0.63 ± 0.04	0.73 ± 0.07	0.90 ± 0.07	0.98 ± 0.07	0.68 ± 0.07	1.00

seed at 37°C, 2 mL effluent at 20°C, and 2 mL commercial BOD seed at 20°C. Figure 31 was obtained when plotting DOC in the seed control against incubation time. The results are similar to Figure 26(c); DOC remains relatively constant throughout the incubation.

The average normalized BDOCs at 28 days shown in Figure 30, can be divided into two groups: the group with the average normalized BDOC from 0.61 to 0.73 and the group with the average normalized BDOC from 0.90 to 1.00. The first group includes all four inocula at 20°C and the commercial BOD seed inoculum at 37°C; the second group consists of the other three inocula at 37°C. This observation resembles the result previously presented in Chapter 2 that $BDOC_{28}$ at 20°C is only 75% of $BDOC_{28}$ at 37°C when using the 2 mL effluent inoculum. Only the 2 mL commercial BOD seed inoculum does not predict distinctly higher BDOC at 37°C. This suggests an inability of the commercial BOD seed inoculum to utilize some organic compounds that are usable for the other inocula at 37°C. To be able to degrade those compounds, the commercial BOD seed inoculum may need to be acclimated.

The first-order model was fitted to the exertion data in Figure 30 using the log transformation method as described in Chapter 2 and Appendix D. The residuals are shown in Figure 32. The residual plots such as shown in Figure 32 are used to examine the fit of the first-order model of BDOC exertion data because the coefficient of correlation (r) of the log transformation is not a good indicator of the fit (r is frequently greater than 0.9). Figure 32 shows that only the data of the second group tend to follow first-order kinetics. However, it should be noted that the actual values are higher than the

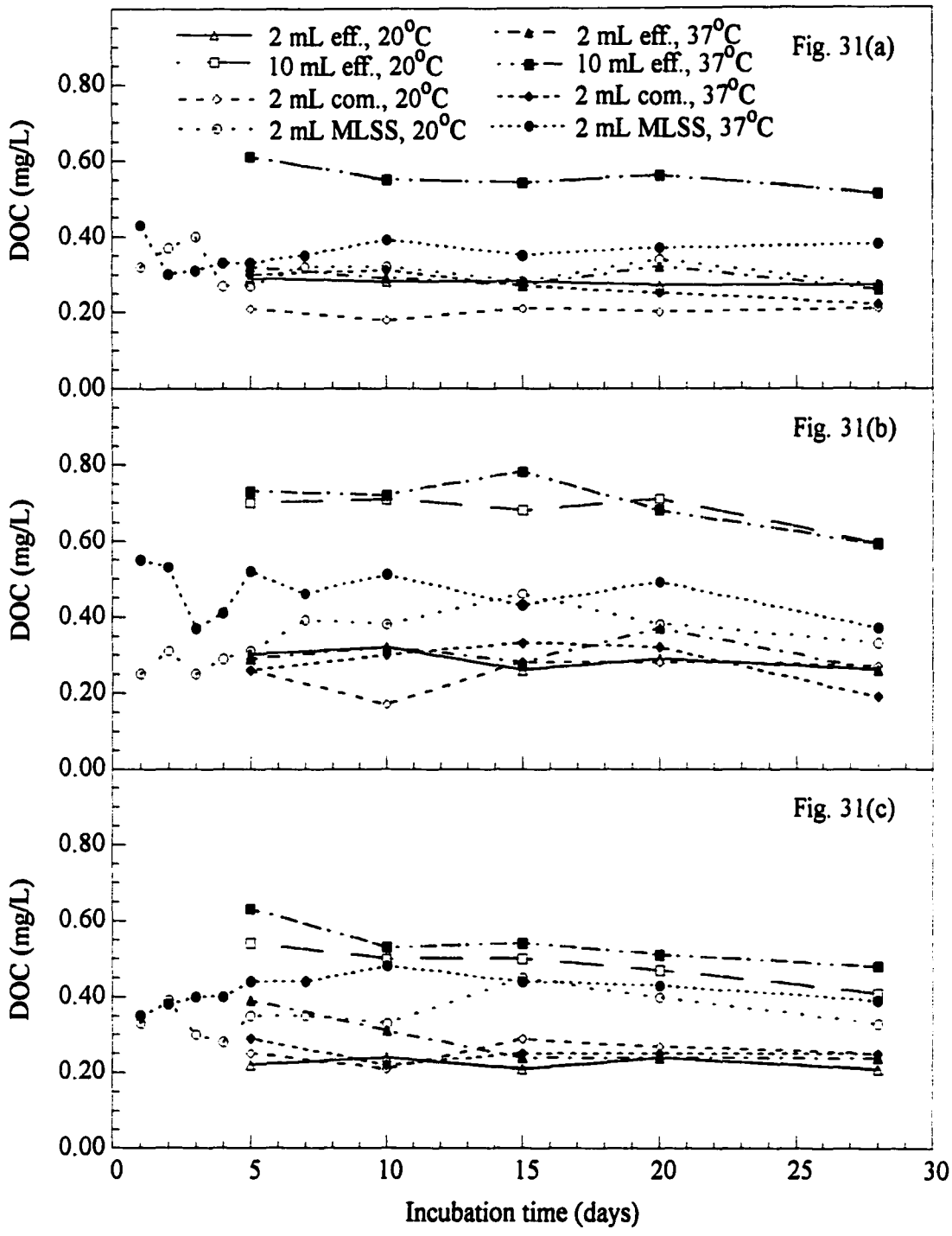


Figure 31 DOC produced by the inoculum in the blank water (seed control) with an initial DOC of 0.14 to 0.18 mg/L for secondary effluent experiment: a) Hyperion WWTP, b) JWPCP, and c) Sacramento Regional WWTP.

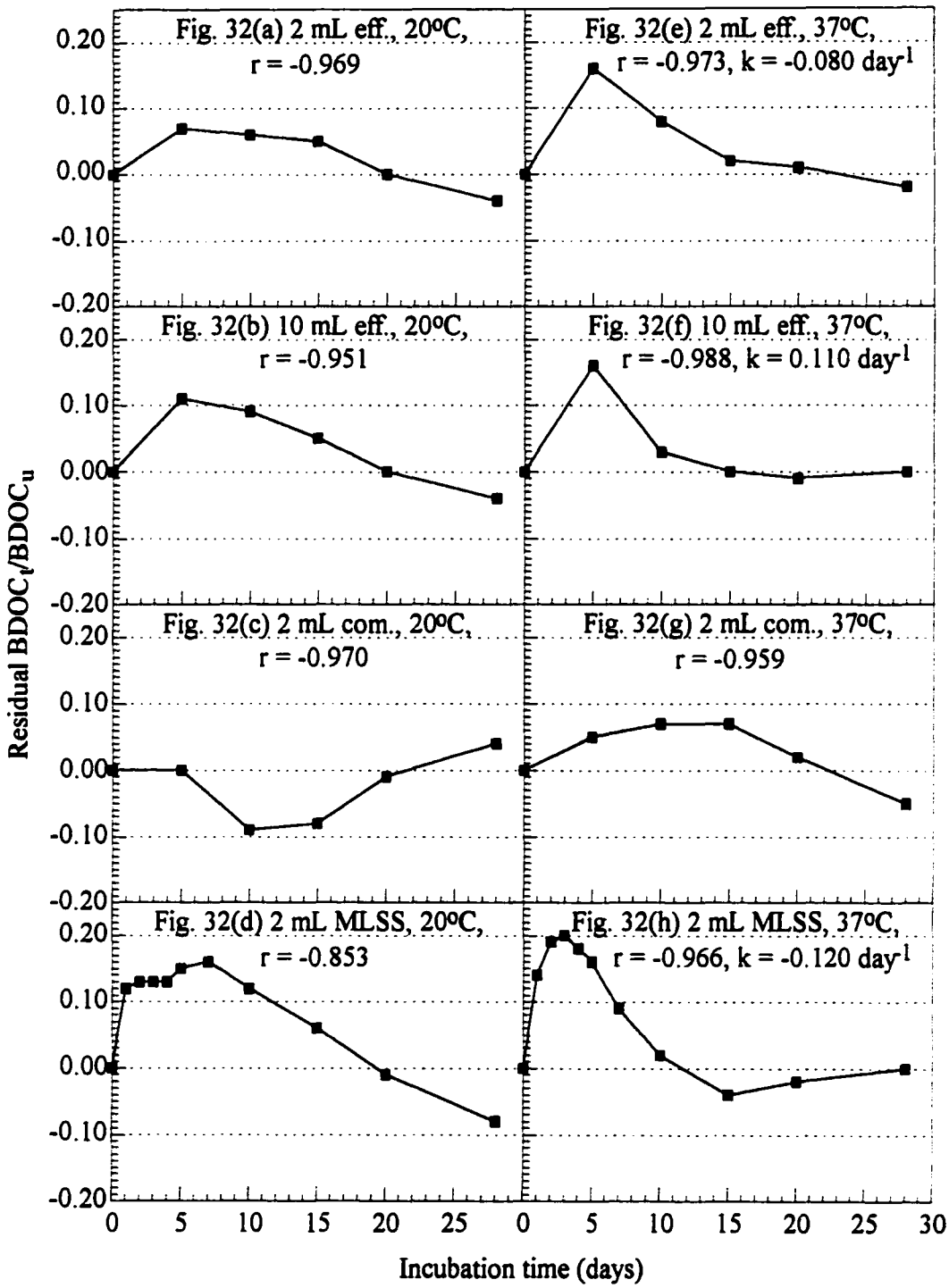


Figure 32 Residuals of the fit of the first-order model of BDOC exertion data of secondary effluent samples from HPO plants in Figure 30.

first-order values during the beginning period of incubation (1 to 5 days). These results also confirm the finding in Chapter 2 that for secondary effluent samples incubated at 20°C and 37°C, only the BDOC exertion at 37°C follows first-order kinetics (except for the commercial BOD seed inoculum). The first-order rate constant (k) values in Figure 32 follow the trends shown in Figure 30; the 2 mL MLSS inoculum provides the fastest rate (highest k) while the 2 mL effluent inoculum provides the slowest rate (lowest k) among the three inocula in the second group.

Figure 33 shows the residuals of the fit of the first-order model of the exertion data of the first group when normalizing with $BDOC_{28}$, determined with the same inoculum and at the same temperature (self-normalization). The exertion data agree with first-order kinetics. This suggests that except for the commercial inoculum, ultimate BDOC ($BDOC_u$) may not be the same for the two temperatures; the biodegradation of some compounds occurring at 37°C, may not occur at 20°C. The rate constants are also shown in Figure 33. It should be noted these rate constants were estimated based on different $BDOC_u$.

To verify that the average normalized BDOCs at 28 days can be divided not only visually but also statistically into two groups, the BDOCs of the lowest and the highest average normalized BDOCs of each group ($BDOC_{28}$, 2 mL effluent versus $BDOC_{28}$, 2 mL MLSS, at both temperatures) were compared (*t*-test). The significance levels of the differences are presented in Table 9. At a significance level of 0.05, 8 out of 12 differences of the first group and all 12 differences of the second group are not statistically

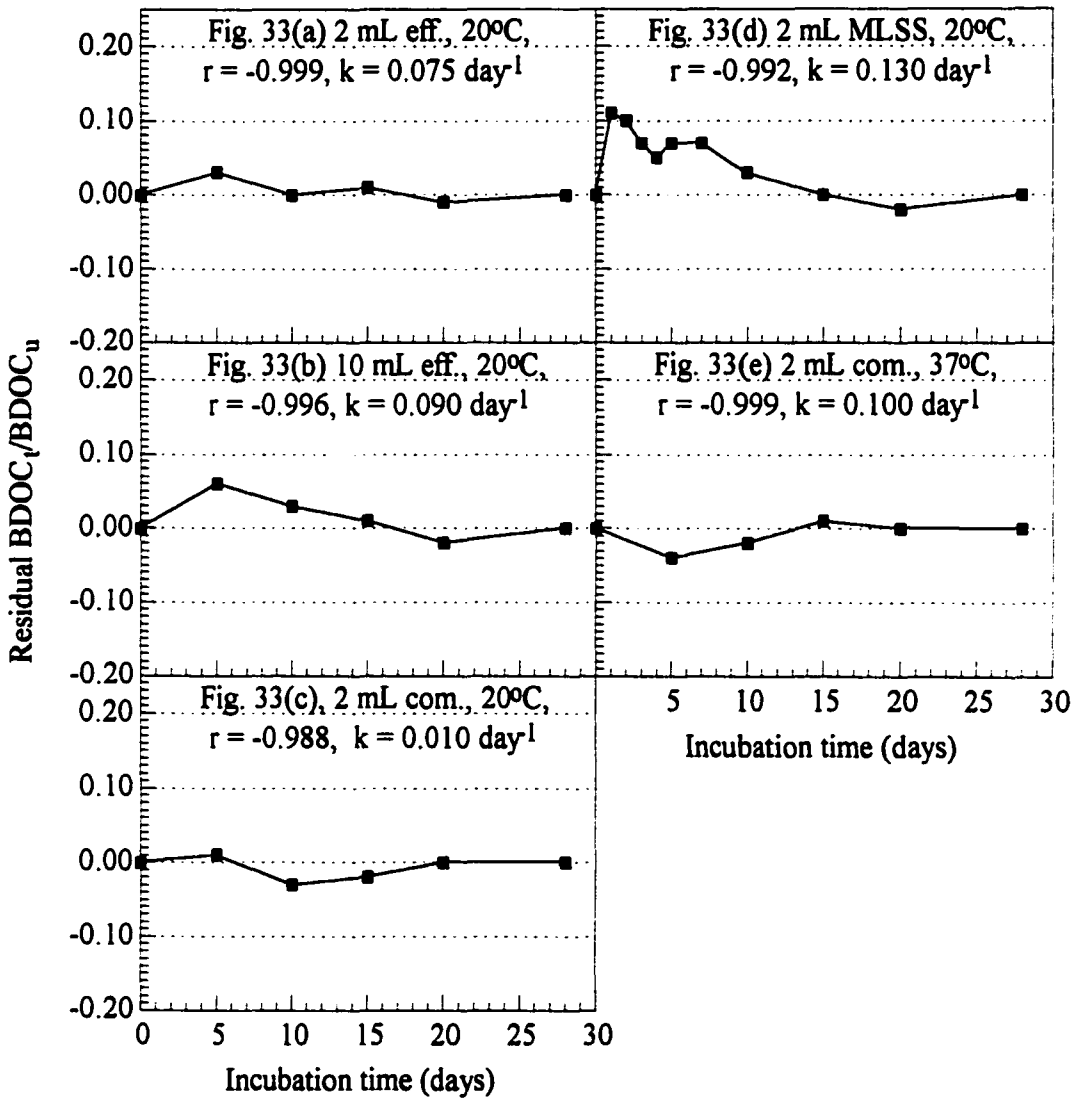


Figure 33 Residuals of the fit of the first-order model of self-normalized BDOC exertion data of secondary effluent samples from HPO plants.

significant. It should be noted that these comparisons are the extreme case for each group (lowest versus highest); the differences for the other comparisons also should not be statistically significant.

Table 9 Significance level of the difference in $BDOC_{28}$ of secondary effluent samples from HPO plants when using different inocula and/or incubating at different temperatures.

Sample no.	Significance level (t-test) of the difference (in the third column of each comparison)								
	$BDOC_{28}$, 2 mL effluent, 20°C vs. $BDOC_{28}$, 2 mL MLSS, 20°C			$BDOC_{28}$, 2 mL effluent, 37°C vs. $BDOC_{28}$, 2 mL MLSS, 37°C			$BDOC_{28}$, 2 mL MLSS, 20°C vs. $BDOC_{28}$, 2 mL effluent, 37°C		
1	2.90	3.40	0.08	4.88	5.19	0.17	3.40	4.88	0.03
2	2.46	3.63	0.03	4.75	4.82	0.38	3.63	4.75	0.04
3	3.67	3.79	0.28	5.09	5.10	0.48	3.79	5.09	0.04
4	3.58	3.99	0.11	5.09	5.56	0.12	3.99	5.09	0.05
5	2.45	2.31	0.20	3.48	4.05	0.08	2.31	3.48	0.03
6	3.09	3.22	0.24	4.38	4.37	0.48	3.22	4.38	0.04
7	2.18	3.01	0.04	2.94	3.64	0.06	3.01	2.94	0.33
8	1.80	2.56	0.04	2.54	3.29	0.05	2.56	2.54	0.44
9	2.41	2.85	0.08	3.63	3.94	0.14	2.85	3.63	0.05
10	2.34	2.79	0.07	3.35	3.80	0.09	2.79	3.35	0.07
11	2.90	3.30	0.09	4.00	4.45	0.11	3.30	4.00	0.06
12	2.42	3.23	0.04	3.40	4.05	0.07	3.23	3.40	0.21

The BDOCs of the highest average, normalized BDOC of the first group and the BDOCs of the lowest average, normalized BDOC of the second group ($BDOC_{28}$, 2 mL MLSS, 20°C versus $BDOC_{28}$, 2 mL effluent, 37°C) were also compared. As shown in Table 9, the results indicate that 5 out of 12 differences are not significant ($p > 0.05$). Of 5 insignificant differences, two differences are barely above a significance level of 0.05 ($p = 0.06$ and 0.07).

It can be seen from Figure 30 that the 2 mL MLSS is the most effective inoculum (fastest rate in the group) and therefore is the main candidate to replace the 2 mL effluent inoculum for shortening the incubation time. The lag period was not observed when inoculating with 2 mL of MLSS at both incubation temperatures. The disadvantages of the commercial BOD inoculum are noted. Although the 10 mL effluent inoculum was able to degrade almost as rapidly as the 2 mL MLSS inoculum, the possible error involved in the use of a large volume of 10 mL (introducing more DOC to the sample) is a potential disadvantage. The use of a larger volume inoculum should be practiced only when a quantitative benefit can be obtained (faster rate or shorter incubation time).

To investigate the possibility in reducing the incubation time to 5 days, the $BDOC_5$ values using the 2 mL MLSS inoculum at both temperatures were compared and correlated to the $BDOC_{28}$ using the 2 mL effluent inoculum at 20°C as shown in Table 10 and Figure 34, respectively. The $BDOC_5$ using the 2 mL MLSS inoculum at 37°C and the $BDOC_{28}$ using the 2 mL effluent inoculum at 20°C are not significantly different (*t*-test, $p > 0.05$) and the concentrations obtained from the two conditions correlates strongly and significantly ($r = 0.89$, $p < 0.0005$). Even though the $BDOC_5$ values using the 2 mL MLSS inoculum at 20°C are statistically lower than the $BDOC_{28}$ values using the 2 mL effluent inoculum at 20°C, the values have a fair but significant relationship with the $BDOC_{28}$ values using the 2 mL effluent inoculum at 20°C ($r = 0.64$, $p < 0.025$). It may be possible to use $BDOC_5$ exerted from the 2 mL MLSS inoculum at 20°C to characterize wastewaters. However, additional studies are required. It should be noted that the

$BDOC_5$ values exerted from this case are not comparable to the $BDOC_{28}$ values using the 2 mL effluent inoculum at 20°C.

Table 10 Significance level of the difference between $BDOC_5$ of secondary effluent samples from HPO plants using 2 mL MLSS inoculum at both temperatures and $BDOC_{28}$ of the same samples using 2 mL effluent inoculum at 20°C.

Sample no.	Significance level (*t*-test) of the difference (in the third column of each comparison)					
	$BDOC_5$, 2 mL MLSS, 20°C vs. $BDOC_{28}$, 2 mL effluent, 20°C			$BDOC_5$, 2 mL MLSS, 37°C vs. $BDOC_{28}$, 2 mL effluent, 20°C		
1	2.02	2.90	0.04	3.17	2.90	0.13
2	1.84	2.46	0.05	3.10	2.46	0.06
3	1.95	3.67	0.02	3.52	3.67	0.24
4	2.32	3.58	0.03	3.82	3.58	0.17
5	1.38	2.45	0.03	2.39	2.45	0.33
6	1.65	3.09	0.02	3.09	3.09	0.50
7	1.09	2.18	0.02	2.59	2.18	0.08
8	1.01	1.80	0.03	1.99	1.80	0.14
9	1.95	2.41	0.07	2.26	2.41	0.19
10	1.89	2.34	0.07	2.15	2.34	0.15
11	2.38	2.90	0.07	2.78	2.90	0.24
12	2.07	2.42	0.09	2.43	2.42	0.47

It is evident that the use of the 2 mL MLSS inoculum at 37°C can shorten the incubation time to 5 days. However, incubating at 37°C prohibits the simultaneous determinations of $SBOD_5$ and BDOC. To preserve the simultaneous determinations, it was decided to abandon the 10 mL effluent and 2 mL commercial BOD seed inocula and to focus on the utilization of larger sizes of MLSS inoculum to increase the exertion rate without increasing the incubation temperature. As a consequence, the use of 5 mL and 10 mL MLSS inocula for determining BDOC in non-ozonated and ozonated secondary

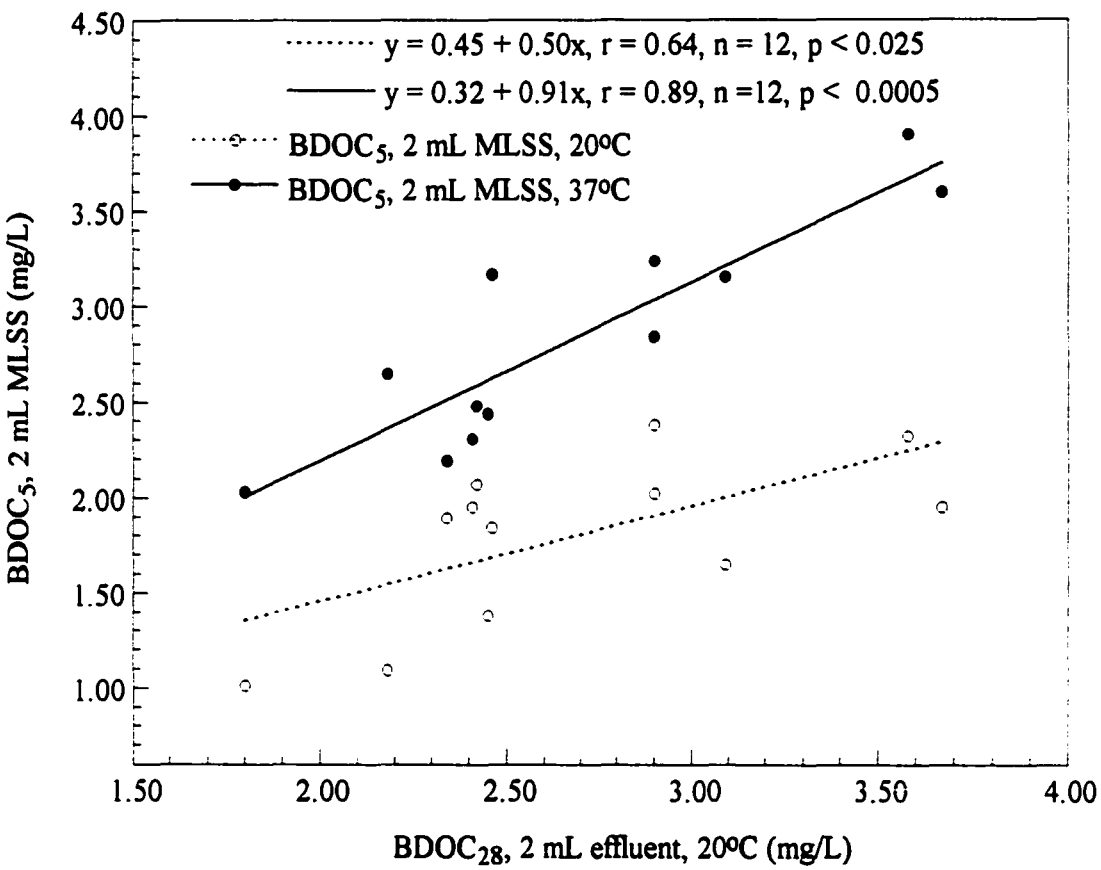


Figure 34 Correlations between $BDOC_{28}$, 2 mL effluent, 20°C and $BDOC_5$, 2 mL MLSS (20°C and 37°C) for secondary effluent samples from HPO plants.

effluents was later studied along with the use of the 2 mL effluent and 2 mL MLSS inocula.

4.3.3 Non-ozonated versus ozonated secondary effluents

The effluent samples from the high SRT plants (listed in the methodology section on non-ozonated versus ozonated secondary effluent experiment), which are bio-refractory (low BDOC), were used for several reasons. If a larger volume of MLSS inoculum can reduce the BDOC incubation time for these samples, it should be able to do that for other secondary effluents as well. When comparing the BDOC exertion rate between non-ozonated and ozonated samples of the same effluent, using the recalcitrant secondary effluents should offer the most distinctive results. Finally, in the reclamation facilities with an ozone/granular activated carbon system, the influent of the system usually is recalcitrant (ozonated secondary effluents represent reclaimed wastewaters).

The 2 L sample collected on the first day (5/15/97) from each plant was filtered and ozonated with an ozone dose of 16 to 20 mg O_3(g)/L at 5.75 liter/min (LPM) for 40 minutes. Such a high dose of ozone was provided to insure the maximum increase in biodegradability. It should be noted that the purpose of this experiment is not to investigate an optimum ozone dose but to test the BDOC procedure performance with different inocula. Figure 35(a) illustrates UV_{254} versus ozonation time for the first three samples. It indicates that the destruction of the UV_{254} absorbing compounds (conjugated double bond) occurred largely in the first five minutes. After 15 minutes of ozonation, an

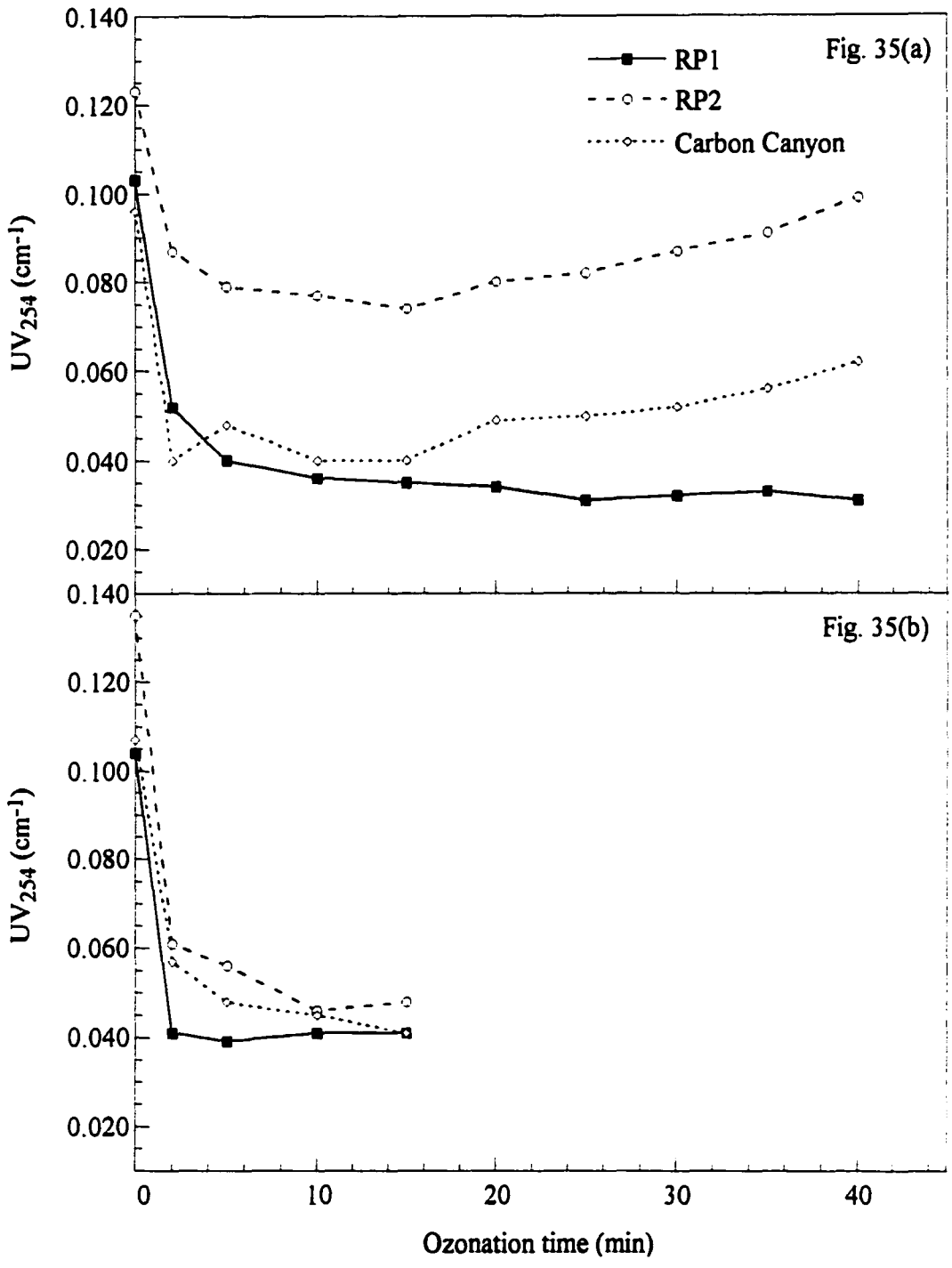


Figure 35 UV_{254} versus ozonation time for secondary effluent samples from high SRT plants collected on a) 5/15/97 and b) 5/16/97.

increase of UV_{254} was observed for the effluent samples from the RP2 and Carbon Canyon plants. The ozone utilization data shown in Table 11 conform with the UV_{254} data; no ozone was utilized after two minutes for the effluent samples from the RP1 and Carbon Canyon plants and after five minutes for the RP2 plant. Thus, the second day samples (5/16/97) were ozonated with the same conditions but for 15 minutes only. The UV_{254} versus ozonation time and ozone utilization data are shown in Figure 35(b) and Table 11, respectively. Additional information on gas phase (in and out) and liquid phase ozone concentrations is presented in Appendix H.

Table 11 Ozone utilization for secondary effluent samples from high SRT plants.

Sample and sampling date	DOC (mg/L)	Ozone utilization (mg ozone/L)		Ozone utilization/DOC (mg ozone/mg DOC)	
		0 to 2 min.	2 to 5 min.	0 to 2 min.	2 to 5 min.
RP1, 5/15/97	4.23	1.50	0.00	0.35	0.00
RP2, 5/15/97	5.20	4.94	0.95	0.95	0.18
Carbon Canyon, 5/15/97	4.31	1.07	0.00	0.25	0.00
RP1, 5/16/97	4.10	1.19	0.60	0.29	0.15
RP2, 5/16/97	5.20	4.29	0.00	0.83	0.00
Carbon Canyon, 5/16/97	4.08	1.42	0.93	0.35	0.23

The DOC concentrations in the seed control for four inocula at both temperatures used in this experiment were plotted against incubation time as shown in Figure 36(a, b, and c for RP1, RP2, and Carbon Canyon, respectively). The initial DOC in the blank before adding the inoculum was between 0.14 to 0.16 mg/L. Tremendous release of DOC due to cell decay was observed in the seed control using the 10 mL MLSS inoculum at both temperatures (4 out of 6 cases). This release occurred as early as 10 days in some cases. These seed control data produced inconsistent and unreliable BDOC results. The

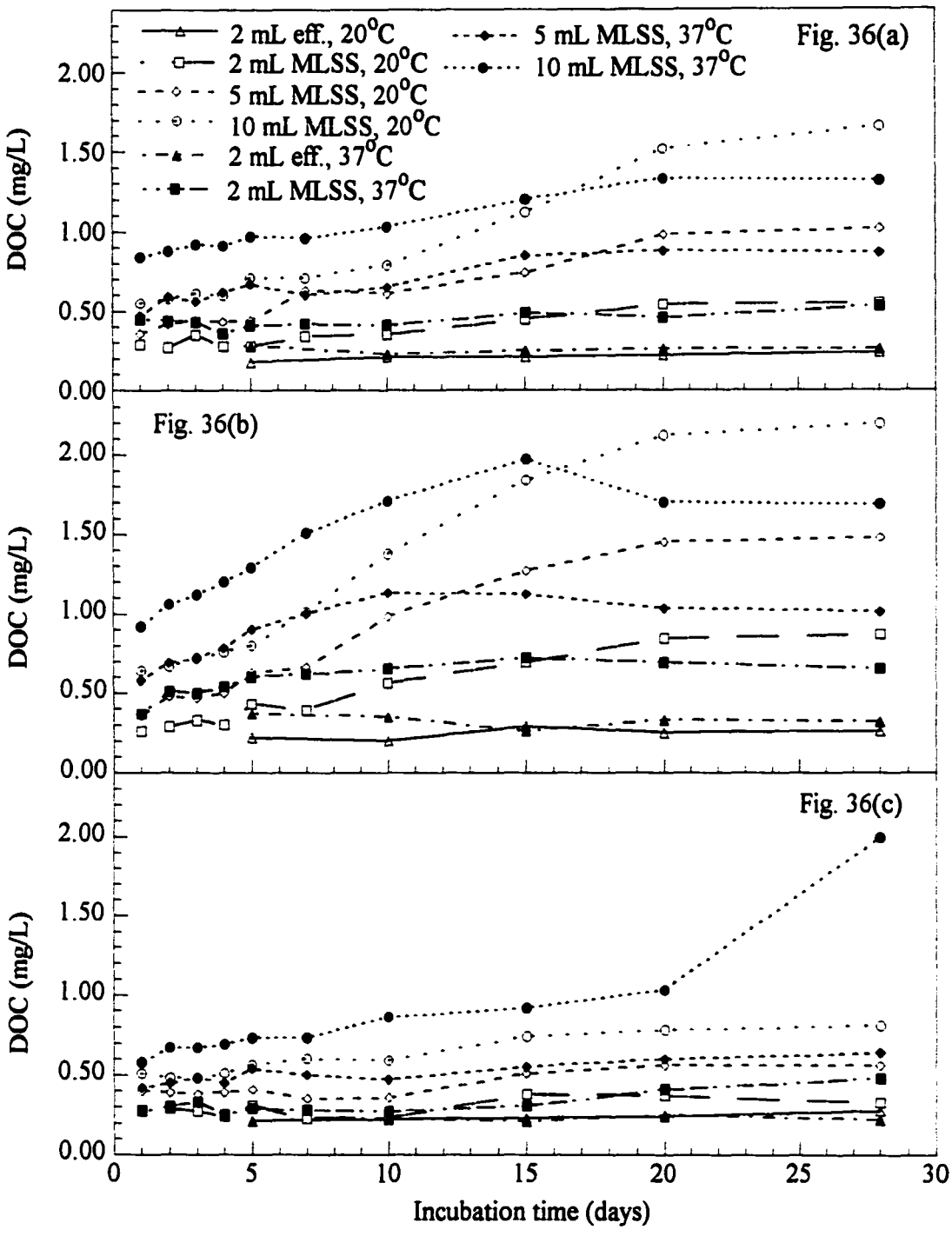


Figure 36 DOC produced by the inoculum in the blank water (seed control) with an initial DOC of 0.14 to 0.16 mg/L for non-ozonated versus ozonated secondary effluent experiment: a) RP1 WWTP, b) RP2 WWTP, and c) Carbon Canyon WWTP.

degree of cell decay (endogenous respiration) in the sample may not be the same as in the seed control since the substrate concentrations are different. At the time of DOC release, the seed control is in the death phase (either accelerating or decelerating autodigestion) of the growth curve while the sample may be in other growth phases.

It is important to stress that the purpose of having a seed control in the procedure is to account for the additional DOC in the sample due to the properties (impurities) of the inoculum and not endogenous respiration. Accounting for the release of DOC due to endogenous respiration in the sample may be possible but will be too complicated for the procedure. Inoculating with 5 mL of MLSS, the release of DOC was found in only one out of six cases (RP2, 20°C). Nevertheless, the BDOC values calculated using this information are consistent and reliable. The release of DOC was not encountered in any cases when inoculating with the other two inocula (2 mL effluent and 2 mL MLSS).

It was decided to normalize $BDOC_t$ for all four inocula at both temperatures with the $BDOC_{28}$ exerted at 37°C using the 5 mL MLSS inoculum and not to report the normalized $BDOC_{t>10}$ for the samples inoculated with 10 mL of MLSS. Figure 37(a and b for non-ozonated and ozonated effluents, respectively) shows the average normalized BDOC (6 samples) versus incubation time. Standard deviations of the normalized BDOCs are presented separately in Table 12(a and b) because they visually impair the other information. Figure 37 clearly illustrates the effects of inoculum and incubation temperature on BDOC exertion rate for both non-ozonated and ozonated samples. Furthermore, a comparison between Figures 37(a) and 37(b) indicates that the exertion

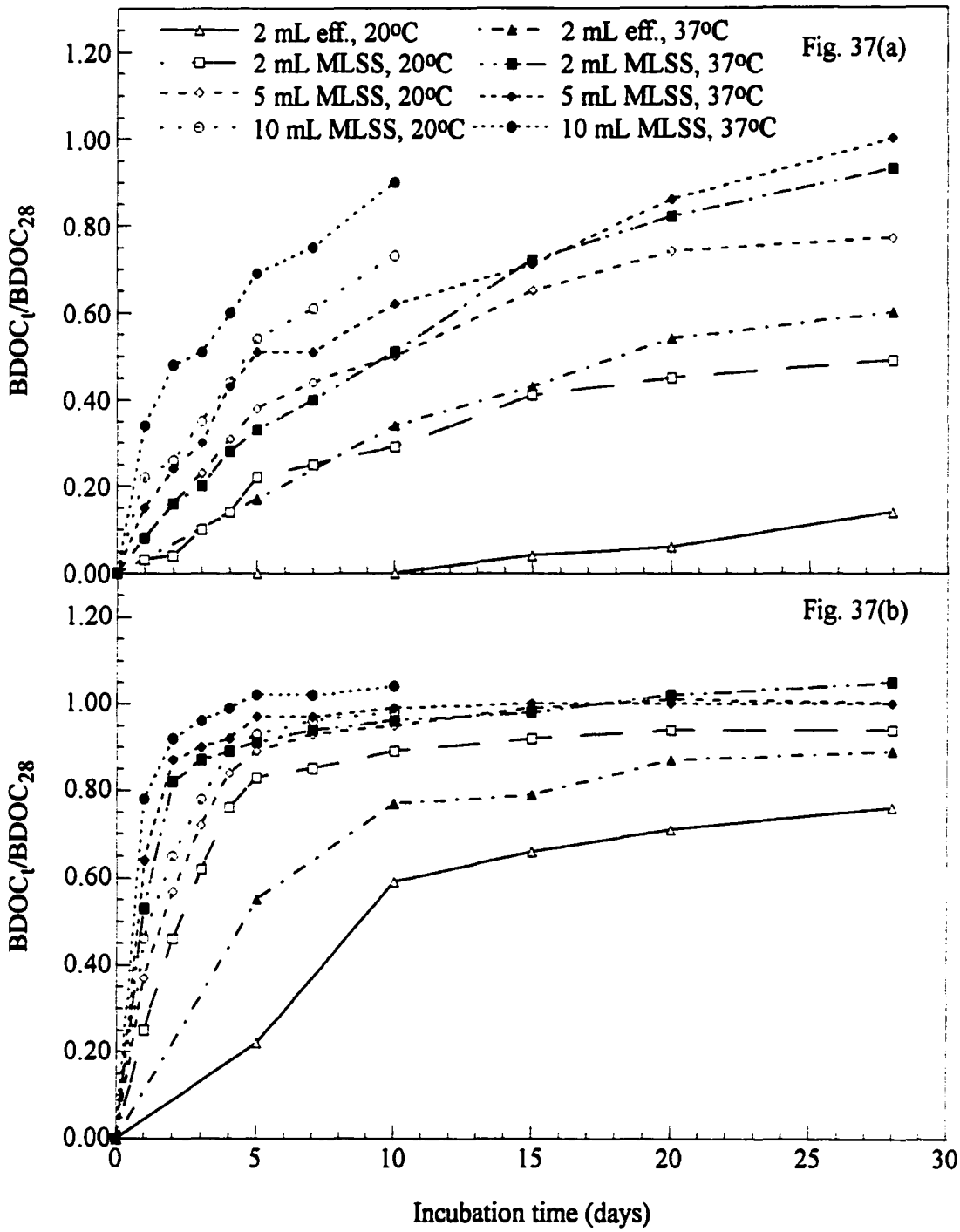


Figure 37 Effects of inoculum and incubation temperature on the exertion of BDOC for secondary effluents from high SRT plants: a) non-ozonated samples and b) ozonated samples.

Table 12(a) Average normalized BDOC and standard deviation for non-ozonated secondary effluent samples from high SRT plants.

Incubation time (days)	Average normalized BDOC ± standard deviation							
	20°C				37°C			
	2 mL eff.	2 mL MLSS.	5 mL MLSS	10 mL MLSS	2 mL eff.	2 mL MLSS.	5 mL MLSS	10 mL MLSS
1	-	0.03 ± 0.05	0.08 ± 0.08	0.22 ± 0.07	-	0.08 ± 0.05	0.15 ± 0.08	0.34 ± 0.11
2	-	0.04 ± 0.06	0.16 ± 0.07	0.26 ± 0.06	-	0.16 ± 0.04	0.24 ± 0.07	0.48 ± 0.03
3	-	0.10 ± 0.06	0.23 ± 0.08	0.35 ± 0.05	-	0.20 ± 0.04	0.30 ± 0.07	0.51 ± 0.09
4	-	0.14 ± 0.06	0.31 ± 0.07	0.44 ± 0.05	-	0.28 ± 0.09	0.43 ± 0.05	0.60 ± 0.07
5	0.00 ± 0.00	0.22 ± 0.06	0.38 ± 0.04	0.54 ± 0.04	0.17 ± 0.11	0.33 ± 0.08	0.51 ± 0.06	0.69 ± 0.06
7	-	0.25 ± 0.02	0.44 ± 0.06	0.61 ± 0.03	-	0.40 ± 0.07	0.51 ± 0.08	0.75 ± 0.10
10	0.00 ± 0.01	0.29 ± 0.04	0.50 ± 0.09	0.73 ± 0.11	0.34 ± 0.16	0.51 ± 0.08	0.62 ± 0.05	0.90 ± 0.11
15	0.04 ± 0.03	0.41 ± 0.07	0.65 ± 0.09	-	0.43 ± 0.16	0.72 ± 0.12	0.71 ± 0.06	-
20	0.06 ± 0.03	0.45 ± 0.05	0.74 ± 0.10	-	0.54 ± 0.18	0.82 ± 0.14	0.86 ± 0.06	-
28	0.14 ± 0.04	0.49 ± 0.06	0.77 ± 0.14	-	0.60 ± 0.21	0.93 ± 0.11	1.00	-

Table 12(b) Average normalized BDOC and standard deviation for ozonated secondary effluent samples from high SRT plants.

Incubation time (days)	Average normalized BDOC ± standard deviation							
	20°C				37°C			
	2 mL eff.	2 mL MLSS.	5 mL MLSS	10 mL MLSS	2 mL eff.	2 mL MLSS.	5 mL MLSS	10 mL MLSS
1	-	0.25 ± 0.09	0.37 ± 0.10	0.46 ± 0.10	-	0.53 ± 0.10	0.64 ± 0.08	0.78 ± 0.05
2	-	0.46 ± 0.06	0.57 ± 0.09	0.65 ± 0.10	-	0.82 ± 0.05	0.87 ± 0.04	0.92 ± 0.05
3	-	0.62 ± 0.06	0.72 ± 0.08	0.78 ± 0.10	-	0.87 ± 0.03	0.90 ± 0.05	0.96 ± 0.03
4	-	0.76 ± 0.04	0.84 ± 0.06	0.89 ± 0.06	-	0.89 ± 0.04	0.92 ± 0.04	0.99 ± 0.04
5	0.22 ± 0.07	0.83 ± 0.04	0.89 ± 0.05	0.93 ± 0.06	0.55 ± 0.16	0.91 ± 0.02	0.97 ± 0.04	1.02 ± 0.04
7	-	0.85 ± 0.04	0.93 ± 0.04	0.96 ± 0.05	-	0.94 ± 0.03	0.97 ± 0.04	1.02 ± 0.03
10	0.59 ± 0.03	0.89 ± 0.03	0.95 ± 0.03	0.98 ± 0.04	0.77 ± 0.06	0.96 ± 0.03	0.99 ± 0.03	1.04 ± 0.05
15	0.66 ± 0.04	0.92 ± 0.05	0.99 ± 0.04	-	0.79 ± 0.07	0.98 ± 0.03	1.00 ± 0.03	-
20	0.71 ± 0.05	0.94 ± 0.05	1.01 ± 0.04	-	0.87 ± 0.06	1.02 ± 0.06	1.00 ± 0.03	-
28	0.76 ± 0.04	0.94 ± 0.03	1.00 ± 0.03	-	0.89 ± 0.06	1.05 ± 0.06	1.00	-

rate of the non-ozonated samples is much slower than that of the ozonated samples of the same effluent using the same inoculum at the same temperature.

Figure 38 presents the residuals of the fit of the first-order model of the exertion data in Figure 37(a). It was decided not to investigate the exertion using the 2 mL effluent inoculum at 20°C because it is obvious that it would not agree with the first-order model. For the 10 mL MLSS inoculum incubated at both temperatures and the 5 mL MLSS inoculum incubated at 37°C, the actual values are higher than the model values from 1 to 5 days. Although the data are insufficient (15, 20, and 28 days), the exertions using the 10 mL MLSS inoculum at both temperatures should agree with the first-order model as observed for the 5 mL MLSS inoculum incubated at 37°C. The exertion using the 2 mL MLSS inoculum at 37°C follows first-order kinetics even at the beginning period of incubation.

Disagreements between the other three cases and first-order kinetics are similar to the results described previously in the secondary effluent section. Figure 39 shows that the exertions agree with the first-order model when they were self-normalized. However, the exertion kinetics at 20°C for the 2 mL effluent inoculum and the 10 mL MLSS inoculum, suggest that $BDOC_u$ may be the same for the two temperatures. If adequate inoculum is used at 20°C, the exertion should approach the same $BDOC_u$ as other effective inocula at 37°C. This also suggests that the 2 mL effluent may not be adequate for use as an inoculum for determining BDOC in secondary effluents from high SRT plants.

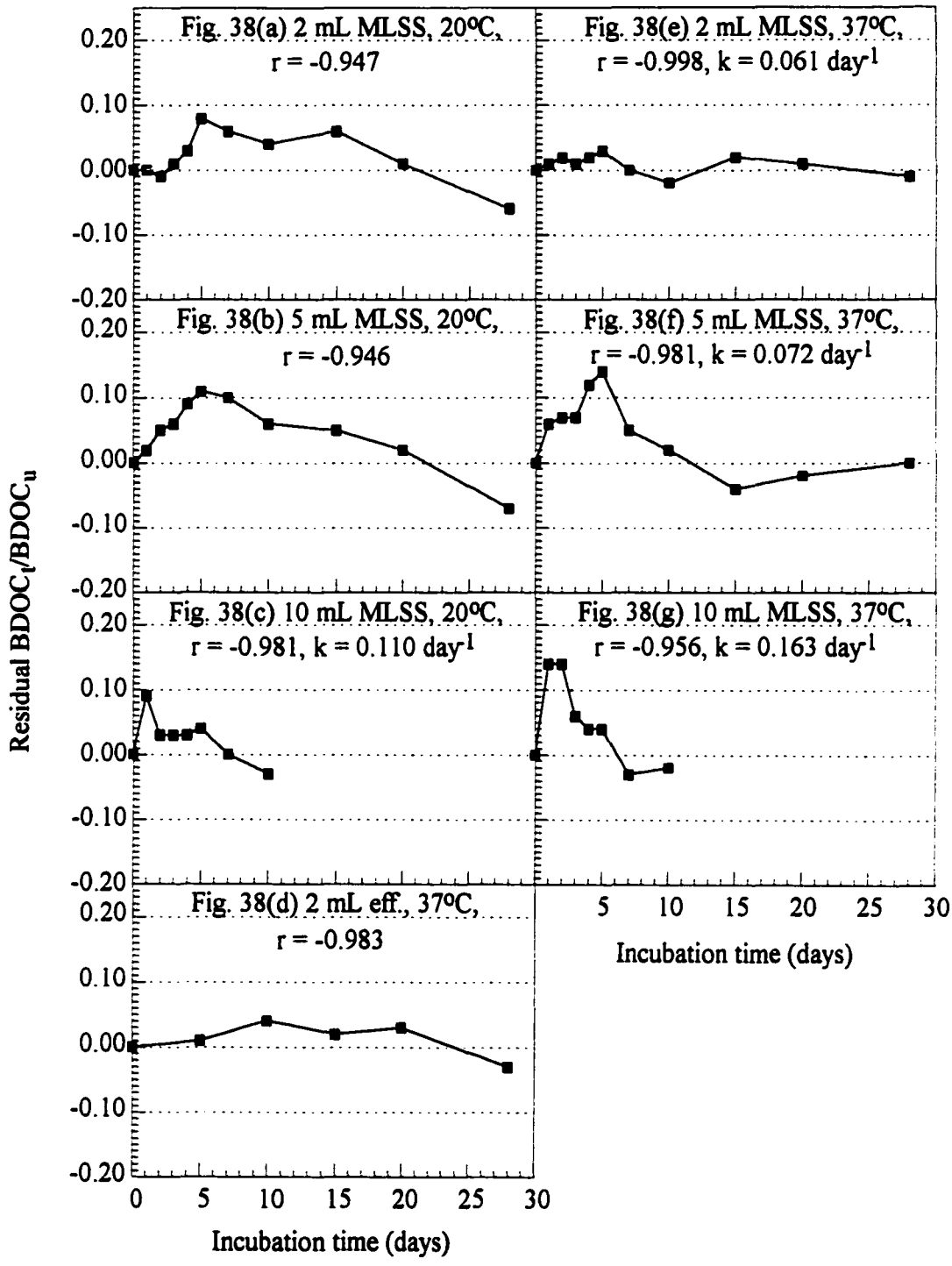


Figure 38 Residuals of the fit of the first-order model of BDOC exertion data of non-ozonated secondary effluent samples from high SRT plants in Figure 37(a).

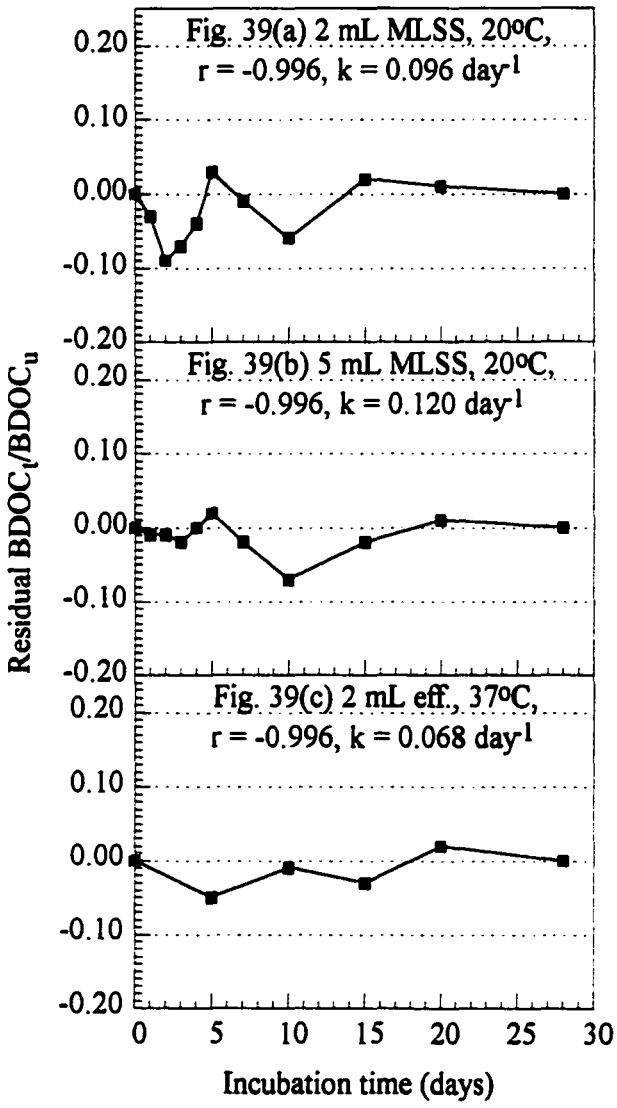


Figure 39 Residuals of the fit of the first-order model of self-normalized BDOC exertion data of non-ozonated secondary effluent samples from high SRT plants.

The residuals of the fit of the first-order model of the exertion data in Figure 37(b), are presented in Figure 40. Some of the exertion data are truncated because their $BDOC_t/BDOC_{28}$ values were either equal or greater than 1.00 after the truncated incubation time. The exertions do not follow first-order kinetics for all cases except for the exertion using the 10 mL inoculum at 37°C. As shown in Figure 37(b), for MLSS inocula at both temperatures, the BDOC exertions approach completion within 4 to 7 days (> 90% exertion). Therefore, fitting the model on the 28-day data using the log transformation method can cause tremendous errors due to the weakness of the method. Figure 41(b, c, d, f, and g) shows better agreements between the first-order model and the MLSS inoculum exertion data (except for the 10 mL MLSS inoculum at 37°C) that were truncated at 5 days. Figure 41(a and e) shows better agreements between the first-order model and the self-normalized effluent inoculum exertion data. This also indicates the ineffectiveness of the 2 mL effluent inoculum.

Using the 2 mL effluent inoculum on non-ozonated samples at 20°C yields very low $BDOC_{28}$ values (barely above the detection limit of 0.15 mg/L). This conforms with the results on the exertion kinetics which indicate that the 2 mL effluent inoculum from high SRT plants sometimes may not provide adequate number of cells and may underestimate the $BDOC_{28}$. The predicted $BDOC_{28}$ concentrations using a more concentrated inoculum such as 2 mL MLSS are comparable to the values reported in Chapter 2 for the same effluents (0.50 to 0.80 mg/L). As can be seen in Figure 37(b), there is a difference in the average normalized $BDOC_{28}$ using the 2 mL effluent inoculum at different temperatures. As shown in Table 13, at a significance level of 0.05 (*t*-test), the

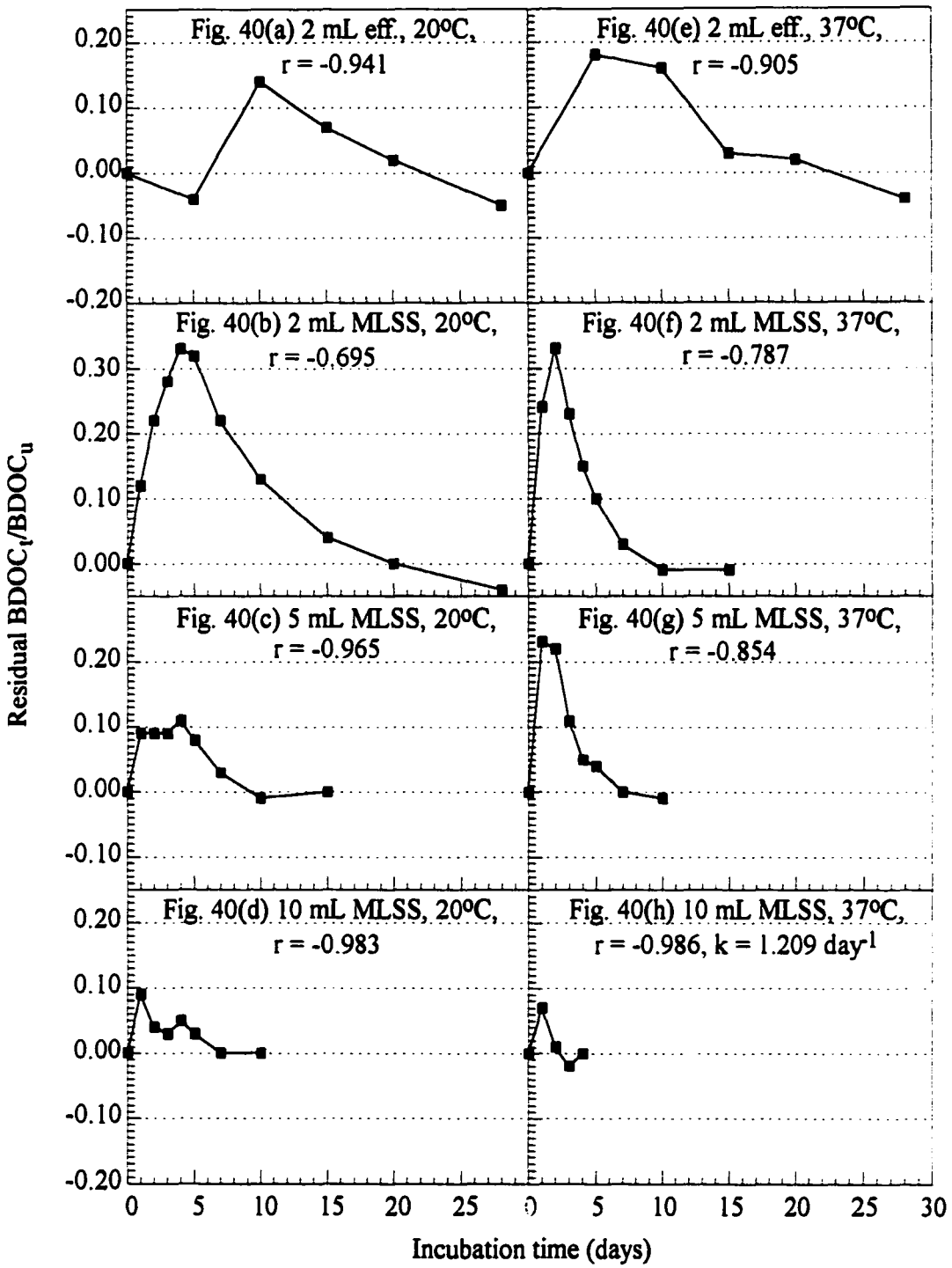


Figure 40 Residuals of the fit of the first-order model of BDOC exertion data of ozonated secondary effluent samples from high SRT plants in Figure 37(b).

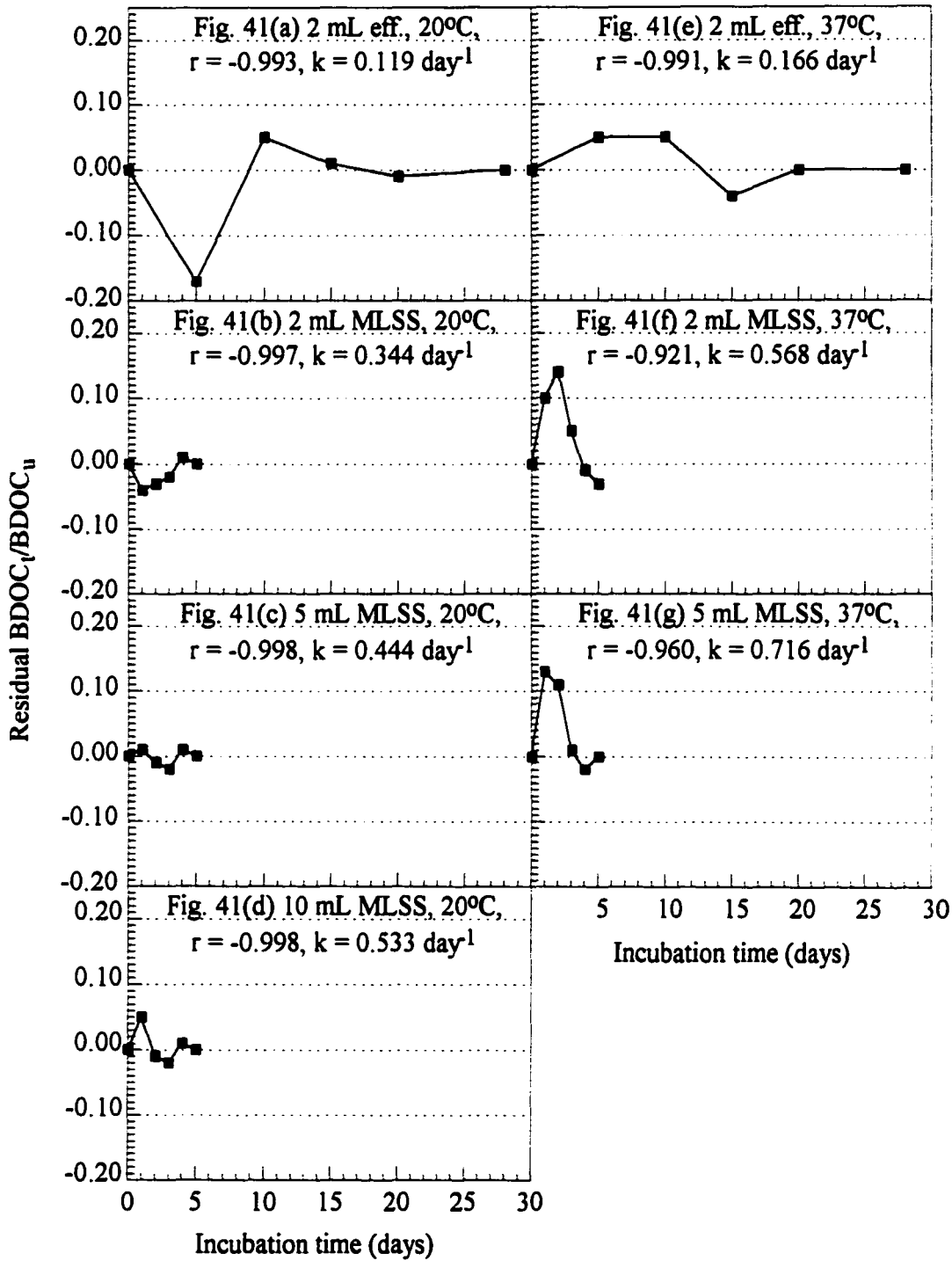


Figure 41 Residuals of the fit of the first-order model of self-normalized or truncated BDOC exertion data of ozonated secondary effluent samples from high SRT plants.

$BDOC_{28}$ differences between the two temperatures using the 2 mL effluent inoculum are not significant. This is similar to the result reported in Chapter 2 and verifies that the difference between the final BDOC ($BDOC_{28}$) of secondary effluents incubated at 20°C and 37°C is because of both inadequate inoculum and the recalcitrant nature of secondary effluents especially those from high SRT plants.

Table 13 Significance level of the difference in BDOC of ozonated and non-ozonated secondary effluent samples from high SRT plants using different inocula and/or incubated at different temperatures.

Sample no.	Significance level (t-test) of the difference (in the third column of each comparison)					
	Ozonated			Non-ozonated		
	$BDOC_{28}$, 2 mL effluent, 20°C vs. $BDOC_{28}$, 2 mL effluent, 37°C			$BDOC_5$, 10 mL MLSS, 20°C vs. $BDOC_{28}$, 2 mL MLSS, 20°C		
1	2.16	2.63	0.07	0.70	0.64	0.22
2	2.42	2.97	0.06	0.63	0.55	0.17
3	2.71	3.19	0.08	0.72	0.85	0.12
4	2.66	3.15	0.07	0.86	0.75	0.15
5	1.42	1.73	0.08	0.79	0.61	0.09
6	1.95	1.89	0.31	0.56	0.50	0.21

The use of the 10 mL MLSS inoculum for determining BDOC in non-ozonated secondary effluent provided the fastest exertion among inocula tested. To retain the ability to perform simultaneous determinations of BDOC and $SBOD_5$, the BDOC procedure has to be performed at 20°C. According to Figure 37(a), the average normalized $BDOC_5$ using the 10 mL MLSS inoculum at 20°C is about the same as the average normalized $BDOC_{28}$ using the 2 mL MLSS inoculum at 20°C. Furthermore, the

$BDOC_5$ using the 10 mL MLSS inoculum at 20°C and the $BDOC_{28}$ using the 2 mL MLSS inoculum at 20°C are not significantly different (*t*-test, $p > 0.05$) as also shown in Table 13. This indicates that the $BDOC_{28}$ using the 2 mL MLSS inoculum at 20°C can be reached in 5 days using the 10 mL MLSS inoculum at 20°C. Due to a small number of samples (6 samples), a fair but less significant correlation ($r = 0.64$, $p < 0.10$) was observed between the $BDOC_5$ using the 10 mL MLSS inoculum at 20°C and the $BDOC_{28}$ using the 2 mL MLSS inoculum at 20°C as shown in Figure 42.

Even though it has not been tested, the 10 mL MLSS inoculum should be able to provide the simultaneous determinations of $SBOD_5$ and BDOC of other secondary effluents, such as those from low SRT and/or HPO plants, as the 2 mL MLSS inoculum since more BDOC is exerted. As an example, adding 10 mL of 1000 mg/L MLSS in a BOD bottle filled with 290 mL filtered sample would produce a suspended solids (SS) concentration of about 33 mg/L which is close to the limit for secondary effluents. This is roughly equivalent to performing the BOD test on some secondary effluents without seeding.

Determination of BDOC in ozonated secondary effluents can be completed in 5 days using any of the MLSS inocula tested at both temperatures. However, employing the 10 mL MLSS inoculum would insure the adequacy of viable cells. An MLSS inoculum larger than 10 mL is not recommended since a tremendous release of DOC due to the endogenous respiration in the seed control may occur during the first few days of incubation. Based on the data shown above, using the 10 mL MLSS inoculum, significant

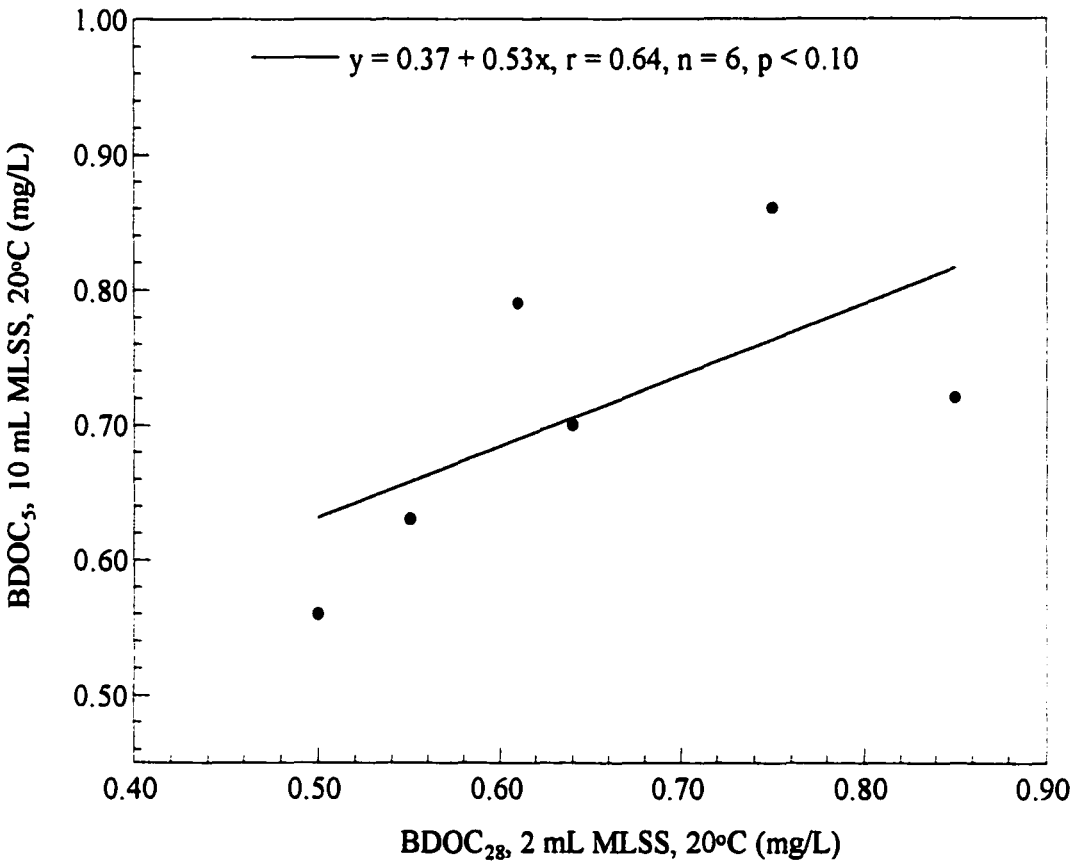


Figure 42 Correlation between $BDOC_{28}$, 2 mL MLSS, 20°C and $BDOC_5$, 10 mL MLSS, 20°C for non-ozonated secondary effluent samples from high SRT plants.

release of DOC in the seed control should not appear before 10 days. This means for reclaimed wastewaters, such as ozonated secondary effluents, the BOD has to be determined in 5 days instead of 28 days.

4.4 Conclusions

This chapter describes the usage of larger size and/or more concentrated inocula in the modified BDOC procedure for reclaimed and secondary treated wastewaters mainly to obtain a shorter incubation period and to accomplish concurrent determinations of $SBOD_5$ and BDOC. These two features are very important for promoting BDOC as a routinely adopted water quality parameter. The modified BDOC protocol using different inocula was tested with standard solutions, secondary effluents from three HPO plants, and non-ozonated and ozonated secondary effluents from three high SRT plants. The kinetics of BDOC exertion were monitored and the results provided by different inocula were compared.

Sodium acetate and phenol were the two compounds used in the standard solution study. Three standard solutions were prepared from each compound to have approximate DOC concentrations of 2, 5, and 10 mg/L, respectively. Four inocula, which were 2 mL of unfiltered effluent, 10 mL of unfiltered effluent, 2 mL of commercial BOD seed, 2 mL of MLSS, were employed. At incubation time of 5 days and 28 days, all four inocula were able to provide accurate and precise BDOC results. An inaccuracy (> 10%) was observed

scarcely (3 out of 32) when applying the protocol to the standard solutions with 2 mg DOC/L which is not in the target initial DOC range of the procedure. The four inocula were further tested with secondary effluents from three HPO plants.

For secondary effluents from three HPO plants, BDOC and $SBOD_5$ could be determined simultaneously only when the 2 mL of MLSS was used as an inoculum. In addition, none of the inocula incubated at 20°C was able to reduce the incubation time to 5 days. $BDOC_{28}$ incubated at 37°C was still higher than $BDOC_{28}$ incubated at 20°C when using the effluent (both 2 mL and 10 mL) and 2 mL MLSS inocula. Although the results show that the incubation time can be reduced to 5 days by inoculating the sample with 2 mL of MLSS and incubating at 37°C, it was decided to explore a larger size of MLSS inoculum at 20°C in order to be able to perform BDOC and $SBOD_5$ determinations concurrently. Also, the testing of the 10 mL effluent and 2 mL commercial seed inocula was discontinued since the inocula provided slower exertion rate than the 2 mL MLSS inoculum.

Non-ozonated and ozonated secondary effluent samples from high SRT plants were inoculated with 2 mL of effluent, 2 mL of MLSS, 5 mL of MLSS, and 10 mL of MLSS. A substantial release of DOC in the seed control due to endogenous respiration was frequently observed after 10 days of incubation when the 10 mL MLSS inoculum was employed. The release causes inconsistent and unreliable BDOC results. Hence, the 10 mL MLSS inoculum should be applied only when the incubation time is equal to or less than 10 days. This also suggests that the use of a MLSS inoculum of larger than 10 mL is

not appropriate for the modified procedure because the significant release of DOC in the seed control may occur at the beginning period of the incubation and produces inaccurate BDOC estimation.

For ozonated secondary effluent samples inoculated with 2 mL of effluent, $BDOC_{28}$ concentrations exerted at 20°C and 37°C are not significantly different. This and the results from the exertion kinetic study on non-ozonated secondary effluent samples confirm that the difference in $BDOC_{28}$ of secondary effluents incubated at 20°C and 37°C is due to inadequate inoculum and the recalcitrant property of secondary effluents. The 10 mL MLSS inoculum provided the fastest exertion rate among all inocula used for determining BDOCs of non-ozonated and ozonated secondary effluent samples. Inoculating with 10 mL of MLSS, $BDOC_5$ concentrations exerted at 20°C are not significantly different from the $BDOC_{28}$ using the 2 mL MLSS inoculum at 20°C. Thus, it is possible to reduce the incubation time to 5 days by employing the 10 mL MLSS inoculum. It is believed that the 10 mL MLSS inoculum can be used to achieve the simultaneous determinations of BDOC and $SBOD_5$ as well as the 2 mL MLSS inoculum. The 10 mL MLSS inoculum demonstrates the ability and potential to remove the disadvantages associated with the use of the 2 mL unfiltered effluent inoculum. The modified BDOC procedure equipped with this new inoculum is a promising alternative method for characterizing reclaimed and treated wastewaters. To promote the procedure with the new inoculum as a standard method, more applications and more studies on the performance (precision and accuracy) of the procedure, are required.

5.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Conclusions

A procedure for measuring biologically reactive organic carbon in reclaimed and secondary treated wastewaters, was developed in this dissertation. A method for determining biodegradable dissolved organic carbon (BDOC) in drinking water was adapted and combined with the classical biochemical oxygen demand (BOD) technique to obtain the modified BDOC procedure. An attempt to find a tool for evaluating the performance of a biological activated carbon system in a wastewater reclamation pilot plant was the original motivation for the development of the modified BDOC procedure. The procedure was subsequently used for assessing the quality of secondary effluents which sometimes cannot be characterized accurately and precisely by traditional methods such as BOD and chemical oxygen demand (COD).

Dissolved oxygen (DO) measurements before and after incubation and dilution technique were included in the modified procedure to insure the adequacy of DO throughout the incubation and to achieve simultaneous determinations of soluble BOD (SBOD) and BDOC. Initially the original method was used to measure BDOC in the effluent samples from the sand filter, five ozonation columns, biological activated carbon (BAC) filter, and nanofilter of a wastewater reuse pilot plant at Lake Arrowhead,

California. Imprecise BDOC results were obtained. It was later discovered that the 0.22 μm cellulose acetate membrane filter used in the original procedure leached out organic carbon and caused the imprecision. Consequently, the modified BDOC procedure requires to use glass fiber filters (GF/F) instead of the membrane filters.

Using the modified procedure, BDOC can be detected to a concentration as low as 0.15 mg/L (detection limit) and is a more precise parameter than COD and BOD. Inoculum source and size, and inoculum filtration after incubation were investigated using reclaimed wastewater samples. Inoculating the samples with sand filtration effluent and biological activated carbon filtration (BAF) effluent provided statistically insignificant differences in BDOC. Insignificant differences in BDOC were also obtained when the samples were inoculated with 1 mL and 2 mL of BAF effluent, and 2 mL and 4 mL of BAF effluent. Filtration after incubation did not have any significant effect on BDOC value.

To reduce incubation time, incubating at a higher temperature of 37°C and shaking the bottles with 30% air space at 100 rpm during the incubation were experimented. For both reclaimed and secondary effluent samples, the agitation had no effect on BDOC exertion kinetics at both temperatures (20°C and 37°C). Increasing the incubation temperature to 37°C resulted in faster BDOC exertions for both types of samples but an incubation time of 10 to 15 days is still required to achieve 60% exertion. The final BDOCs ($BDOC_{28}$) of reclaimed wastewater samples incubated at the two temperatures were not significantly different while the $BDOC_{28}$ at 20°C was only 75% of that at 37°C

for secondary effluent samples. First-order kinetics can be used to describe the exertions of BDOC only at 37°C for both reclaimed wastewater and secondary effluent samples. Only ultimate SBOD ($SBOD_u$) and BDOC of reclaimed wastewater samples could be determined concurrently. It is believed that the use of a small-size inoculum (2 mL of effluent) and/or the biorefractory nature of secondary effluents may attribute to the lower $BDOC_{28}$ values for secondary effluent samples, the disagreement with the first-order model for both reclaimed wastewater and secondary effluent samples, and the inability to perform simultaneous determinations of BDOC and $SBOD_5$ for secondary effluent samples at 20°C.

Using the modified procedure, BDOC can indicate the efficiency of BAC systems. BDOC was able to successfully indicate a gradual increase in biodegradability during the five step ozonation of sand filtration effluent at the Lake Arrowhead wastewater reuse pilot plant. Furthermore, the procedure could detect a BDOC decrease in the BAC filter following the last ozonation step. $SBOD_u$ was able to provide the same indication occasionally. Significant and strong positive relationships were observed among DOC, BDOC, and $SBOD_u$.

BDOC can clearly differentiate the quality of secondary effluent samples from activated sludge wastewater treatment plants. BDOC in secondary effluents decrease with the increase of solids retention time (SRT) of the processes. A sharp BDOC decrease was observed between a SRT of 0.5 to 5 days. BDOC remains relatively constant when the SRT is greater than 10 days. This observation resembles the results provided by an

effluent substrate concentration-SRT model proposed in 1970. The results have not been experimentally reproduced due to a lack of sensitivity of existing parameters such as BOD and COD. BDOC correlates strongly and significantly with DOC and soluble COD.

After the successful development and applications, the modified BDOC procedure was evaluated as a replacement for BOD in characterizing water quality and wastewater treatment and reclamation plant efficiencies. Four disadvantages were identified: long incubation time, lag period, inability to determine BDOC and $SBOD_5$ of secondary effluents simultaneously, and difference between $BDOC_{28}$ of secondary effluents incubated at 20°C and 37°C. The use of the small-size inoculum may cause these disadvantages.

Several larger size and/or more concentrated inocula, such as commercial BOD seed and mixed liquor suspended solids (MLSS), were tested to alleviate the disadvantages associated with the use of the modified BDOC procedure. The modified procedure was used to measure BDOC in standard solutions of sodium acetate and phenol, secondary effluent samples from high purity oxygen (HPO) plants, and ozonated and non-ozonated secondary effluent samples from high SRT plants.

Four inocula were used in determining BDOC in standard solutions: 2 mL of effluent, 10 mL of effluent, 2 mL of commercial BOD seed, and 2 mL of MLSS. Complete BDOC exertions occurred in 5 days and accurate and precise BDOC concentrations were obtained regardless of the inoculum used in the procedure. It was found that the commercial BOD seed inoculum qualitatively provides the slowest exertion. Similar results may not be obtained when using these four inocula to determine BDOC in

secondary effluents since the properties of the samples are different. Therefore, the same four inocula were further tested with secondary effluent samples from HPO plants.

Concurrent determinations of BDOC and $SBOD_5$ of secondary effluent samples were achieved only when the 2 mL MLSS inoculum was tested. Furthermore, the MLSS inoculum provided the fastest exertion rate while the commercial BOD seed inoculum provided the slowest rate. The 10 mL effluent inoculum was able to provide the exertion rate comparable to the rate obtained when using the MLSS inoculum. However, it was decided not to pursue any further investigation on the 10 mL effluent inoculum due to the larger amount of DOC produced when adding the inoculum to the samples. Although the 2 mL MLSS inoculum is the most effective inoculum, the reduction of incubation time to 5 days is possible only if incubating at 37°C. The use of larger sizes of MLSS (5 and 10 mL) was subsequently focused when determining BDOC in ozonated and non-ozonated secondary effluent samples from high SRT plants.

Using the 10 mL MLSS inoculum at 20°C, approximately 50% of BDOC in non-ozonated samples and 90% of BDOC in ozonated samples exerted within the first 5 days of incubation. $BDOC_5$ using the 10 mL MLSS inoculum at 20°C is comparable to $BDOC_{28}$ using the 2 mL MLSS inoculum at 20°C. Although it has not been tested, the 10 mL MLSS inoculum should be able to provide the simultaneous determinations of BDOC and $SBOD_5$ as the 2 mL MLSS inoculum. It was found that the 2 mL effluent inoculum may not provide enough viable cells and consequently causes a dramatic underestimation of BDOC in secondary effluents. Also, it was confirmed that the difference between

$BDOC_{28}$ of secondary effluents incubated at 20°C and 37°C is due to inadequate inoculum and the recalcitrant nature of secondary effluents. The 10 mL MLSS inoculum has demonstrated the ability to mitigate all disadvantages associated with the use of the modified BDOC procedure. Incorporating the inoculum to the procedure and proposing it as a standard method for water quality assessment are possible.

5.2 Recommendations for Future Work

The modified BDOC procedure equipped with the 10 mL MLSS inoculum has demonstrated its ability to be a routine water quality procedure. However, several important aspects of the procedure using this new inoculum, such as detection limit, precision, and accuracy, have not been studied. These aspects were investigated for the BDOC procedure using the 2 mL effluent inoculum but the values may not be the same. Studies on these aspects for the 10 mL MLSS inoculum can be performed in the same way. These aspects must be studied thoroughly before proposing the procedure as a standard method. An interlaboratory study, such as a "round-robin" test of BDOC measurement, is also recommended for this case. It is very important to determine the reproducibility and the variability of BDOC measurement among laboratories. Currently, a collaborative research on BDOC is being conducted at the Environmental Engineering Laboratory, Department of Civil Engineering, University of Hawaii. It is expected to have more laboratories involved in this work after the procedure is widely known.

In this research, the modified BDOC procedure was mainly used for characterizing reclaimed and secondary treated domestic wastewaters. In principle the procedure is not necessarily limited to these two types of wastewater; however, the procedure has not been tested with other types of wastewater such as primary treated wastewaters or secondary treated industrial wastewaters. Adjustments to the methodology may be required. Research on applications of the procedure to other types of water should be conducted. Applicability of the procedure to other types of water will increase the popularity of the procedure.

Up to this time, the mechanisms of the modified BDOC procedure have yet been well understood. A study on the mechanisms of the procedure should be conducted. Moderately recalcitrant standard compounds can be used. In addition to following the DOC reduction, concentrations of the standard compounds and volatile suspended solids (representing cell mass) can be monitored periodically during the incubation. This will provide a better understanding on cell synthesis, respiration, and cell decay (endogenous respiration) during the procedure before and after the depletion of substrate. Substrate and cell mass balances can be performed to enumerate how much substrate is being used for each mechanism. Modeling work to describe all these mechanisms during the procedure is also strongly suggested.

It is possible to use BDOC as a design parameter for water and wastewater treatment processes. BDOC can be used for designing BAC systems in water treatment and wastewater reclamation. Development of mathematical expressions for designing

BAC systems has not been researched. Currently, BAC systems are designed by up-scaling pilot systems. Having the design equations with parameters such as BDOC, empty bed contact time (EBCT), and velocity, the pilot systems may not be necessary. If BDOC can be applied to primary effluents, replacing BOD in the design equations for activated sludge processes with BDOC may be possible and may provide better design equations. BDOC removal (instead of BOD removal) may better describe the efficiency activated sludge processes. This can be another interesting topic for future research.

APPENDIX A
BDOC DATA USED FOR DETERMINING METHOD DETECTION LIMIT (MDL) OF THE MODIFIED BDOC PROTOCOL

To evaluate the method detection limit of the modified BDOC protocol, five deionized water samples were spiked with sodium acetate to have a dissolved organic carbon (DOC) concentration between 0.40 to 0.50 mg/L (excluding the background DOC in deionized water). The procedure described in *Standard Methods* (1989) for determining method detection limit, was then followed. The results are shown in Table A-1.

Table A-1 BDOC data used for determining method detection limit.

	BDOC (mg/L)				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
DOC (mg/L)	0.49	0.42	0.41	0.47	0.46
Portion 1	0.43	0.41	0.35	0.43	0.38
Portion 2	0.44	0.42	0.36	0.40	0.44
Portion 3	0.49	0.42	0.42	0.49	0.43
Portion 4	0.52	0.38	0.42	0.44	0.41
Portion 5	0.46	0.45	0.35	0.48	0.44
Portion 6	0.54	0.45	0.38	0.48	0.50
Portion 7	0.54	0.35	0.41	0.49	0.47
Standard deviation (SD)	0.046	0.036	0.032	0.035	0.039
MDL (3.14 × SD)	0.15	0.11	0.10	0.11	0.12

APPENDIX B
BDOC DATA USED FOR DETERMINING PRECISION OF THE MODIFIED BDOC PROTOCOL (EQUATION 3, CHAPTER 2)

BDOC data (mean and standard deviation of triplicate) shown in Table B-1, were used in the procedure for determining the precision of the modified BDOC protocol described in Chapter 2. Figure B-1 shows the linear regression (equation 3, Chapter 2) of the data in Table B-1 (mean BDOC versus standard deviation).

Table B-1 BDOC data used for determining precision of the modified BDOC protocol.

Reclaimed wastewater samples				Secondary effluent samples			
No.	DOC (mg/L)	Mean BDOC (mg/L)	Standard Deviation (mg/L)	No.	DOC (mg/L)	Mean BDOC (mg/L)	Standard Deviation (mg/L)
1	7.12	1.73	0.20	1	5.38	0.58	0.03
2	6.84	2.03	0.01	2	5.16	0.56	0.05
3	7.01	1.88	0.13	3	5.00	0.48	0.05
4	7.26	1.23	0.13	4	4.72	0.50	0.05
5	7.00	1.81	0.06	5	4.56	0.47	0.02
6	7.59	1.23	0.11	6	5.69	0.72	0.07
7	7.38	1.81	0.15	7	5.79	0.67	0.03
8	7.35	1.87	0.07	8	5.87	0.67	0.04
9	6.51	2.36	0.04	9	5.58	0.59	0.04
10	6.57	2.05	0.06	10	5.54	1.00	0.02
11	6.19	0.97	0.03	11	4.99	0.58	0.03
12	6.17	1.33	0.07	12	4.96	0.80	0.05
13	6.42	0.84	0.05	13	5.09	0.90	0.01
14	6.40	1.51	0.15	14	7.33	0.63	0.02
15	6.18	1.15	0.04	15	7.64	0.81	0.02
16	6.17	2.39	0.04	16	7.85	0.91	0.05
17	11.70	3.40	0.03	17	7.68	0.73	0.02
18	9.79	3.37	0.05	18	7.84	1.04	0.02
19	10.90	2.19	0.12	19	8.70	1.51	0.11
20	5.32	0.88	0.04	20	9.55	1.94	0.09
21	5.06	0.58	0.06	21	9.71	1.92	0.12
22	5.29	1.63	0.11	22	9.95	2.16	0.21
23	5.37	0.99	0.06	23	9.01	2.21	0.22
24	5.29	1.21	0.03	24	8.84	2.04	0.13
25	9.44	4.74	0.24	25	8.44	1.5	0.04
26	8.67	2.13	0.12	26	8.57	1.73	0.08
27	8.36	3.05	0.17	27	8.6	1.74	0.03
28	8.05	1.99	0.12	28	6.78	0.85	0.11
29	8.47	3.13	0.04	29	8.98	2.47	0.10
				30	8.45	1.64	0.04
				31	9.11	1.86	0.16
				32	10.05	3.00	0.08
				33	11.61	3.11	0.15
				34	11.76	3.86	0.18
				35	10.93	3.02	0.12
				36	14.98	4.32	0.17
				37	15.34	4.77	0.07
				38	13.74	3.13	0.06
				39	13.89	3.52	0.21
				40	6.11	0.70	0.01
				41	6.26	0.74	0.05
				42	6.76	0.76	0.05
				43	6.89	0.77	0.04

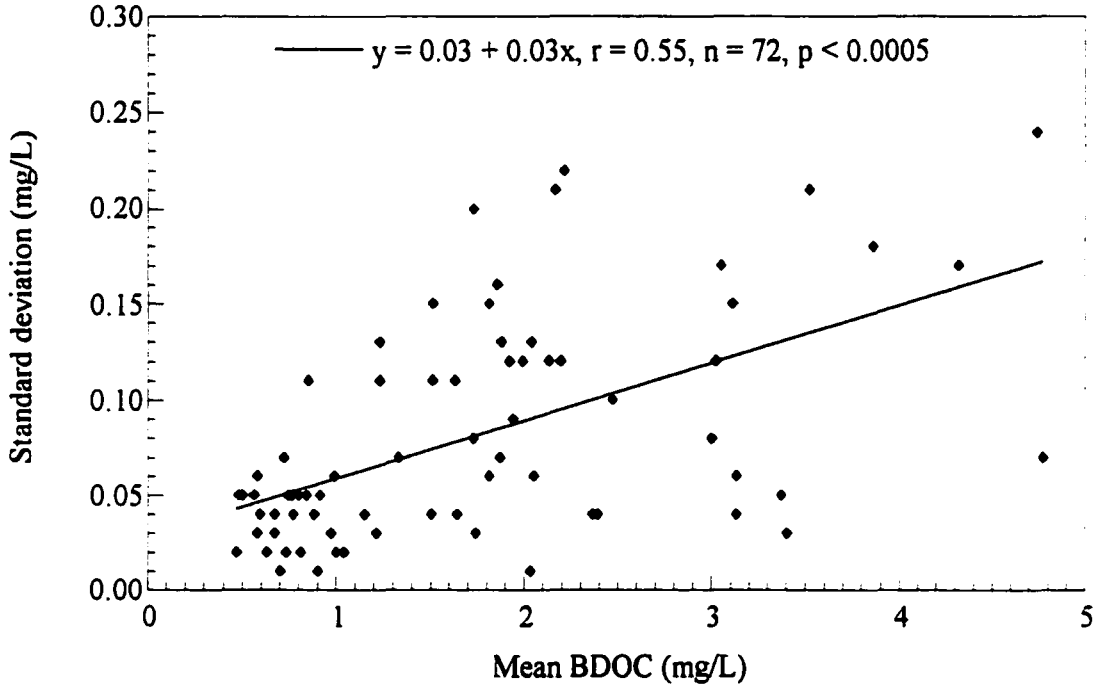


Figure B-1 Linear regression between mean BDOC and standard deviation data shown in Table B-1.

APPENDIX C
SIGNIFICANCE LEVEL (T-TEST) OF THE BDOC DIFFERENCE

The significance level of the BDOC difference resulting from different incubation conditions (time, temperature, inoculum type and size, and agitation) was calculated in the same manner as shown in Table C-1. Table C-1 illustrates how to calculate the significance level of the BDOC difference resulting from using different inocula (2 mL biological activated carbon filtration effluent and 2 mL sand filtration effluent). First, the average of the two BDOCs was computed (column 4). The value was next substituted into equation (3) in Chapter 2 (external reference distribution) to obtain standard deviation (column 5). The standard deviation was then used to calculate t value (BDOC difference/SD, in column 6). Finally, the significance level corresponding to the t value in column 6 (one tail and one degree of freedom), was estimated using either the t-distribution table or statistical software.

Table C-1 Example on how to calculate the significance level of the BDOC difference.

BDOC (mg/L)		BDOC difference (mg/L)	Average BDOC (mg/L)	SD according to eq. (3), Chapter 2	BDOC difference/SD	Significance level of the difference, (*t*-test)
2 mL BAC fil. inoculum	2 mL sand fil. inoculum					
1.61	1.28	0.33	1.45	0.073	4.499	0.07
1.85	1.91	0.06	1.88	0.086	0.694	0.31
0.67	0.40	0.27	0.54	0.046	5.863	0.05
2.26	2.02	0.24	2.14	0.094	2.548	0.12
2.95	3.34	0.39	3.15	0.124	3.136	0.10
1.56	1.56	0.00	1.56	0.077	0.000	0.50
0.98	1.23	0.25	1.11	0.063	3.959	0.08
2.18	2.10	0.08	2.14	0.094	0.849	0.28
0.85	0.80	0.05	0.83	0.055	0.913	0.26

APPENDIX D
FIT OF THE FIRST-ORDER KINETIC MODEL OF BDOC EXERTION DATA

The following equations (first-order kinetic expressions) were used to examine the fit of the first-order kinetic model of BDOC exertion data:

$$BDOC_t = BDOC_u\left(1 - e^{-kt}\right) \quad \text{(D-1)}$$

$$Ln\left(1 - \frac{BDOC_t}{BDOC_u}\right) = -kt \quad \text{(D-2)}$$

where $BDOC_t$ = BDOC at time t (mg/L),

$BDOC_u$ = ultimate BDOC (mg/L),

k = first-order rate constant (day^{-1}),

t = incubation time (day).

The BDOC exertion data of reclaimed wastewater samples during the incubation at 37°C shown in column 2 of Table D-1 (also in Figure 6, Chapter 2) will be used as an example. First, the assumption that $BDOC_{28}$ is approximately equal to $BDOC_u$, was made. The values of Ln (1 - $BDOC_t/BDOC_u$) were calculated (column 3) and were later plotted against incubation time as shown in Figure D-1. As shown in Figure D-1,

multiplying the slope of a linear regression between Ln (1 - $BDOC_t/BDOC_u$) and incubation time by -1, an initial estimate of k (0.119 day^{-1}) was obtained. Using equation (D-1) and the initial k value, $BDOC_t/BDOC_{28}$ value shown in the last row of column 4, was computed. The new $BDOC_t/BDOC_{28}$ values presented in the other rows, were calculated by multiplying the values in column 2 by $BDOC_{28}/BDOC_u$. A new k value was obtained in the same way described above using the new $BDOC_t/BDOC_u$ value (including $BDOC_{28}/BDOC_u$). The procedure was repeated until there was no change in the k value. The final regression (k = 0.095 day^{-1}) is shown in Figure 7, Chapter 2. The final $BDOC_t/BDOC_{28}$ values (model versus actual) are shown in columns 5 and 6, respectively. It can be seen that the assumption made above ($BDOC_{28} \approx BDOC_u$) was valid since $BDOC_{28}/BDOC_u$ is equal to 0.93. The residual at each time can be obtained by subtracting the actual value by the model value.

Table D-1 Example on how to examine the fit of the first-order model of BDOC exertion data.

Incubation time (days)	$BDOC_t/BDOC_{28}$	Ln (1-$BDOC_t/BDOC_u$)	New $BDOC_t/BDOC_u$	Final $BDOC_t/BDOC_u$	
				model	actual
0	0	0	0	0	0
5	0.314	-0.377	0.303	0.378	0.292
10	0.603	-0.924	0.581	0.613	0.561
15	0.815	-1.687	0.786	0.759	0.758
20	0.929	-2.645	0.896	0.850	0.864
28	1.000	-	0.964	0.930	0.930

For the case that the data were not normalized by $BDOC_{28}$ determining with the same inoculum and at the same temperature (self-normalization) as described above, the fit of the first-order model of the data set whose $BDOC_{28}$ was used to normalize, must be

first examined and the final $BDOC_{28}/BDOC_u$ (after final iteration) was then used to determine $BDOC_t/BDOC_u$ of the non-self-normalized data ($BDOC_{28}/BDOC_u$ times $BDOC_t/BDOC_{28}$). To obtain the k value, the log transformation and linear regression processes described above, were finally applied without any iteration since the $BDOC_u$ was no longer an unknown.

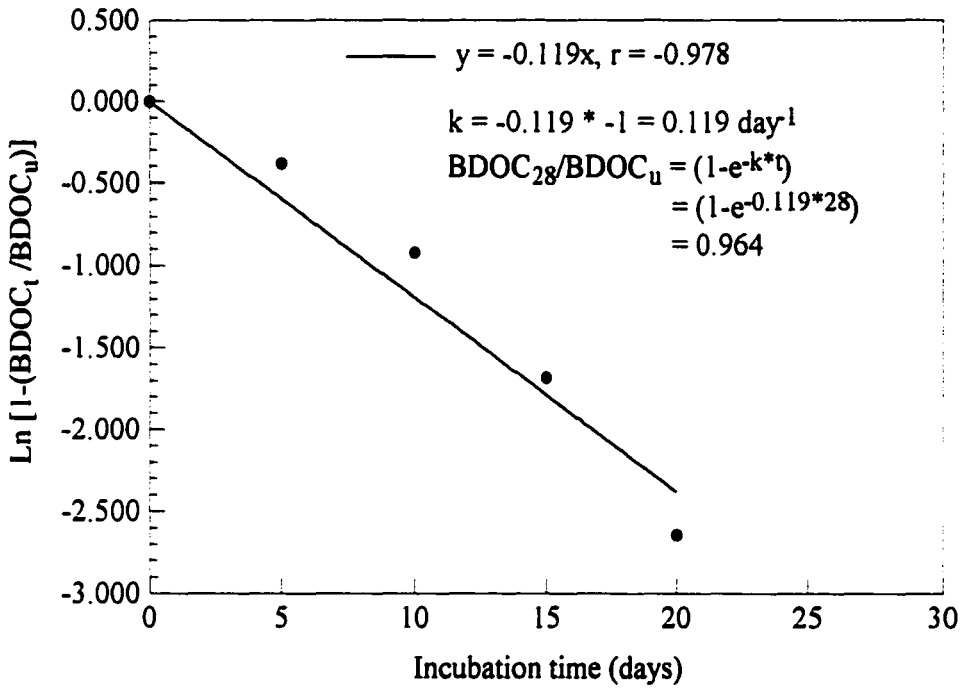


Figure D-1 Linear regression between Ln (1- BDOC$_t$/BDOC$_u$) and incubation time for estimating initial first-order rate constant (k).

APPENDIX E
RAW DATA SUMMARY FOR RECLAIMED WASTEWATER SAMPLES FROM THE LAKE ARROWHEAD PILOT PLANT

Table E-1 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 09/09/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	7.12	1.71	7.92	0.116
Ozone column 1	7.02	2.04	6.12	0.120
Ozone column 2	6.93	1.59	6.42	0.096
Ozone column 3	6.71	1.65	5.79	0.080
Ozone column 4	6.76	1.98	5.82	0.077
Ozone column 5	6.84	2.04	6.51	0.072
BAC filter	5.32	0.92	3.10	0.057
Nanofilter	0.23	< detection limit	< detection limit	0.027

Table E-2 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 09/13/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	6.19	0.94	4.80	0.101
Ozone column 1	6.15	0.82	5.28	0.100
Ozone column 2	6.12	0.94	5.85	0.102
Ozone column 3	6.08	1.03	5.85	0.092
Ozone column 4	6.11	1.09	5.64	0.093
Ozone column 5	6.17	1.42	5.76	0.093
BAC filter	5.38	0.46	3.22	0.078
Nanofilter	1.33	< detection limit	< detection limit	0.023

Table E-3 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 09/28/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	6.42	0.80	2.91	0.117
Ozone column 1	6.35	1.02	3.27	0.123
Ozone column 2	7.08	1.29	4.23	0.119
Ozone column 3	7.09	1.44	5.19	0.100
Ozone column 4	7.22	1.44	5.61	0.095
Ozone column 5	7.01	1.71	5.67	0.085
BAC filter	5.06	0.67	2.15	0.065
Nanofilter	1.95	0.18	< detection limit	0.025

Table E-4 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 10/06/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	7.26	1.41	5.70	0.122
Ozone column 1	6.93	1.67	7.32	0.097
Ozone column 2	7.08	2.06	8.19	0.082
Ozone column 3	7.24	2.42	9.24	0.071
Ozone column 4	7.83	3.26	12.63	0.070
Ozone column 5	9.44	4.58	16.92	0.071
BAC filter	5.29	1.61	6.48	0.050
Nanofilter	5.01	-	-	0.012

Table E-5 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 10/13/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	8.49	1.28	6.69	0.139
Ozone column 1	7.70	1.94	5.70	0.105
Ozone column 2	7.29	1.83	6.24	0.096
Ozone column 3	6.90	1.49	6.33	0.082
Ozone column 4	6.18	1.40	6.12	0.072
Ozone column 5	5.89	1.85	5.55	0.066
BAC filter	4.71	0.67	2.00	0.048
Nanofilter	1.45	< detection limit	< detection limit	0.017

Table E-6 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 10/20/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	8.03	1.98	6.09	0.167
Ozone column 1	8.44	3.19	10.53	0.152
Ozone column 2	8.45	3.46	8.64	0.140
Ozone column 3	9.07	3.58	10.65	0.132
Ozone column 4	9.07	3.61	11.52	0.124
Ozone column 5	9.13	3.49	11.58	0.117
BAC filter	5.68	0.88	4.53	0.053
Nanofilter	1.96	0.29	< detection limit	0.019

Table E-7 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 10/25/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	8.67	2.02	13.41	0.168
Ozone column 1	7.62	2.20	10.23	0.144
Ozone column 2	7.88	2.35	8.67	0.129
Ozone column 3	7.87	2.74	10.11	0.112
Ozone column 4	8.48	2.74	9.96	0.106
Ozone column 5	8.36	2.95	11.43	0.105
BAC filter	6.40	1.56	4.93	0.077
Nanofilter	1.90	< detection limit	< detection limit	0.028

Table E-8 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 11/01/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	7.45	1.23	3.12	0.116
Ozone column 1	6.77	1.64	4.59	0.101
Ozone column 2	6.92	1.85	4.20	0.102
Ozone column 3	6.69	1.88	5.13	0.091
Ozone column 4	6.60	1.61	4.65	0.087
Ozone column 5	6.99	2.18	5.82	0.083
BAC filter	5.05	0.85	2.00	0.064
Nanofilter	-	-	-	-

Table E-9 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 11/07/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	8.98	1.65	5.73	0.134
Ozone column 1	7.25	2.31	5.70	0.114
Ozone column 2	7.06	1.47	6.51	0.097
Ozone column 3	-	-	-	0.086
Ozone column 4	7.01	2.58	6.39	0.083
Ozone column 5	6.65	2.46	6.51	0.078
BAC filter	5.80	1.11	4.77	0.055
Nanofilter	-	-	-	-

Table E-10 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 11/15/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	8.05	1.83	6.18	0.163
Ozone column 1	8.60	2.56	6.42	0.139
Ozone column 2	9.41	3.16	9.63	0.125
Ozone column 3	9.55	3.82	10.08	0.098
Ozone column 4	8.69	3.10	9.15	0.095
Ozone column 5	8.47	3.16	9.27	0.090
BAC filter	7.00	1.89	5.30	0.071
Nanofilter	0.30	< detection limit	< detection limit	< detection limit

Table E-11 DOC, BDOC, $SBOD_u$, and UV_{254} of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 11/22/94.

Sample	DOC (mg/L)	BDOC (mg/L)	$SBOD_u$ (mg/L)	UV_{254} (cm^{-1})
Sand filter	7.59	1.36	4.11	0.125
Ozone column 1	7.39	1.45	3.60	0.131
Ozone column 2	7.35	1.60	3.63	0.130
Ozone column 3	7.49	1.66	5.07	0.129
Ozone column 4	7.18	1.66	3.96	0.132
Ozone column 5	7.38	1.93	4.23	0.133
BAC filter	6.18	1.18	4.70	0.108
Nanofilter	0.29	< detection limit	< detection limit	0.006

Table E-12 DOC and BDOC of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 5/17/95.

Sample, incubation temperature, and agitation condition	DOC (mg/L)	$BDOC_t$ (mg/L)				
		5	10	15	20	28
Sand filter, 20°C	6.04	0.32	0.57	0.86	1.25	1.38
Sand filter, 20°C, duplicate		0.38	0.62	0.80	1.30	1.24
Sand filter, 20°C, agitation		0.41	0.61	0.92	1.25	1.42
Sand filter, 20°C, agitation, duplicate		0.42	0.65	0.84	1.23	1.48
Sand filter, 37°C		0.37	0.82	1.16	1.34	1.41
Sand filter, 37°C, duplicate		0.43	0.67	1.15	1.22	1.34
Sand filter, 37°C, agitation		0.36	0.77	1.11	1.19	1.23
Sand filter, 37°C, agitation, duplicate		0.35	0.69	1.11	1.17	1.26
Ozone column 5, 20°C	5.78	0.10	0.09	0.91	1.21	1.53
Ozone column 5, 20°C, duplicate		0.10	0.07	0.81	1.18	1.51
Ozone column 5, 20°C, agitation		0.06	0.11	0.83	1.24	1.55
Ozone column 5, 20°C, agitation, duplicate		0.04	0.11	0.84	1.25	1.42
Ozone column 5, 37°C		0.35	0.56	1.23	1.48	1.45
Ozone column 5, 37°C, duplicate		0.31	0.55	1.26	1.54	1.49
Ozone column 5, 37°C, agitation		0.34	0.58	1.07	1.38	1.47
Ozone column 5, 37°C, agitation, duplicate		0.33	0.65	1.12	1.43	1.50

Table E-13 DOC and BDOC of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 5/24/95.

Sample, incubation temperature, and agitation condition	DOC (mg/L)	$BDOC_t$ (mg/L)				
		5	10	15	20	28
Sand filter, 20°C	6.79	0.67	0.85	1.28	1.38	1.70
Sand filter, 20°C, duplicate		0.62	0.77	1.30	1.52	1.87
Sand filter, 20°C, agitation		0.60	0.83	1.30	1.44	1.85
Sand filter, 20°C, agitation, duplicate		0.70	0.85	1.34	1.48	1.82
Sand filter, 37°C		0.75	1.18	1.40	1.53	1.89
Sand filter, 37°C, duplicate		0.83	1.20	1.45	1.43	1.89
Sand filter, 37°C, agitation		0.76	1.21	1.37	1.50	1.82
Sand filter, 37°C, agitation, duplicate		0.80	1.10	1.52	1.67	1.87
Ozone column 5, 20°C	6.56	0.33	0.91	1.49	1.87	2.21
Ozone column 5, 20°C, duplicate		0.38	0.85	1.50	1.81	2.18
Ozone column 5, 20°C, agitation		0.43	0.98	1.45	1.81	2.39
Ozone column 5, 20°C, agitation, duplicate		0.41	0.91	1.49	1.87	2.25
Ozone column 5, 37°C		0.63	1.31	1.84	2.02	2.26
Ozone column 5, 37°C, duplicate		0.85	1.38	1.70	1.97	2.18
Ozone column 5, 37°C, agitation		0.72	1.54	1.89	2.12	2.32
Ozone column 5, 37°C, agitation, duplicate		0.93	1.44	1.71	1.89	2.20
BAC filter, 20°C	7.05	0.52	1.04	1.39	1.71	2.07
BAC filter, 20°C, duplicate		0.63	1.06	1.30	1.62	2.16
BAC filter, 20°C, agitation		0.74	1.04	1.38	1.65	2.21
BAC filter, 20°C, agitation, duplicate		0.47	1.05	1.47	1.64	2.20
BAC filter, 37°C		0.55	1.25	1.62	1.96	2.08
BAC filter, 37°C, duplicate		0.83	1.24	1.51	1.94	2.06
BAC filter, 37°C, agitation		0.88	1.32	1.68	1.90	2.06
BAC filter, 37°C, agitation, duplicate		0.73	1.38	1.71	1.78	2.05

Table E-14 DOC and BDOC of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 5/31/95.

Sample, incubation temperature, and agitation condition	DOC (mg/L)	$BDOC_t$ (mg/L)				
		5	10	15	20	28
Sand filter, 20°C	8.60	0.90	1.60	2.03	2.29	2.72
Sand filter, 20°C, duplicate		1.00	1.56	2.04	2.35	2.80
Sand filter, 20°C, agitation		1.05	1.50	1.84	2.18	2.75
Sand filter, 20°C, agitation, duplicate		0.99	1.55	1.82	2.21	2.92
Sand filter, 37°C		1.22	1.77	2.48	2.57	2.75
Sand filter, 37°C, duplicate		1.22	1.98	2.51	2.56	2.89
Sand filter, 37°C, agitation		1.22	1.65	2.62	2.81	2.94
Sand filter, 37°C, agitation, duplicate		1.12	1.66	2.41	2.43	2.86
Ozone column 5, 20°C	8.42	0.58	1.63	2.19	2.74	2.99
Ozone column 5, 20°C, duplicate		0.66	1.66	2.19	2.85	3.14
Ozone column 5, 20°C, agitation		0.79	1.62	2.25	2.75	2.92
Ozone column 5, 20°C, agitation, duplicate		0.76	1.54	2.25	2.63	3.24
Ozone column 5, 37°C		1.10	1.96	2.50	2.80	3.18
Ozone column 5, 37°C, duplicate		1.02	1.91	2.32	2.88	3.02
Ozone column 5, 37°C, agitation		1.11	1.99	2.31	3.02	3.17
Ozone column 5, 37°C, agitation, duplicate		0.99	1.83	2.38	3.05	3.21
BAC filter, 20°C	8.01	0.71	1.57	2.05	2.45	3.20
BAC filter, 20°C, duplicate		0.83	1.73	2.36	2.69	3.22
BAC filter, 20°C, agitation		0.79	1.73	2.16	2.62	3.31
BAC filter, 20°C, agitation, duplicate		0.94	1.83	2.10	2.55	3.31
BAC filter, 37°C		1.11	2.17	2.62	3.12	3.10
BAC filter, 37°C, duplicate		1.19	2.16	2.65	3.14	3.10
BAC filter, 37°C, agitation		1.05	2.15	2.60	3.09	3.19
BAC filter, 37°C, agitation, duplicate		1.15	2.22	2.58	3.17	3.19

Table E-15 DOC and BDOC of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 06/07/95.

Sample, incubation temperature, and agitation condition	DOC (mg/L)	$BDOC_t$ (mg/L)				
		5	10	15	20	28
Sand filter, 20°C	7.33	0.41	0.73	1.28	1.61	2.15
Sand filter, 20°C, duplicate		0.47	0.80	1.39	1.71	2.27
Sand filter, 20°C, agitation		0.50	0.88	1.26	1.70	2.26
Sand filter, 20°C, agitation, duplicate		0.48	0.88	1.29	1.75	2.43
Sand filter, 37°C		0.70	1.48	1.83	2.02	2.16
Sand filter, 37°C, duplicate		0.60	1.49	1.79	1.92	2.20
Sand filter, 37°C, agitation		0.59	1.48	1.84	1.91	2.02
Sand filter, 37°C, agitation, duplicate		0.64	1.45	1.70	1.87	2.05
Ozone column 5, 20°C	6.37	0.44	0.79	1.30	1.82	2.39
Ozone column 5, 20°C, duplicate		0.44	0.84	1.44	1.94	2.41
Ozone column 5, 20°C, agitation		0.35	0.94	1.41	1.87	2.57
Ozone column 5, 20°C, agitation, duplicate		0.47	0.97	1.50	1.86	2.53
Ozone column 5, 37°C		0.81	1.25	1.67	2.01	2.36
Ozone column 5, 37°C, duplicate		0.67	1.21	1.64	2.11	2.44
Ozone column 5, 37°C, agitation		0.79	1.22	1.65	2.12	2.35
Ozone column 5, 37°C, agitation, duplicate		0.66	1.36	1.66	1.86	2.16
BAC filter, 20°C	6.54	0.11	0.65	1.30	1.91	2.25
BAC filter, 20°C, duplicate		0.07	0.71	1.38	1.77	2.37
BAC filter, 20°C, agitation		0.24	0.63	1.29	1.73	2.38
BAC filter, 20°C, agitation, duplicate		0.11	0.69	1.33	1.80	2.42
BAC filter, 37°C		0.57	1.30	1.95	2.26	2.43
BAC filter, 37°C, duplicate		0.48	1.31	1.86	2.18	2.29
BAC filter, 37°C, agitation		0.43	1.49	2.09	2.40	2.47
BAC filter, 37°C, agitation, duplicate		0.53	1.58	2.11	2.29	2.52

Table E-16 DOC and BDOC of reclaimed wastewater samples from the Lake Arrowhead pilot plant, sampling date: 6/15/95.

Sample, incubation temperature, and agitation condition	DOC (mg/L)	$BDOC_t$ (mg/L)				
		5	10	15	20	28
Sand filter, 20°C	7.08	0.39	0.64	1.26	1.68	2.18
Sand filter, 20°C, duplicate		0.29	0.60	1.23	1.47	1.96
Sand filter, 20°C, agitation		0.30	0.66	1.01	1.64	2.13
Sand filter, 20°C, agitation, duplicate		0.41	0.75	1.11	1.45	1.98
Sand filter, 37°C		0.46	1.36	1.76	1.89	2.20
Sand filter, 37°C, duplicate		0.59	1.45	1.76	2.00	2.13
Sand filter, 37°C, agitation		0.60	1.29	1.70	1.77	2.07
Sand filter, 37°C, agitation, duplicate		0.46	1.20	1.70	1.90	2.03
Ozone column 5, 20°C	8.36	0.45	0.96	1.98	2.88	3.37
Ozone column 5, 20°C, duplicate		0.45	0.97	1.91	2.74	3.37
Ozone column 5, 20°C, agitation		0.59	0.86	1.87	2.69	3.33
Ozone column 5, 20°C, agitation, duplicate		0.57	0.83	1.68	2.54	3.13
Ozone column 5, 37°C		1.02	2.07	2.89	3.38	3.44
Ozone column 5, 37°C, duplicate		1.09	2.26	3.04	3.55	3.51
Ozone column 5, 37°C, agitation		1.01	1.99	2.76	3.26	3.23
Ozone column 5, 37°C, agitation, duplicate		0.97	2.00	2.57	3.20	3.32
BAC filter, 20°C	7.67	0.38	0.80	1.72	2.37	2.95
BAC filter, 20°C, duplicate		0.31	0.71	1.60	2.25	2.93
BAC filter, 20°C, agitation		0.38	0.72	1.53	2.12	3.06
BAC filter, 20°C, agitation, duplicate		0.40	0.77	1.61	1.98	2.88
BAC filter, 37°C		0.89	1.87	2.62	3.05	3.06
BAC filter, 37°C, duplicate		0.81	1.91	2.78	3.05	3.05
BAC filter, 37°C, agitation		0.74	1.62	2.64	2.90	2.92
BAC filter, 37°C, agitation, duplicate		0.74	1.71	2.68	2.95	2.87

APPENDIX F
RAW DATA SUMMARY FOR SECONDARY EFFLUENT SAMPLES

Table F-1 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from RP1 WWTP.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L) 5	10	15	20	28
08/20/95	20°C	16.0	5.38	0.00	0.00	0.15	0.50	0.60
* Plant	20°C, duplicate	16.5		0.03	0.00	0.18	0.50	0.53
not	20°C, agitation			0.00	0.00	0.25	0.53	0.58
running	20°C, agitation, duplicate			0.00	0.08	0.20	0.45	0.60
in normal	37°C			0.08	0.30	0.43	0.65	0.65
condition	37°C, duplicate			0.18	0.28	0.38	0.60	0.63
	37°C, agitation			0.23	0.43	0.55	0.67	0.70
	37°C, agitation, duplicate			0.30	0.45	0.53	0.63	0.73
08/21/95	20°C	16.0	5.16	0.00	0.00	0.10	0.33	0.50
	20°C, duplicate	15.5		0.00	0.00	0.13	0.43	0.55
	20°C, agitation			0.00	0.00	0.25	0.30	0.63
	20°C, agitation, duplicate			0.00	0.03	0.20	0.33	0.55
	37°C			0.10	0.13	0.30	0.63	0.73
	37°C, duplicate			0.03	0.15	0.30	0.65	0.65
	37°C, agitation			0.15	0.15	0.43	0.60	0.68
	37°C, agitation, duplicate			0.05	0.05	0.40	0.53	0.65
08/22/95	20°C	14.0	5.00	0.00	0.05	0.05	0.30	0.43
	20°C, duplicate	14.0		0.00	0.00	0.00	0.45	0.43
	20°C, agitation			0.00	0.00	0.00	0.45	0.50
	20°C, agitation, duplicate			0.00	0.00	0.00	0.43	0.55
	37°C			0.00	0.10	0.10	0.55	0.63
	37°C, duplicate			0.00	0.13	0.13	0.43	0.63
	37°C, agitation			0.13	0.10	0.18	0.40	0.63
	37°C, agitation, duplicate			0.18	0.15	0.18	0.53	0.58
08/23/95	20°C	11.0	4.72	0.00	0.00	0.15	0.50	0.45
	20°C, duplicate	10.5		0.00	0.00	0.13	0.50	0.50
	20°C, agitation			0.00	0.03	0.13	0.38	0.58
	20°C, agitation, duplicate			0.00	0.03	0.15	0.38	0.48
	37°C			0.00	0.05	0.18	0.45	0.58
	37°C, duplicate			0.08	0.23	0.20	0.50	0.65
	37°C, agitation			0.18	0.23	0.20	0.53	0.73
	37°C, agitation, duplicate			0.10	0.10	0.15	0.63	0.65

Table F-1 (cont'd)

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
08/24/95	20°C	12.5	4.56	0.00	0.05	0.13	0.35	0.50
	20°C, duplicate	12.0		0.00	0.03	0.13	0.28	0.45
	20°C, agitation			0.00	0.05	0.13	0.40	0.48
	20°C, agitation, duplicate			0.00	0.10	0.15	0.33	0.45
	37°C			0.05	0.20	0.25	0.48	0.60
	37°C, duplicate			0.10	0.18	0.30	0.45	0.58
	37°C, agitation			0.18	0.23	0.23	0.48	0.63
	37°C, agitation, duplicate			0.10	0.18	0.25	0.53	0.68
08/27/95	20°C	15.5	4.55	0.00	0.00	0.00	0.00	0.27
	20°C, duplicate	15.5		0.00	0.00	0.00	0.00	0.25
08/28/95	20°C	16.0	4.81	0.00	0.00	0.00	0.00	0.35
	20°C, duplicate	16.0		0.00	0.00	0.00	0.00	0.31
08/29/95	20°C	17.0	5.20	0.00	0.17	0.20	0.39	0.46
	20°C, duplicate	16.5		0.00	0.15	0.23	0.33	0.46
08/30/95	20°C	13.5	4.96	0.00	0.00	0.01	0.13	0.26
	20°C, duplicate	13.5		0.00	0.00	0.08	0.15	0.23
08/31/95	20°C	13.0	5.22	0.00	0.21	0.28	0.40	0.60
	20°C, duplicate	14.0		0.00	0.18	0.20	0.34	0.58

Table F-2 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from RP2 WWTP.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
08/21/95	20°C	16.0	5.69	0.00	0.10	0.10	0.60	0.75
	20°C, duplicate	16.0		0.00	0.03	0.15	0.63	0.60
	20°C, agitation			0.00	0.03	0.20	0.70	0.78
	20°C, agitation, duplicate			0.00	0.03	0.18	0.58	0.75
	37°C			0.00	0.35	0.73	0.95	1.00
	37°C, duplicate			0.00	0.38	0.78	0.85	0.90
	37°C, agitation			0.03	0.35	0.83	0.93	0.85
	37°C, agitation, duplicate			0.00	0.18	0.80	0.80	0.88
08/22/95	20°C	17.0	5.79	0.00	0.00	0.15	0.43	0.68
	20°C, duplicate	16.5		0.00	0.10	0.15	0.45	0.63
	20°C, agitation			0.00	0.03	0.10	0.48	0.70
	20°C, agitation, duplicate			0.00	0.00	0.18	0.53	0.65
	37°C			0.00	0.10	0.55	1.00	0.98
	37°C, duplicate			0.00	0.20	0.45	0.90	0.85
	37°C, agitation			0.00	0.15	0.60	0.90	0.85
	37°C, agitation, duplicate			0.00	0.05	0.65	0.90	0.88
08/23/95	20°C	16.0	5.87	0.13	0.18	0.38	0.60	0.68
	20°C, duplicate	17.0		0.08	0.25	0.38	0.48	0.60
	20°C, agitation			0.00	0.38	0.50	0.58	0.70
	20°C, agitation, duplicate			0.10	0.25	0.38	0.50	0.70
	37°C			0.20	0.45	0.73	0.85	0.93
	37°C, duplicate			0.13	0.35	0.63	0.85	0.95
	37°C, agitation			0.30	0.33	0.75	0.93	1.05
	37°C, agitation, duplicate			0.15	0.33	0.68	0.85	1.00
08/24/95	20°C	15.0	5.58	0.00	0.05	0.10	0.40	0.65
	20°C, duplicate	16.0		0.00	0.13	0.18	0.40	0.58
	20°C, agitation			0.00	0.03	0.28	0.50	0.55
	20°C, agitation, duplicate			0.00	0.15	0.20	0.45	0.58
	37°C			0.00	0.33	0.58	0.93	0.83
	37°C, duplicate			0.00	0.33	0.55	0.88	0.88
	37°C, agitation			0.00	0.30	0.65	0.93	0.93
	37°C, agitation, duplicate			0.00	0.23	0.55	0.78	0.83
08/25/95	20°C	17.0	5.72	0.00	0.15	0.16	0.22	0.98
	20°C, duplicate	16.5		0.00	0.19	0.26	0.35	1.01
08/27/95	20°C	16.0	5.65	0.00	0.17	0.29	0.51	0.81
	20°C, duplicate	18.5		0.00	0.10	0.38	0.46	0.70
08/28/95	20°C	18.5	5.70	0.00	0.26	0.40	0.51	0.70
	20°C, duplicate	17.0		0.00	0.18	0.38	0.54	0.75
08/29/95	20°C	15.5	5.77	0.11	0.31	0.33	0.61	0.74
	20°C, duplicate	15.0		0.07	0.27	0.41	0.68	0.70
08/30/95	20°C	18.0	5.74	0.25	0.24	0.34	0.59	0.69
	20°C, duplicate	17.0		0.29	0.26	0.25	0.54	0.62
08/31/95	20°C	17.0	5.65	0.00	0.16	0.29	0.49	0.66
	20°C, duplicate	15.5		0.00	0.20	0.26	0.40	0.69

Table F-3 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from Carbon Canyon WWTP.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L) 5	10	15	20	28
08/20/95	20°C	15.0	5.54	0.13	0.50	0.65	0.68	1.00
	20°C, duplicate	16.0		0.13	0.60	0.68	0.65	0.98
	20°C, agitation			0.18	0.53	0.58	0.68	0.98
	20°C, agitation, duplicate			0.18	0.55	0.70	0.65	1.03
	37°C			0.23	0.68	0.68	1.10	1.20
	37°C, duplicate			0.28	0.65	0.73	1.05	1.13
	37°C, agitation			0.13	0.78	0.73	1.00	1.13
	37°C, agitation, duplicate			0.13	0.78	0.83	1.00	1.15
08/21/95	20°C	11.0	4.99	0.00	0.38	0.40	0.48	0.60
	20°C, duplicate	10.0		0.10	0.30	0.48	0.53	0.55
	20°C, agitation			0.23	0.23	0.53	0.58	0.55
	20°C, agitation, duplicate			0.25	0.33	0.53	0.50	0.63
	37°C			0.28	0.53	0.78	0.88	0.80
	37°C, duplicate			0.33	0.60	0.83	0.85	0.80
	37°C, agitation			0.15	0.53	0.73	0.75	0.85
	37°C, agitation, duplicate			0.13	0.53	0.73	0.78	0.83
08/22/95	20°C	11.5	4.96	0.05	0.45	0.53	0.63	0.80
	20°C, duplicate	10.5		0.00	0.38	0.55	0.65	0.78
	20°C, agitation			0.05	0.40	0.45	0.63	0.75
	20°C, agitation, duplicate			0.00	0.48	0.55	0.73	0.88
	37°C			0.15	0.60	0.88	1.00	1.03
	37°C, duplicate			0.05	0.60	0.85	0.93	1.00
	37°C, agitation			0.10	0.63	0.80	0.90	1.03
	37°C, agitation, duplicate			0.03	0.70	0.83	0.93	1.03
08/23/95	20°C	10.0	5.09	0.13	0.48	0.53	0.68	0.88
	20°C, duplicate	10.0		0.05	0.45	0.65	0.78	0.90
	20°C, agitation			0.03	0.40	0.58	0.75	0.90
	20°C, agitation, duplicate			0.13	0.43	0.55	0.70	0.90
	37°C			0.23	0.60	0.70	0.88	0.83
	37°C, duplicate			0.15	0.58	0.75	0.85	0.85
	37°C, agitation			0.15	0.68	0.68	0.73	0.83
	37°C, agitation, duplicate			0.15	0.68	0.85	0.80	0.75
08/24/95	20°C	10.0	4.85	0.19	0.33	0.39	0.51	0.57
	20°C, duplicate	10.0		0.23	0.31	0.39	0.48	0.56
08/27/95	20°C	10.5	4.68	0.06	0.38	0.41	0.53	0.57
	20°C, duplicate	10.0		0.16	0.40	0.58	0.56	0.58
08/28/95	20°C	11.0	4.67	0.27	0.29	0.31	0.45	0.61
	20°C, duplicate	11.0		0.28	0.27	0.26	0.51	0.65
08/29/95	20°C	10.0	4.72	0.11	0.25	0.32	0.38	0.50
	20°C, duplicate	10.5		0.04	0.26	0.32	0.49	0.56
08/30/95	20°C	10.0	4.78	0.17	0.48	0.46	0.70	0.70
	20°C, duplicate	10.5		0.38	0.60	0.59	0.62	0.59
08/31/95	20°C	10.5	4.86	0.11	0.26	0.24	0.54	0.54
	20°C, duplicate	11.0		0.07	0.23	0.27	0.38	0.50

Table F-4 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from Tapia WWTP.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
09/24/95	20°C	20.5	7.33	0.03	0.31	0.54	0.59	0.63
	20°C, duplicate	20.5		0.11	0.27	0.55	0.56	0.61
	20°C, agitation			0.17	0.37	0.57	0.63	0.62
	20°C, agitation, duplicate			0.09	0.39	0.52	0.61	0.65
	37°C			0.38	0.53	0.82	1.06	1.18
	37°C, duplicate			0.41	0.47	0.83	1.03	1.18
	37°C, agitation			0.32	0.48	0.86	0.96	1.24
	37°C, agitation, duplicate			0.29	0.55	0.83	1.00	1.19
09/25/95	20°C	21.5	7.64	0.12	0.29	0.34	0.59	0.80
	20°C, duplicate	21.0		0.13	0.32	0.52	0.54	0.79
	20°C, agitation			0.20	0.19	0.42	0.62	0.84
	20°C, agitation, duplicate			0.18	0.31	0.46	0.64	0.79
	37°C			0.30	0.78	1.05	1.16	1.27
	37°C, duplicate			0.34	0.60	0.91	1.25	1.25
	37°C, agitation			0.30	0.59	0.92	1.09	1.24
	37°C, agitation, duplicate			0.35	0.59	0.90	1.03	1.21
09/26/95	20°C	20.5	7.85	0.28	0.44	0.69	0.74	0.83
	20°C, duplicate	21.5		0.30	0.39	0.68	0.78	0.93
	20°C, agitation			0.31	0.44	0.73	0.76	0.95
	20°C, agitation, duplicate			0.25	0.47	0.73	0.74	0.92
	37°C			0.54	0.73	1.06	1.36	1.47
	37°C, duplicate			0.55	0.63	1.03	1.47	1.52
	37°C, agitation			0.39	0.82	0.92	1.34	1.47
	37°C, agitation, duplicate			0.43	0.83	1.01	1.36	1.55
09/27/95	20°C	21.0	7.68	0.13	0.24	0.61	0.64	0.74
	20°C, duplicate	20.5		0.15	0.20	0.59	0.62	0.70
	20°C, agitation			0.15	0.29	0.57	0.68	0.74
	20°C, agitation, duplicate			0.13	0.35	0.49	-	-
	37°C			0.11	0.30	0.79	1.10	1.35
	37°C, duplicate			0.18	0.25	0.89	1.13	1.29
	37°C, agitation			0.17	0.26	0.81	1.16	1.27
	37°C, agitation, duplicate			0.20	0.26	0.79	1.08	1.26
09/28/95	20°C	21.0	7.84	0.30	0.38	0.76	0.85	1.05
	20°C, duplicate	21.5		0.44	0.50	0.72	0.94	1.02
	20°C, agitation			0.40	0.42	0.71	0.91	1.06
	20°C, agitation, duplicate			0.29	0.37	0.72	0.93	1.06
	37°C			0.64	0.64	1.21	1.42	1.59
	37°C, duplicate			0.64	0.66	1.19	1.43	1.59
	37°C, agitation			0.59	0.66	1.23	1.39	1.57
	37°C, agitation, duplicate			0.58	0.67	1.14	1.43	1.63

Table F-4 (cont'd)

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
10/01/95	20°C	20.5	7.60	-	0.37	0.66	0.77	0.92
	20°C, duplicate	21.0		-	0.33	0.70	0.80	0.83
10/02/95	20°C	21.0	7.55	-	0.00	0.29	0.49	0.57
	20°C, duplicate	21.0		-	0.00	0.23	0.40	0.62
10/03/95	20°C	22.0	7.78	-	0.12	0.46	0.57	0.68
	20°C, duplicate	21.0		-	0.16	0.50	0.58	0.74
10/04/95	20°C	20.5	7.71	-	0.22	0.39	0.71	0.74
	20°C, duplicate	21.0		-	0.23	0.45	0.67	0.72
10/05/95	20°C	20.5	7.57	-	0.36	0.54	0.53	0.65
	20°C, duplicate	22.0		Bottle was broken				

Table F-5 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from Glendale WWTP.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
09/26/95	20°C	25.5	8.70	-	-	-	-	1.34
	20°C, duplicate	26.0		0.06	0.52	0.97	1.13	1.50
	20°C, agitation			0.03	0.48	0.95	1.18	1.62
	20°C, agitation, duplicate			0.06	0.56	0.95	1.19	1.58
	37°C			0.65	1.53	2.14	2.64	2.78
	37°C, duplicate			0.63	1.50	2.20	2.53	2.74
	37°C, agitation			0.63	1.47	2.17	2.58	2.70
	37°C, agitation, duplicate			0.60	1.52	2.16	2.61	2.71
09/27/95	20°C	27.0	9.55	-	-	-	-	1.78
	20°C, duplicate	27.5		0.39	0.85	1.18	1.58	1.97
	20°C, agitation			0.45	0.85	1.24	1.64	2.01
	20°C, agitation, duplicate			0.49	0.89	1.21	1.67	2.00
	37°C			1.28	1.94	2.63	3.17	3.41
	37°C, duplicate			1.25	1.98	2.65	3.25	3.46
	37°C, agitation			1.36	2.05	2.83	3.43	3.58
	37°C, agitation, duplicate			1.28	2.03	2.76	3.31	3.48
09/28/95	20°C	30.0	9.71	-	-	-	-	1.72
	20°C, duplicate	29.5		0.20	0.57	1.31	1.67	1.95
	20°C, agitation			0.20	0.42	1.24	1.79	2.03
	20°C, agitation, duplicate			0.21	0.48	1.29	1.69	1.96
	37°C			1.20	1.93	2.60	3.04	3.46
	37°C, duplicate			1.19	1.97	2.58	3.15	3.44
	37°C, agitation			1.11	2.11	2.85	3.19	3.55
	37°C, agitation, duplicate			1.24	2.08	2.75	3.16	3.51
09/29/95	20°C	33.0	9.95	-	-	-	-	1.82
	20°C, duplicate	32.0		0.23	0.68	1.49	1.95	2.13
	20°C, agitation			0.17	0.69	1.60	2.08	2.28
	20°C, agitation, duplicate			0.26	0.72	1.66	2.10	2.39
	37°C			1.51	2.21	2.94	3.43	3.65
	37°C, duplicate			1.36	2.08	2.86	3.38	3.74
	37°C, agitation			1.47	2.28	3.21	3.67	3.77
	37°C, agitation, duplicate			1.46	2.26	3.09	3.47	3.60
10/01/95	20°C	29.0	9.09	-	0.74	0.86	1.40	1.50
	20°C, duplicate	28.5		0.35	0.55	0.70	0.90	1.30
10/02/95	20°C	27.5	9.05	-	0.70	0.82	1.26	1.40
	20°C, duplicate	28.0		0.14	0.88	1.10	1.34	1.49
10/03/95	20°C	27.5	9.10	-	0.66	0.94	1.38	1.64
	20°C, duplicate	26.5		0.03	0.86	1.07	1.24	1.66
10/04/95	20°C	26.0	8.83	-	0.68	0.88	1.22	1.40
	20°C, duplicate	26.5		0.11	0.66	0.84	1.02	1.51
10/05/95	20°C	26.5	8.92	-	0.30	0.60	1.16	1.36
	20°C, duplicate	27.0		0.05	0.57	0.75	0.99	1.27

Table F-6 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from Tillman WWTP.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
09/28/95	20°C	27.0	9.01	-	-	-	-	1.83
	20°C, duplicate	26.5		0.28	1.21	1.46	1.85	2.33
	20°C, agitation			0.28	1.28	1.42	1.91	2.33
	20°C, agitation, duplicate			0.35	1.24	1.48	1.91	2.35
	37°C			0.77	2.14	2.65	2.92	2.98
	37°C, duplicate			0.74	2.14	2.73	2.96	3.11
	37°C, agitation			0.68	2.04	2.58	2.89	3.06
	37°C, agitation, duplicate			0.72	2.23	2.67	2.88	2.94
09/29/95	20°C	28.5	8.84	-	-	-	-	1.83
	20°C, duplicate	28.0		0.33	1.11	1.39	1.86	2.08
	20°C, agitation			0.31	1.08	1.44	1.96	2.16
	20°C, agitation, duplicate			0.28	1.13	1.28	1.94	2.10
	37°C			0.49	1.91	2.48	2.72	3.24
	37°C, duplicate			0.53	1.94	2.38	2.68	3.24
	37°C, agitation			0.55	1.96	2.42	2.64	3.15
	37°C, agitation, duplicate			0.55	2.03	2.51	2.58	3.19
09/30/95	20°C	28.5	8.44	-	-	-	-	1.56
	20°C, duplicate	28.0		0.05	0.76	1.02	1.34	1.49
	20°C, agitation			0.11	0.72	1.02	1.31	1.47
	20°C, agitation, duplicate			0.17	0.69	0.97	1.36	1.47
	37°C			0.42	1.28	1.52	1.99	2.39
	37°C, duplicate			0.40	1.23	1.59	1.97	2.42
	37°C, agitation			0.47	1.40	1.56	1.94	2.33
	37°C, agitation, duplicate			0.36	1.41	1.56	1.94	2.45
10/01/95	20°C	28.0	8.57	-	-	-	-	1.62
* Plant	20°C, duplicate	28.5		0.18	0.74	1.10	1.40	1.81
not	20°C, agitation			0.21	0.78	1.14	1.30	1.70
running	20°C, agitation, duplicate			0.23	0.81	1.23	1.45	1.80
in normal	37°C			0.28	1.26	1.73	2.17	2.43
condition	37°C, duplicate			0.33	1.25	1.81	2.27	2.57
	37°C, agitation			0.44	1.69	2.02	2.18	2.59
	37°C, agitation, duplicate			0.48	1.64	2.05	2.14	2.48
10/02/95	20°C	28.0	8.60	-	-	-	-	1.77
	20°C, duplicate	28.0		0.10	1.02	1.25	1.35	1.75
	20°C, agitation			0.11	0.98	1.24	1.33	1.71
	20°C, agitation, duplicate			0.17	1.08	1.22	1.35	1.71
	37°C			0.35	1.48	1.96	2.20	2.90
	37°C, duplicate			0.38	1.38	2.00	2.22	2.77
	37°C, agitation			0.53	1.87	2.13	2.22	2.84
	37°C, agitation, duplicate			0.56	1.98	2.25	2.45	2.91

Table F-6 (cont'd)

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
10/03/95	20°C	30.0	9.08	-	0.81	1.92	2.34	2.40
	20°C, duplicate	29.5		0.34	1.01	1.39	1.58	2.01
10/04/95	20°C	28.0	8.86	-	0.72	0.93	1.83	1.98
	20°C, duplicate	28.0		0.34	0.64	0.83	1.00	1.61
10/05/95	20°C	27.5	8.46	-	0.66	1.35	1.56	1.53
	20°C, duplicate	27.0		0.24	0.42	0.76	0.88	1.19
10/06/95	20°C	27.0	8.41	-	0.72	1.17	1.29	1.32
	20°C, duplicate	27.5		0.22	0.63	0.78	0.80	1.18
10/07/95	20°C	28.0	9.08	-	0.39	1.29	1.44	1.41
	20°C, duplicate	29.0		0.33	0.50	0.72	0.98	1.37

Table F-7 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from Orange County WWTP no. 1.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L) 5	10	15	20	28
10/30/95	20°C	24.5	6.78	-	-	-	-	0.80
* Plant	20°C, duplicate	24.5		0.03	0.31	0.44	0.50	0.75
not	20°C, agitation			0.16	0.37	0.53	0.73	1.01
running	37°C			0.44	0.86	1.24	1.43	1.98
in normal	37°C, duplicate			0.40	0.86	1.23	1.38	2.01
condition	37°C, agitation			0.30	0.87	1.07	1.24	2.06
10/31/95	20°C	27.0	8.98	-	-	-	-	2.34
	20°C, duplicate	27.5		0.90	1.09	1.33	1.88	2.59
	20°C, agitation			1.10	1.33	1.57	1.78	2.47
	37°C			1.57	1.91	2.29	2.53	2.72
	37°C, duplicate			1.54	2.00	2.27	2.46	2.88
	37°C, agitation			1.46	1.89	2.07	2.50	2.77
11/01/95	20°C	27.5	8.45	-	-	-	-	1.60
	20°C, duplicate	28.5		0.27	0.69	0.90	1.23	1.69
	20°C, agitation			0.35	0.70	0.87	1.05	1.64
	37°C			0.75	0.94	1.48	1.72	2.19
	37°C, duplicate			0.69	0.83	1.41	1.70	2.05
	37°C, agitation			0.74	0.92	1.35	1.63	1.99
11/02/95	20°C	28.0	9.11	-	-	-	-	1.76
	20°C, duplicate	28.0		0.20	0.66	1.15	1.49	1.73
	20°C, agitation			0.20	0.68	1.30	1.52	2.08
	37°C			0.78	1.32	1.61	2.21	2.08
	37°C, duplicate			0.83	1.25	1.50	1.80	2.29
	37°C, agitation			0.69	1.21	1.39	2.00	2.14
11/06/95	20°C	29.0	7.95	0.23	0.59	0.99	1.26	1.42
	20°C, duplicate	28.5		0.22	0.68	1.05	1.18	1.26
11/07/95	20°C	28.0	8.98	0.35	0.80	1.34	1.80	2.13
	20°C, duplicate	29.0		0.39	1.16	1.46	1.80	2.00
11/08/95	20°C	29.5	8.50	0.16	0.50	0.76	1.22	1.70
	20°C, duplicate	27.5		0.10	0.54	0.89	1.33	1.68
11/09/95	20°C	31.0	9.08	0.37	0.74	1.01	1.25	1.42
	20°C, duplicate	31.0		0.32	0.97	1.22	1.31	1.45

Table F-8 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from Orange County WWTP no. 2.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
10/30/95	20°C	32.5	10.05	-	-	-	-	2.98
	20°C, duplicate	31.5		0.83	1.97	2.44	2.60	3.10
	20°C, agitation			0.91	1.90	2.66	2.71	2.91
	37°C			2.44	3.11	3.63	3.80	4.20
	37°C, duplicate			2.24	3.31	3.66	4.02	4.44
	37°C, agitation			2.47	3.05	3.60	3.59	4.28
10/31/95	20°C	35.5	11.61	-	-	-	-	3.20
	20°C, duplicate	36.5		0.93	2.06	2.51	2.79	2.90
	20°C, agitation			1.13	2.29	2.89	3.15	3.22
	37°C			2.86	3.77	4.14	4.21	4.62
	37°C, duplicate			2.82	3.64	4.24	4.19	4.52
	37°C, agitation			2.55	3.39	3.79	4.16	4.54
11/01/95	20°C	36.5	11.76	-	-	-	-	3.66
	20°C, duplicate	36.0		0.75	2.06	2.73	3.34	4.10
	20°C, agitation			0.86	2.08	2.88	3.32	3.81
	37°C			2.45	3.84	3.99	4.44	4.78
	37°C, duplicate			2.66	3.99	4.36	4.43	4.65
	37°C, agitation			2.82	3.72	3.95	4.20	4.84
11/02/95	20°C	34.5	10.93	-	-	-	-	2.86
	20°C, duplicate	34.5		0.51	1.67	2.29	2.69	3.15
	20°C, agitation			0.64	1.90	2.50	2.61	3.06
	37°C			2.35	3.22	3.41	3.52	3.74
	37°C, duplicate			2.32	2.73	3.52	3.66	3.93
	37°C, agitation			2.18	2.74	3.27	3.42	3.72
11/06/95	20°C	33.0	10.12	0.85	1.87	2.32	2.64	3.01
	20°C, duplicate	31.5		0.84	1.79	2.34	3.03	3.04
11/07/95	20°C	33.5	10.97	0.69	1.11	1.60	2.11	2.33
	20°C, duplicate	32.5		0.74	1.40	1.83	2.16	2.36
11/08/95	20°C	35.5	11.20	0.44	1.81	2.34	3.36	3.33
	20°C, duplicate	35.0		0.44	1.63	2.27	2.92	2.99
11/09/95	20°C	37.5	11.38	0.65	1.88	2.66	3.53	3.42
	20°C, duplicate	37.5		1.17	2.03	2.85	3.30	3.16

Table F-9 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from Union Sanitary District (USD) WWTP.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
10/30/95	20°C	41.0	14.98	0.81	2.73	4.17	4.59	4.41
	20°C, duplicate	41.5		0.81	2.67	4.23	4.35	4.47
	20°C, agitation			0.90	3.00	3.90	4.20	4.08
	37°C			2.04	3.51	4.65	5.37	5.55
	37°C, duplicate			2.16	3.42	4.89	5.31	5.64
	37°C, agitation			2.19	3.45	4.50	5.22	5.73
10/31/95	20°C	40.5	15.34	0.60	2.19	3.48	4.05	4.80
	20°C, duplicate	41.0		0.60	2.37	3.75	3.96	4.68
	20°C, agitation			0.60	2.46	3.81	4.11	4.83
	37°C			2.22	3.39	4.47	4.35	4.89
	37°C, duplicate			2.28	3.57	4.32	4.68	4.92
	37°C, agitation			2.34	3.18	4.20	4.29	5.04
11/01/95	20°C	38.0	13.74	0.21	1.92	2.52	2.55	3.12
	20°C, duplicate	39.0		0.18	1.47	2.10	2.43	3.21
	20°C, agitation			0.21	1.83	2.19	2.25	3.06
	37°C			2.22	3.24	4.23	4.56	4.86
	37°C, duplicate			2.22	3.57	3.84	4.14	4.83
	37°C, agitation			2.25	3.30	3.81	4.17	4.68
11/02/95	20°C	40.0	13.89	0.66	2.01	3.24	3.84	3.81
	20°C, duplicate	39.0		0.57	2.13	3.36	3.51	3.39
	20°C, agitation			0.63	2.13	3.21	3.36	3.36
	37°C			2.37	3.42	4.32	4.53	4.92
	37°C, duplicate			2.67	3.51	4.20	4.44	4.80
	37°C, agitation			2.31	3.27	3.78	4.50	4.74
11/06/95	20°C	38.0	13.19	0.29	2.27	3.56	4.00	4.11
	20°C, duplicate	37.5		0.35	2.26	3.45	3.76	3.96
11/07/95	20°C	38.5	13.05	0.37	2.33	3.49	3.66	3.76
	20°C, duplicate	38.0		0.34	2.33	3.55	3.64	3.74
11/08/95	20°C	37.0	12.82	0.56	2.37	3.29	3.86	3.89
	20°C, duplicate	37.0		0.42	2.11	3.48	3.55	3.81
11/09/95	20°C	36.5	12.77	0.43	1.98	3.63	3.77	3.88
	20°C, duplicate	36.5		0.57	2.19	3.48	3.65	3.77

Table F-10 SCOD, DOC, and BDOC (2 mL effluent inoculum) of secondary effluent samples from Las Vegas WWTP.

Sampling date	Incubation temperature, and agitation condition	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)				
				5	10	15	20	28
11/05/95	20°C	17.5	6.11	0.00	0.09	0.27	0.24	0.69
	20°C, duplicate	17.5		0.00	0.12	0.09	0.18	0.72
	20°C, agitation			0.00	0.12	0.18	0.12	0.69
	37°C			0.00	0.24	0.36	0.57	0.81
	37°C, duplicate			0.00	0.09	0.33	0.39	0.72
	37°C, agitation			0.00	0.09	0.30	0.45	0.63
11/06/95	20°C	17.5	6.26	0.36	0.48	0.66	0.57	0.69
	20°C, duplicate	17.0		0.24	0.42	0.54	0.69	0.72
	20°C, agitation			0.39	0.36	0.51	0.63	0.81
	37°C			0.42	0.75	0.87	0.90	0.93
	37°C, duplicate			0.36	0.66	0.84	1.05	1.02
	37°C, agitation			0.33	0.69	0.75	0.90	0.84
11/07/95	20°C	19.0	6.76	0.03	0.27	0.42	0.60	0.69
	20°C, duplicate	18.0		0.00	0.12	0.33	0.60	0.78
	20°C, agitation			0.00	0.24	0.33	0.66	0.81
	37°C			0.03	0.39	0.66	0.69	0.75
	37°C, duplicate			0.06	0.60	0.75	0.78	0.93
	37°C, agitation			0.00	0.39	0.57	0.60	0.78
11/08/95	20°C	18.5	6.89	0.06	0.30	0.39	0.51	0.72
	20°C, duplicate	17.5		0.06	0.12	0.39	0.60	0.78
	20°C, agitation			0.15	0.30	0.39	0.57	0.81
	37°C			0.51	0.72	0.81	0.99	1.11
	37°C, duplicate			0.48	0.63	0.93	0.96	0.99
	37°C, agitation			0.45	0.54	0.66	0.93	0.99
11/09/95	20°C	19.5	6.47	0.13	0.37	0.41	0.54	0.65
	20°C, duplicate	19.5		0.13	0.42	0.47	0.62	0.68
11/10/95	20°C	18.0	6.11	0.12	0.17	0.30	0.35	0.50
	20°C, duplicate	18.0		0.12	0.22	0.30	0.43	0.56
11/11/95	20°C	17.0	5.99	0.22	0.34	0.41	0.49	0.55
	20°C, duplicate	17.0		0.25	0.35	0.38	0.46	0.55
11/12/95	20°C	17.5	5.85	0.21	0.35	0.37	0.45	0.56
	20°C, duplicate	17.0		0.24	0.39	0.49	0.55	0.63

Table F-11 SCOD, DOC, $SBOD_5$, and BDOC of secondary effluent samples from Hyperion WWTP.

Inoculum and incubation temperature	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L) 1	2	3	4	5	7	10	15	20	28
Sampling date: 9/17/96												
2 mL effluent, 20°C	33.0	10.43	-	-	-	-	1.06	-	1.58	2.07	2.22	2.90
10 mL effluent, 20°C	33.0		-	-	-	-	1.53	-	Bottle was broken			
2 mL com., 20°C			-	-	-	-	0.74	-	1.02	1.84	2.64	3.32
2 mL MLSS, 20°C			0.88	1.09	1.33	1.59	2.02	2.50	2.63	3.15	3.29	3.40
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.85	-	0.98	1.25	2.15	3.09
2 mL MLSS, 20°C, dupl.			2.80				1.68	2.15	2.82	3.02	3.02	3.20
2 mL effluent, 37°C			-	-	-	-	2.90	-	3.63	3.69	4.31	4.88
10 mL effluent, 37°C			-	-	-	-	3.29	-	4.14	4.54	5.02	5.25
2 mL com., 37°C			-	-	-	-	1.56	-	2.13	2.16	3.05	3.60
2 mL MLSS, 37°C			1.27	2.12	2.92	3.02	3.17	3.47	3.59	4.05	4.65	5.19
Sampling date: 9/18/96												
2 mL effluent, 20°C	32.5	10.08	-	-	-	-	1.16	-	1.40	1.67	2.04	2.46
10 mL effluent, 20°C	32.5		-	-	-	-	1.52	-	1.75	2.39	2.55	2.86
2 mL com., 20°C			-	-	-	-	0.45	-	0.44	1.38	1.95	2.93
2 mL MLSS, 20°C			0.77	1.07	1.31	1.55	1.84	2.35	2.87	2.97	3.31	3.63
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.86	-	0.96	1.53	2.27	3.21
2 mL MLSS, 20°C, dupl.			2.60				1.39	1.83	2.61	2.82	2.85	3.02
2 mL effluent, 37°C			-	-	-	-	2.52	-	3.72	4.12	4.44	4.75
10 mL effluent, 37°C			-	-	-	-	3.10	-	4.10	4.32	4.67	5.15
2 mL com., 37°C			-	-	-	-	1.03	-	2.04	2.44	2.76	3.27
2 mL MLSS, 37°C			1.02	2.04	2.72	2.99	3.10	3.33	3.35	3.78	4.45	4.82
Sampling date: 9/19/96												
2 mL effluent, 20°C	33.5	10.91	-	-	-	-	1.37	-	2.07	2.69	3.08	3.67
10 mL effluent, 20°C	33.5		-	-	-	-	1.61	-	2.37	2.91	3.23	3.93
2 mL com., 20°C			-	-	-	-	0.73	-	0.73	1.28	1.97	3.27
2 mL MLSS, 20°C			0.93	1.21	1.62	1.69	1.95	2.34	3.20	3.39	3.51	3.79
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.84	-	1.36	1.88	2.64	3.31
2 mL MLSS, 20°C, dupl.			3.15				1.90	2.25	3.06	3.34	3.40	3.59
2 mL effluent, 37°C			-	-	-	-	3.04	-	4.10	4.49	4.73	5.09
10 mL effluent, 37°C			-	-	-	-	3.41	-	4.14	4.74	5.40	5.62
2 mL com., 37°C			-	-	-	-	1.48	-	2.37	3.63	4.00	4.14
2 mL MLSS, 37°C			1.34	2.26	3.07	3.46	3.52	3.90	4.28	4.54	4.78	5.10

Table F-11 (cont'd)

Inoculum and incubation temperature	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L) 1	2	3	4	5	7	10	15	20	28
Sampling date: 9/20/96												
2 mL effluent, 20°C	33.5	10.79	-	-	-	-	1.39	-	2.35	3.11	3.19	3.58
10 mL effluent, 20°C	34.0		-	-	-	-	2.02	-	2.98	3.48	3.87	4.17
2 mL com., 20°C			-	-	-	-	0.82	-	0.95	1.95	2.82	3.69
2 mL MLSS, 20°C			1.06	1.24	1.83	1.99	2.32	2.94	3.38	3.58	3.75	3.99
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				1.04	-	1.14	1.90	2.53	3.40
2 mL MLSS, 20°C, dupl.			2.25				1.94	2.42	3.05	3.14	3.27	3.50
2 mL effluent, 37°C			-	-	-	-	3.09	-	4.32	4.48	4.72	5.09
10 mL effluent, 37°C			-	-	-	-	3.46	-	4.49	4.69	4.99	5.36
2 mL com., 37°C			-	-	-	-	2.06	-	2.42	3.06	3.24	3.48
2 mL MLSS, 37°C			1.53	2.27	3.34	3.58	3.82	4.22	4.42	4.64	5.12	5.56
Sampling date: 9/24/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	29.5	9.86	-				1.13	-	-	-	-	3.34
2 mL MLSS, 20°C	29.5		3.85				1.73	-	-	-	-	3.52
Sampling date: 9/25/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	33.5	11.37	-				1.73	-	-	-	-	3.47
2 mL MLSS, 20°C	34.0		6.85				2.09	-	-	-	-	3.94
Sampling date: 9/26/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	35.0	11.96	-				2.11	-	-	-	-	3.85
2 mL MLSS, 20°C	35.0		7.05				2.50	-	-	-	-	4.40
Sampling date: 9/27/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	36.5	12.25	-				2.27	-	-	-	-	4.46
2 mL MLSS, 20°C	37.0		6.90				2.18	-	-	-	-	4.79

Table F-12 SCOD, DOC, $SBOD_5$, and BDOC of secondary effluent samples from Joint Water Pollution Control Plant (JWPCP).

Inoculum and incubation temperature	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L) 1	2	3	4	5	7	10	15	20	28
Sampling date: 9/17/96												
2 mL effluent, 20°C	38.0	12.55	-	-	-	-	0.91	-	1.51	1.90	2.12	2.45
10 mL effluent, 20°C	39.5		-	-	-	-	1.37	-	2.00	2.20	2.48	2.45
2 mL com., 20°C			-	-	-	-	0.38	-	0.59	0.77	1.74	2.30
2 mL MLSS, 20°C			0.69	0.95	1.11	1.20	1.38	1.79	2.14	2.53	2.42	2.31
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.45	-	0.66	1.04	1.64	2.13
2 mL MLSS, 20°C, dupl.			4.30				1.23	1.58	1.92	2.54	2.59	2.71
2 mL effluent, 37°C			-	-	-	-	1.72	-	2.14	2.56	2.75	3.48
10 mL effluent, 37°C			-	-	-	-	2.23	-	2.50	2.87	3.24	3.74
2 mL com., 37°C			-	-	-	-	1.05	-	1.82	2.03	2.38	2.40
2 mL MLSS, 37°C			0.93	1.96	1.90	2.28	2.39	2.84	2.82	2.96	3.48	4.05
Sampling date: 9/18/96												
2 mL effluent, 20°C	37.5	12.72	-	-	-	-	1.23	-	2.01	2.42	2.83	3.09
10 mL effluent, 20°C	38.0		-	-	-	-	1.69	-	2.35	2.72	3.11	3.40
2 mL com., 20°C			-	-	-	-	0.86	-	0.94	1.25	2.20	2.67
2 mL MLSS, 20°C			1.00	1.27	1.35	1.51	1.65	2.03	2.44	2.89	3.04	3.22
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.84	-	0.85	1.16	1.75	2.43
2 mL MLSS, 20°C, dupl.			2.35				1.50	1.67	2.11	2.86	2.91	3.25
2 mL effluent, 37°C			-	-	-	-	2.20	-	2.67	2.92	4.07	4.38
10 mL effluent, 37°C			-	-	-	-	2.70	-	3.04	3.65	4.03	4.37
2 mL com., 37°C			-	-	-	-	1.35	-	1.94	2.31	2.68	2.75
2 mL MLSS, 37°C			1.31	1.97	2.03	2.50	3.09	2.99	3.19	3.67	4.02	4.37
Sampling date: 9/19/96												
2 mL effluent, 20°C	37.0	11.95	-	-	-	-	0.75	-	1.03	1.68	1.68	2.18
10 mL effluent, 20°C	37.0		-	-	-	-	1.08	-	1.81	2.28	2.22	2.48
2 mL com., 20°C			-	-	-	-	0.78	-	0.77	0.83	1.64	2.30
2 mL MLSS, 20°C			0.67	0.88	0.74	0.81	1.09	1.57	1.73	2.28	2.63	3.01
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.59	-	0.58	0.98	1.65	2.09
2 mL MLSS, 20°C, dupl.			2.10				0.96	1.21	1.72	2.18	2.45	2.82
2 mL effluent, 37°C			-	-	-	-	1.45	-	1.93	2.66	2.88	2.94
10 mL effluent, 37°C			-	-	-	-	2.04	-	2.52	2.88	2.81	3.26
2 mL com., 37°C			-	-	-	-	1.03	-	1.85	2.10	2.06	2.37
2 mL MLSS, 37°C			0.88	1.39	1.87	2.28	2.59	2.54	2.62	2.95	3.42	3.64

Table F-12 (cont'd)

Inoculum and incubation temperature	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L)									
			1	2	3	4	5	7	10	15	20	28
Sampling date: 9/20/96												
2 mL effluent, 20°C	36.0	11.21	-	-	-	-	0.43	-	0.81	1.33	1.75	1.80
10 mL effluent, 20°C	36.0		-	-	-	-	0.80	-	1.55	1.76	2.20	2.19
2 mL com., 20°C			-	-	-	-	0.27	-	0.30	0.61	1.15	1.88
2 mL MLSS, 20°C			0.13	0.55	0.47	0.78	1.01	1.31	1.48	2.14	2.51	2.56
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.47	-	0.34	0.58	1.18	1.98
2 mL MLSS, 20°C, dupl.			2.05				0.77	1.03	1.48	1.94	2.15	2.52
2 mL effluent, 37°C			-	-	-	-	1.16	-	1.62	2.01	2.43	2.54
10 mL effluent, 37°C			-	-	-	-	1.61	-	1.82	2.41	2.51	2.89
2 mL com., 37°C			-	-	-	-	0.64	-	1.05	1.60	1.66	1.94
2 mL MLSS, 37°C			0.72	1.17	1.44	1.77	1.99	1.94	2.43	2.71	3.06	3.29
Sampling date: 9/24/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	40.0	12.98	-				1.39	-	-	-	-	3.00
2 mL MLSS, 20°C	40.0		6.80				1.59	-	-	-	-	3.50
Sampling date: 9/25/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	38.5	12.61	-				0.92	-	-	-	-	3.18
2 mL MLSS, 20°C	38.5		5.70				1.60	-	-	-	-	3.13
Sampling date: 9/26/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	39.5	12.65	-				1.19	-	-	-	-	2.48
2 mL MLSS, 20°C	39.0		6.70				1.44	-	-	-	-	3.34
Sampling date: 9/27/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	37.5	12.14	-				1.09	-	-	-	-	2.70
2 mL MLSS, 20°C	37.0		6.00				1.63	-	-	-	-	3.43

Table F-13 SCOD, DOC, $SBOD_5$, and BDOC of secondary effluent samples from Sacramento Regional WWTP.

Inoculum and incubation temperature	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L) 1	2	3	4	5	7	10	15	20	28
Sampling date: 10/21/96												
2 mL effluent, 20°C	24.5	8.35	-	-	-	-	0.85	-	1.59	2.11	2.24	2.41
10 mL effluent, 20°C	23.5		-	-	-	-	1.26	-	1.91	2.41	2.64	2.92
2 mL com., 20°C			Sample was accidentally contaminated by another inoculum									
2 mL MLSS, 20°C			0.73	1.19	1.35	1.64	1.95	2.34	2.41	2.62	2.63	2.85
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.71	-	0.80	1.29	2.08	2.47
2 mL MLSS, 20°C, dupl.			7.20				1.60	2.03	2.44	2.49	2.75	3.02
2 mL effluent, 37°C			-	-	-	-	1.94	-	2.35	2.84	3.23	3.63
10 mL effluent, 37°C			-	-	-	-	2.26	-	2.82	3.38	3.72	4.07
2 mL com., 37°C			-	-	-	-	1.09	-	1.88	2.55	2.80	2.86
2 mL MLSS, 37°C			1.04	1.55	1.91	2.12	2.26	2.63	3.08	3.36	3.67	3.94
Sampling date: 10/22/96												
2 mL effluent, 20°C	22.5	7.80	-	-	-	-	1.03	-	1.50	1.83	2.06	2.34
10 mL effluent, 20°C	22.5		-	-	-	-	1.30	-	1.82	2.15	2.25	2.79
2 mL com., 20°C			-	-	-	-	0.52	-	0.86	1.31	1.83	2.68
2 mL MLSS, 20°C			0.66	0.93	1.20	1.45	1.89	2.08	2.24	2.34	2.36	2.79
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.56	-	0.79	1.57	2.06	2.17
2 mL MLSS, 20°C, dupl.			5.90				1.50	1.89	2.11	2.26	2.34	2.43
2 mL effluent, 37°C			-	-	-	-	1.99	-	2.35	2.84	3.11	3.35
10 mL effluent, 37°C			-	-	-	-	2.22	-	2.47	3.15	3.42	3.65
2 mL com., 37°C			-	-	-	-	0.60	-	1.37	2.05	2.26	2.44
2 mL MLSS, 37°C			0.79	1.51	1.73	1.92	2.15	2.52	2.81	3.20	3.59	3.80
Sampling date: 10/23/96												
2 mL effluent, 20°C	23.5	8.54	-	-	-	-	1.32	-	2.16	2.53	2.64	2.90
10 mL effluent, 20°C	25.0		-	-	-	-	1.87	-	2.55	2.79	2.85	3.37
2 mL com., 20°C			-	-	-	-	0.79	-	1.18	1.77	2.31	2.76
2 mL MLSS, 20°C			1.17	1.29	1.68	2.00	2.38	2.64	2.90	3.19	3.14	3.30
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				1.10	-	1.24	1.89	2.49	3.09
2 mL MLSS, 20°C, dupl.			7.40				2.08	2.64	2.93	2.92	3.00	3.29
2 mL effluent, 37°C			-	-	-	-	2.60	-	3.00	3.35	3.82	4.00
10 mL effluent, 37°C			-	-	-	-	3.00	-	3.16	3.75	4.07	4.38
2 mL com., 37°C			-	-	-	-	1.06	-	2.47	2.95	3.28	3.39
2 mL MLSS, 37°C			1.45	2.02	2.40	2.53	2.78	2.89	3.50	3.78	4.17	4.45

Table F-13 (cont'd)

Inoculum and incubation temperature	SCOD (mg/L)	DOC (mg/L)	$BDOC_t$ (mg/L) 1	2	3	4	5	7	10	15	20	28
Sampling date: 10/24/96												
2 mL effluent, 20°C	23.0	8.05	-	-	-	-	1.08	-	1.62	1.94	2.04	2.42
10 mL effluent, 20°C	23.5		-	-	-	-	1.15	-	1.62	2.08	2.34	2.95
2 mL com., 20°C			-	-	-	-	0.57	-	0.87	1.46	1.82	2.53
2 mL MLSS, 20°C			0.76	1.18	1.55	1.87	2.07	2.46	2.62	2.69	2.84	3.23
			$SBOD_5$ (mg/L)									
2 mL com., 20°C, dupl.			< detection limit				0.49	-	1.05	1.81	2.41	2.81
2 mL MLSS, 20°C, dupl.			7.20				1.87	2.32	2.53	2.68	2.86	3.13
2 mL effluent, 37°C			-	-	-	-	2.29	-	2.71	2.96	3.13	3.40
10 mL effluent, 37°C			-	-	-	-	2.65	-	2.78	3.37	3.76	3.99
2 mL com., 37°C			-	-	-	-	0.88	-	1.73	2.53	2.70	3.03
2 mL MLSS, 37°C			1.28	1.70	2.06	2.32	2.43	2.68	3.06	3.29	3.76	4.05
Sampling date: 10/25/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	24.5	8.87	-				1.76	-	-	-	-	3.23
2 mL MLSS, 20°C	25.0		6.85				2.33	-	-	-	-	3.47
Sampling date: 10/26/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	25.0	9.05	-				1.51	-	-	-	-	3.15
2 mL MLSS, 20°C	24.5		6.85				2.18	-	-	-	-	3.39
Sampling date: 10/27/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	25.0	9.27	-				1.17	-	-	-	-	3.25
2 mL MLSS, 20°C	26.0		6.70				2.07	-	-	-	-	3.24
Sampling date: 10/28/96			$SBOD_5$ (mg/L)									
2 mL effluent, 20°C	24.5	8.73	-				1.13	-	-	-	-	2.85
2 mL MLSS, 20°C	23.5		6.35				2.19	-	-	-	-	2.97

Table F-14 DOC_0 and DOC_t of blank water used for determining BDOC of secondary effluent samples from Hyperion WWTP, JWPCP, and Sacramento Regional WWTP.

Inoculum and incubation	DOC_0	DOC_t (mg/L)									
temperature	(mg/L)	1	2	3	4	5	7	10	15	20	28
Hyperion											
2 mL effluent, 20°C	0.18	-	-	-	-	0.29	-	0.28	0.28	0.27	0.27
10 mL effluent, 20°C		-	-	-	-	0.61	-	0.55	0.54	0.56	0.51
2 mL com., 20°C		-	-	-	-	0.21	-	0.18	0.21	0.20	0.21
2 mL MLSS, 20°C		0.32	0.37	0.40	0.27	0.27	0.32	0.32	0.28	0.34	0.27
2 mL com., 20°C, dupl.		-	-	-	-	0.32	-	0.21	0.22	0.22	0.17
2 mL MLSS, 20°C, dupl.		-	-	-	-	0.26	0.24	0.25	0.31	0.32	0.26
2 mL effluent, 37°C		-	-	-	-	0.32	-	0.29	0.27	0.32	0.26
10 mL effluent, 37°C		-	-	-	-	0.61	-	0.55	0.54	0.56	0.51
2 mL commer., 37°C		-	-	-	-	0.30	-	0.31	0.27	0.25	0.22
2 mL MLSS, 37°C		0.43	0.30	0.31	0.33	0.33	0.35	0.39	0.35	0.37	0.38
JWPCP											
2 mL effluent, 20°C	0.17	-	-	-	-	0.30	-	0.32	0.26	0.29	0.26
10 mL effluent, 20°C		-	-	-	-	0.70	-	0.71	0.68	0.71	0.59
2 mL com., 20°C		-	-	-	-	0.26	-	0.17	0.28	0.28	0.27
2 mL MLSS, 20°C		0.25	0.31	0.25	0.29	0.31	0.39	0.38	0.46	0.38	0.33
2 mL com., 20°C, dupl.		-	-	-	-	0.24	-	0.21	0.19	0.24	0.18
2 mL MLSS, 20°C, dupl.		-	-	-	-	0.23	0.29	0.41	0.45	0.40	0.30
2 mL effluent, 37°C		-	-	-	-	0.29	-	0.32	0.28	0.37	0.26
10 mL effluent, 37°C		-	-	-	-	0.73	-	0.72	0.78	0.68	0.59
2 mL commer., 37°C		-	-	-	-	0.26	-	0.30	0.33	0.32	0.19
2 mL MLSS, 37°C		0.55	0.53	0.37	0.41	0.52	0.46	0.51	0.43	0.49	0.37
Sacramento											
2 mL effluent, 20°C	0.14	-	-	-	-	0.22	-	0.24	0.21	0.24	0.21
10 mL effluent, 20°C		-	-	-	-	0.54	-	0.50	0.50	0.47	0.41
2 mL com., 20°C		-	-	-	-	0.25	-	0.21	0.29	0.27	0.25
2 mL MLSS, 20°C		0.33	0.39	0.30	0.28	0.35	0.35	0.33	0.45	0.40	0.33
2 mL com., 20°C, dupl.		-	-	-	-	0.20	-	0.19	0.23	0.21	0.20
2 mL MLSS, 20°C, dupl.		-	-	-	-	0.26	0.29	0.36	0.31	0.37	0.32
2 mL effluent, 37°C		-	-	-	-	0.39	-	0.31	0.24	0.24	0.24
10 mL effluent, 37°C		-	-	-	-	0.63	-	0.53	0.54	0.51	0.48
2 mL commer., 37°C		-	-	-	-	0.29	-	0.22	0.25	0.25	0.25
2 mL MLSS, 37°C		0.35	0.38	0.40	0.40	0.44	0.44	0.48	0.44	0.43	0.39

APPENDIX G
RAW DATA SUMMARY FOR STANDARD SOLUTION SAMPLES

Table G-1 DOC and BDOC of sodium acetate standard solutions.

Inoculum and incubation temperature	DOC (mg/L)	$BDOC_t$ (mg/L)									
		1	2	3	4	5	7	10	15	20	28
2 mL effluent, 20°C	1.94	0.18	1.85	1.81	1.88	1.82	1.72	1.77	1.69	1.65	1.93
10 mL effluent, 20°C		0.37	1.80	1.87	1.90	1.80	1.96	1.85	1.80	1.80	1.88
2 mL commer., 20°C		0.25	1.87	1.78	1.89	1.93	1.75	1.74	1.71	1.74	1.91
2 mL MLSS, 20°C		0.32	1.61	1.68	1.84	1.89	1.69	1.76	1.65	1.67	1.90
2 mL effluent, 37°C		1.87	1.66	1.74	1.83	1.97	1.99	1.73	1.71	1.67	1.96
10 mL effluent, 37°C		1.85	1.92	1.81	1.87	1.93	2.01	2.07	1.94	1.74	1.91
2 mL commer., 37°C		1.88	1.84	1.74	1.84	1.81	1.80	1.81	1.84	1.81	1.92
2 mL MLSS, 37°C		1.74	1.71	1.65	1.63	1.68	1.71	1.86	1.66	1.72	1.85
2 mL effluent, 20°C	4.89	0.35	4.86	4.80	4.88	4.85	4.86	4.81	4.64	4.67	4.86
10 mL effluent, 20°C		1.64	4.93	4.94	4.82	4.72	4.80	4.78	4.84	4.71	4.80
2 mL commer., 20°C		1.03	4.77	4.78	4.86	4.89	4.89	4.89	4.74	4.78	4.89
2 mL MLSS, 20°C		0.56	4.80	4.82	4.85	4.86	4.74	4.60	4.67	4.69	4.83
2 mL effluent, 37°C		4.77	4.78	4.80	4.92	5.02	4.96	4.90	4.79	4.80	4.96
10 mL effluent, 37°C		4.61	4.82	4.81	5.02	4.89	4.97	4.95	5.05	4.73	4.86
2 mL commer., 37°C		4.71	4.90	4.82	4.86	4.88	4.90	4.93	4.96	4.88	4.91
2 mL MLSS, 37°C		4.80	4.89	4.75	4.55	4.56	4.64	4.77	4.79	4.78	4.78
2 mL effluent, 20°C	9.97	0.10	8.91	9.95	10.01	9.99	9.95	9.74	9.71	9.68	9.89
10 mL effluent, 20°C		1.49	10.07	10.07	9.96	9.90	9.98	9.91	9.96	9.77	9.81
2 mL commer., 20°C		0.42	5.72	7.37	8.57	9.60	9.81	9.64	9.64	9.82	9.88
2 mL MLSS, 20°C		1.56	10.00	9.94	9.93	9.88	9.71	9.67	9.68	9.68	9.69
2 mL effluent, 37°C		8.52	9.95	9.93	10.03	10.06	10.12	9.98	9.98	9.88	10.08
10 mL effluent, 37°C		9.03	10.06	9.91	10.12	9.92	9.96	9.89	9.85	9.95	9.86
2 mL commer., 37°C		6.60	9.77	9.86	10.07	9.93	9.97	10.03	10.08	10.01	9.98
2 mL MLSS, 37°C		9.40	10.03	9.84	9.73	9.65	9.69	9.78	9.76	9.95	9.77

Table G-2 DOC and BDOC of phenol standard solutions.

Inoculum and incubation temperature	DOC (mg/L)	$BDOC_t$ (mg/L)									
		1	2	3	4	5	7	10	15	20	28
2 mL effluent, 20°C	1.87	0.04	1.83	1.87	1.83	1.75	1.89	1.79	1.75	1.72	1.84
10 mL effluent, 20°C		0.37	2.03	1.97	2.04	1.82	2.03	2.01	2.00	1.89	1.88
2 mL commer., 20°C		0.01	1.29	1.81	1.85	1.80	1.78	1.79	1.75	1.74	1.79
2 mL MLSS, 20°C		0.04	1.80	1.74	1.78	1.87	1.79	1.75	1.81	1.78	1.77
2 mL effluent, 37°C		0.33	1.79	1.76	1.75	1.88	1.97	1.85	1.78	1.73	1.91
10 mL effluent, 37°C		1.87	2.03	1.84	2.13	2.09	2.16	2.21	2.18	1.89	2.00
2 mL commer., 37°C		0.00	1.91	1.80	1.88	1.84	1.84	1.75	1.79	1.71	1.82
2 mL MLSS, 37°C		1.80	1.74	1.66	1.69	1.61	1.68	1.74	1.69	1.74	1.71
2 mL effluent, 20°C	4.60	0.08	0.39	4.50	4.58	4.66	4.77	4.69	4.60	4.57	4.54
10 mL effluent, 20°C		0.30	1.25	5.01	4.93	4.77	4.90	4.89	4.79	4.79	4.76
2 mL commer., 20°C		0.02	2.15	4.46	4.52	4.50	4.44	4.49	4.54	4.55	4.54
2 mL MLSS, 20°C		0.11	4.22	4.57	4.57	4.59	4.40	4.47	4.49	4.46	4.47
2 mL effluent, 37°C		0.35	4.57	4.58	4.64	4.74	4.76	4.63	4.55	4.47	4.67
10 mL effluent, 37°C		4.37	4.74	4.68	4.78	4.82	4.89	4.97	4.88	4.68	4.73
2 mL commer., 37°C		0.69	4.64	4.54	4.71	4.62	4.59	4.62	4.66	4.53	4.54
2 mL MLSS, 37°C		3.92	4.63	4.59	4.43	4.42	4.40	4.52	4.49	4.51	4.49
2 mL effluent, 20°C	9.81	0.27	2.37	9.18	9.39	9.35	9.62	9.64	9.58	9.51	9.59
10 mL effluent, 20°C		0.55	4.50	10.02	9.92	9.94	10.05	10.01	9.82	9.69	9.74
2 mL commer., 20°C		0.15	0.69	6.05	9.19	9.34	9.48	9.51	9.46	9.62	9.73
2 mL MLSS, 20°C		0.25	7.16	9.70	9.79	9.70	9.64	9.53	9.48	9.47	9.70
2 mL effluent, 37°C		4.71	9.07	9.63	9.65	9.70	9.75	9.69	9.63	9.62	9.68
10 mL effluent, 37°C		5.42	10.04	9.81	9.94	9.94	9.93	10.02	9.99	9.82	9.97
2 mL commer., 37°C		0.19	5.55	8.07	9.64	9.54	9.53	9.67	9.59	9.69	9.72
2 mL MLSS, 37°C		5.30	9.68	9.70	9.45	9.39	9.42	9.51	9.53	9.57	9.56

Table G-3 DOC_0 and DOC_t of blank water used for determining BDOC of sodium acetate and phenol standard solutions.

Inoculum and incubation temperature	DOC_0 (mg/L)	DOC_t (mg/L)									
		1	2	3	4	5	7	10	15	20	28
2 mL effluent, 20°C	0.12	0.81	0.82	0.78	0.78	0.80	0.85	0.83	0.78	0.75	0.81
10 mL effluent, 20°C		2.78	3.05	3.00	2.91	2.82	2.93	2.92	2.90	2.90	2.78
2 mL commer., 20°C		0.36	0.36	0.30	0.37	0.37	0.36	0.37	0.34	0.29	0.30
2 mL MLSS, 20°C		0.44	0.54	0.55	0.56	0.59	0.53	0.55	0.58	0.55	0.57
2 mL effluent, 37°C		0.92	0.82	0.77	0.83	0.92	0.96	0.86	0.81	0.81	0.85
10 mL effluent, 37°C		2.80	2.93	2.82	2.89	2.92	2.96	3.04	2.97	2.79	2.71
2 mL commer., 37°C		0.45	0.42	0.34	0.47	0.41	0.36	0.40	0.40	0.34	0.31
2 mL MLSS, 37°C		0.65	0.64	0.62	0.57	0.58	0.63	0.72	0.65	0.67	0.58

APPENDIX H
OZONE CONCENTRATION AND UTILIZATION AND UV ABSORBANCE DATA FOR OZONATED SECONDARY EFFLUENT EXPERIMENT

Table H-1 Ozone gas (in and out) and liquid concentrations, UV_{254}, and ozone utilization for sample from RP 1 WWTP, sampling date: 5/15/97.

Ozonation time (min)	0	2	5	10	15	20	25	30	35	40	Avg. 5 - 40
Ozone in (mg/L)		16.89									18.09
Ozone out (mg/L)		16.41	17.48								18.15
Residual ozone (mg/L)		1.26	2.76	3.14	3.33	3.43	3.55	3.60	3.69	3.62	
UV_{254} absorbance (cm^{-1})	0.103	0.052	0.040	0.036	0.035	0.034	0.031	0.032	0.033	0.031	
Ozone utilization (mg/L)		1.50	0								

Table H-2 Ozone gas (in and out) and liquid concentrations, UV_{254}, and ozone utilization for sample from RP 2 WWTP, sampling date: 5/15/97.

Ozonation time (min)	0	2	5	10	15	20	25	30	35	40	Avg. 5 - 40
Ozone in (mg/L)		17.98									18.10
Ozone out (mg/L)		16.89	17.79								18.33
Residual ozone (mg/L)		1.33	2.36	2.93	3.17	3.40	3.45	3.52	3.74	3.69	
UV_{254} absorbance (cm^{-1})	0.123	0.087	0.079	0.077	0.074	0.080	0.082	0.087	0.091	0.099	
Ozone utilization (mg/L)		4.94	0.95								

Table H-3 Ozone gas (in and out) and liquid concentrations, UV_{254}, and ozone utilization for sample from Carbon Canyon WWTP, sampling date: 5/15/97.

Ozonation time (min)	0	2	5	10	15	20	25	30	35	40	Avg. 5 - 40
Ozone in (mg/L)			18.11								18.80
Ozone out (mg/L)		17.35	18.22								18.92
Residual ozone (mg/L)		2.40	2.86	3.14	3.57	3.33	3.81	3.90	4.02	3.99	
UV_{254} absorbance (cm^{-1})	0.096	0.040	0.048	0.040	0.040	0.049	0.050	0.052	0.056	0.062	
Ozone utilization (mg/L)		1.97	0								

Table H-4 Ozone gas (in and out) and liquid concentrations, UV_{254}, and ozone utilization for sample from RP 1 WWTP, sampling date: 5/16/97.

Ozonation time (min)	0	2	5	10	15
Ozone in (mg/L)			17.96	18.23	
Ozone out (mg/L)		17.43	17.80	18.23	18.74
Residual ozone (mg/L)		1.86	2.64	3.00	3.42
UV_{254} absorbance (cm^{-1})	0.104	0.041	0.039	0.041	0.041
Ozone utilization (mg/L)		1.19	0.60		

Table H-5 Ozone gas (in and out) and liquid concentrations, UV_{254}, and ozone utilization for sample from RP 2 WWTP, sampling date: 5/16/97.

Ozonation time (min)	0	2	5	10	15
Ozone in (mg/L)			20.99	17.62	
Ozone out (mg/L)		18.33	21.02	-	17.00
Residual ozone (mg/L)		2.36	3.67	-	3.81
UV_{254} absorbance (cm^{-1})	0.135	0.061	0.056	0.046	0.048
Ozone utilization (mg/L)		4.29	0		

Table H-6 Ozone gas (in and out) and liquid concentrations, UV_{254}, and ozone utilization for sample from Carbon Canyon WWTP, sampling date: 5/16/97.

Ozonation time (min)	0	2	5	10	15
Ozone in (mg/L)			18.84	-	
Ozone out (mg/L)		18.33	18.44	-	-
Residual ozone (mg/L)		2.33	2.90	4.52	-
UV_{254} absorbance (cm^{-1})	0.107	0.057	0.048	0.045	0.041
Ozone utilization (mg/L)		1.42	0.93		

APPENDIX I
RAW DATA SUMMARY FOR OZONATED AND NON-OZONATED SECONDARY EFFLUENT EXPERIMENT

Table I-1 DOC and BDOC of ozonated and non-ozonated secondary effluent samples from RP1 WWTP.

Inoculum and incubation temperature	DOC (mg/L)	$BDOC_t$ (mg/L)									
		1	2	3	4	5	7	10	15	20	28
5/15/97, no O_3											
2 mL effluent, 20°C	4.23	-	-	-	-	0.00	-	0.00	0.04	0.08	0.19
2 mL MLSS, 20°C		0.12	0.16	0.21	0.19	0.23	0.34	0.42	0.48	0.59	0.64
5 mL MLSS, 20°C		0.01	0.23	0.34	0.47	0.48	0.64	0.72	0.80	0.99	1.01
10 mL MLSS, 20°C		0.30	0.34	0.50	0.58	0.70	0.78	0.90	1.16	1.47	1.41
2 mL effluent, 37°C		-	-	-	-	0.18	-	0.30	0.48	0.71	0.88
2 mL MLSS, 37°C		0.22	0.28	0.28	0.38	0.44	0.49	0.70	1.02	1.11	1.24
5 mL MLSS, 37°C		0.15	0.21	0.26	0.57	0.73	0.63	0.80	0.92	0.95	1.23
10 mL MLSS, 37°C		0.51	0.62	0.74	0.82	0.88	0.84	1.19	0.65	0.79	1.11
5/15/97, O_3											
2 mL effluent, 20°C	3.30	-	-	-	-	0.75	-	1.64	1.94	2.04	2.16
2 mL MLSS, 20°C		0.85	1.50	1.99	2.26	2.36	2.48	2.50	2.52	2.60	2.63
5 mL MLSS, 20°C		1.32	1.87	2.28	2.44	2.51	2.72	2.72	2.73	2.83	2.85
10 mL MLSS, 20°C		1.44	1.95	2.29	2.49	2.65	2.67	2.70	2.88	3.08	3.22
2 mL effluent, 37°C		-	-	-	-	2.10	-	2.30	2.50	2.54	2.63
2 mL MLSS, 37°C		1.82	2.47	2.54	2.49	2.58	2.63	2.60	2.78	2.62	2.75
5 mL MLSS, 37°C		1.89	2.53	2.61	2.64	2.70	2.62	2.66	2.84	2.83	2.84
10 mL MLSS, 37°C		2.17	2.61	2.77	2.83	2.85	2.84	2.75	2.69	2.63	2.48
5/16/97, no O_3											
2 mL effluent, 20°C	4.10	-	-	-	-	0.00	-	0.00	0.00	0.04	0.23
2 mL MLSS, 20°C		0.00	0.00	0.12	0.10	0.16	0.25	0.28	0.36	0.44	0.55
5 mL MLSS, 20°C		0.10	0.16	0.20	0.29	0.36	0.60	0.62	0.65	0.79	0.79
10 mL MLSS, 20°C		0.21	0.20	0.39	0.47	0.63	0.72	0.74	0.89	1.18	1.26
2 mL effluent, 37°C		-	-	-	-	0.08	-	0.31	0.55	0.60	0.74
2 mL MLSS, 37°C		0.09	0.16	0.18	0.21	0.34	0.39	0.47	0.62	0.74	1.00
5 mL MLSS, 37°C		0.22	0.30	0.38	0.51	0.56	0.46	0.62	0.80	0.99	1.18
10 mL MLSS, 37°C		0.47	0.54	0.42	0.60	0.73	0.80	0.84	0.98	1.09	1.05
5/16/97, O_3											
2 mL effluent, 20°C	3.85	-	-	-	-	1.08	-	2.05	2.22	2.32	2.42
2 mL MLSS, 20°C		1.19	1.65	2.08	2.41	2.61	2.77	2.86	2.96	2.95	2.96
5 mL MLSS, 20°C		1.49	2.10	2.41	2.67	2.73	3.01	2.95	3.02	3.14	3.18
10 mL MLSS, 20°C		1.79	2.35	2.71	2.80	2.94	2.97	2.96	3.12	3.26	3.21
2 mL effluent, 37°C		-	-	-	-	2.22	-	2.58	2.57	2.94	2.97
2 mL MLSS, 37°C		2.10	2.70	2.77	2.77	2.86	3.02	3.01	3.03	3.24	3.25
5 mL MLSS, 37°C		2.21	2.84	2.85	2.81	3.09	3.05	3.05	3.19	3.20	3.21
10 mL MLSS, 37°C		2.58	2.94	3.12	3.15	3.23	3.19	3.17	3.25	2.96	2.84

Table I-2 DOC and BDOC of ozonated and non-ozonated secondary effluent samples from RP2 WWTP.

Inoculum and incubation temperature	DOC (mg/L)	$BDOC_t$ (mg/L)									
		1	2	3	4	5	7	10	15	20	28
5/15/97, no O_3											
2 mL effluent, 20°C	5.20	-	-	-	-	0.00	-	0.00	0.07	0.09	0.12
2 mL MLSS, 20°C		0.00	0.00	0.06	0.12	0.29	0.39	0.51	0.71	0.76	0.85
5 mL MLSS, 20°C		0.02	0.06	0.21	0.30	0.55	0.60	0.68	1.03	1.13	1.26
10 mL MLSS, 20°C		0.21	0.39	0.40	0.52	0.72	0.91	1.24	1.57	1.76	1.72
2 mL effluent, 37°C		-	-	-	-	0.47	-	0.90	0.92	1.08	1.19
2 mL MLSS, 37°C		0.04	0.16	0.27	0.33	0.49	0.56	0.80	1.26	1.43	1.50
5 mL MLSS, 37°C		0.00	0.19	0.34	0.50	0.78	0.85	0.97	1.17	1.28	1.45
10 mL MLSS, 37°C		0.19	0.62	0.67	0.73	1.10	1.20	1.40	1.58	1.57	1.67
5/15/97, O_3											
2 mL effluent, 20°C	4.20	-	-	-	-	0.61	-	2.12	2.45	2.64	2.71
2 mL MLSS, 20°C		0.52	1.49	2.21	2.64	2.89	2.89	3.13	3.19	3.29	3.31
5 mL MLSS, 20°C		0.86	1.75	2.34	2.85	3.08	3.14	3.44	3.53	3.63	3.53
10 mL MLSS, 20°C		1.32	2.20	2.79	3.05	3.12	3.32	3.55	3.64	3.75	3.71
2 mL effluent, 37°C		-	-	-	-	2.25	-	2.76	2.88	3.18	3.19
2 mL MLSS, 37°C		1.58	2.79	3.01	3.21	3.18	3.30	3.39	3.48	3.52	3.66
5 mL MLSS, 37°C		2.05	2.97	3.09	3.27	3.40	3.37	3.56	3.46	3.44	3.48
10 mL MLSS, 37°C		2.49	3.17	3.34	3.49	3.55	3.62	3.70	3.79	3.56	3.58
5/16/97, no O_3											
2 mL effluent, 20°C	5.20	-	-	-	-	0.00	-	0.00	0.12	0.14	0.23
2 mL MLSS, 20°C		0.00	0.03	0.12	0.29	0.39	0.40	0.46	0.69	0.67	0.75
5 mL MLSS, 20°C		0.03	0.26	0.26	0.45	0.61	0.63	0.99	1.25	1.38	1.52
10 mL MLSS, 20°C		0.23	0.36	0.59	0.76	0.86	0.88	1.38	1.76	1.95	1.83
2 mL effluent, 37°C		-	-	-	-	0.43	-	0.67	0.92	1.16	1.16
2 mL MLSS, 37°C		0.08	0.24	0.37	0.61	0.59	0.70	0.81	1.01	1.03	1.18
5 mL MLSS, 37°C		0.22	0.43	0.50	0.62	0.70	0.68	0.98	1.12	1.27	1.56
10 mL MLSS, 37°C		0.59	0.82	0.81	1.02	1.13	1.43	1.58	1.94	1.91	1.96
5/16/97, O_3											
2 mL effluent, 20°C	4.48	-	-	-	-	0.79	-	2.14	2.31	2.32	2.66
2 mL MLSS, 20°C		0.48	1.41	2.07	2.60	2.89	2.93	3.17	3.25	3.36	3.41
5 mL MLSS, 20°C		0.89	1.62	2.18	2.80	3.12	3.22	3.43	3.67	3.6	3.74
10 mL MLSS, 20°C		1.15	1.73	2.20	2.98	3.15	3.45	3.79	4.11	4.19	3.48
2 mL effluent, 37°C		-	-	-	-	1.65	-	2.66	2.74	2.98	3.15
2 mL MLSS, 37°C		1.67	2.84	3.11	3.20	3.40	3.39	3.58	3.67	3.83	3.83
5 mL MLSS, 37°C		2.32	2.98	3.21	3.39	3.53	3.59	3.74	3.61	3.64	3.78
10 mL MLSS, 37°C		2.69	3.14	3.42	3.49	3.61	3.70	3.82	3.90	3.49	2.05

Table I-3 DOC and BDOC of ozonated and non-ozonated secondary effluent samples from Carbon Canyon WWTP.

Inoculum and incubation temperature	DOC (mg/L)	$BDOC_t$ (mg/L)									
		1	2	3	4	5	7	10	15	20	28
5/15/97, no O_3											
2 mL effluent, 20°C	4.31	-	-	-	-	0.00	-	0.02	0.08	0.11	0.15
2 mL MLSS, 20°C		0.12	0.16	0.22	0.30	0.40	0.34	0.36	0.61	0.63	0.61
5 mL MLSS, 20°C		0.23	0.27	0.44	0.49	0.55	0.54	0.53	0.83	0.87	0.86
10 mL MLSS, 20°C		0.42	0.46	0.49	0.63	0.79	0 79	0.84	0.97	1.02	1.05
2 mL effluent, 37°C		-	-	-	-	0.19	-	0.40	0.38	0.46	0.57
2 mL MLSS, 37°C		0.10	0.23	0.31	0.47	0.57	0.65	0.78	0.98	1.20	1.29
5 mL MLSS, 37°C		0.30	0.38	0.48	0.62	0.63	0.79	0.81	0.85	1.21	1.33
10 mL MLSS, 37°C		0.45	0.64	0.77	0.85	0.82	0.91	1.11	1.16	1.14	1.95
5/15/97, O_3											
2 mL effluent, 20°C	2.53	-	-	-	-	0.34	-	1.01	1.11	1.34	1.42
2 mL MLSS, 20°C		0.56	0.95	1.19	1.48	1.54	1.64	1.61	1.77	1.84	1.75
5 mL MLSS, 20°C		0.72	1.12	1.39	1.66	1.72	1.76	1.77	1.89	1.92	1.76
10 mL MLSS, 20°C		0.95	1.25	1.55	1.74	1.84	1.87	1.83	1.62	1.83	1.90
2 mL effluent, 37°C		-	-	-	-	0.77	-	1.50	1.54	1.71	1.73
2 mL MLSS, 37°C		0.82	1.45	1.60	1.63	1.73	1.75	1.78	1.82	2.03	2.06
5 mL MLSS, 37°C		0.96	1.62	1.60	1.66	1.76	1.83	1.84	1.93	1.95	1.85
10 mL MLSS, 37°C		1.50	1.74	1.73	1.89	1.95	1.87	2.04	1.91	1.92	2.79
5/16/97, no O_3											
2 mL effluent, 20°C	4.08	-	-	-	-	0.00	-	0.00	0.00	0.02	0.20
2 mL MLSS, 20°C		0.00	0.00	0.02	0.16	0.27	0.27	0.32	0.46	0.51	0.50
5 mL MLSS, 20°C		0.21	0.29	0.32	0.40	0.44	0.47	0.49	0.68	0.75	0.76
10 mL MLSS, 20°C		0.33	0.29	0.42	0.53	0.56	0.76	0.78	0.86	1.04	1.02
2 mL effluent, 37°C		-	-	-	-	0.08	-	0.19	0.28	0.38	0.33
2 mL MLSS, 37°C		0.05	0.17	0.20	0.24	0.23	0.38	0.49	0.82	0.98	1.15
5 mL MLSS, 37°C		0.26	0.37	0.44	0.53	0.66	0.64	0.73	0.80	1.10	1.18
10 mL MLSS, 37°C		0.44	0.58	0.63	0.74	0.81	0.83	1.05	1.05	1.07	2.23
5/16/97, O_3											
2 mL effluent, 20°C	3.16	-	-	-	-	0.41	-	1.38	1.58	1.77	1.95
2 mL MLSS, 20°C		0.59	1.03	1.35	1.86	2.10	2.13	2.25	2.38	2.39	2.37
5 mL MLSS, 20°C		0.98	1.43	1.81	2.20	2.30	2.29	2.36	2.45	2.48	2.47
10 mL MLSS, 20°C		1.18	1.64	1.95	2.32	2.41	2.44	2.45	2.48	2.44	2.47
2 mL effluent, 37°C		-	-	-	-	0.90	-	1.60	1.66	1.93	1.89
2 mL MLSS, 37°C		1.30	2.11	2.19	2.25	2.20	2.36	2.40	2.46	2.60	2.70
5 mL MLSS, 37°C		1.78	2.19	2.34	2.38	2.47	2.51	2.43	2.48	2.36	2.39
10 mL MLSS, 37°C		2.02	2.36	2.37	2.48	2.52	2.55	2.58	2.61	2.37	3.29

Table I-4 DOC_0 and DOC_t of blank water used for determining BDOC of ozonated and non-ozonated secondary effluent samples from RP1, RP2, Carbon Canyon WWTPs.

Inoculum and incubation temperature	DOC_0 (mg/L)	DOC_t (mg/L)									
		1	2	3	4	5	7	10	15	20	28
RP1											
2 mL effluent, 20°C	0.14	-	-	-	-	0.18	-	0.21	0.21	0.22	0.24
2 mL MLSS, 20°C		0.29	0.27	0.35	0.28	0.28	0.34	0.35	0.45	0.54	0.55
5 mL MLSS, 20°C		0.36	0.42	0.44	0.43	0.44	0.63	0.61	0.74	0.98	1.02
10 mL MLSS, 20°C		0.55	0.58	0.61	0.60	0.71	0.71	0.79	1.12	1.52	1.66
2 mL effluent, 37°C		-	-	-	-	0.28	-	0.23	0.25	0.26	0.26
2 mL MLSS, 37°C		0.45	0.44	0.43	0.36	0.41	0.42	0.41	0.49	0.46	0.53
5 mL MLSS, 37°C		0.47	0.59	0.56	0.62	0.67	0.60	0.65	0.85	0.88	0.87
10 mL MLSS, 37°C		0.84	0.88	0.92	0.91	0.97	0.96	1.03	1.20	1.33	1.32
RP2											
2 mL effluent, 20°C	0.16	-	-	-	-	0.22	-	0.20	0.29	0.25	0.26
2 mL MLSS, 20°C		0.26	0.29	0.33	0.30	0.43	0.39	0.56	0.69	0.84	0.87
5 mL MLSS, 20°C		0.36	0.48	0.47	0.50	0.63	0.66	0.98	1.27	1.45	1.48
10 mL MLSS, 20°C		0.64	0.67	0.72	0.76	0.80	1.01	1.38	1.84	2.12	2.19
2 mL effluent, 37°C		-	-	-	-	0.37	-	0.35	0.26	0.33	0.32
2 mL MLSS, 37°C		0.37	0.51	0.50	0.54	0.60	0.62	0.65	0.72	0.69	0.65
5 mL MLSS, 37°C		0.58	0.69	0.72	0.78	0.90	1.00	1.13	1.12	1.03	1.01
10 mL MLSS, 37°C		0.92	1.06	1.12	1.20	1.29	1.51	1.71	1.97	1.70	1.69
Carbon Canyon											
2 mL effluent, 20°C	0.16	-	-	-	-	0.21	-	0.22	0.23	0.24	0.28
2 mL MLSS, 20°C		0.28	0.29	0.27	0.24	0.31	0.23	0.23	0.38	0.37	0.33
5 mL MLSS, 20°C		0.40	0.39	0.38	0.39	0.41	0.35	0.36	0.51	0.56	0.56
10 mL MLSS, 20°C		0.51	0.48	0.48	0.51	0.56	0.60	0.59	0.74	0.78	0.81
2 mL effluent, 37°C		-	-	-	-	0.21	-	0.23	0.21	0.25	0.22
2 mL MLSS, 37°C		0.27	0.30	0.33	0.25	0.29	0.28	0.27	0.31	0.41	0.48
5 mL MLSS, 37°C		0.42	0.45	0.48	0.45	0.54	0.50	0.47	0.55	0.60	0.64
10 mL MLSS, 37°C		0.58	0.67	0.67	0.69	0.73	0.73	0.86	0.92	1.03	1.99

REFERENCES

Albertson, O. E. (1995) Is $CBOD_5$ Test Viable for Raw and Settled Wastewater? *J. Envir. Engr.*, ASCE, **121** (7), 515.

Collins, A. G., Farvardin, M. R., and Shen, Z. (1989) An Alternative Approach to Gas Phase Ozone Determination. *Ozone Sci. Engrg.*, **11** (1), 115.

Edzwald, J. K. and Van Benschoten, J. E. (1990) Aluminum Coagulation of Natural Organic Matter. In *Chemical Water and Wastewater Treatment*. H. H. Hahn and R. Klute (Eds.), Springer-Verlag, Berlin, Germany.

Frias, J., Lucena, F., and Ribas, F. (1992) A Method for the Measurement of Biodegradable Organic Carbon in Waters. *Water Res.*, **26** (2), 255.

Frias, J., Ribas, F., and Lucena, F. (1995) Comparison of Methods for the Measurement of Biodegradable Organic Carbon and Assimilable Organic Carbon in Water. *Water Res.*, **29** (12), 2785.

Gaudy, A. F. Jr. (1972) Biochemical Oxygen Demand. In *Water Pollution Microbiology Vol. 1*. R. Mitchell (Ed.), John Wiley & Sons, Inc., New York, NY, 305.

Gaudy A. F. Jr. and Gaudy, E. T. (1988) Elements of Bioenvironmental Engineering. Engineering Press, Inc., San Jose, CA.

Hascoet, M. C., Servais, P., and Billen, G. (1986) Use of Biological Analytical Methods to Optimize Ozonation and GAC Filtration in Surface Water Treatment. In *Proc. 1986 AWWA Ann. Conf.*, Denver, CO, AWWA, Denver, CO.

Hiser, L. L. and Busch, A. W. (1964) An 8-Hour Biological Oxygen Demand Test Using Mass Culture Aeration and COD. *J. Water Pollut. Control Fed.*, **36** (4), 505.

Huck, P. M. (1990) Measurement of Biodegradable Organic Matter and Bacterial Growth Potential in Drinking Water. *J. Am. Water Works Assoc.*, **82** (7), 78.

Joret, J. C. and Levi, Y. (1986) Method Rapide D'evaluation du Carbone Eliminable des Eaux par Voie Biologique. *Trib. Cebedeau*, **510** (39), 3.

Joret, J. C., Levi, Y., Dupin, T., and Gilbert, M. (1988) Rapid Method for Estimating Bio-Eliminable Organic Carbon in Water. In *Proc. 1988 AWWA Ann. Conf.*, Orlando, FL, AWWA, Denver, CO.

Kaplan, L. A. and Newbold, J. D. (1995) Measurement of Streamwater Biodegradable Dissolved Organic Carbon with a Plug-Flow Bioreactor. *Water Res.*, **29** (12), 2696.

Kemmy, F. A., Fry, J. C., and Breach, R. A. (1989) Development and Operational Implementation of a Modified and Simplified Method for Determination of Assimilable Organic Carbon (AOC) in Drinking Water. *Water Sci. Tech.*, **21** (3), 155.

Lawrence, A. W. and McCarty, P. L. (1970) Unified Basis for Biological Treatment. *J. Sanit. Engr. Div.*, ASCE, **96**(SA3), 757.

Le Chevalier, M. W., Cawthon, C. D., and Lee, R. G. (1988) Inactivation of Biofilm Bacteria. *Appl. Environ. Microbiol.*, **54**, 2492.

Lucena, F., Frias, J., and Ribas, F. (1990) A New Dynamic Approach to the Determination of Biodegradable Dissolved Organic Carbon in Water. *Environ. Tech.*, **12** (4), 343.

Madireddi, K., Babcock, R. W., Levine, B., Huo, T. L., Khan, E., Ye, Q. F., Neethling, J. B., Suffet, I. H., and Stenstrom, M. K. (1997) Wastewater Reclamation at Lake Arrowhead, California: An Overview. *Water Environ. Res.*, **69** (3), 350.

Malley, P. J., Eighmy, T. T., Collins, M. R., Royce, J. A., and Mogran, D. F. (1993) The Performance and Microbiology of Ozone-Enhanced Biological Filtration. *J. Am. Water Works Assoc.*, **85** (12), 47.

Merlet, N., Merlet, Y., Prevost, M., Desjardins, R., and Bablon, G. (1991) Removal of Organic Matter in BAC Filters: the Link between BDOC and Chlorine Demand. In *Proc. 1991 Water Qual. Tech. Conf.*, Orlando, FL, AWWA, Denver, CO.

Mogren, E. M., Scarpino, P., and Summers, R. S. (1990) Measurement of Biodegradable Dissolved Organic Carbon in Drinking Water. In *Proc. 1990 AWWA Ann. Conf.*, Cincinnati, OH, AWWA, Denver, CO.

Ribas, F., Frias, J., and Lucena, F. (1991) A New Dynamic Method for the Rapid Determination of the Biodegradable Dissolved Organic Carbon in Drinking Water. *J. Appl. Bacteriol.*, **71** (4), 371.

Ribas, F., Frias, J., Huguet, J. M., and Lucena, F. (1992) Monitoring of the Biodegradable Organic Carbon in a Water Treatment Plant with Sand-GAC Filtration-Ozonation Using a Fixed Biomass Reactor. In *Proc. 1992 Water Qual. Tech. Conf.*, Toronto, Ontario, AWWA, Denver, CO.

Rittmann, B. E. and Snoeyink, V. L. (1984) Achieving Biologically Stable Drinking Water. *J. Am. Water Works Assoc.*, **76** (10), 106.

Servais, P., Billen, G., and Hascoet, M. C. (1987) Determination of the Biodegradable Fraction of Dissolved Organic Matter in Water. *Water Res.*, **21** (4), 445.

Servais, P., Anzil, A., and Ventresque, C. (1989) Simple Method for Determination of Biodegradable Dissolved Organic Carbon in Water. *Appl. Environ. Microbiol.*, **55** (10), 2732.

Servais, P., Billen, G., Ventresque, C., and Bablon, G. P. (1991) Microbial Activity in GAC Filters at the Choisy-le-Roi Treatment Plant. *J. Am. Water Works Assoc.*, **83** (2), 62.

Servais, P., Laurent, P., and Randon, G. (1993) Impact of Biodegradable Dissolved Organic Carbon (BDOC) on Bacterial Dynamics in Distribution Systems. In *Proc. 1993 Water Qual. Tech. Conf.*, Miami, FL, AWWA, Denver, CO.

Standard Methods for the Examination of Water and Wastewater (1989). 17th ed., APHA, AWWA, and WEF, Washington, D. C.

van der Kooij, D., Visser, A., and Hijnen, W. A. M. (1982) Determining the Concentration of Easily Assimilable Organic Carbon in Drinking Water. *J. Am. Water Works Assoc.*, **74** (10), 540.

van der Kooij, D. (1987) The Effect of Treatment on Assimilable Organic Carbon in Drinking Water. In *Proc. Second Natl. Conf. on Drinking Water.* P. M. Huck and P. Toft (Eds.), Pergamon Press, NY.

van der Kooij, D., Hijnen, W. A. M., and Kruithof, J. C. (1989) The Effects of Ozonation, Biological Filtration, and Distribution on the Concentration of Easily Assimilable Organic Carbon in Drinking Water. *Ozone Sci. Engrg.*, **11** (3), 297.

Volk, C., Renner, C., Roche, P., Paillard, H., and Joret, J. C. (1993) Effects of Ozone on the Production of Biodegradable Dissolved Organic Carbon (BDOC) during Water Treatment. *Ozone Sci. & Engrg.*, **15** (5), 389.