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Effectiveness of supplemental aeration and an enlarged first stage in improving RBC performance

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EFFECTIVENESS OF SUPPLEMENTAL AERATION AND AN ENLARGED FIRST STAGE IN IMPROVING RBC PERFORMANCE

Iowa State University PH.D. 1985

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Effectiveness of supplemental aeration and an enlarged first stage in improving RBC performance

by

Rao Yadagiri Surampalli

A Dissertation Submitted to the
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BOD_5	Five-day biochemical oxygen demand
$CaCO_3$	Calcium carbonate
Cfm	Cubic foot per minute
Cm	Centimeter
COD	Chemical oxygen demand
°C	Degrees Celsius
DO	Dissolved oxygen
°F	Degrees Fahrenheit
ft	Feet
ft^2	Square foot
gal	Gallon
gm	Gram
gpd	Gallons per day
hp	Horsepower
hr	Hour
in	Inch
L	Length
lb	Pound
M	Mass
m	Meter
m^2	Square meter
mg	Milligram
mgd	million gallons daily

mg/L	Milligrams per liter
min	Minutes
ml	Milliliter
mm	Millimeter
NH_3-N	Ammonia nitrogen
pH	Logarithm of the reciprocal of the hydrogen ion concentration
RBC	Rotating Biological Contactor
rpm	Rotations per minute
S	Influent waste concentration
$SBOD_5$	Five-day soluble carbonaceous biochemical oxygen demand
SCOD	Soluble chemical oxygen demand
SD	Standard deviation
SS	Suspended solids
sq ft	Square feet
T or t	Time
$TBOD_5$	Total five-day biochemical oxygen demand
TKN	Total kjeldahl nitrogen
VSS	Volatile suspended solids

DEDICATION

THIS IS DEDICATED WITH MUCH LOVE TO MY FATHER

INTRODUCTION

Fixed-film biological processes found early application in wastewater treatment but their use declined with the advent and wide scale use of the activated sludge process. However, with the development of plastic media in the early 1960s interest in fixed-film processes has grown once again. During the late 1960s, this new interest in plastic media led to the development and commercialization of rotating biological contactors (RBCs) which provided many of the advantages of old rock-media trickling filters without some of their disadvantages. Because of the new media developments and the smaller energy requirements of RBC treatment units compared with those of activated sludge units, engineers employed RBC units extensively for wastewater treatment during the mid and late 1970s.

Fixed-film biological growth can be found on any available surface in many natural environments such as rivers, swamps, lakes, soils and seawater. Where conditions are favorable, the bacteria attach themselves to any surface available. The RBC consists of circular plastic media mounted on a horizontal shaft. The shafts are rotated by either a mechanical or a compressed air drive such that the media is immersed in a tank containing wastewater up to 40 percent of its diameter. The wastewater being treated flows through the contactor by simple displacement and gravity. Bacteria and other microorganisms which are naturally present in the wastewater adhere and grow on the surface of the rotating media. Within one to two weeks of start-up, the bacteria will form a fixed biological film covering the entire surface of the media. The biological film sloughs off whenever the biomass growth becomes too heavy on the media surface after reaching a critical thickness. The thickness of the biofilm is determined by many factors which are not yet completely understood. The sloughed biofilm and other suspended solids are carried away in wastewater and are removed in the secondary clarifier.

The RBC process has been extensively used at hundreds of locations in this country for treating municipal and industrial wastewater. Numerous reports in the literature and RBC facility surveys (29, 57, 121, 130, 131) have reported difficulties with the initial stages of RBC systems reflected by heavy biofilm growth, the presence of nuisance organisms such as Beggiatoa, and a reduction in organic removal rates. These problems have been attributed to excessive organic loadings that result in low dissolved oxygen conditions which subsequently lead to development of Beggiatoa growth deteriorating process efficiency. Beggiatoa organisms compete with heterotrophic organisms for oxygen and for space on RBC media surfaces. Their predominance can result in an increase in the concentration of biomass on the media while at the same time causing substantial reduction in organic removal per unit area.

A survey of 23 RBC installations (29) suggested that whenever the first-stage load exceeded 6.4 lbs of total BOD_5/day/1000 sq ft, the media surface was associated with the presence of sulfide oxidizing organisms. This loading should correspond approximately to a soluble BOD_5 loading in the range of 2.6 to 3.8 lb/day/1000 sq ft. A total of 45 RBC plants were included in an inventory and analysis study conducted by the EPA Region VII (130). Approximately half of the treatment plants in the EPA study have experienced a failure of some type due to high organic loadings and low dissolved oxygen conditions, predominantly relating to shaft or media. Beggiatoa growth was observed in several of these plants.

A recent nationwide RBC teleconference (131) publicized the results of the EPA study. A significant finding of the study was that the heavy biological growth due to high organic loadings and the corresponding low dissolved oxygen concentrations which lead to the development of heavy sulfide oxidizing organisms were in part responsible for the failure of shafts and media observed at a number of plants. The EPA study suggested that RBC plants should be designed with adequate flexibility, including wastewater recirculation, positively-controlled alternate flow systems, such as step feed or use of an enlarged first stage, supplemental aeration, and other such means of operating flexibility to optimize performance. To date, however, no RBC plant has been constructed with extensive step feeding facilities and relatively few plants have extensive operating data to quantify the significance of supplemental aeration. Consequently, a study was designed with the objective to better understand the effectiveness of the use of supplemental aeration and use of an enlarged first stage to improve the operational flexibility and performance of the RBCs.

OBJECTIVES AND SCOPE OF STUDY

In the EPA Region VII study (130) conducted in Iowa, it was observed that a number of RBC treatment plants were not in compliance with the state NPDES Discharge Permit. One such plant was that serving the city of Maquoketa, Iowa. Operated at flows of approximately 0.7 mgd and with only 68 percent of the design organic loading, the new 1.1 mgd RBC plant had difficulty consistently meeting its effluent standards. Upon review, it was found that the early stages of the RBC train were organically overloaded, had low dissolved oxygen concentrations and heavy Beggiatoa growth in all stages. The dissolved oxygen levels varied from 0.2 to 0.5 mg/L in stage 1 of the RBC unit and remained very low over most of the summer months.

It has been observed (131) that Beggiatoa growth is predominant whenever the soluble BOD_5 loadings in the first stage exceeded 2.5 lb/day/1000 sq ft, or when dissolved oxygen concentrations in the incoming wastewater were low. At higher organic loadings, zero-order kinetics have been found to prevail in the beginning RBC stages because of the oxygen-limiting conditions. Thus, at most of the observed RBC plants, available oxygen was the limiting factor and not the organic load in the incoming wastewater. The lack of adequate oxygen resulted in nuisance organism growth. Supplemental aeration can increase the dissolved oxygen levels in the early stages and also control the thickness of the biomass, thereby increasing the diffusion of substrate and oxygen into the biofilm. This would improve RBC performance and simultaneously eliminate the growth of undesirable Beggiatoa and other nuisance organisms (121, 122).

It is desirable to operate RBC plants with an enlarged first stage, particularly when the first stage is organically overloaded. Stepfeeding, or step aeration, as it is called when applied to activated sludge processes, is used extensively in activated sludge plants to improve the oxygen demand situation at the head end of treatment systems which would otherwise be organically overloaded. To avoid a high oxygen demand at the beginning end of an activated sludge aeration tank, the incoming wastewater is distributed along the aeration tank at several locations to result in a more even oxygen demand throughout the tank. Similarly, an enlarged first stage can be used effectively to avoid overloading the first stage of an RBC plant and to attenuate variations in wastewater characteristics, thereby eliminating oxygen-limiting conditions and the development of nuisance organisms (123). Fortunately, an enlarged first stage can be created simply by removal of the baffle between the first and second stages of RBC treatment.

The supplemental air and an enlarged first stage can be incorporated in the design of an RBC plant with little additional cost and these flexible operating tools could be used effectively in controlling the higher organic loadings, biofilm thickness, dissolved oxygen levels, and in improving RBC performance. Further, the elimination of Beggiatoa growth due to improved dissolved oxygen levels and a better distribution of biomass growth are expected to enhance both shaft and media life.

With the above considerations in mind, the specific objectives of this study were:

1. To investigate the effectiveness of supplemental aeration and an enlarged first stage in improving overloaded RBC performance.
2. To understand more clearly the relationship between variable organic loading rates, the dissolved oxygen levels, and biological growth kinetics.
3. To develop design and operational recommendations for future RBC plants.

To achieve these objectives, it was necessary to conduct the study in a treatment plant that had a minimum of two parallel RBC trains so that one train could be used as a control and the other train could be equipped and operated with supplemental aeration and an enlarged first stage. The Maquoketa RBC plant has two parallel RBC trains, with four stages in each train. Also, at the begining of this research program, it had heavy Beggiatoa growth in all stages, further indicating oxygen-limiting conditions due to organic overloading. The City agreed to use of this plan in the proposed study since, if successful, it would be possible to extend the treatment capacity of the Maquoketa RBC plant further into the future without costly modifications to the existing system.

LITERATURE REVIEW

Development of RBC

It is estimated that more than 550 RBC plants are presently used for industrial and municipal wastewater treatment in the United States (131). There are more than 3,000 RBC installations in the world, and the plants range from small to large multimillion gallon treatment facilities (59). Most of the plants in the United States are designed and used for organic carbon removal and a few for combined organic carbon and nitrogen removal (65). The first full-scale municipal RBC installation in the United States was in Pewaukee, Wisconsin (7) and the largest municipal RBC system is the 54 mgd plant at Alexandria, Virginia.

According to Hartman (54), the original thought which resulted in the development of the RBC process is due to the work of Travis in 1901. In his attempt to improve the performance of the hydrolytic tank, a precursor to the Imhoff tank, Travis placed thin wooden strips in the settling compartment of this system. He observed that solids accumulated on these wooden strips and sloughed off in the tank after reaching a critical thickness. The accumulated solids did not slough off very often, as assumed, due to the low velocities in the settling tank and so periodic manual cleaning of the solids from the wooden strips was necessary. Travis observed that whenever the wooden strips were clean, the effluent quality from the system improved. By 1916 Poujoulat (99) developed a treatment system which had a hollow cylinder made of brick which rotated about the horizontal axis. Wastewater was distributed by a perforated pipe which was located above the rotary brick.

Buswell (1929), observing the work of Travis, noted that the slime on the wooden strips was biological in nature and its removal was necessary to improve treatment performance. To get rid of the biological solids, Buswell and Pearson (24) experimented with shaking the wooden strips, and called this new system the Nidus Rack. Buswell's idea of mechanical moving led to the development of the biological wheel system. The Paige and Jones chemical company developed an experimental biological wheel unit which consisted of a series of paddle wheels that rotated partially submerged in a tank. Biological solids developed on the system when it was exposed alternately to atmosphere and wastewater in the tank. BOD removal in the system was observed to reach 80 percent. Buswell concluded that the advantages of this process were that the area required was 1/10 that of rock-filled trickling filters, the energy cost was low when compared to the activated sludge processes, and nitrification could be accomplished with this process.

In 1927 Hays cited in Steel (114) tried to improve on the work of Travis. He thought that decomposition of solids deposited on the wooden slats could be eliminated by providing an air diffuser under the wooden slats. The process was called contact aeration, and was known as an immersion-drip filter in Europe. In 1929, Doman (38) developed a system similar to current plastic-media RBCs but made from galvanized steel plates which rotated in the wastewater partially submerged. It was called a contact filter. In the beginning, sulfide generation reduced the removal rates, but subsequent step aeration (stepfeeding) of the influent wastewater increased the removal rates. The organic loading, biofilm thickness and hydraulic detention time were observed to be 1.0 lb BOD_5/day/1000 sq ft, 0.03 inch and 2.4 hours, respectively. However, the process generated little attention until Hartman (54) reported the results of his experimental study in 1960.

In 1952, Gloyna et al. (49) experimented with a rotating tube reactor that had similarities to the RBC. Many advantages of the system were emphasized, but no attempt was made to develop the concept.

In 1958, Hartman (54) made an attempt to experiment with the forgotten rotating biological contactor process. He concluded, after experiments with so-called immersion-drip filters that: the optimum range of rotational velocity for his 3-ft disks was from five to seven rpm; the disks should be submerged as deep as possible but the drive shaft should be above the wastewater surface; the spacing between two disk plates should be at least 0.50 inch so that the wastewater can flow through uninterrupted; the disks should be rotated in the direction of the wastewater flow; staging was not necessary to improve performance but will simplify construction; the system was not sensitive to either organic or hydraulic shock loadings; and finally, the operation and maintenance costs were lower when compared to activated sludge and trickling filter systems.

Since the Hartman study was based on small-scale units, Popel (98) conducted a two-year study in 1963 to investigate full-scale RBC performance. His findings were: the process is a completely mixed system; the process removed certain amounts of pollutants because of adsorption irrespective of concentration; and the system was insensitive to shock loadings because of the large adsorption and storage capacity of the biological slime. The Popel and Hartman studies led to the development and manufacture of full-scale RBCs. Subsequently, the J. Conrad Stengelin company manufactured six- and nine-foot diameter plastic disks for small-flow commercial use, which made the process popular in Europe.

As the development of RBCs and their commercial use was taking place in Europe, simultaneous research at Allis Chambers in the United States led to the development of a two-phase RBC to be used for industrial waste treatment. An experimental study in 1965 with 3-foot diameter disks at the Jones Island Treatment Facility, and additional studies with aluminum disks, suggested that RBCs had excellent potential for wastewater treatment in the United States. Subsequent agreement between the Stengelin and Allis Chambers companies led to the commercial marketing of RBCs in the United States (10). In 1970 Allis Chambers was purchased by the Autotrol Corporation which developed a corrugated polyethylene disk media in 1972. The development of this new media increased tremendously the surface area available per unit volume of media. The reduced costs in construction due to the development of the new media further made the RBC process a viable cost-effective alternative for wastewater treatment in the United States. At present, several manufacturers are supplying RBC equipment for municipal and industrial wastewater treatment.

Attached Biofilm Growth and Characteristics

In the primary biofilm forming period, several processes might contribute to an overall biofilm development (128) such as: adsorption of organics; attachment of microorganisms to the media surface; growth of attached microorganisms; transport of microbial particles to the surface; and biofilm re-entrainment by fluid shear. It has been reported that electrostatic attractions, hydrophobic interactions, van der Waals forces and Brownian motion all affect the attachment of microorganisms to the media surfaces (81). Following attachment the microorganisms will establish contact with the substrate by means of extracellular polymers (25, 26, 81). Subsequently, temporary or permanent adhesion might take place with or without chemical affinity (26, 81). According to Atkinson and Howell (12), three basic types of biofilms exist on fixed media surfaces and these are shown in Figure 1.

Once a monolayer of microorganisms has covered the surface, growth and further attachment of microorganisms increases the thickness of the biofilm. The growth rate of microorganisms can be described by the Monod equation (84) which is as follows:

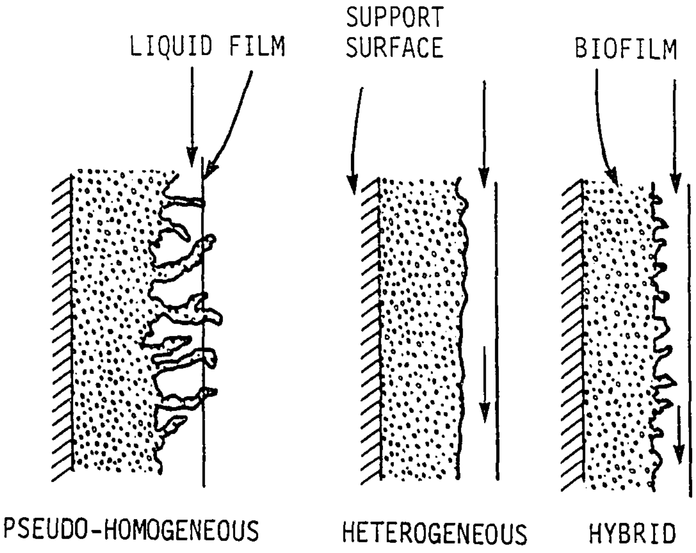


Figure 1. Types of bacterial films (12)

$$\mu = \mu_{max} \frac{S}{K_s + S} \qquad (1)$$

where μ = specific growth rate (T^{-1})

μ_{max} = maximum specific growth rate (T^{-1})

S = limiting substrate concentration (ML^{-3})

K_s = saturation constant (ML^{-3})

Monod's equation was developed empirically and has been used extensively for describing both substrate utilization and the bacterial growth rate.

Depending upon the relative concentrations of substrate and the saturation constant, the Monod kinetics can be described by pseudo-first or pseudo-zero order with respect to S. When the substrate concentration is much less than the saturation constant, the kinetics are considered first order. When the substrate concentration is much greater than the saturation constant, the kinetics are considered to be zero order. Both μ_{max} and K_s vary depending upon the characteristics of substrate and bacterial culture.

Further, the substrate utilization rate and growth rate are related by introducing a microbial decay and yield constant (75) which is as follows:

$$\frac{dX}{dt} = Y\left(-\frac{dS}{dt}\right) - K_d X \qquad (2)$$

$$-\frac{dS}{dt} = \frac{k\ X\ S}{K_s + S} \qquad (3)$$

where X = microorganisms concentration (ML^{-3})

Y = growth yield coefficient

K_d = microorganism decay constant (T^{-1})

k = maximum substrate utilization rate (T^{-1})

Nitrification has been studied by many and Monod equations have been used successfully in describing RBC nitrification kinetics. The rate of nitrification in RBCs is reported to follow zero order to first order kinetics (8, 10, 62, 85, 107).

The simple reactions below will describe the ammonia nitrification by nitrifying organisms:

$$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + H_2O + 2H^+ \qquad (4)$$

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^- \qquad (5)$$

Ammonia is oxidized to nitrite by nitrosomonas organisms and nitrite is oxidized to nitrate by nitrobacter organisms under aerobic conditions. It can be seen that the nitrification process reduces the alkalinity of wastewater because of acid production. Approximately 7.14 mg/L of alkalinity is destroyed for each mg/L of ammonia oxidized. Based on the above reactions, theoretically 4.57 mg/L of oxygen is required for complete oxidation of 1 mg/L of ammonia to nitrate nitrogen. The biomass yield due to nitrification of ammonia is quite small when compared to biomass yield due to carbon removal by heterotrophs. The total yield for both nitrosomonas and nitrobacter has been observed to be in the range of 0.06 - 0.20 lb/lb NH_3-N (129).

Because of the low concentrations of nitrite in the wastewater, it is assumed that the oxidation of ammonia to nitrite is the rate-limiting reaction in nitrification. This fact is supported by the higher growth rates for nitrobacter than the growth rates for nitrosomonas (90, 129).

Microorganisms on the biofilm surface could be detached from the surface due to the shearing effect of the passing wastewater stream. A net increase in the thickness of the biofilm continues as long as the adhesive force between the microorganisms is greater than the passing stream shear force. It was observed by Heukelekian (56) and Sanders (108) that, in spite of higher shear forces, the biofilm thickness increased when the velocities across the film surface were higher. This could be due to better diffusion of substrate and oxygen from the bulk liquid into the biofilm. Characklis (25) reported that biofilms grown at higher velocities could withstand higher shear forces and adhered more firmly to the surface.

Several microbiological studies (3, 59, 94, 100, 123) of RBC biofilms indicated that the microbial population tends to differ from stage to stage. The microbial population color in RBCs changes rapidly from thick gray or black filamentous organisms in the beginning stages to a brownish tan growth in the subsequent stages, followed by patchy growth in the last stages. The growth on the first few stages was predominantly filamentous, comprising organisms such as sphaerotilus and the autotrophic sulfur bacteria Beggiatoa. The growth of Beggiatoa is usually observed when the RBCs are organically overloaded and/or when the dissolved oxygen concentration in the wastewater is low. A study of RBC filamentous growth by Alleman et al. (1) concluded that a stratification in the biofilm exists under such growth conditions and the appearance of dense filamentous growth in the outer layer is mainly Beggiatoa. The brownish tan growth identified in the subsequent stages was believed to be nitrifiers. In the last stages of the RBCs, the growth of rotifiers, stalked ciliates, nematodes and fungi was predominant.

A recent study of RBC biofilms reported by Kinner et al. (69) suggests that the surface biofilm in the first stages was gray-brown and filamentous and the subsurface layer composition was black. An electron microscope study confirmed the presence of filamentous and non-filamentous single cell bacteria. The predominant filaments were found to be a species of sphaerotilus. Even under low dissolved oxygen concentrations, the sphaerotilus-based biofilms were believed to contribute significantly to organic carbon removal. The high removal efficiencies in RBCs, when compared to activated sludge, were due to the logical succession of specialized microorganisms that are required in various stages to utilize the substrate composition that is changing with treatment from stage to stage (20, 81, 126).

In an RBC study (89) using primary municipal wastewater, it was reported that the chemical composition of the biofilm is made up of 35.2 to 39.1 percent carbon, 5.8 to 6.9 percent nitrogen, 5.4 to 6.7 percent hydrogen, 21.4 to 25.1 percent oxygen, and 23.7 to 32.2 percent ash. An RBC performance study (83) using cheese processing wastewater reported a nitrogen content of 6 to 8 percent for biofilm in the beginning stages and 2 to 5 percent in the remaining stages. The nitrogen content percentages were based on total suspended solids using a four stage RBC. Kornegay and Andrews (73) in a fixed-film kinetic study reported carbon, nitrogen and hydrogen percentages of 42.8, 9.95 and 7.6, respectively, based on the volatile suspended solids.

The concentration of the attached biomass can be measured by scraping the biomass from a known area of the media surface. Total solids concentrations in the range of 100,000 mg/L and higher have been observed (21). However, the volatile solids concentrations were observed to be low because of internal digestion within the biofilm.

Relatively few studies have been conducted on factors affecting the detachment and decay of the biofilm. Biofilm usually sloughs off periodically, however, reattachment of sloughed-off biofilm does not seem to happen due to its own weight. Generally, the biofilm thickness will increase as long as the rate of growth exceeds the rate of loss by decay and detachment. It was observed that in highly turbulent reactors, the biofilm detachment was usually constant because of the increased shear stress at the interface (128). Further, the biofilm detachment rate increased as the shear stress and biofilm mass increased. A steady state biofilm development is possible due to the availability of low substrate concentrations which could balance the growth and decay rate. Hoehn and Ray (60) explained that biofilm detachment could be due to substrate depletion at the biofilm media interface. Characklis and Trulear (26) suggested that biofilm detachment was caused by the shearing forces, starvation and anaerobic conditions within the biofilm.

Active Biofilm Thickness

Biofilm thickness is of great importance in the RBC process, thus, a distinction must be made between the total film thickness and the active film thickness. A measurement of biofilm thickness in several studies suggested that total film thickness varies from 0.07 mm to 4.0 mm depending on the hydrodynamic conditions (11). However, it has been observed that biofilm thickness rarely exceeds 1 mm in turbulent systems (27). Substrate removal rates within the thicker biofilms are not likely to be greater than in thin films due to the diffusional resistances within the biofilm (23, 43, 50, 60, 73, 108). The active portion of the biofilm that is contributing to substrate removal has been called the active biofilm thickness. The active biofilm thickness has been estimated by several investigators to be between 20 and 600 μm.

The earliest observations of substrate removal as the biofilm thickness increased indicate that the rate of substrate utilization increased as the biofilm thickness increased up to a thickness of 70 - 100 μm, after which any increase in biofilm thickness did not increase further the substrate removal rate (73, 125). These investigators defined the active biofilm thickness as that thickness beyond which the substrate removal rate became constant after reaching a maximum value. In other words, the active film thickness is that thickness at which the substrate removal rate becomes independent of biofilm thickness (72). Trulear and Characklis (128) observed that at a certain biofilm thickness the substrate removal rate reaches a steady state value and they defined this thickness as the active biofilm thickness. However, they reported that the active film thickness increased as the substrate concentration increased. They concluded that the observed increase in thickness probably will cease when the substrate or oxygen diffusion becomes limiting. Others defined active film thickness as one at which the substrate penetration becomes limiting (61).

Subsequent microprobe studies by Bungay et al. (23) to determine the oxygen profiles within the biofilms indicated that respiration ceased at depths of 50 - 150 μm, depending upon the substrate concentrations. This further suggests that substrate removal is only caused by the microorganisms within the active biofilm layer. Similar observations have been made by others (28, 60) as shown in Figure 2. However, these authors have indicated that active biofilm thickness could be due to depletion of either the substrate or the oxygen within the biofilm. Sanders (108) in a study of bacterial slimes observed that the active film thickness was found to be 21.2 μm and he related this limiting thickness to diffusion of oxygen. It is now generally believed that the active biofilm thickness is a result of oxygen and/or substrate transport or diffusional limitations within the biomass. Most of the studies conclude that due to diffusional limitations of oxygen or substrate, there exists an active film thickness, at which substrate removal rates become maximum and beyond that active thickness the removal rates become constant.

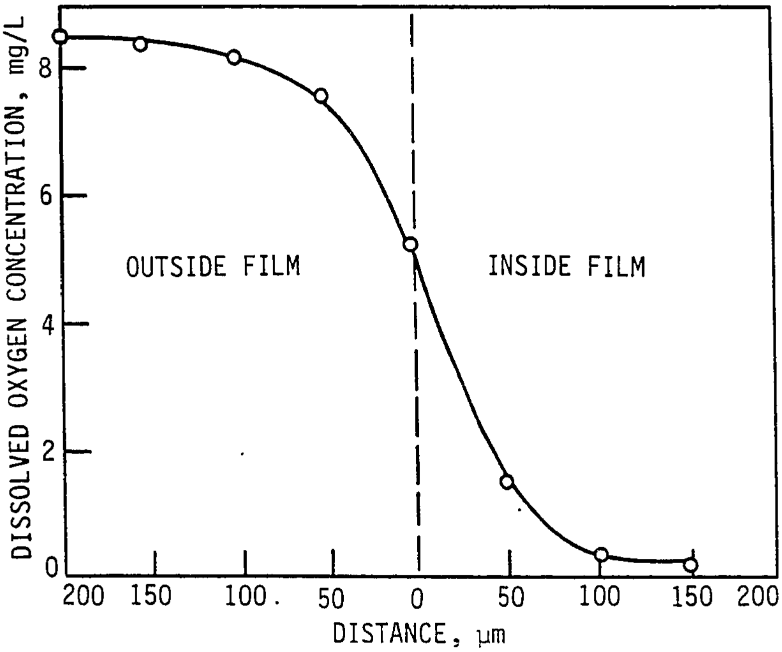


Figure 2. Dissolved oxygen profile through a biofilm (28)

Significance of Dissolved Oxygen

The importance of dissolved oxygen in aerobic wastewater treatment has been stressed in the past as it could be a major factor in a process failure. Activated sludge, trickling filter, rotating biological contactor, aerated stabilization ponds and other aerobic processes depend on the availability of sufficient quantities of oxygen for proper biological performance. In the RBC process, the level of available dissolved oxygen has an important role among the several operational variables which affect process performance. Several researchers have noted the necessity of maintaining a minimum level of dissolved oxygen of 2 mg/L to retain process performance (21, 30, 44, 58, 133).

Ohgaki et al. (86) developed a mathematical relationship between the substrate removal rate and the oxygen consumption rate. They found that the substrate removal rate was dependent upon the substrate concentration and substrate loading rate. They also found that the oxygen consumption rate had a linear relationship with the substrate removal rate. However, they observed that there was no relationship between the oxygen consumption rate and the hydraulic residence time. Whalen et al. (135) observed that the oxygen concentration within a biofilm is a function of substrate concentration in the bulk liquid. They found that the overall reaction rate was limited by the substrate when the substrate concentration was low. However, the availability of oxygen controlled the overall reaction rate when the substrate concentration was high. Howell and Atkinson (61) incorporated the effect of oxygen as a possible limiting reactant in a multi-substrate biofilm system. They observed that the overall reaction rate depends on both the substrate and oxygen concentration within a limited concentration range. Bungay et al. (23) further revealed that oxygen concentrations within the biofilm were functions of the nutrient concentrations within the bulk liquid. Reaction rates within the biofilm were found to be affected by both the oxygen and nutrient concentrations. Steiner (115) indicated that proper concentrations of dissolved oxygen in the RBC process are as important as the proper nutrient balance.

Welch (133) reported that the dissolved oxygen level in RBCs was as important as in activated sludge. As shown in Figure 3, he observed that COD removal efficiency declined considerably when the bulk liquid dissolved oxygen dropped below 1.5 mg/L. In this study, the wastewater concentration was 300 mg/L with a hydraulic residence time of 30 minutes. Weng and Molof (134) also indicated that an RBC process efficiency depended upon the dissolved oxygen concentrations.

A study by Torpey et al. (126, 127) using ten-stage, 3-ft. diameter disks reported that the dissolved oxygen was less than 1 mg/L or absent in the first two stages. However, the dissolved oxygen level improved in the subsequent stages, reaching a maximum of 6 mg/L in stage 10. These authors tried to improve the efficiency of the oxygen-deficient first stage by providing oxygen-enriched air. Their results indicated a 50 % improvement in the first stage efficiency. Similar observations were made by Bintanja et al. (17) in their study of enclosed oxygen RBC systems. The treatment efficiencies with and

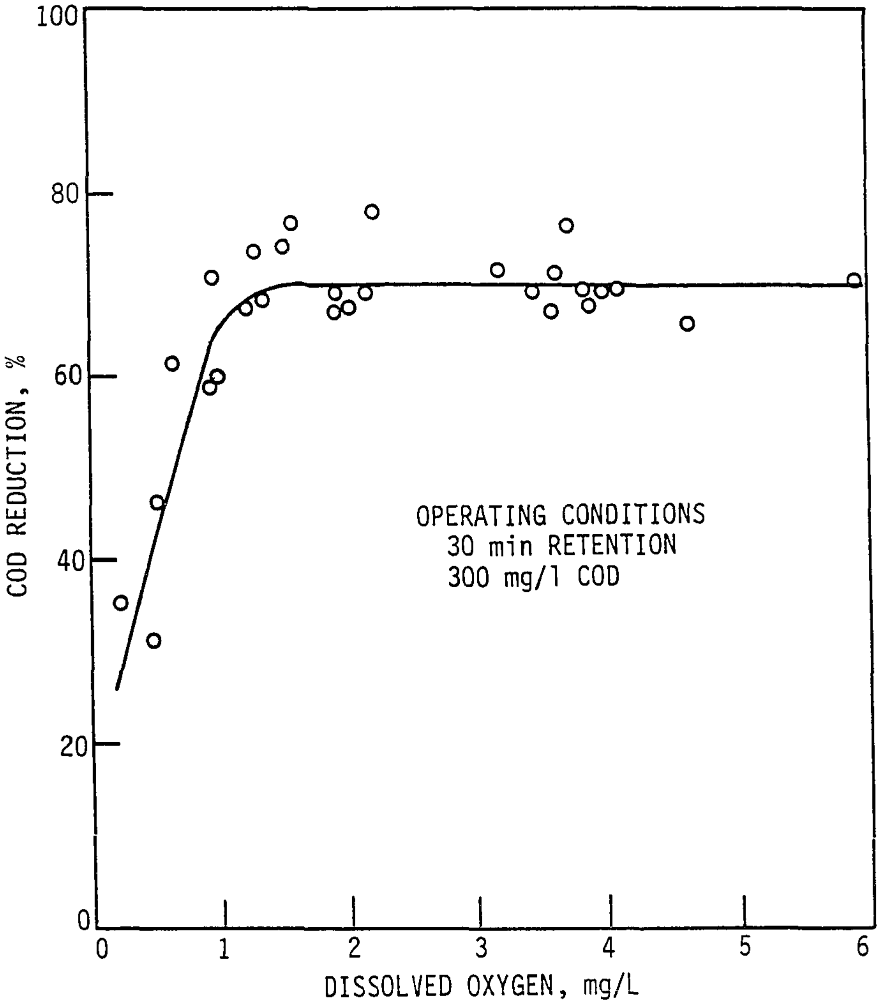


Figure 3. Dissolved oxygen effect on COD removal efficiency (133)

without oxygen enriched air were 64 % and 34 %, respectively. The COD concentration of feed wastewater in the study was approximately 800 mg/L.

Chittenden and Wells (32) conducted a study using three-stage, 4-ft. diameter disks for the treatment of beef processing waste pretreated by anaerobic lagoons. At a loading rate of 8 gpd/ft^2 and a disk speed of 3 rpm, the BOD removal efficiency for the first stage was 42.5 % and over 3 stages was 50.2 %. Dissolved oxygen was absent in all stages. Filamentous growth was predominant in the first stage made up of Sphaerotilus, Beggiatoa and zoogloea. The growth became heavier, particularly at higher loadings. When the loading rate was reduced to 4 gpd/ft^2, the dissolved oxygen levels in the first stage increased to 1.5 mg/L. The increased dissolved oxygen levels in the first stage improved the BOD removal efficiency in the first stage to 79.5 percent and 83.2 percent overall. They observed that at higher loadings, the BOD removal efficiencies were limited by the oxygen-limiting conditions. It was reported that the dissolved oxygen concentration in a pilot-scale reactor dropped below 0.5 mg/L when the organic loading rate exceeded 14.7 g SBOD$_5$/day/m^2 (3.01 lb/day/1000 sq ft) to the first stage (19). When the organic loadings to the first stage exceeded 29.4 g SBOD$_5$/day/m^2 (6.02 lb/day/1000 sq ft), dissolved oxygen was not detectable in the first stage.

Hitdlebaugh et al. (57) reported that an RBC facility designed for carbonaceous BOD removal and nitrification failed to meet design effluent limits during both winter and summer operations. The effluent limit violations in the summer were attributed to the low DO levels experienced, less than 1 mg/L. However, the dissolved oxygen levels increased during the winter operations, contributing to sufficient carbonaceous BOD removal to achieve design expectations. Nitrification rates also improved during winter operations but not sufficiently to achieve design effluent limits. The initial stages of RBCs had heavy Beggiatoa growth. They concluded that low dissolved oxygen concentrations in the initial stages adversely affected both BOD removal and nitrification. They recommended that supplemental aeration be used to overcome dissolved oxygen limiting conditions. The increased carbonaceous and nitrification removal rates during winter operation was attributed to increasing dissolved oxygen saturation values with decreasing temperature, which promotes increased oxygen transfer (102, 121).

The growth of Beggiatoa often suggests oxygen-limiting conditions. The low dissolved oxygen levels at higher loadings promote sulfide production within a thick biofilm which enhances the growth of sulfide-oxidizing organisms such as Beggiatoa (1). Beggiatoa can also grow on sulfide present in the influent wastewater. Beggiatoa, whitish autotrophic sulfur bacteria, utilize hydrogen sulfide and sulfur as energy sources in the presence of oxygen. These sulfide-using organisms compete with heterotrophic organisms for the available oxygen and for space on the RBC media surface. Their predominance can result in an increase in the concentration or thickness of biomass on an RBC unit while at the same time causing a substantial reduction in organic removal. A survey of 23 RBC installations by Chesner and Iannone (29) suggested that the presence of sulfide-oxidizing organisms was related to overloading caused by a high hydraulic loading or high influent BOD concentrations. As can be seen in Figure 4, the growth of Beggiatoa was observed whenever the first stage total BOD_5 loading exceeded about 6.4 lb/day/1000 sq ft, which corresponds approximately to a soluble BOD_5 of 2.6 lb/day/1000 sq ft. Several other investigations indicated similar problems (57, 121, 130, 131).

In a study of a 36-shaft RBC plant consisting of six trains or rows of six shafts each, Albert (2) observed 96 % and 86 % removals of soluble BOD_5 and ammonia nitrogen, respectively, when supplemental air was applied. The dissolved oxygen in all stages never dropped below 1.5 mg/L. The growth of Beggiatoa was eliminated with the exception of sparse growth on the media of the first stage. It is suggested that for complete inhibition of Beggiatoa growth, the inner anaerobic layers that are the source of sulfide should be removed from the media surface prior to the use of supplemental aeration (93). Prior to the addition of supplemental air, the dissolved oxygen concentrations in the first four stages were measured at less than 1 mg/L and Beggiatoa growth was predominant. Without supplemental air, soluble BOD_5 removals of only 75 % were common and only about 60 % nitrification was achieved. Albert concluded that the supplemental air eliminated the Beggiatoa growth and enhanced $SBOD_5$ and NH_3-N removals.

The level of dissolved oxygen is also an important consideration in the RBC nitrification process as aerobic nitrifying organisms are

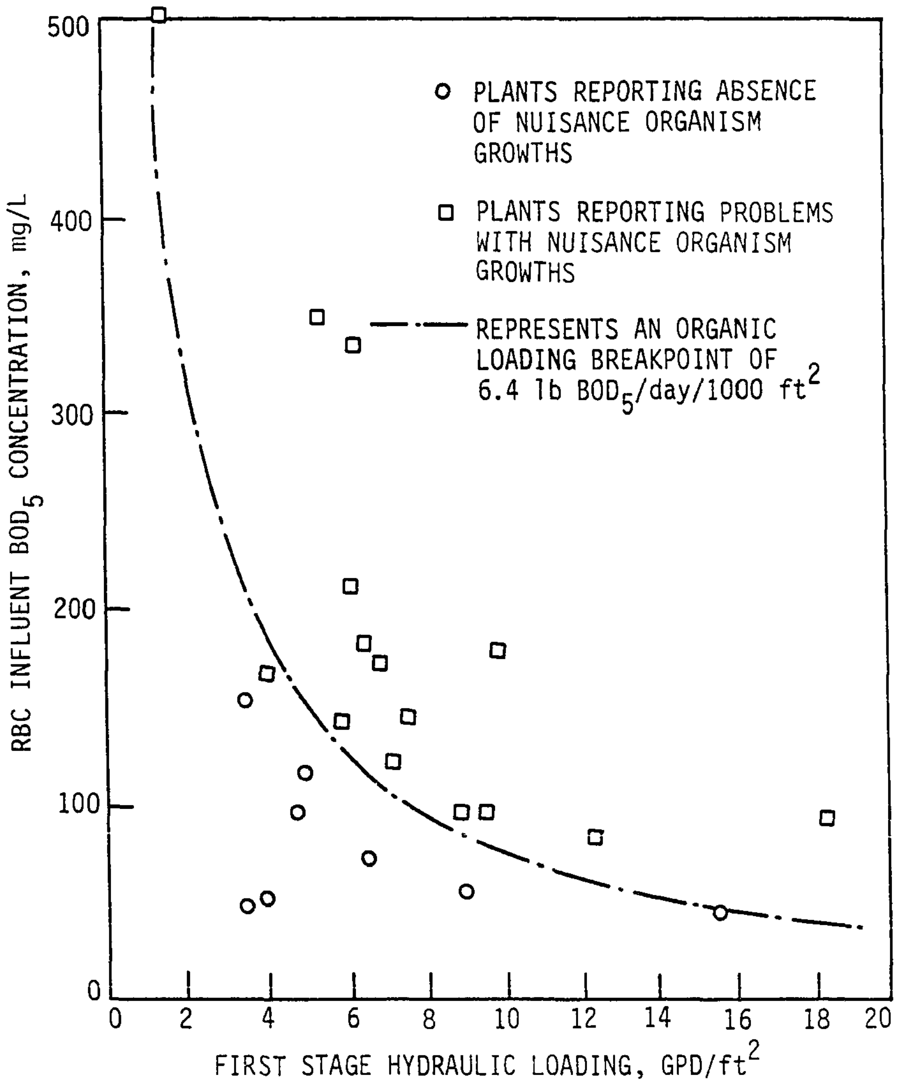


Figure 4. Dissolved oxygen limiting conditions related to influent organic concentration and hydraulic loading (29)

considered to be more sensitive to dissolved oxygen levels than the heterotrophic organisms. The literature reported minimum DO levels needed for nitrification vary from 0.5 - 4.0 mg/L, however, a minimum DO level of 2 mg/L is often quoted (4, 90, 131). But, cases can be found in the literature in which only 40 to 90 percent nitrification was achieved at a DO level of 2 mg/L (129, 132, 142). Wuhrmann (142) reported poor nitrification in a treatment plant when the DO was 1 mg/L and a high degree of nitrification when the DO was increased to 4 mg/L. Wild et al. (139) observed some degree of nitrification at oxygen levels greater than 1.0 mg/L, while Downing and Bayley (39) suggested 0.5 mg/L as a lower oxygen limit for nitrification. Haug and McCarty (55) reported that increasing oxygen levels up to 60 mg/L did not affect the nitrification in the submerged filter. Downing and Bayley (39) indicated that when the DO exceeds 1 mg/L, it would not affect the nitrification process.

Nitrification of trickling filter effluent by a six-stage RBC unit with 4-ft diameter disks showed that a DO level of at least 3.5 mg/L was necessary in the first three stages to prevent retardation of oxygen uptake rates (21). A study at Indianapolis (103) revealed that high DO concentrations at the effluent end of an RBC unit combined with very low soluble BODs reduced nitrification rates because of bacterial predators which ingested nitrifying organisms. Recirculation of primary effluent retarded the predatory activity and nitrification rates increased subsequently. A full-scale RBC system designed for combined carbon oxidation and nitrification showed that nitrification increased 50 percent when the DO range increased from a level of 1.3 - 3.2 to a level of 3.5 - 4.8 mg/L (58).

Several authors (2, 74, 82, 112, 121) have recently suggested the use of supplemental aeration to relieve operational problems. The reported benefits included:

1. Elimination of Beggiatoa growth
2. Production of thinner biofilms on the media
3. Increasing dissolved oxygen levels
4. Providing higher soluble BOD_5 removal rates
5. Providing higher NH_3-N removal rates, and
6. Enhancing shaft and media life.

Other alternatives suggested (131) for increasing the dissolved oxygen levels in the RBC systems were: recirculation of RBC effluent and step feeding or use of an enlarged first stage for load distribution. However, no in-depth study on supplemental aeration and step feeding or use of an enlarged first stage has been made to date.

Operating Experiences

Many authors (3, 6, 18, 67, 101) report excellent performance of RBCs in municipal and industrial wastewater treatment. The rotating biological contactors have many advantages (7, 10, 20, 88) such as: low power consumption; low hydraulic detention time; low headloss; no short circuiting; stability to shock loads; relatively high treatment efficiency; and simple and stable operation. It has been reported that power consumption using an RBC process is approximately 50 percent less than that of the activated sludge process (36, 110).

The first full-scale RBC plant to treat domestic wastewater in the United States was built in Pewaukee, Wisconsin (7). The plant was operated under various loading conditions. The operating results from this plant indicated fluctuations in the effluent BOD whenever there were fluctuations in the influent BOD. At low hydraulic rates, BOD removal was 91 percent, however, the BOD removal decreased to 85 percent at higher loading rates. Temperature effects on BOD removal were found to be insignificant. Nitrification was observed when the BOD concentration in a stage dropped below 30 mg/L. The hydraulic loading rates at this plant varied between 0.5 and 2.8 gpd/sq ft.

Malhotra et al. (80) reported on the performance of a full-scale RBC plant treating municipal wastewater. The plant capacity was 1 mgd and had six stages. The mean operating results indicated a BOD_5 removal of 86.9 percent. The mean RBC influent hydraulic loading rate and BOD_5 concentration were 1.52 gpd/sq ft and 114 mg/L, respectively. Alum and polymer were used in the final clarifier to create better settling conditions. The ratio of particulate BOD_5 to SS indicated stabilization of sloughed biomass even though the SS concentration did not change from stage to stage. The mean operating temperature of the plant was 55°F.

Dupont and McKinney (40) investigated the performance of a 5 mgd, six-stage, full-scale RBC plant treating municipal wastewater. At a hydraulic loading rate of 1.3 gpd/sq ft, and an influent BOD_5

concentration of 192 mg/L, the overall BOD_5 removal was found to be approximately 90 percent. It was observed that when the influent BOD_5 concentrations increased, the BOD_5 removal also increased to 94 percent, however, the hydraulic loadings were found to be the same and remained constant over the period of increased BOD_5 concentration. However, at higher hydraulic loading rates the treatment efficiency was reduced due to less contact time and surges on the final clarifiers.

Pretorius (100) used an RBC pilot plant to treat anaerobic digester effluent. The bench-scale unit consisted of nine stages with disk diameters of 40 cm. The results indicated that the rate of COD removal was 12.7 g/day/m^2 (2.6 lb/day/1000 sq ft). Pretorious also expressed this COD removal in terms of unit biomass as 0.49 g COD removed per gram of attached biomass. The maximum attached biomass observed on the disks was 45 g/m^2. First stage COD removal was approximately 44 percent, based on COD concentrations.

Gillespie et al. (47) studied the effect of organic shock loadings on RBC performance. Their results indicate that organic shock load, not coupled with hydraulic shock load, will have great capacity to deteriorate effluent quality. Similar studies were also conducted by Stover and Kincannon (117). These authors investigated the effect of organic shock loads two to four times the normal loading rate using synthetic wastewater. They observed increased levels of COD and ammonia nitrogren concentrations in the effluent. Dupont and McKinney (40) made similar observations during one particular operation period when the influent BOD_5 concentration was very high.

Several investigators have studied the effect of varying flow rates on RBC performance. Popel (98) observed the effect of hydraulic shock lasting 2.5 hours which was equal to four times the normal flow. He indicated that the BOD removal efficiency increased during the 2.5 hour surge. However, when the hydraulic shock duration was increased up to five hours, the BOD removal efficiency deteriorated. Gillespie et al. (47) also investigated the effect of hydraulic surge for four hours at four times the normal flow rate. The BOD_5 removal decreased from 70 percent to 30 percent within three hours of the surge. However, the BOD_5 removal efficiencies returned to 70 percent within three hours after termination of the hydraulic surge. It seems that a hydraulic surge effect is minimal when the detention time in the RBC system exceeds the surge duration.

Antonie (4) investigated the responses of RBC units under unsteady flow conditions such as intermittent flow, varying flow, and hydraulic surges using dairy-based synthetic wastewater. Overnight flow reduction to zero required a four-hour recovery period to attain steady state COD removal with return of the normal daytime flow rate. He observed that the overall organic removal remained constant over the varying flow condition, even though results indicated a high percent removal at high flow and a low percent removal at low flow. However, Borchardt et al. (21) made a different observation in RBC nitrification. These authors indicated that part of the hydraulic surge will be dampened in the RBC unit and the surge not dampened will pass on to the effluent.

Pilot study results using a four-stage RBC unit reported by Hao and Hendricks (51, 52) indicated that BOD removal varied between 83 to 94 percent at a hydraulic loading rate of 2.5 gpd/sq ft. As the flow rate was increased, there was no significant effect on BOD removal but nitrification efficiency decreased. The RBC nitrification efficiency was 92 percent at a flow rate of 1.5 gpd/sq ft but was reduced to 53 percent at 2.5 gpd/sq ft. In a six-stage, 2-ft diameter RBC unit, approximately 100 percent ammonia nitrogen removal was achieved by Stover and Kincannon (116). The hydraulic flow rate was 0.5 gpd/sq ft with a COD concentration of 250 mg/L and an ammonia nitrogen concentration of 27.6 mg/L.

Given (48) used a five-stage pilot RBC unit to treat dilute primary effluent waste with a BOD_5 concentration range of 11 to 34 mg/L and obtained an overall BOD_5 removal of 92 percent at a flow rate of 1.38 gpd/sq ft. At a flow rate of 6.0 gpd/sq ft, the BOD_5 removal decreased to 50 percent. In an RBC pilot plant study treating cheese processing waste, Mikula et al. (83) observed 88 percent COD removal at a hydraulic loading rate of 0.3 gpd/sq ft. The COD removal decreased to 71 percent at a hydraulic loading rate of 0.69 gpd/sq ft. Banerji (15) found a linear relationship between BOD_5 removal and hydraulic loading rate while analyzing the results obtained from a four-stage RBC unit treating industrial wastewater.

The rotational speed is one of the controllable operational variables in the RBC process. Friedman et al. (46) reported that increasing the rpm resulted in increased COD removal rates in the first stage of an eight-stage RBC pilot plant. Overall COD removal rates were not affected by increased rpm. However, the overall COD removal rates for the entire RBC system were directly related to the total organic loading rate. These authors noted that increasing rpm was important under high organic loading conditions but increased speed was not beneficial at low organic loadings.

Antonie (10) and Antonie et al. (7) indicated that BOD removal is enhanced with increased rpm to a certain degree beyond which further increase in rpm will not increase BOD removal. Based on their pilot plant studies, they suggested a peripheral velocity of 60 ft/min to obtain optimum BOD removal. Poon et al. (96) claimed that peripheral speeds ranging from 36 to 69.5 ft/min had no impact on RBC performance. The study was based on a four-stage, 1.6-ft diameter RBC pilot unit. Lue-Hing et al. (78) reported that nitrification rates were not significantly affected when rotational speed was changed from 3 to 13 rpm.

Klemetson and Lang (71) investigated the effect of treating diluted seawater on the RBC nitrification performance. Their results indicated that to obtain the same effluent ammonia concentration, the influent ammonia load must be lower when treating a 10 percent dilution of seawater waste than when treating a fresh water waste. Lawton and Eggert (76) investigated the effect of salt concentration on biofilm performance. They observed that organic removal efficiency deteriorated when the sodium chloride concentration exceeded about 20,000 mg/L. However, the system performance recovered within a day when the salt concentrations were reduced. A similar decline in organic removal efficiency was observed when the feed wastewater had a ferric chloride concentration of 100 to 250 mg/L (13). The efficiency decreased as the ferric chloride concentration was increased. Results from an RBC pilot plant study treating different industrial processing wastes indicated BOD_5 removals of 71 to 98 percent (6).

Ellis and Banga (42) studied the effect of effluent recycling on RBC performance when treating municipal wastewater. They found that an effluent recycle at 1:1 ratio had no effect on carbon or ammonia nitrogen removal. Lue-Hing et al. (78) tried to improve RBC nitrification by recycling the clarified effluent. Their results indicated that effluent recycling had minimal impact on nitrification performance. With sludge recirculation, Huang (63) observed a 16 percent increase in ammonia nitrogen removal. Ito and Matsuo (66) reported that effluent recycle to the first stage initiated denitrification under high organic loading conditions and simultaneously improved the RBC nitrogen removal efficiency.

The temperature effects on RBC performance are similar to those reported for other biological treatment processes (7, 25). Antonie (10) evaluated the performance of several RBC plants and concluded that organic removal efficiency was not affected by wastewater temperatures above 55°F, however, performance deteriorated at lower temperatures. It is commonly accepted that decreasing wastewater temperature affects nitrification efficiency significantly but different opinions exist concerning the range of temperature impact.

Past and present energy conservation measures have resulted in the utilization of RBC treatment plants for the nitrification of secondary wastewater effluents. Ammonia nitrogen removal rates in the range of 0.3 to 0.35 lb/day/1000 sq ft have been observed for full-scale RBC units (14) but higher nitrification rates have been reported in pilot-scale studies. Borchardt et al. (21) observed ammonia removal rates as high as 0.74 to 0.78 lb/day/1000 sq ft. Pano et al. (91) showed that nitrification rates of 0.45 to 0.68 lb NH_3-N/day/1000 sq ft can be achieved. With pH control, Stratta and Long (120) achieved nitrification rates of 0.52 to 0.62 lb NH_3-N/day/1000 sq ft. Crawford (35) attained a maximum nitrification rate of 0.50 lb/day/1000 sq ft. Higher nitrification rates in pilot RBC studies were due to scale-up factors which will be discussed further in a subsequent design section.

Based on data gathered from ten RBC installations, Antonie (9) developed curves showing percent ammonia removal for various hydraulic loading rates and influent BOD concentrations. For an influent BOD_5 concentration of 150 mg/L, he suggested a hydraulic loading rate of 1.9 gpd/sq ft to achieve 90 percent nitrification. Temperatures above 13°C were considered to have no significant effect on nitrification.

Wild et al. (139) reported that nitrification removal rates did not deteriorate under high organic shock loadings. However, many investigators have indicated that there is a limiting organic loading rate above which nitrification is significantly reduced. Ito and Matsuo (66) reported that nitrification could not proceed when the COD loading exceeded 20 g COD/day/m^2 (4.1 lb/day/1000 ft^2). Pano and

Middlebrooks (92) concluded that nitrification inhibition in the first stage was proportional to the organic loading rate. They observed overall ammonia removal of 87 to 98 percent at 15°C and no ammonia removal at 5°C.

Wastewater pH has significant effects on nitrification rates. The optimum pH reported for nitrification varies between a range of 7 to 9. However, it has been reported that nitrifying bacteria can acclimate to a new pH environment over a period of time. Haug and McCarty (55) showed that nitrification rates were the same at pH 6.0 and 7.0, after ten days of acclimation, but no acclimation resulted at pH levels below 6.0. Poduska (97) made similar observations. When he reduced the pH from 7.2 to 6.4, there was no significant affect on nitrification rates, however, nitrification rates decreased at pH 5.8.

Current Design Approaches and Models

The substrate removal mechanism within a fixed-film process is very complex. The phenomena that take place when a fixed-film is brought into contact with a wastewater containing substrate and oxygen are as follows:

1. Transport of the substrate and oxygen from the wastewater to the surface of the biofilm.
2. Internal transport of the substrate and oxygen through the biofilm by diffusional processes.
3. Oxidation of the substrate within the biofilm.
4. Diffusion of by-products back to the wastewater.

Current RBC system design procedures are primarily based on empirical relationships developed by RBC manufacturers in which carbon or ammonia nitrogen removal efficiencies are defined in terms of the applied hydraulic loading and BOD_5 and NH_3-N concentrations in the influent to the RBC units. This empirical design approach has ignored the complex transport mechanism and substrate removal kinetics within the biofilm. The manufacturer-recommended empirical design curves are based on data from full-scale plants operated as pilot plants because effective scale-up methodology has not been developed to date.

Most RBC studies reported in the literature have been carried out using small, pilot-scale plants (26, 68, 73, 137, 138). The pilot-scale-generated RBC data are not directly useful for full-scale plant design because sufficient information is not presently available to predict accurately the appropriate scale-up factors (37). Studies have shown that pilot-scale systems exhibit higher removal capacities, particularly under higher organic loading conditions (102, 119, 140). Wilson et al. (140) reported that small scale units had 16 percent higher mass organic removal rates than larger scale units. Stover and Kincannon (119) indicated that smaller diameter RBCs provide better oxygen transfer and higher removal rates at higher organic loadings compared to larger diameter systems. They concluded that to accomplish scale-up of RBCs from pilot data effectively, the oxygen transfer limitations of the full-scale systems must be defined. It is suggested that pilot-scale units be used only in determining the treatability characteristics of wastewater rather than to establish full-scale design parameters.

Several mathematical models have been proposed to describe organic carbon or ammonia nitrogen removal within the RBC system. Most of the mathematical models are based on either Monod growth kinetics or transport phenomena. There are some models which assume first or second order kinetics and the remaining few are statistical predictive models based on multiple regression analysis of operating data.

Several authors have concluded that RBC removal of organic substrates follows first order kinetics with respect to substrate concentration (5, 10, 41, 45, 117). Eckenfelder and Vandervenne (41) developed a first order kinetic model for industrial wastewater treatment which is shown below:

$$\frac{S_n}{S_o} = \frac{1}{(1 + kA/Q)^n} \qquad (6)$$

in which

S_n = effluent substrate concentration, ML^{-3}

S_o = influent substrate concentration, ML^{-3}

A = wetted area of the disc in every stage, L^2

n = number of stage

Q = flow applied to the system, L^3/T

k = proportionality constant, L^3/L^2T

They concluded that this simple relationship reasonably fits experimental data and can be used to design RBC plants. However, they suggested special emphasis on the first-stage removal and noted that a maximum removal limitation, in some cases, could be due to oxygen limitations. The k values were found to be in the range of 0.204 to 0.701 $m^3/m^2/day$.

Similarly, Benjes (16) developed two equations which he verified using full-scale RBC performance data:

$$\frac{L_e}{L_o} = e^{-k(V/Q)^{0.5}} \tag{7}$$

$$\frac{L_e}{L_o} = e^{-S(A_s/Q)^{0.5}} \tag{8}$$

in which

L_o = influent substrate concentration, ML^{-3}

L_e = effluent substrate concentration, ML^{-3}

Q = hydraulic loading rate, L^3/T

A_s = RBC media surface area, L^2

V = volume of the reactor, L^3

k = proportionality constant

S = proportionality constant

Kincannon and Groves (70) reported that the mixed liquor suspended solids in RBC stages play an important role in substrate removal, particularly at low hydraulic loading rates that allow suspended solids to accumulate. Assuming first order kinetics, they developed an equation incorporating the suspended solids in the expression

$$\frac{(S_i - S_e)F}{X_m + X_s V} = 0.13\ S_e \tag{9}$$

in which

S_i = influent substrate concentration, mg/L

S_e = effluent substrate concentration, mg/L

V = liquid volume of RBC reactor, liter

X_s = suspended solids in reactor, mg/L

X_m = mass of microorganisms on discs, mg

F = hydraulic loading rate, liters/day

Their results indicated that suspended solids in the mixed liquor play an important role in RBC kinetics and should not be ignored completely. First-stage, mixed-liquor suspended solids concentrations as high as 1300 mg/L were observed.

Opatken (87) assumed second order kinetics in predicting the stage performance of RBCs in series using the Levenspiel equation (77). Opatken compared the predicted values with the measured values obtained from nine full-scale plants (64). Levenspiel's equation for staged reactors that follow second order kinetics is mathematically derived from a mass balance and is applicable for calculating the soluble substrate concentration at any stage if the reaction rate constant, residence time and the influent substrate concentration are known. The equation is given as

$$C_n = \frac{-1 + \sqrt{1 + 4kt(C_{n-1})}}{2kt} \qquad (10)$$

in which

C_n = soluble substrate concentration in the n-th stage, mg/L

t = hydraulic residence time in the n-th stage, hrs

k = second order reaction rate constant, L/mg/hr

C_{n-1} = influent substrate concentration entering the n-th stage, mg/L

The k value was derived from full-scale RBC data and was found to be 0.083 L/mg/hr. Opatken assumed this value to be constant for all RBCs treating municipal wastewater. However, the RBC data obtained from the facilities where the organic loadings were high did not fit the second order kinetics because of oxygen-limiting conditions.

Joost (67) and Wu et al. (141) developed statistical predictive models based on multiple regression analysis to predict BOD removal in RBC units. Joost's (67) model which predicted BOD removal in each stage is as follows:

$$\frac{\text{BOD reduction}}{\text{stage}} = k\ C^{a}\ R^{b}\ T^{c}\ S^{d} \tag{11}$$

in which

C = substrate concentration in the stage, mg/L

R = RBC physical configuration constant

T = wastewater temperature, °C

k = treatability factor

S = stage residence time, hrs

a, b, c, d = constants

Using available RBC operating data, Wu et al. (141) developed a predictive statistical model for BOD_5 removal:

$$F = \frac{14.2\ Q^{0.5579}}{e^{0.32N}\ L_0^{\ 0.6837}\ T^{0.2477}} \tag{12}$$

in which

Q = hydraulic loading rate, gpd/sq ft

N = number of RBC stages

L_0 = influent soluble BOD_5 concentration, mg/L

T = wastewater temperature, °C

F = fraction of soluble BOD_5 remaining in the effluent, mg/L

The authors concluded that the BOD removal capacity of the RBC system mainly depended upon the hydraulic loading rate, influent soluble BOD concentration, wastewater temperature, and RBC stage number. However, the data obtained from another RBC operating facility did not fit this predictive model (109). Wu et al. (141) also developed a similar predictive model for ammonia nitrogen removal.

Weng and Molof (134) derived a statistical model using multiple regression analysis of data obtained from pilot-scale RBC units to describe ammonia nitrogen removal in RBC systems:

$$F = \frac{0.0545\, L_0^{\;0.644}\, Q^{0.414}}{S^{0.53}\, A^{1.276}} \tag{13}$$

in which

F = fraction of ammonia nitrogen concentration remaining in the effluent, mg/L

Q = hydraulic loading rate, liters/day

L_0 = influent ammonia nitrogen concentration, mg/L

S = RBC rotating speed, rpm

A = area of RBC discs, sq ft.

Several authors developed RBC models based on Monod growth kinetics to describe carbonaceous substrate removal (33, 73, 83, 92). Kornegay and Andrews (73), using a rotating drum reactor with synthetic substrate, developed a model based on Monod growth kinetics which was simple to use.

$$F(S_o - S_i) = \frac{\mu}{Y} A_w X d \frac{S_i}{K_s + S_i} \qquad (14)$$

in which

S_o = influent substrate concentration, M/L^3

S_i = effluent substrate concentration, M/L^3

F = hydraulic loading rate, L^3/T

Y = cell yield coefficient

μ = maximum specific growth rate, $1/T$

A_w = effective surface area, L^2

X = attached biomass concentration, M/L^3

d = active depth of biofilm, μm

K_s = half saturation constant, M/L^3

The active depth of biofilm was assumed to be 70 μm. This model assumes that substrate is the only limiting factor and oxygen is available in unlimited quantities. Clark et al. (33) and Mikula et al. (83) also developed similar models based on Monod growth kinetics.

Pano and Middlebrooks (92) developed a kinetic model applicable to the substrate removal in the first stage of an RBC system based on Monod growth kinetics which is as follows:

$$Q\ (S_o - S_1) = A_1 \frac{K\ X_1\ S_1}{K_s + S_1} \tag{15}$$

in which

S_o = influent total COD, mg/L

S_1 = first stage filtered effluent COD, mg/L

Q = influent flow rate, m^3/day

A_1 = area of first stage disks, m^2

K = maximum reaction rate, 1/day

X_1 = first stage attached biomass, g vss/m^2

K_s = half saturation constant, mg/L

The authors reported that this model can be applied to design RBC systems where a minimum dissolved oxygen of 2 mg/L is available. They emphasized that the model cannot be applied to first-stage loads where oxygen is limiting.

Williamson and McCarty (137, 138) presented a steady-state biofilm model in which an assumption is made that a single substrate limits the biochemical reaction throughout the biofilm. However, they presented a relationship between electron donor and electron acceptor to define a limiting substrate.

$$C < \frac{K_c}{K_s} S \tag{16}$$

in which

C = electron acceptor concentration

S = electron donor concentration

K_c = electron acceptor saturation concentration

K_s = electron donor saturation concentration

Williamson and Chung (136) extended the work of Williamson and McCarty (137, 138) by including both the electron donor and electron acceptor, making it a dual-substrate limiting model.

Harris and Hansford (53) predicted that the performance of bacterial films could be limited by a lack of organic substrate, oxygen or both simultaneously, which in turn limits the thickness of the active biofilm. Their model had two equations to describe both the substrate and oxygen transport, and the biochemical reactions within the biofilm. This was the first model to show that RBC performance depended upon both the substrate and oxygen concentrations.

$$\frac{d^2S}{dZ^2} = \frac{\mu X}{YD_s} \left(\frac{S}{K_s + S}\right) \left(\frac{O}{K_o + O}\right)$$

$$\frac{d^2O}{dZ^2} = \frac{\mu XF}{YD_o} \left(\frac{S}{K_s + S}\right) \left(\frac{O}{K_o + O}\right)$$

in which

μ = maximum specific growth rate, 1/T

X = attached biomass concentration, M/L^3

Y = yield coefficient

D_s = substrate diffusion constant, L^2/T

S = substrate concentration, M/L^3

O = dissolved oxygen concentration, M/L^3

Z = depth of biofilm, L

D_o = oxygen diffusion constant, L^2/T

F = constant related to substrate and oxygen use

K_s = substrate half-saturation constant, M/L^3

K_o = dissolved oxygen half-saturation constant, M/L^3

The studies indicated that oxygen-limiting conditions prevailed at an influent COD concentration of 500 mg/L. The active biofilm depth was found to be 70 μm. Kornegay and Andrews (73) observed a similar active biofilm depth. To solve these second order equations, trial and error analysis was required using numerical techniques.

Rittman and McCarty (104, 105, 106) presented a steady state biofilm model that included transport phenomena and biochemical reactions for a single substrate. They predicted in their model and verified that there exists a minimum substrate concentration at which substrate transport and biofilm activity declines rapidly.

Famularo (43) developed a model for RBC systems which defines both the substrate and oxygen in the system. This model describes and includes the effect of oxygen on RBC performance. The following equations describe the use of substrate and oxygen within the RBC system:

$$-\frac{dS}{dt} = K_1 \left(\frac{S}{K_s + S}\right) \left(\frac{C}{K_c + C}\right) \qquad (19)$$

$$-\frac{dC}{dt} = \left(K_2 \frac{S}{K_s + S} + K_3 X\right) \left(\frac{S}{K_c + S}\right) \qquad (20)$$

in which

S = substrate concentration, M/L^3

C = dissolved oxygen concentration, M/L^3

K_1, K_2, K_3 = constants

X = attached biomass concentration, M/L^3

K_s = substrate saturation constant, M/L^3

K_c = dissolved oxygen saturation constant, M/L^3

The authors reported reasonable agreement of operating data with the model after careful selection of various constants from the existing literature regardless of zero or first order reaction simulation. This model assumes that both substrates are limiting irrespective of their concentrations.

Stover and Kincannon (117, 119) observed that there is a definite relationship between substrate concentration and hydraulic loading with the substrate removal rate and efficiency. They indicated that substrate removal is not strictly a function of hydraulic loading or the influent substrate concentration, but is dependent on the combination of these two factors, namely the total organic loading to the system. They suggested that the total organic loading concept be used for design purposes. Several other authors, Dupont and McKinney (40), U.S. EPA (131), Poon et al. (95), and Wilson et al. (140) stressed the importance of the total organic loading concept (lb BOD/day/1000 sq ft) as a design parameter. The significance of the total organic loading concept is that it not only reflects the driving force required for the diffusion of substrate into the biofilm through the substrate concentration term but also reflects the reaction time or detention time in the system as indicated by the hydraulic loading.

Several mathematical models have been developed to describe carbon oxidation and nitrification. However, most of these models use oversimplifying assumptions neglecting major mass transfer relationships.

The few models that incorporated basic substrate and oxygen mass transfer relationships resulted in complicated models requiring computer solutions that cannot be used by design engineers due to the lack of available constants such as active biofilm thickness and diffusion coefficients that cannot be determined easily. An adverse effect of this is that RBC systems are marketed by equipment manufacturers without a sound basis for treatment system design. Until a usable satisfactory model is developed, incorporating complex substrate and oxygen mass transfer phenomena, the total organic loading concept is being and should be used in the design of RBC systems. The system should be designed in such a way that the oxygen-limiting conditions are prevented by limiting the organic load to each stage and also by providing operational flexibility which will increase the oxygen levels in early stages of RBC systems.

EXPERIMENTAL EQUIPMENT, MATERIALS AND METHODS

Wastewater Treatment Plant

Maquoketa, a city with a population of approximately 6000, is located in northeast Iowa. The wastewater treatment plant includes a manual bar screen, communitors, a grit chamber, a raw sewage pumping station, two primary clarifiers, rotating biological contactors, three final clarifiers, two chlorine contact chambers and two anaerobic sludge digesters. A plant flow diagram is shown in Figure 5. The wastewater flows by gravity though a barscreen, a grit chamber and a communitor to the raw sewage pumping station. The wastewater is then pumped to the primary clarifiers and then flows by gravity to the RBC units, the final clarifiers and the chlorine contact chambers. The disinfected effluent is discharged to the Maquoketa river.

The wastewater treatment plant was designed to meet standard secondary effluent limits of 30 mg/L BOD_5 and 30 mg/L SS. However, the new RBC plant has had difficulty consistently meeting its standards when operating at 68 percent of design load because of operational problems such as the presence of low dissolved oxygen conditions in the beginning RBC stages due to higher organic loadings which lead to the development of heavy Beggiatoa growth thereby deteriorating process efficiency. The plant had experienced shaft and media failure because of heavy biomass growths in all stages. Odors from the RBC system have been so significant that residents living in the vicinity of the plant have complained consistently. Table 1 shows the design basis of this 1.1 mgd RBC plant.

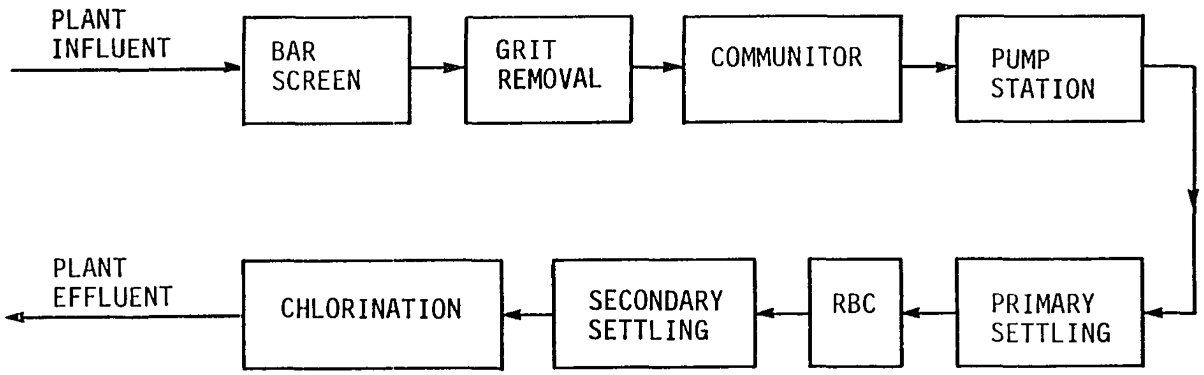


Figure 5. Wastewater treatment plant flow diagram

Table 1. Wastewater treatment plant design data

Parameter	
Average design flow, mgd	1.1
Maximum design flow, mgd	2.5
Influent BOD_5, lbs/day	2028.0 (221)[a]
Influent S.S, lbs/day	2458.0 (268)

[a] The numbers in parentheses indicate concentration in mg/L at average design flow.

Rotating Biological Contactor Study

The objective of this study was to investigate the effectiveness of supplemental aeration and an enlarged first stage in improving RBC performance at the Maquoketa plant as a basis for making recommendations concerning their inclusion in designs for new plants. To accomplish this goal, it was necessary to have a treatment plant that had a minimum of two parallel RBC trains, so that one train could be used as a control and the other train could be used to evaluate treatment improvement using supplemental aeration and an enlarged first stage. The RBC treatment plant at Maquoketa has two parallel trains with four stages in each train, as shown in Figure 6. The RBC design criteria and dimensions are shown in Table 2. The north RBC train was used as a test unit to study the operational modifications while the south RBC train was used as a control unit.

The research study was conducted in two separate phases. Phase I was designed and conducted to investigate the effectiveness of adding supplemental aeration alone on RBC performance. All of the north RBC units were provided with supplemental air by installing fine-bubble Reef diffusers manufactured by Environmental Dynamics, Inc. Four Reef diffusers (2 ft x 1.5 ft) were provided in each RBC stage and a total of 16 diffusers were installed in the four stages. The air was supplied from an existing 320 cfm blower using PVC and flexible piping. Some of the pictures taken during the aeration equipment installation are shown in Figure 7. These fine-bubble diffusers had high oxygen transfer capacities with air flow rate capacities of 0 to 30 cfm/ft^2.

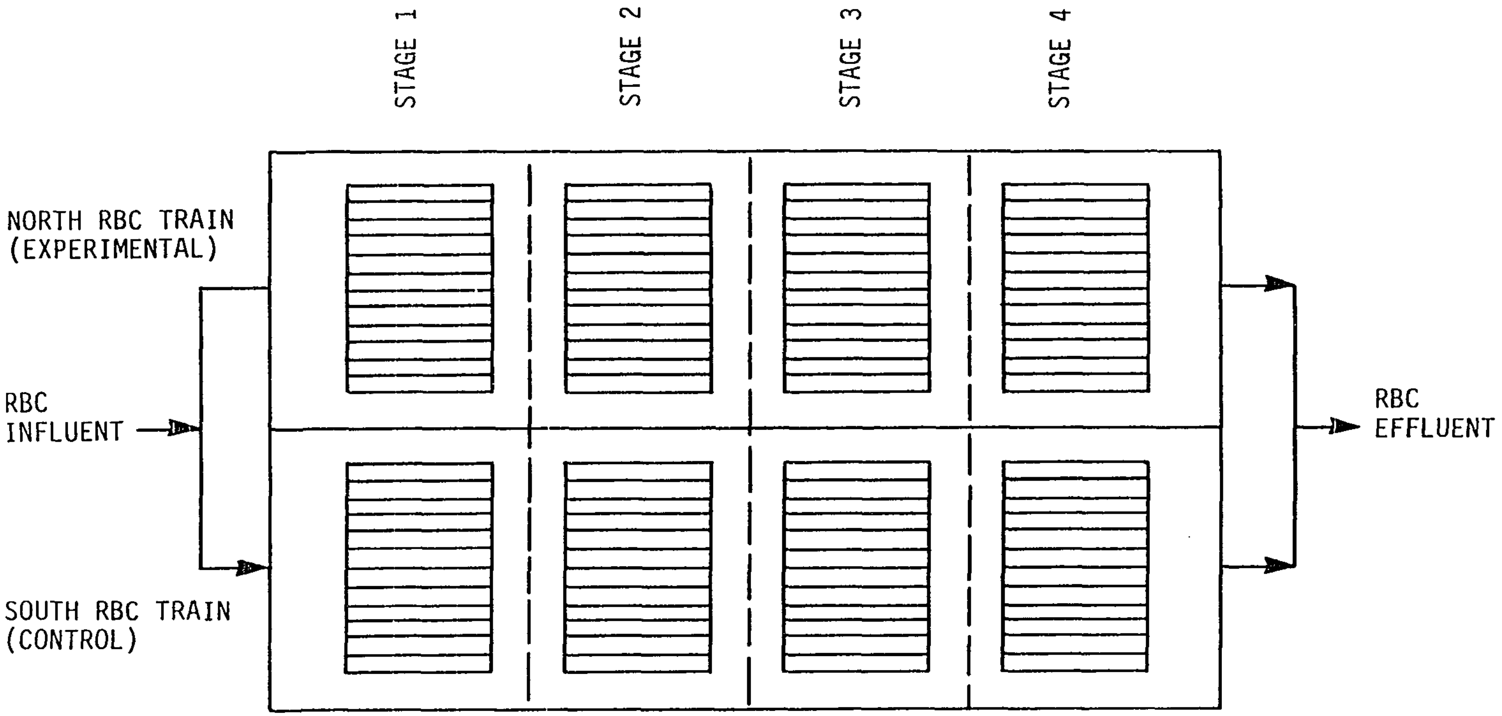
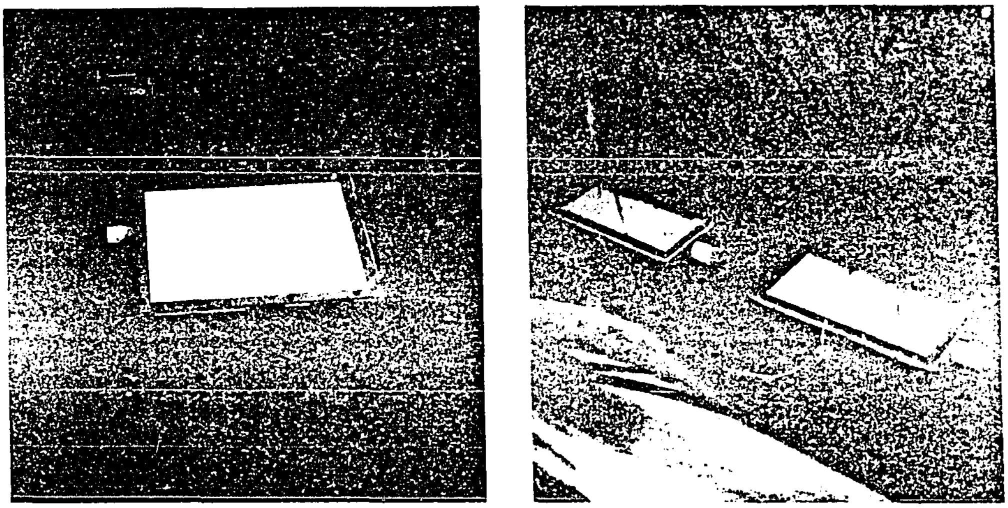


Figure 6. Schematic layout of RBC units

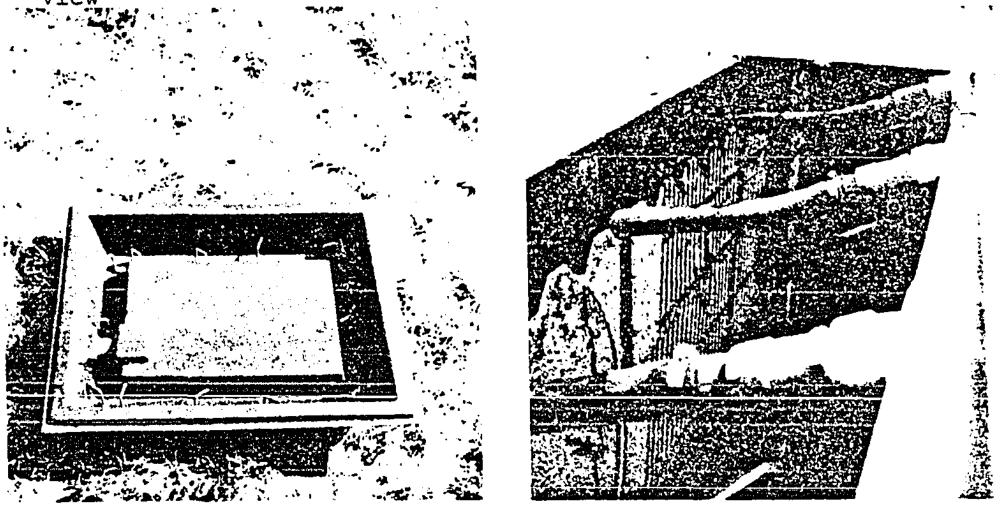
Table 2. Maquoketa RBC design criteria and dimensions

Parameter	
Design flow, mgd	1.1
Influent BOD_5, mg/L	155.0
Influent BOD_5, lbs/day	1422.0
Hydraulic loading rate for design, gpd/sq ft	2.2
Percent BOD_5 removal assumed	87.1
Overall hydraulic detention time, hrs	1.30
Number of RBC trains	2
Stages in each train	4
Total media surface area, sq ft	500,000
Surface media area of each stage, sq ft	62,500
RBC disc diameter, ft	11.5
Number of shafts	4
Length of each shaft, ft	24.0
Shaft drive motor hp	7.5
Rotational speed, rpm	1.4



a. Fine-bubble reef diffuser-top view

b. Reef diffuser under RBC disc



c. Reef diffuser-bottom view

d. Flexible air supply piping

Figure 7. Pictures taken during installation of the aeration equipment

Each air diffuser unit was provided with separate shut-off valves so that each unit could be individually removed, inspected, cleaned and returned to service in the basin without disturbing the air flow through the other units.

In the Phase II study, the combined effect of supplemental aeration and use of an enlarged first stage on RBC performance was investigated by removing the wooden baffles between the first and second stages of the north RBC train. The supplemental aeration provided in the north RBC train during the Phase I study was undisturbed, and the south train, without supplemental air but with an enlarged first stage, was used as a control. An enlarged first stage can be considered as partial stepfeed to equalize the organic load in the first two stages.

During the Phase I and Phase II studies, the RBC performance was investigated separately under low and high organic loading conditions with the intent to find an optimum organic loading range above which oxygen limiting conditions would prevail. In the beginning of each phase and during the transition from low to high organic loadings, an RBC acclimation period of 10 to 15 days was allowed to attain a steady-state operating condition. During the higher loadings, the plant loading was increased in an incremental fashion over a period of time by adjusting the degree of pretreatment provided for an industrial waste originating at a dairy plant.

Wastewater Characteristics

The wastewater entering this plant is a mixture of domestic and partially treated industrial dairy processing wastes. The highly soluble industrial dairy waste is pretreated in an activated sludge plant (located at the dairy) prior to discharge to the city sewer system. Based on design BOD_5 loadings, the industrial waste was approximately 9 percent of the total load to this RBC plant. During the past year, the average influent total BOD_5 concentration to the plant varied between 167 and 310 mg/L with an average of 213 mg/L. The average flow to the plant was 0.656 mgd and the design flow limit was exceeded only in the month of April due to inflow/infiltration problems. Plant influent ammonia nitrogen varied between 22 to 36 mg/L and phosphate was present in sufficient quantities to meet biological requirements. The dissolved oxygen concentration varied between 0.2 to 0.5 mg/L in Stage 1 of the RBC unit and remained low for most of the summer months. Wastewater pH was always between 7 and 8. Sulfide concentrations in the influent wastewater were insignificant.

Sampling Procedures

The research study at this plant was conducted for approximately six months to evaluate the effect of supplemental aeration, and the combined effect of supplemental aeration and an enlarged first stage on the RBC process parameters such as: soluble COD removal rates; stage and overall soluble COD removal efficiencies; ammonia nitrogen removal rates and efficiencies; stage dissolved oxygen levels; sludge production; and related kinetic constants.

Eleven 24-hour composite samplers were used to collect influent and effluent wastewater samples from each north and south RBC stage. As explained earlier, the north RBC train was used to experiment with supplemental air and an enlarged first stage, and the south RBC train was used as a control to compare the results. Actually, only nine samplers were necessary to sample influent and effluent of each stage in both trains. However, two spare samplers were provided in case the others on the line malfunctioned. The composite samples were collected at intervals of 15 minutes over a period of 24 hours.

The 24-hour composite samples of the influent and effluent of each stage were analyzed for soluble COD, ammonia nitrogen, suspended solids, and volatile suspended solids on a daily basis for five days in a week. Samples were also analyzed for soluble BOD_5 (inhibited) once a week. Stage oxygen uptake rates were measured periodically. In situ wastewater temperature, pH and dissolved oxygen levels were measured in each stage at about 9 a.m. and in the afternoon at the time of peak loading. The biomass thickness in the beginning stages was measured periodically, and the growth conditions were observed and noted on a daily basis. For quality control, several times during the sampling period, the samples collected were split for analysis at other wastewater analytical services laboratories to compare the results.

Analytical Methods

The analytical methods employed in this study were conducted according to Standard Methods (113). All pH measurements were made using a Fisher pH meter manufactured by Fisher Scientific Company. Temperature was measured in all the stages using a mercury thermometer. Temperature loss between the stages was insignificant. Dissolved oxygen was measured according to Standard Methods (113) using an oxygen analyzer, YSI Model 54 manufactured by Yellow Springs Instrument Company, Inc. In situ measurements were made in each stage to record pH, temperature, and dissolved oxygen.

Soluble BOD_5 tests were conducted according to Standard Methods (113) adding allylthiourea to suppress nitrification. Chemical oxygen demand (COD) determinations were made using the dichromate reflux method (113). It should be emphasized that during this study only soluble COD and soluble BOD_5 measurements were made since these are the organic parameters normally used in RBC design. The test samples were filtered using Whatman 934-AH glass fiber filters.

Ammonia nitrogen measurements were conducted according to procedures outlined in Standard Methods (113). An Orion auto analyzer manufactured by Orion Research Inc. was used in these determinations. Oxygen uptake rate measurements were made as per Standard Methods (113). The dissolved oxygen concentration was measured every five minutes for fifteen minutes and the oxygen uptake rate was expressed in mg/L/hr.

Total and volatile suspended solids determinations were made according to Standard Methods (113) using Whatman 934-AH glass fiber filters. Total suspended solids (TSS) were measured after drying the sample at 105°C for a minimum of 12 hours. Volatile suspended solids (VSS) were determined after placing the filter papers in a muffle furnace at 550°C for 1.5 hours. The biomass thickness was measured by scraping biomass from a known amount of area on the media. Knowing the biofilm weight and the area measurements, the biofilm thickness was calculated.

RESULTS AND DISCUSSION

Start-Up and Operating Conditions

The research study was conducted for approximately six months from late June, 1984 until the end of November, 1984. The study was conducted in two phases. Phase I work involved experimentation with supplemental aeration. In Phase II, the combined effect of supplemental aeration and an enlarged first stage was investigated. In each Phase work, the north RBC train was used for experimental operational modifications and the south train was used as a control to evaluate normal plant operating performance under identical hydraulic and organic loading conditions.

After installation of aeration equipment in the north RBC train, air was introduced through the sixteen fine-bubble reef diffusers (four in each stage), from a 320 cfm existing blower. During the first few days of air use, the biomass from the north RBC units sloughed off heavily, creating a solids overloading problem in the final clarifiers. It was noticed that biomass slough off was significantly less in the second week of operation. Since the biomass was thick and heavy in all stages prior to air use, it was decided to continue the aeration for three weeks prior to initiation of sampling. Intermittent 24-hour composite sampling of each stage was carried out to observe when steady-state conditions prevailed. The sampling results indicated steady-state conditions existed at the beginning of the third week.

Similarly, in the beginning of Phase II work, an enlarged first stage was created by removing the baffles between the first two stages of the north and south RBC train. Supplemental aeration was provided only in the north RBC train. An acclimation period of two weeks was allowed to achieve steady-state conditions. At the end of the second week, a uniform biomass growth was observed in the first two stages due to baffle removal. After a few weeks of operation in both Phases, the north RBC train turned gray in color in the first two stages and a brownish red tan color appeared in the last two stages, particularly during the Phase I study. Beggiatoa growth disappeared from all stages in the north RBC train with supplemental air and use of an enlarged first stage. However, the south RBC train which was used as a control, had heavy, thick biomass growth and Beggiatoa was prevalent in all stages, particularly in the Phase I study.

During Phase I and Phase II, the RBC rotational speed and the air flow were kept constant at 1.4 rpm and 320 cfm, respectively. In each Phase, the RBC performance was studied under a range of low and high organic loading rates. During the low loadings, the RBC performance was observed under normal, regular plant operating conditions. The organic load to the plant was subsequently increased in step increments by reducing the pretreatment provided at the dairy activated sludge plant. An acclimation period of approximately a week to ten days was allowed during the transition from low to high loading rates to obtain steady-state conditions. During the entire period of this study, steady-state conditions were based primarily on the effluent COD of each stage.

Performance During Phase I

In the discussion to follow, performance will be evaluated in terms of wastewater characteristics, kinetics, dissolved oxygen and oxygen uptake, COD removal, ammonia nitrogen removal, and suspended solids and attached biomass characteristics.

Wastewater characteristics

As discussed earlier, the wastewater coming to the Maquoketa plant is a mixture of domestic and industrial waste. However, the industrial waste contribution to organic load is insignificant when compared to the total domestic waste load that is contributed to the plant. During lower loading studies, the soluble COD varied between 86 and 210 mg/L with a mean of 164.4 mg/L. During the higher loading studies, the mean value of soluble COD was 430 mg/L and varied from 240 to 690 mg/L. Influent wastewater characteristics for the Phase I study are shown in Tables 3 and 4 for low and high organic loading rate studies.

As can be seen from the tables, flows to the plant remained within the design limit of 1.1 mgd except for a couple of days during the higher loadings when the flows exceeded the design limit with a maximum flow of 1.4 mgd. The mean flows during low and high organic loadings were 0.707 and 0.852 mgd, respectively. Overall, the flows remained high during the higher organic loadings. Mean ammonia nitrogen values remained approximately the same during both low and high organic loading periods. However, during low loadings the ammonia nitrogen

Table 3. RBC influent wastewater characteristics at lower loadings during the Phase I study

Parameter	Mean	Range	Standard Deviation
Flow, mgd	0.707	0.618-0.912	0.063
Soluble COD, mg/L	164.4	86-210	35.6
Ammonia-N, mg/L	24.8	16-42	7.50
SS-mg/L	107.0	68-240	40.6
VSS-mg/L	84.8	62.2-192.0	29.6
DO-mg/L	1.23	0.80-1.50	0.18
pH	7.33	7.20-7.50	0.09
Temperature, °F	72.3	70-75	1.40

Table 4. RBC influent wastewater characteristics at higher loadings during the Phase I study

Parameter	Mean	Range	Standard Deviation
Flow, mgd	0.852	0.636-1.423	0.242
Soluble COD, mg/L	430.0	240-690	152.9
Ammonia-N, mg/L	22.3	18-25	2.71
SS-mg/L	149.2	74-234	40.7
VSS-mg/L	123.9	72.5-184.9	29.6
DO-mg/L	1.07	0.80-1.40	0.22
pH	7.26	6.8-7.4	0.19
Temperature, °F	71.3	70-72	0.90

varied between 16 and 42 mg/L, whereas it varied only between 18 and 25 mg/L during higher loadings. Sufficient phosphate was measured in the wastewater to fulfill the nutritional requirements of the RBC process.

Influent (primary effluent) dissolved oxygen to the RBCs varied between 0.8 to 1.5 mg/L. Mean dissolved oxygen values during low and high organic loadings were 1.23 and 1.07 mg/L, respectively. The lower mean value during higher organic loadings could be due to the high influent COD concentrations which varied between 240 and 690 mg/L. The mean pH values remained approximately the same at both low and high organic loadings. The pH of the RBC influent always remained between 7 and 7.5 except for one day during the higher organic loading period when the pH was observed to be 6.8 coincident with the highest influent COD concentraion of 690 mg/L measured during this study. Wastewater temperature during the Phase I studies varied between 70 and 75°F.

The influent total and volatile suspended solids were observed to be higher during the high organic loading period when compared to the low organic loading period. This could be due to reduced pre-treatment at the dairy plant that was required to increase the wastewater strength treated on the RBC units during the higher organic loading studies. The RBC influent total suspended solids varied from 68 to 240 mg/L with mean values of 107 and 149 mg/L at the lower and higher organic loadings, respectively. The percent volatile suspended solids in the influent were approximately 80 percent of the total and increased little in the higher organic loading studies.

Kinetics

One of the objectives of this study was to investigate the kinetics involved in wastewater treatment using the RBC units. Using the mean sampling results from the Phase I study in which the soluble COD concentrations in each stage were measured as a function of time, an attempt was made to fit these mean data into several kinetic models as described below.

Zero order	$-r_s = k$	Plot of S versus time
First order	$-r_s = kS$	Plot of logS versus time
Second order	$-r_s = kS^2$	Plot of 1/S versus time

where the k's are not the same and dimensions vary with order of reaction.

A zero order kinetic model would be applicable when the appearance of substrate from stage to stage or at equal time intervals is constant. A zero order rate model would yield a straight line when the substrate concentration, S, is plotted against time or stage. One way of showing that the process is first order with respect to substrate removal is to plot the substrate remaining, S, as a function of retention time or stage on semilog paper. A resulting straight line indicates first order kinetics and the slope of this line is the reaction rate constant. A second order rate model would yield a straight line when the reciprocal of substrate concentration, or 1/S, is plotted against time or stage.

Figure 8 shows that the experimental data provided a reasonable fit to the first order kinetic model. Figures 9 and 10 show plots of the data in Phase I to determine their fit to zero and second order kinetics. It can be seen from these plots that the data fit first order

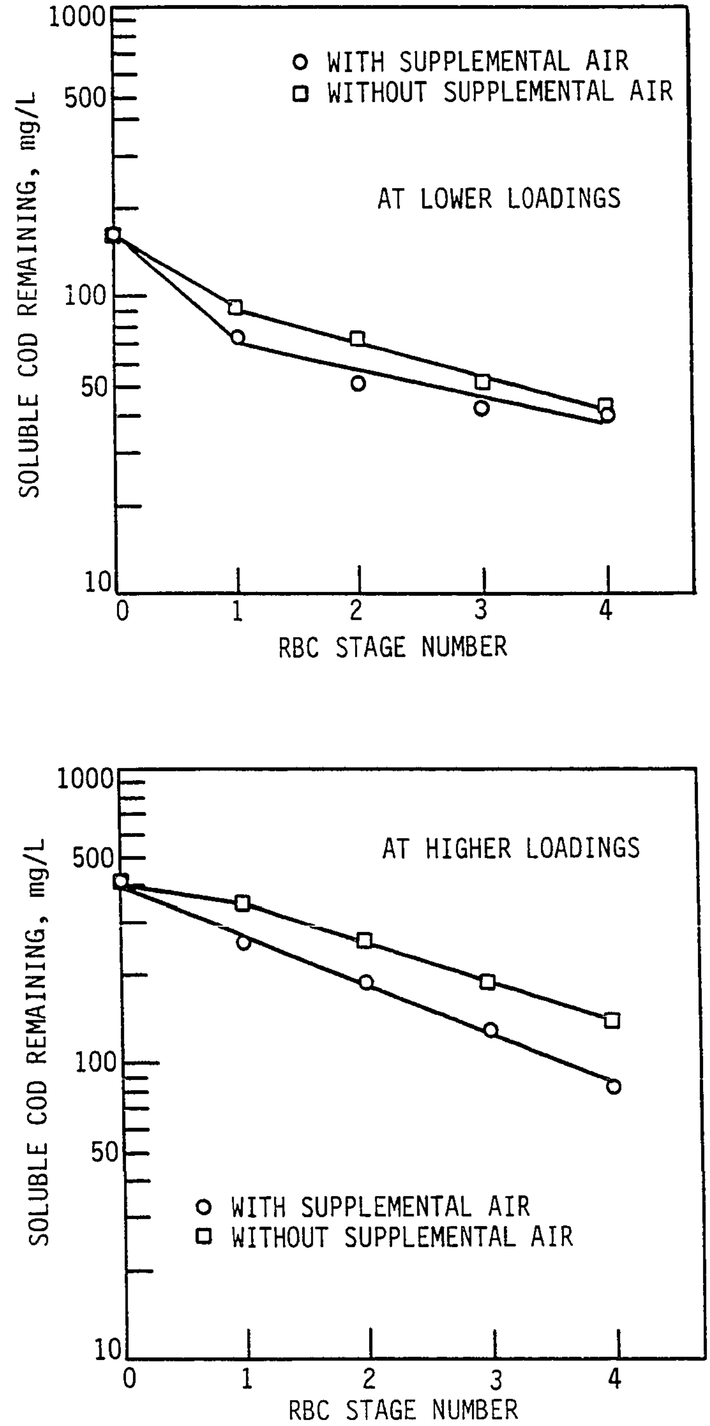


Figure 8. Log soluble COD remaining vs stage for first order kinetics during the Phase I study

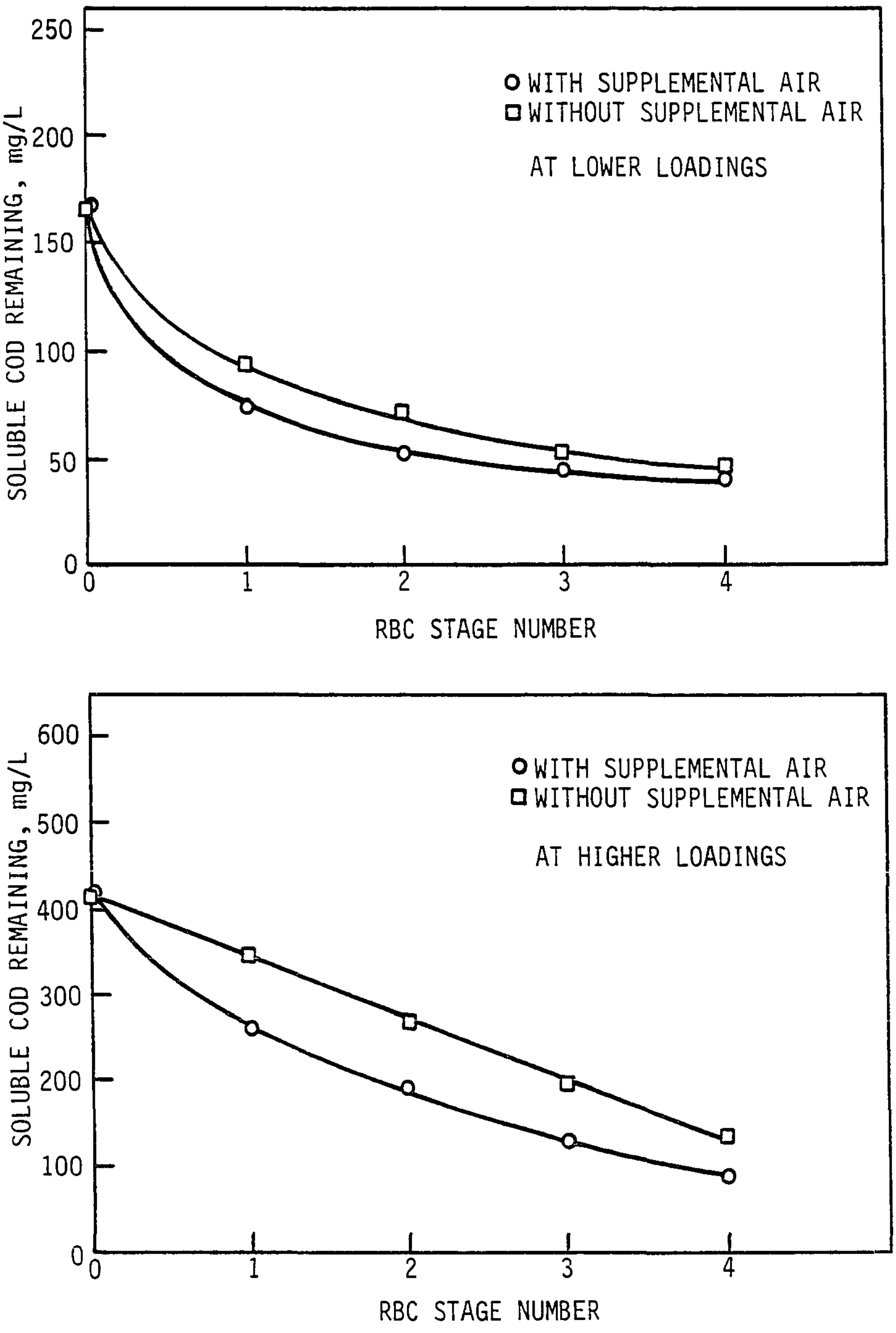


Figure 9. Soluble COD remaining vs stage for second order kinetics during the Phase I study

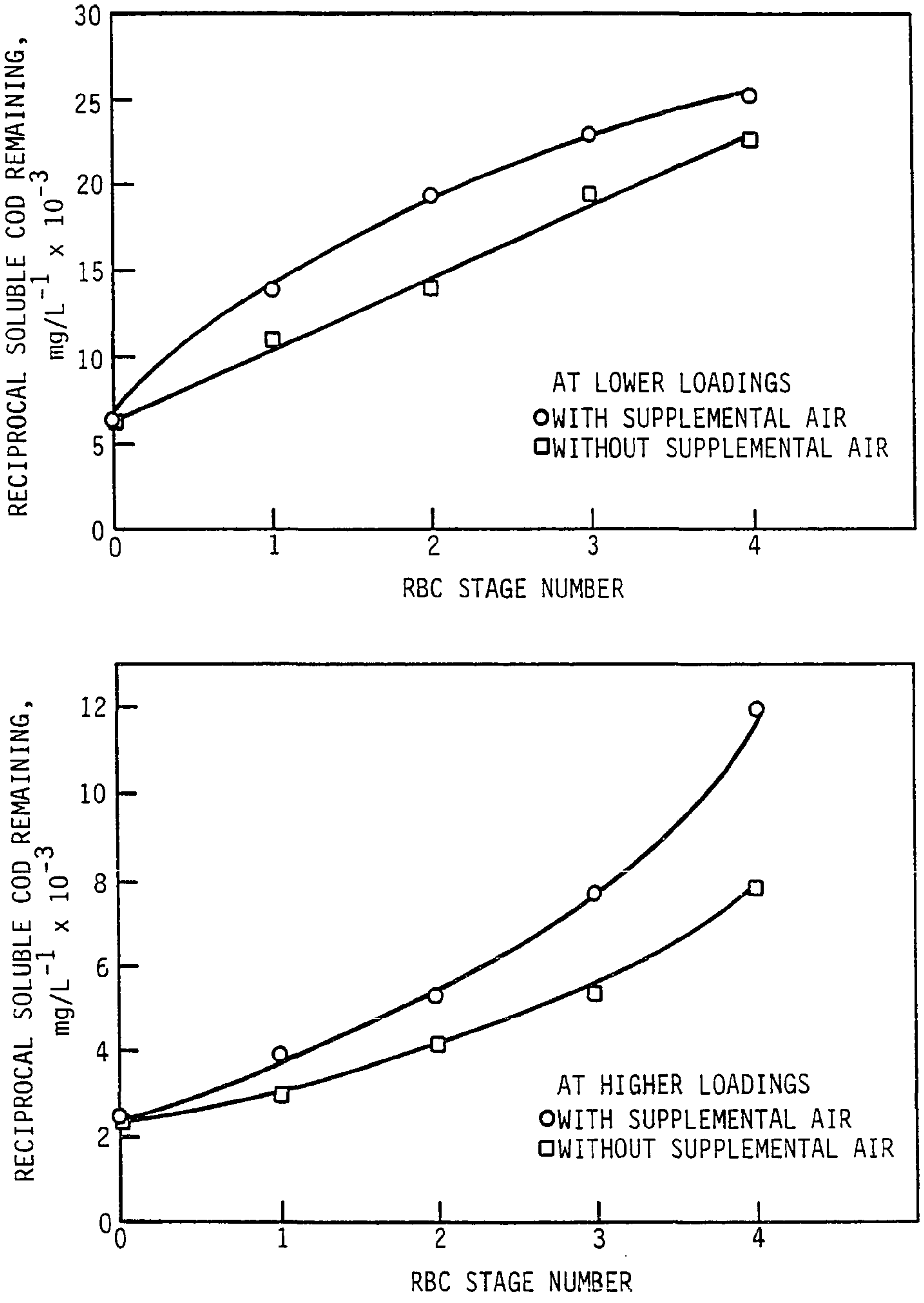


Figure 10. Reciprocal of soluble COD remaining vs stage for second order kindetics during the Phase I study

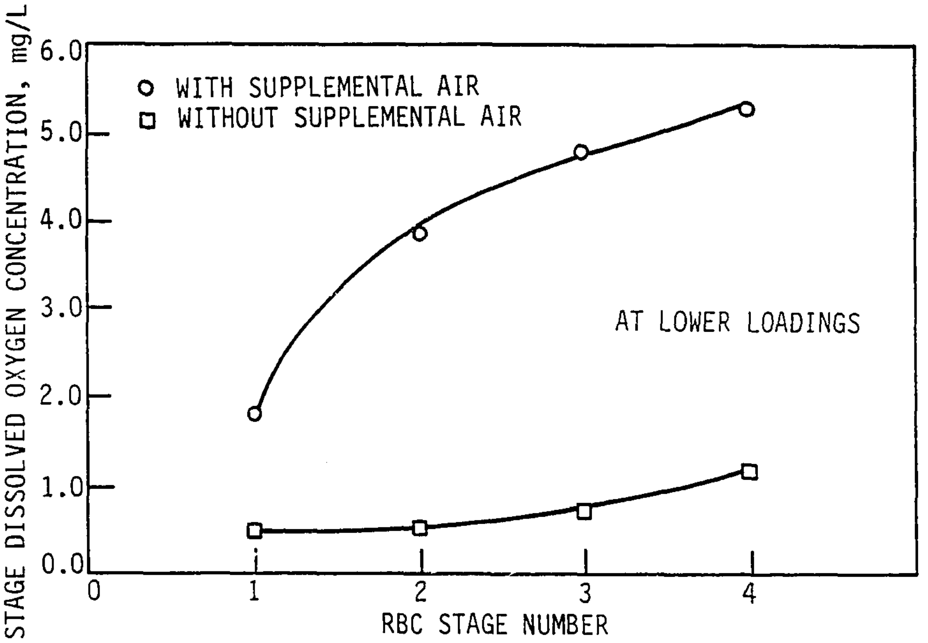
kinetic models at higher organic loadings with supplemental air (Figure 8) and a zero order model without supplemental air (Figure 9). The zero order behavior in the RBC units without supplemental air was due to oxygen-limiting conditions at higher organic loadings that prevailed in the south RBC units because of low dissolved oxygen concentrations in the stage wastewaters. Also, the attached biomass on the south RBC units was thick and heavy. This could have caused mass diffusion limitations both in terms of substrate and oxygen.

At lower organic loadings, Figure 8 suggests that first order substrate removal occurs with supplemental air, and without the supplemental air, the data approximately fit a second order kinetic model as can be seen in Figure 10. However, there is a distinct slope change in Figure 8 following the first stage of the system, particularly at lower loadings. These slope changes correspond to a change in the rate of substrate utilization in the subsequent stages. Most of the substrate is removed in the first stage with the first stage removal being much higher than the removal in the remaining stages. Such phenomena indicating higher substrate removal in the first stage was observed by several other investigators (40, 92, 118). However, these substrate removal rates decrease and approach a constant limiting value at the higher organic loadings indicating saturation with substrate, oxygen limitation, or both. At these high loading conditions, the data show a linear relationship of substrate removal with stage which indicates zero order kinetics as was observed in Figure 9 without the supplemental air.

The second order kinetics, as was observed in Figure 10 at lower organic loadings without the supplemental air, was also observed by Opatken (87) in his investigation. Opatken showed that second order kinetics could be applied to describe RBC substrate removal particularly at lower organic loadings. He indicated that a primary advantage of second order rate reactions was that one kinetic rate constant could be used to describe substrate removal throughout the RBC system. However, this second order kinetic concept cannot predict the substrate removal at higher organic loadings where zero order kinetics occur because of substrate saturation and/or oxygen limitation. In a subsequent section, the importance of total organic loading concepts as a design parameter rather than the use of first, second and zero order models for design purposes will be discussed.

Dissolved oxygen

The dissolved oxygen in the mixed liquor in each stage generally revealed a pattern. Figure 11 shows that the dissolved oxygen concentrations in the mixed liquor increased from stage to stage reaching a maximum value in the fourth stage. At lower loadings, the mean dissolved oxygen in the first stage was 0.5 mg/L in the absence of supplemental air and varied between 0.30 to 0.7 mg/L. Table 5 shows the mixed liquor dissolved oxygen concentrations obtained during the Phase I study. Most of the time the dissolved oxygen in the first three stages remained less than 1 mg/L, subsequently reaching a maximum mean value of 1.13 mg/L in the fourth stage. The dissolved oxygen



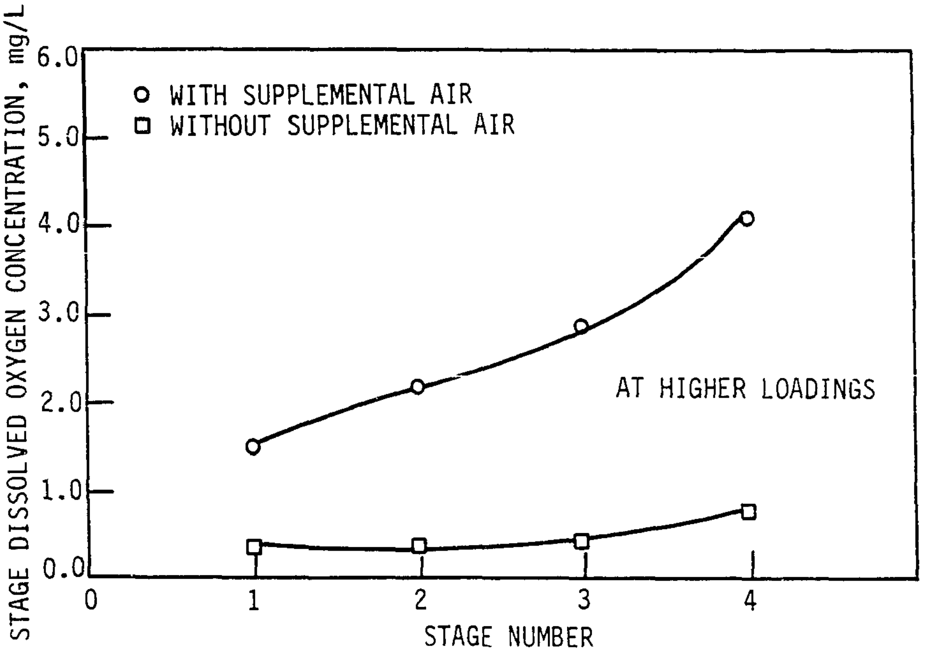


Figure 11. Stage mixed-liquor dissolved oxygen concentrations during the Phase I study

levels were even lower in the south RBC units at higher organic loadings and the mean values remained less than 0.4 mg/L in the first three stages. Mixed liquor dissolved oxygen in the first two stages varied from 0.2 to 0.5 mg/L and overall, the mean dissolved oxygen was less than 0.75 mg/L in all stages. These low dissolved oxygen levels at higher loadings could explain the zero order kinetic behavior observed in Figure 9. Heavy Beggiatoa growth, which becomes prevalent at low dissolved oxygen concentrations, and high organic loadings were observed in all stages.

With supplemental aeration, the mean dissolved oxygen concentrations in the first stage varied between 1.5 and 1.8 mg/L and always increased in subsequent stages. At lower loadings, the fourth stage dissolved oxygen levels varied from 4.5 to 6.2 mg/L with a mean value of 5.2 mg/L. The first order substrate removals observed in the north RBC units, as shown in Figure 8, could be due to these high dissolved oxygen concentrations which eliminated both the Beggiatoa growth and oxygen limiting conditions. These high dissolved oxygen levels also enhanced nitrification in the north RBC train and this will be discussed further in a subsequent section. However, during operation with very high organic loading rates, the mixed liquor dissolved oxygen concentrations with supplemental air were reduced but were never observed to be less than 1 mg/L. At high hydraulic loadings, the dissolved oxygen levels in the stages increased because of the diluted wastewater and reduced oxygen demand.

Table 5. Summary of stage dissolved oxygen concentrations (mg/L) in the Phase I study

	With Supplemental Air						Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Stage 1	1.80	1.1-2.6	0.42	1.48	1.0-2.3	0.43	0.50	0.3-0.7	0.10	0.36	02.-0.5	0.11
Stage 2	3.82	2.6-4.8	0.52	2.17	1.0-3.0	0.82	0.51	0.3-0.9	0.16	0.35	0.2-0.4	0.10
Stage 3	4.75	3.8-5.7	0.49	2.86	1.3-4.5	1.40	0.70	0.4-1.3	0.26	0.39	0.3-0.7	0.13
Stage 4	5.23	4.5-6.2	0.48	4.03	1.1-6.0	1.87	1.13	0.8-1.8	0.35	0.72	0.3-1.5	0.43

Soluble COD removal

In both phases of this research study, the carbonaceous content of the wastewater was measured in terms of soluble COD. Inhibited soluble BOD_5 tests were conducted periodically to correlate with the SCOD results. As discussed earlier, both the flow rate and organic concentration have definite relationships with organic removal rates and process efficiency. It has been observed that removal rates and process efficiency were indeed dependent on the total organics applied to the RBC rather than its concentration or flow rate. One advantage of using the total organic loading concept in design is the ability to predict organic removal rates and treatment efficiency at any loading condition, irrespective of whether the RBC units are functioning under zero-, first-, or second-order kinetics. Organic removal relationships are established in terms of the total organics applied and the loading points or conditions at which zero order kinetics occur can be observed. These points correspond to loading conditions where the system changes from a biochemical reaction limiting process to an oxygen limiting process. Several authors (40, 95, 131, 140) have suggested the use of total organic loading concepts to determine the required surface area for RBC design and to predict process performance. In this study, the total organic loading approach has been used to evaluate RBC performance.

Figures 12 and 13 show the relationship between soluble COD applied and removed. As can be seen in Figure 12, there is a linear relationship between soluble COD applied and removed in the first RBC stage both with and without supplemental air at lower loadings. However, the linear relationships show a distinct change in slopes indicating higher removal rates when the RBC unit is supplied with supplemental air. The calculated slopes were 0.909 and 0.707 with and without the supplemental air, respectively. Linear regression analysis indicated high correlation coefficients for both curves. Table 6 shows the difference in first-stage treatment capabilities with and without the supplemental air at lower loadings as determined from the curves in Figure 12. The results in Table 6 indicate higher removal rates with supplemental air for a loading range of 4 to 9.5 lb SCOD/day/1000 sq ft. For a maximum loading rate of 9.5 lb SCOD/day/1000 sq ft, the removal rate with supplemental air is 6 lb SCOD/day/1000 sq ft whereas the removal rate is only 4.8 lb SCOD/day/1000 sq ft without the supplemental air. These increased removal rates with supplemental air are attributed to higher dissolved oxygen concentrations and thinner Beggiatoa-free biomass growth which enhanced mass diffusion of substrate and oxygen into the inner layers of the active biomass.

Table 7 and Figure 13 show total RBC plant performance capabilities at overall COD loading rates with and without supplemental air during the lower loading period. Both curves in Figure 13 have high correlation coefficients and approximately the same (0.988 and 0.986) slope. In similar relationships, Dupont and McKinney (40) obtained a slope of 0.893 based upon BOD_5 data collected from a full-scale RBC plant treating municipal wastewater. Pano and Middlebrooks (92) reported slopes similar to those observed in this study using COD data from pilot plant analysis. Table 7 shows that the overall COD removal rates

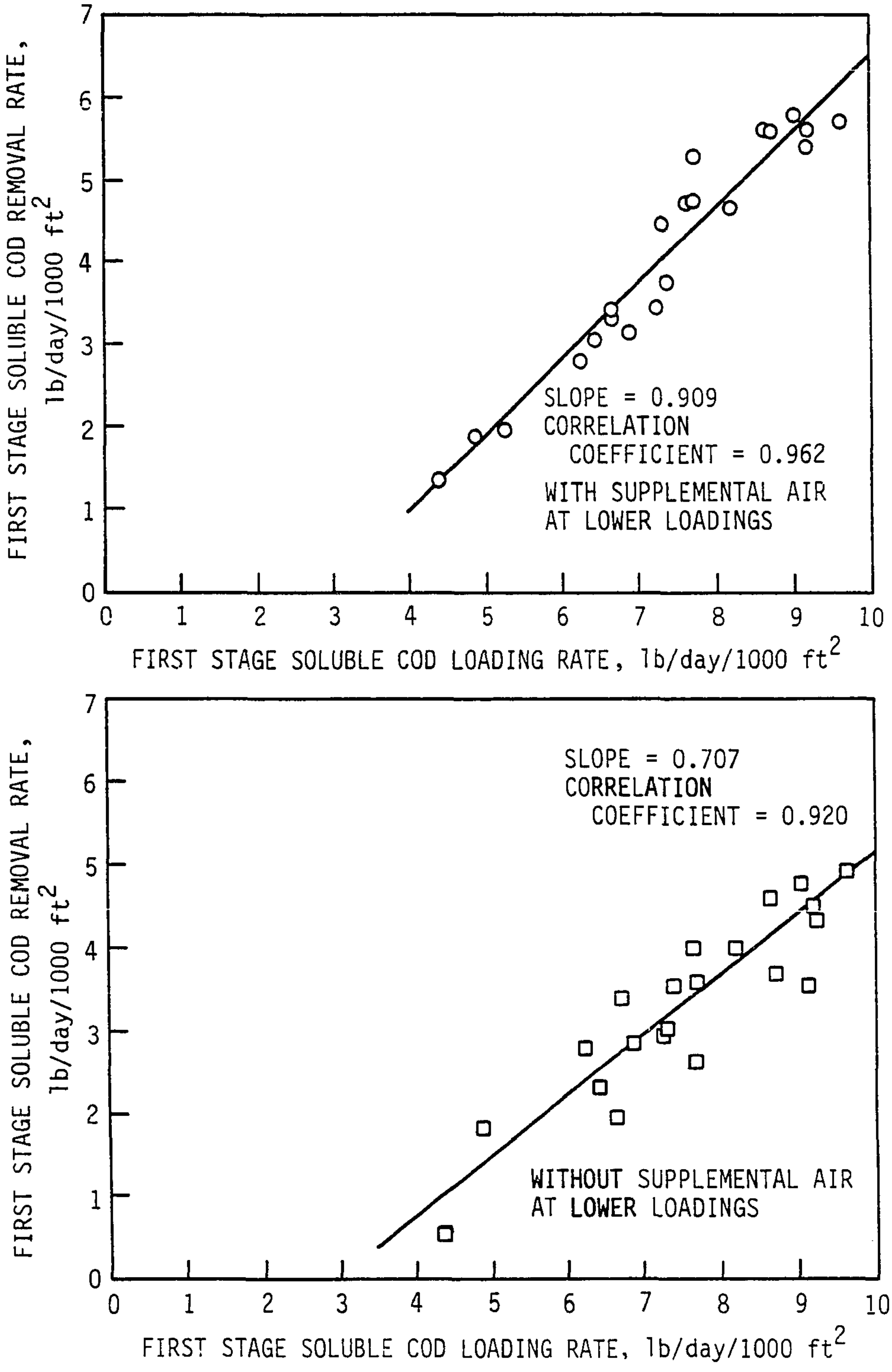


Figure 12. First-stage soluble COD removal vs loading at lower loadings during the Phase I study

Table 6. First stage soluble COD removal rates at lower loadings during the Phase I study

	With Supplemental Air		Without Supplemental Air	
Soluble COD Loading Rate lb/day/1000 ft^2	Soluble COD Removal Rate lb/day/1000 ft^2	Percent Removal	Soluble COD Removal Rate lb/day/1000 ft^2	Percent Removal
4.0	1.00	25.0	0.75	18.8
4.5	1.45	32.2	1.10	24.4
5.0	1.90	38.0	1.50	30.0
5.5	2.35	42.7	1.85	33.6
6.0	2.80	46.7	2.25	37.5
6.5	3.25	50.0	2.60	40.0
7.0	3.75	53.6	2.95	42.1
8.0	4.65	58.1	3.70	46.3
8.5	5.10	60.0	4.05	47.6
9.0	5.55	61.7	4.40	48.9
9.5	6.00	63.2	4.80	50.5

were approximately the same for a loading range of 1.0 to 2.75 lb SCOD/day/1000 sq ft with and without supplemental air, but with a tendency to slightly better performance with supplemental aeration. The differences between the two sets of results are probably not significant.

At lower organic loadings, most of the SCOD is removed in the first stage, leaving the subsequent stages in a starving mode that depend on the mixed-liquor particulate COD for survival. In other words, after the first stage, the limiting nutrient is substrate and this could be the reason why the RBC performance is the same at overall COD loading rates with and without supplemental air. However, it should be recognized that RBC systems with supplemental aeration will have higher COD removal rate capabilities when substrate is not limiting as was observed in the first stage and this will be shown further in the study results at higher organic loadings in the subsequent discussion.

The significance of the supplemental aeration which provides higher stage dissolved oxygen levels shows up well in the results at higher organic loadings, as indicated by Figures 14 and 17. Figure 14 shows that higher first-stage SCOD removal rates can be achieved with supplemental aeration when compared to the removal rates obtained without the supplemental air. Table 8 shows that first-stage COD removal rates were always higher with supplemental aeration for the entire loading range from 10 to 42 lb SCOD/day/1000 sq ft. At an initial loading rate of 10 lb SCOD/day/1000 sq ft, the removal rate with supplemental aeration was 6 lb SCOD/day/1000 sq ft, whereas without the supplemental air the removal rate was only 4.3 lb SCOD/day/

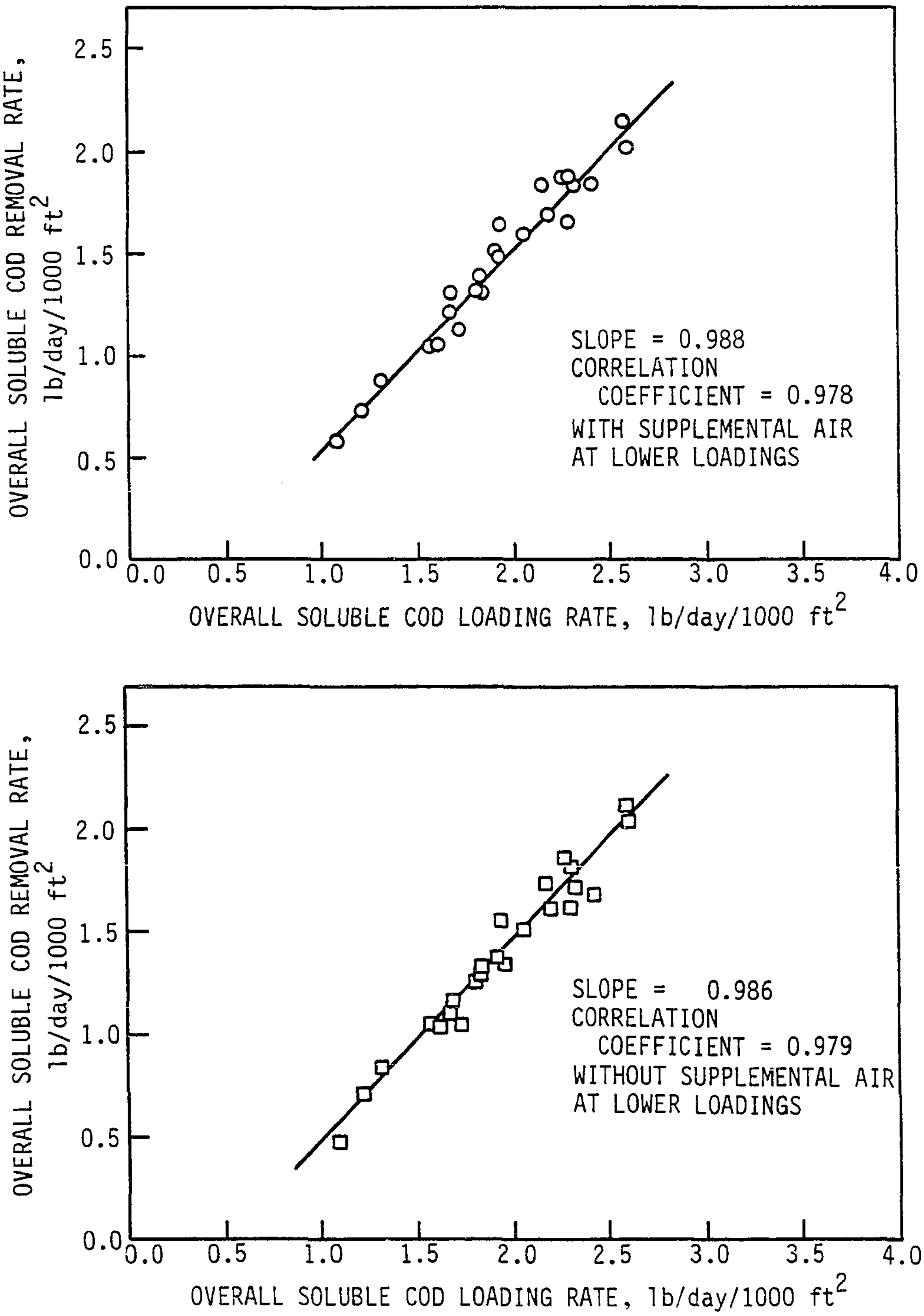


Figure 13. Overall soluble COD removal vs loading at lower loadings during the Phase I study

Table 7. Overall soluble COD removal rates at lower loadings during the Phase I study

	With Supplemental Air		Without Supplemental Air	
Soluble COD Loading Rate lb/day/1000 ft^2	Soluble COD Removal Rate lb/day/1000 ft^2	Percent Removal	Soluble COD Removal Rate lb/day/1000 ft^2	Percent Removal
1.00	0.53	53.0	0.49	49.0
1.25	0.78	62.4	0.74	59.2
1.50	1.02	68.0	0.99	66.0
1.75	1.27	72.6	1.23	70.3
2.00	1.52	76.0	1.48	74.0
2.25	1.76	78.2	1.73	76.9
2.50	2.01	80.4	1.98	79.2
2.75	2.26	82.2	2.23	81.1

1000 sq ft. With supplemental air, the SCOD removal rate increased in a linear fashion up to a maximum load of 32 lb SCOD/day/1000 sq ft and after that removal rate became constant, reaching a maximum value of 13 lb SCOD/day/1000 sq ft, indicating a zero-order removal rate at maximum loading. Without the supplemental aeration, the SCOD removal rates varied between 4.3 and 5.6 lb SCOD/day/1000 sq ft and remained constant for most of the loading range, suggesting a zero-order removal condition. It was observed earlier in Figure 9 that RBC kinetics at higher loadings followed the zero-order model without use of supplemental aeration.

The observed lower SCOD removal rates in the absence of supplemental air could be due to mass diffusional resistances, because of the thick heavy biomass, substrate saturation and oxygen limitation. During the higher loading period, Beggiatoa growth in the south RBC units became predominant in all stages. Beggiatoa, whitish autotrophic sulfur bacteria, are often an indication of an oxygen-limiting condition. Beggiatoa organisms compete with other heterotrophic organisms for a place in the active surface layer of biomass and utilize reduced sulfur (H_2S) as an energy source in the presence of oxygen, further deteriorating SCOD removal rates. Although Beggiatoa organisms exist under aerobic conditions, anaerobic conditions must be present in the biofilm layer for the formation of hydrogen sulfide or it should be readily available in the incoming wastewater. The COD removal rates in Figure 14 suggest that with supplemental aeration up to 30 lb SCOD/day/1000 sq ft loadings can be achieved

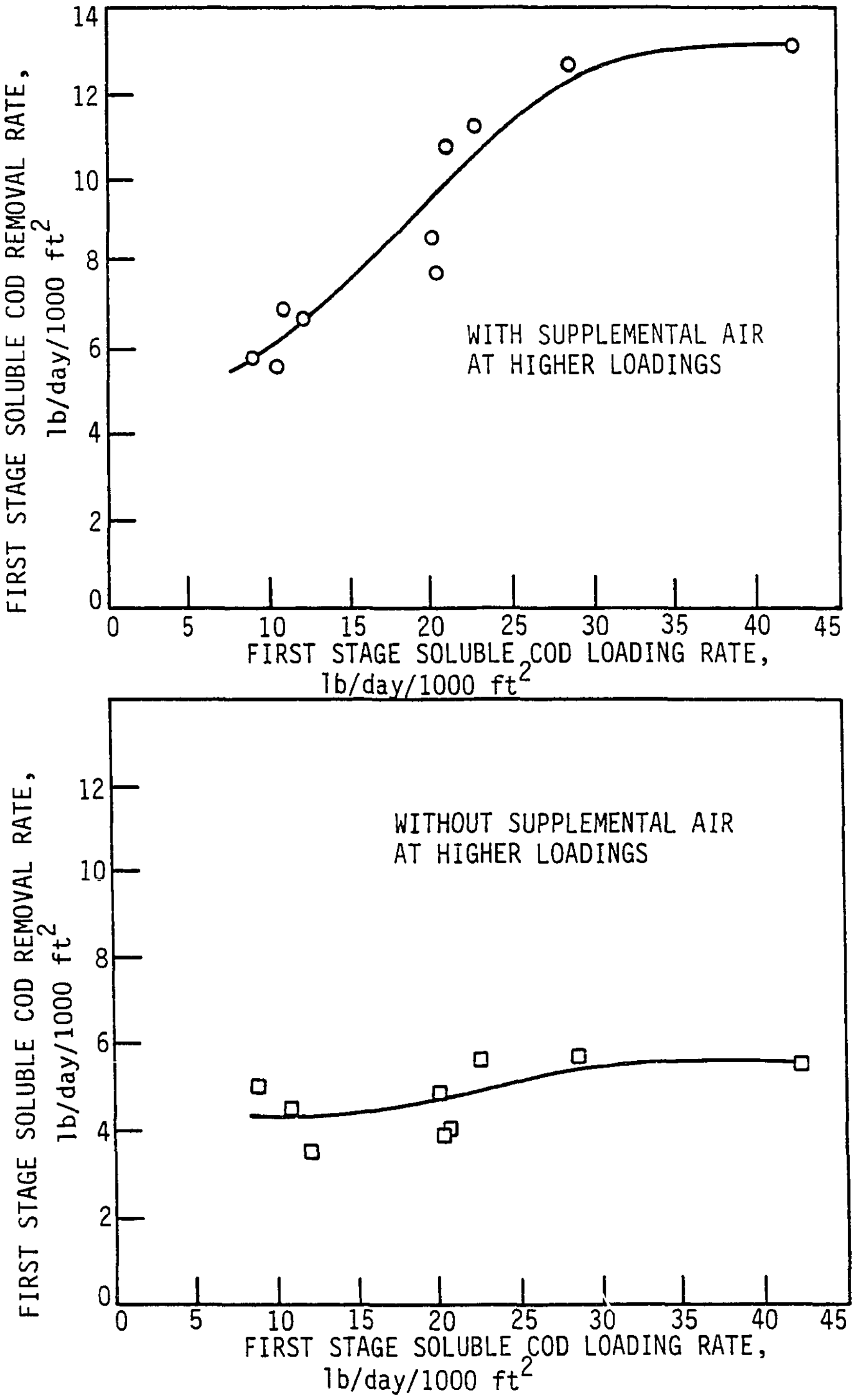


Figure 14. First-stage soluble COD removal vs loading at higher loadings during the Phase I study

Table 8. First stage soluble COD removal rates at higher loadings during the Phase I study

	With Supplemental Air		Without Supplemental Air	
Soluble COD Loading Rate lb/day/1000 ft^2	Soluble COD Removal Rate lb/day/1000 ft^2	Percent Removal	Soluble COD Removal Rate lb/day/1000 ft^2	Percent Removal
10.0	6.00	60.0	4.30	43.0
12.0	6.50	54.2	4.30	35.8
14.0	7.20	51.4	4.40	31.4
16.0	7.90	49.4	4.50	28.1
18.0	8.65	48.1	4.60	25.6
20.0	9.40	47.0	4.75	23.8
22.0	10.15	46.1	4.90	22.3
24.0	10.85	45.2	5.10	21.3
26.0	11.50	44.2	5.25	20.2
28.0	12.10	43.2	5.40	19.3
30.0	12.45	41.5	5.55	18.5
32.0	12.70	39.7	5.60	17.5
34.0	12.90	37.9	5.60	16.5
36.0	13.00	36.1	5.60	15.6
38.0	13.00	34.2	5.60	14.7
40.0	13.00	32.5	5.60	14.0
42.0	13.00	31.0	5.60	13.3

with a maximum removal rate of 12.5 lb SCOD/day/1000 sq ft without any oxygen limitation.

Table 9 shows SCOD concentrations observed in the several RBC stages during the Phase I study. The stage SCOD concentrations from the second stage onwards remained low at lower loadings, suggesting substrate limiting conditions because of which the overall SCOD removal plots in Figure 13 showed the same removal rates with and without the supplemental air. Based on a regression analysis, a relationship between influent soluble COD and influent soluble BOD_5, and effluent soluble COD and effluent soluble BOD_5, was established as shown in Figures 15 and 16. The relationship between the effluent soluble BOD_5 and soluble COD in Figure 16 suggests that there is a fraction of soluble COD in the RBC final effluent that cannot be removed in the wastewater process. This is evident from the low effluent soluble BOD_5 values in Figure 16. This fraction of soluble COD could be due to complex organics that do not exert biological oxygen demand.

Figure 17 shows the relationship between the overall SCOD load applied and removed at higher organic loadings with and without the supplemental air. The linear relationship observed with supplemental air suggest that there was no oxygen limitation. This is further substantiated by the fact that the SCOD removal data conform to first order kinetics removal as observed earlier in Figure 8 and the maintenance of higher dissolved oxygen concentrations, as shown in Figure 11. The correlation coefficent and slope representing the linear

Table 9. Summary of stage soluble COD concentrations (mg/L) observed during the Phase I study

	With Supplemental Air						Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Stage 1	72.8	54-98	12.1	258.3	130-480	124.5	92.2	68-116	14.1	348.3	180-600	141.8
Stage 2	51.5	30-64	6.5	195.7	84-430	124.9	72.2	50-96	13.8	262.0	160-445	115.5
Stage 3	43.6	30-56	6.5	130.7	64-260	75.3	51.8	32-66	9.7	193.0	85-425	120.2
Stage 4	39.8	26-52	7.0	83.2	50-140	33.4	44.4	30-58	7.7	140.0	77-205	47.5

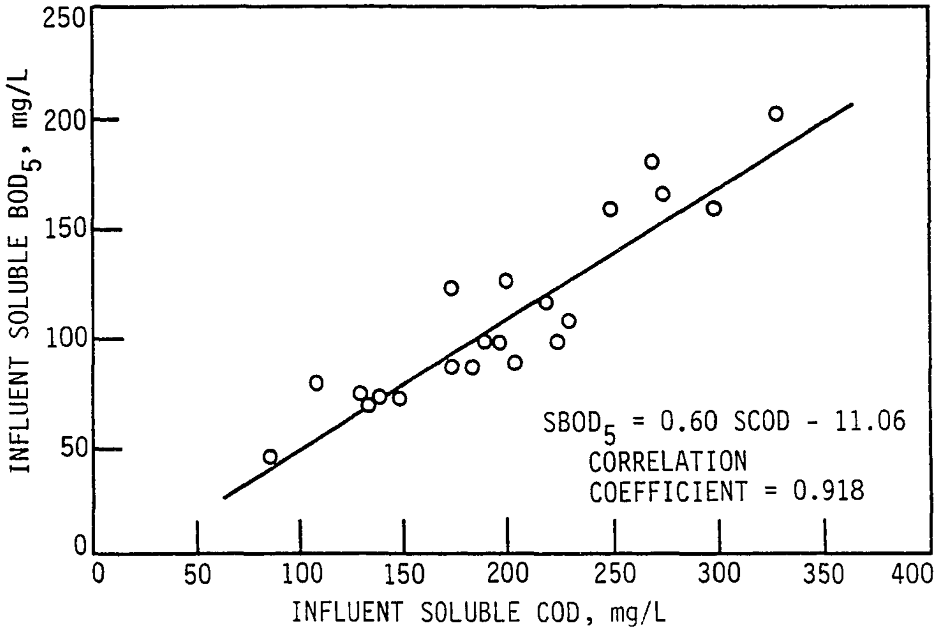


Figure 16. Relationship between SBOD$_5$ and SCOD in RBC effluent

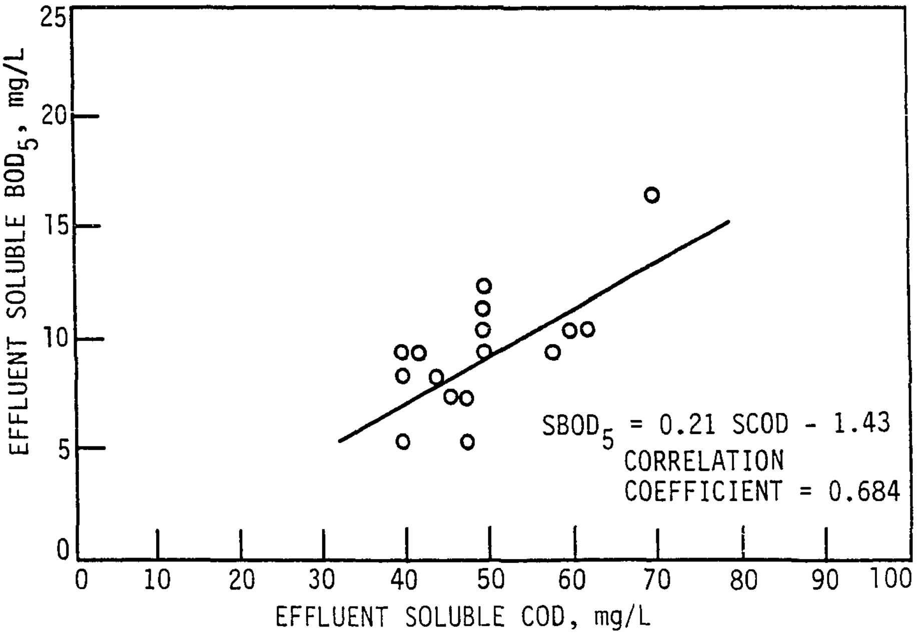


Figure 15. Relationship between SBOD$_5$ and SCOD in RBC influent

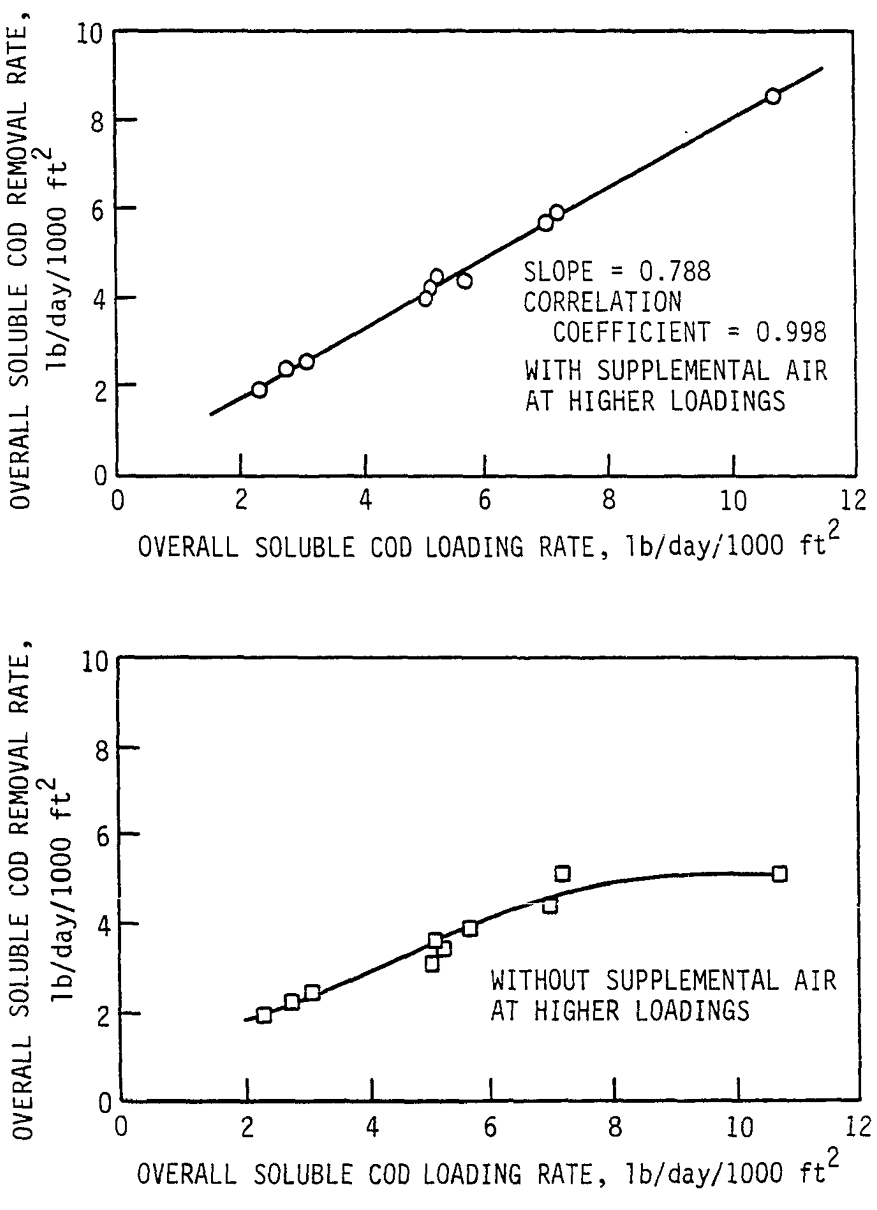


Figure 17. Overall soluble COD removal vs loading at higher loadings during the Phase I study

relationship when supplemental aeration was used were 0.998 and 0.788, respectively. This slope was significantly less than that found in Figure 13 for operation under lower loading conditions. Stage SCOD concentrations shown in Table 9 also suggest that substrate was not limiting after the first stage at higher organic loadings as was observed at lower loadings.

Table 10 shows the SCOD removal rates obtained at higher loadings as determined from Figure 17. These results indicate that for a maximum loading rate of 11 lb SCOD/day/1000 sq ft, the SCOD removal rate with supplemental air was 8.8 lb SCOD/day/1000 sq ft. However, the removal rate was only 5.0 lb SCOD/day/1000 sq ft without the supplemental air. It can also be seen that percent SCOD removal decreased rapidly without supplemental aeration as the organic load increased but that was not the case with supplemental aeration. Figure 17 indicates that maximum overall SCOD removal rate without the supplemental air was approximately 5 lb SCOD/day/1000 sq ft and remained constant at this level at higher loadings, suggesting oxygen limitation. Similar maximum organic removal rates with oxygen limitation were also observed by Stover and Kincannon (119). At higher organic loadings, zero order kinetics were observed (Fig. 9) in the absence of air and the dissolved oxygen concentrations dropped very low, to a level less than 0.4 mg/L in the first three stages. Also, biomass growth in the south RBC units was thick and heavy, and Beggiatoa growth was dominant in all stages. With supplemental air, a few white patches of Beggiatoa growth developed on the first stage at very high organic loadings but

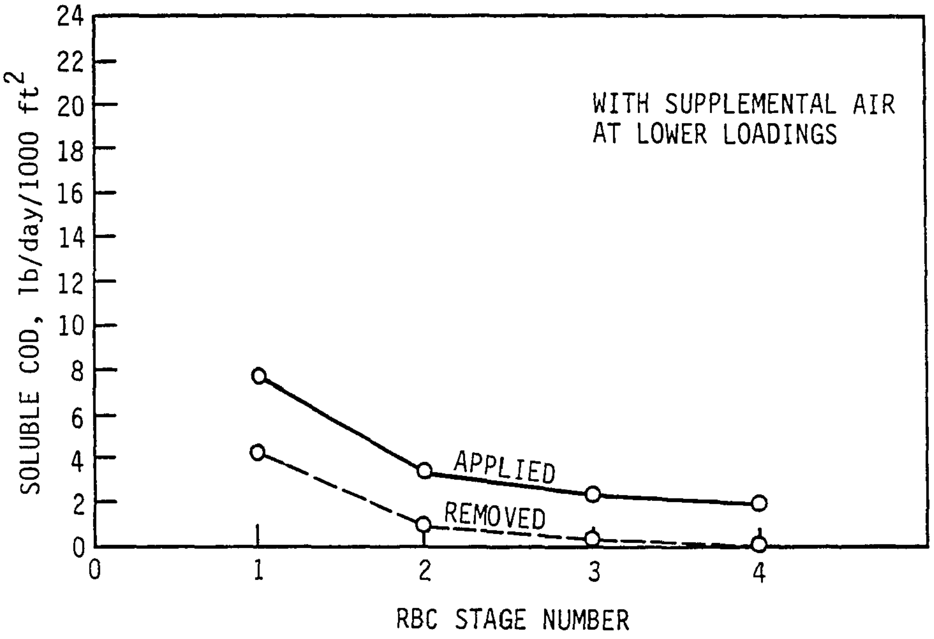
Table 10. Overall soluble COD removal rates at higher loadings during the Phase I study

	With Supplemental Air		Without Supplemental Air	
Soluble COD Loading Rate lb/day/1000 ft^2	Soluble COD Removal Rate lb/day/1000 ft^2	Percent Removal	Soluble COD Removal Rate lb/day/1000 ft^2	Percent Removal
3.0	2.50	83.3	2.35	78.3
4.0	3.30	82.5	2.90	72.5
5.0	4.10	82.0	3.55	71.0
6.0	4.90	81.7	4.10	68.3
7.0	5.65	80.7	4.60	65.7
8.0	6.45	80.6	4.90	61.3
9.0	7.20	80.0	5.05	56.1
10.0	8.00	80.0	5.10	51.0
11.0	8.80	80.0	5.10	46.4

the subsequent stages were free of Beggiatoa growths and these white patches disappeared as the load decreased. Several investigators (29, 30, 58, 130) have noted the Beggiatoa growth due to the combined effect of high organic loadings and low dissolved oxygen concentrations, particularly in the beginning stages.

Figures 18 and 19 show the stage soluble COD loadings and removal profile for the Phase I study. It can be seen that, at the lower loadings, there was not much difference in stage COD removal rates with or without the supplemental air, except for the first stage, where higher COD removal was observed with supplemental air. Table 11 indicates a first-stage removal rate of 4.32 lb SCOD/day/1000 sq ft at a loading rate of 7.75 lb SCOD/day/1000 sq ft with supplemental air, whereas at the same first stage loading, the removal rate without the supplemental air was only 3.40 lb SCOD/day/1000 sq ft. The lower organic loadings in the succeeding stages suggests that substrate mass loading was limited.

At higher organic loadings, first-stage SCOD removal rates were always higher with supplemental air than those observed without the air. Figure 29 shows that first-stage SCOD removal rates were approximately double with supplemental air because of the higher dissolved concentrations. Without the supplemental air, the SCOD removal rates in the first three stages remained approximately the same because of oxygen and mass diffusion limitations. However, mass organic loading was not limiting, that is, enough substrate was available in these stages. Table 11 shows that at a first stage loading of 24.4 lb SCOD/day/1000



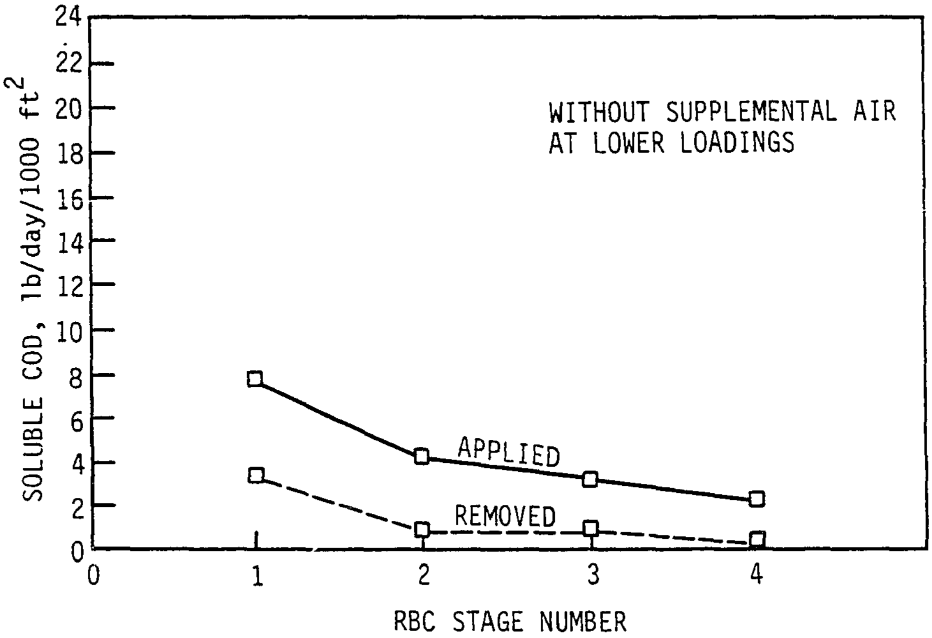


Figure 18. Stage soluble COD loadings and removal profile at lower loadings during the Phase I study

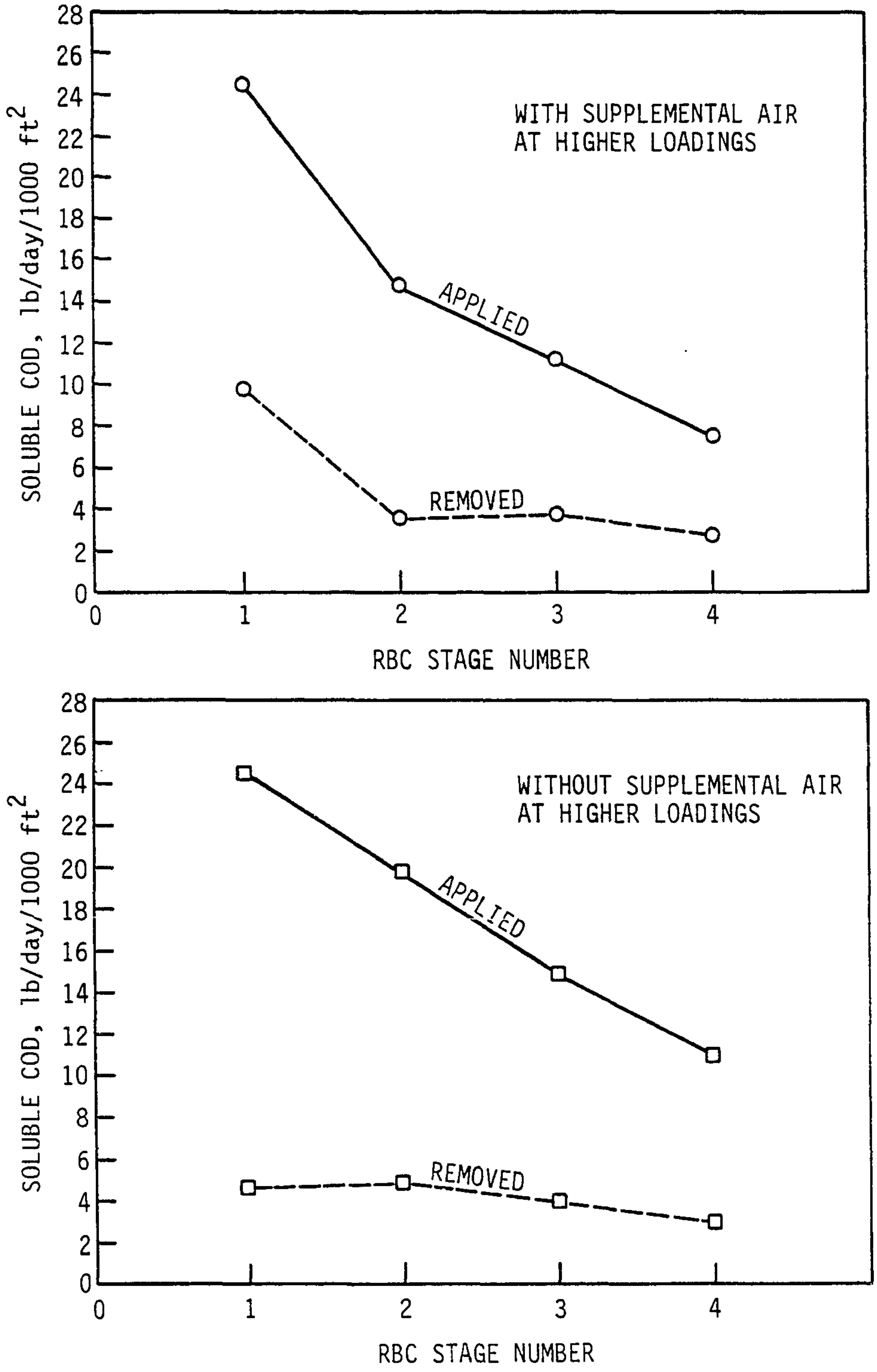


Figure 19. Stage soluble COD loadings and removal profile at higher loadings during the Phase I study

Table 11. Stage soluble COD loadings and removal rates during the Phase I study

Stage	With Supplemental Air				Without Supplemental Air			
	At Lower Loadings		At Higher Loadings		At Lower Loadings		At Higher Loadings	
	SCOD Applied lb/day/1000 ft^2	SCOD Removed lb/day/1000 ft^2	SCOD Applied lb/day/1000 ft^2	SCOD Removed lb/day/1000 ft^2	SCOD Applied lb/day/1000 ft^2	SCOD Removed lb/day/1000 ft^2	SCOD Applied lb/day/1000 ft^2	SCOD Removed lb/day/1000 ft^2
Stage 1	7.75	4.32	24.44	9.76	7.75	3.40	24.44	4.64
Stage 2	3.43	1.00	14.68	3.56	4.35	0.94	19.80	4.91
Stage 3	2.43	0.37	11.12	3.70	3.41	0.96	14.89	3.92
Stage 4	2.06	0.18	7.43	2.70	2.44	0.35	10.97	3.01

sq ft, the removal rate with supplemental air was 9.76 lb SCOD/day/1000 sq ft whereas the removal rate was approximately half that, or about 4.64 lb SCOD/day/1000 sq ft, in the absence of supplemental aeration.

The higher mixed liquor suspended solids that were observed with supplemental aeration also contributed to the higher SCOD removal rates. The excess volatile suspended solids production in the presence of high dissolved oxygen concentrations formed a suspended growth system within the tank contributing to SCOD removal in addition to the RBC fixed-film system whose removal rate was also enhanced due to the elimination of oxygen and mass-diffusion limitations because of thin, Beggiatoa-free biofilm growth. Most of the existing models developed for RBC performance ignore these mixed-liquor suspended solids and consider them insignificant. However, at the increased solids concentrations observed in this study, these solids will have a significant effect on SCOD removal, particularly at high (above 1.5 mg/L) stage dissolved oxygen concentrations. Kincannon and Groves (70) suggested that stage mixed-liquor suspended solids be taken into consideration in RBC design as these solids play an important role under low hydraulic loadings and high hydraulic retention times. The role of mixed-liquor suspended solids will be further discussed in the subsequent suspended solids section.

Table 12 summarizes the stage soluble COD removal efficiencies obtained during the Phase I study. First-stage efficiencies always remained higher with supplemental air. The significance of supplemental aeration at higher loadings is evident in both the higher

Table 12. Summary of soluble COD removal efficiencies (%) during the Phase I study

Stage	With Supplemental Air At Lower Loadings	With Supplemental Air At Higher Loadings	Without Supplemental Air At Lower Loadings	Without Supplemental Air At Higher Loadings
Stage 1	55.7	39.9	43.9	19.0
Stage 2	29.3	24.2	21.7	24.8
Stage 3	15.3	33.2	28.3	26.3
Stage 4	8.7	36.3	14.3	27.5
Overall	75.8	80.7	72.7	67.4

overall and higher first-stage removal efficiencies. First-stage SCOD removal efficiency was 39.9 %, double the efficiency observed without the supplemental air. The overall efficiency was 80.7 % which was also considerably higher than the efficiency of 67.4 % obtained without the air. Higher oxygen-uptake rates observed with supplemental aeration correspond to obtained higher SCOD removal rates or efficiencies. Mixed-liquor oxygen uptake rates in the various stages, as shown in Figure 20, decreased as the stage organic loads decreased. Such decreasing oxygen uptake rates as a function of stage were observed earlier at this plant (22). It is interesting to note that oxygen uptake rates were approximately 5 mg/L/hr in the RBC influent and increased in the first stage up to 6 mg/L/hr with supplemental aeration. However, the rate decreased in the stages where no supplemental air was provided.

Figures 21 and 22 show the relationship between percent SCOD removal and both overall and first-stage loading rates. The results in Figure 21 indicate that the percetange of SCOD removal decreased linearly as the loading increased when supplemental aeration was provided. However, the increased loading had a significant impact on the percent of SCOD removal in the south RBC units where no air was provided. The percentage of SCOD removal with supplemental air remained approximately constant at 80 percent at overall loadings, whereas it decreased without the supplemental air as the loading increased. The observed results in Figures 21 and 22 suggest that increased SCOD loadings will have less impact on percentage removal of

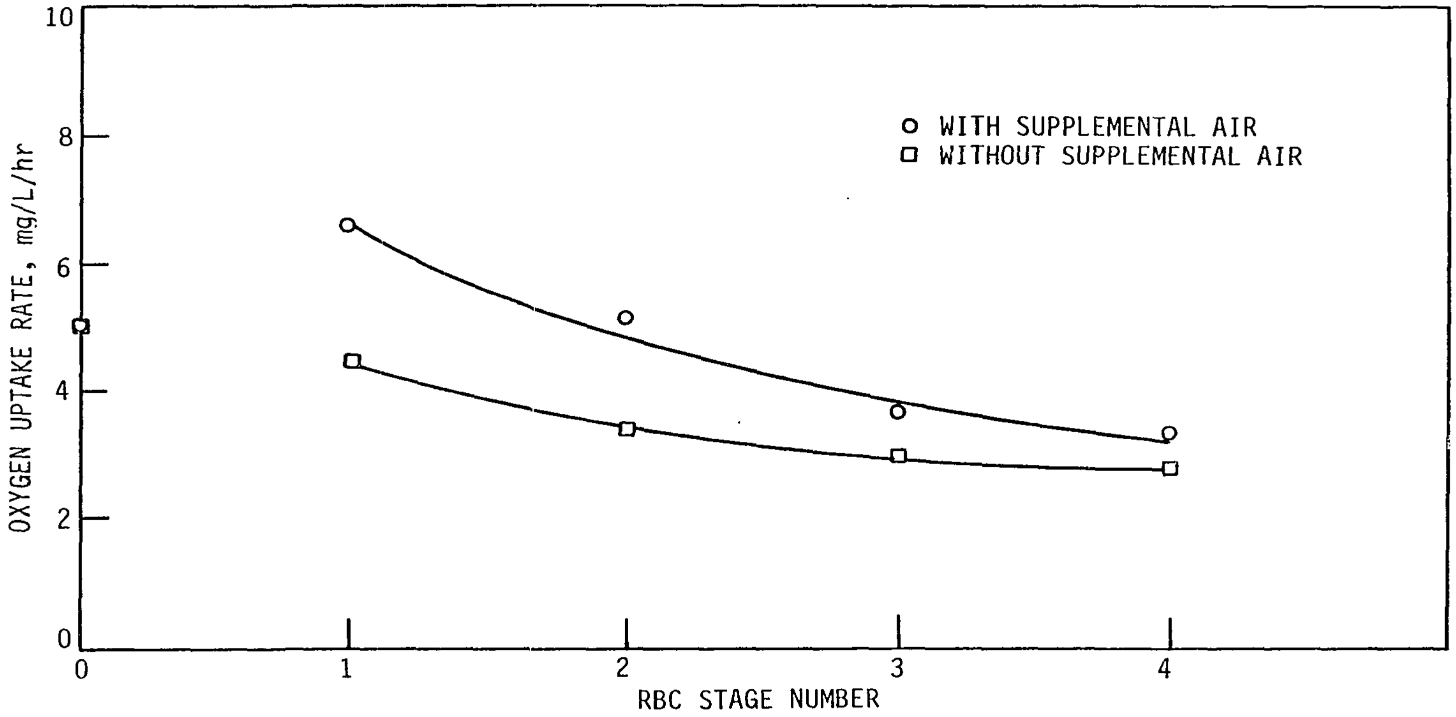


Figure 20. Stage oxygen uptake rates during the Phase I study

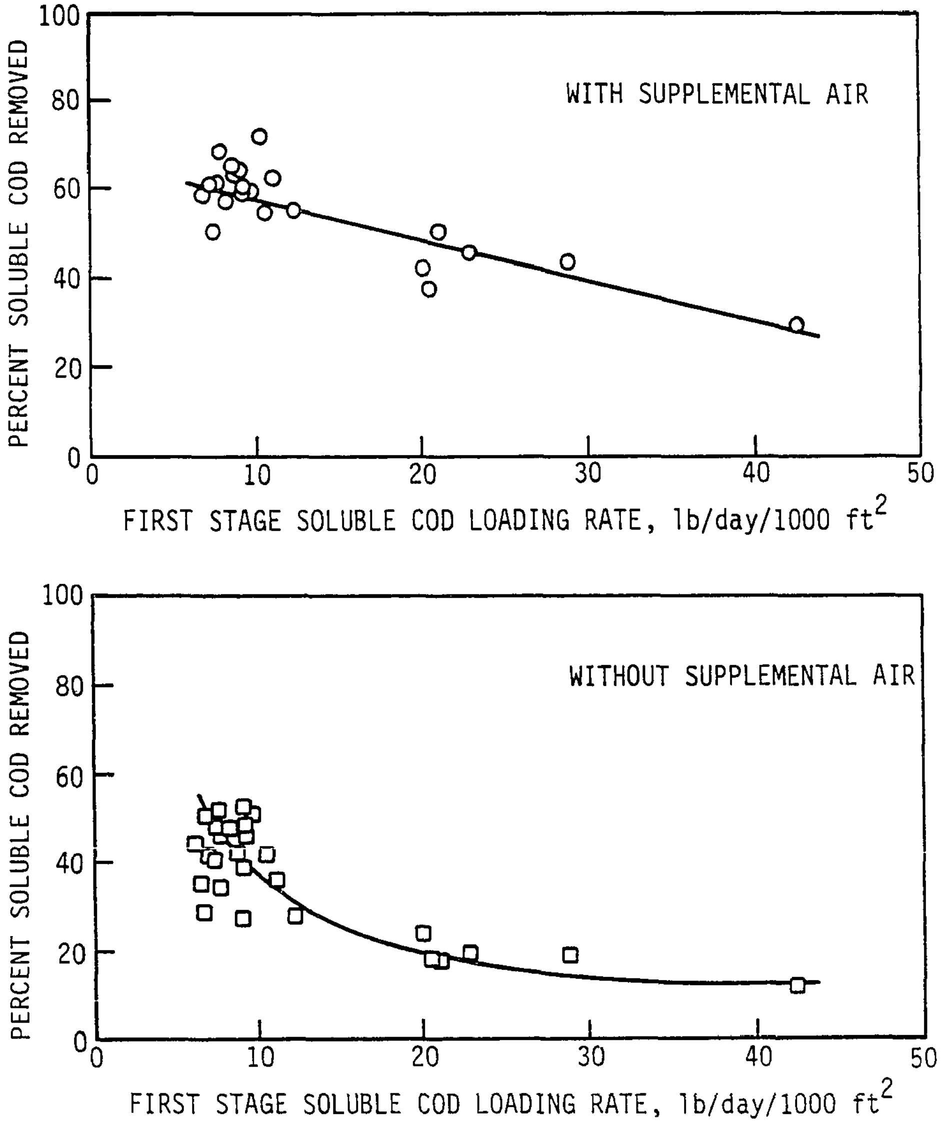


Figure 21. Percent soluble COD removal vs first-stage loading during the Phase I study

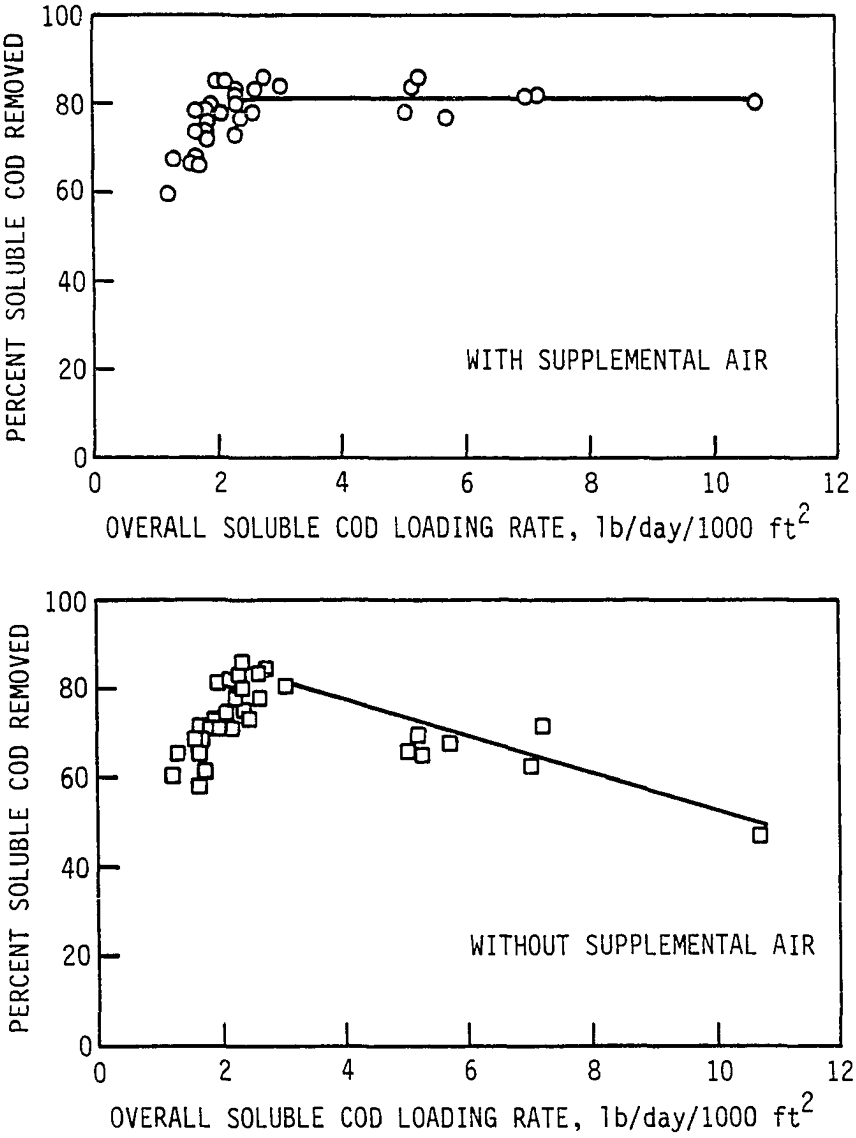


Figure 22. Percent soluble COD removal vs overall loading during the Phase I study

SCOD if supplemental aeration is provided. Such decreases in percentage removals as the organic loading increased were also observed by others (10, 40, 74, 92).

Figures 23 and 24 show the percent removal of SCOD as a function of the hydraulic loading. Correlation between the variables was low; however, increased hydraulic loadings generally produced a slight decrease in SCOD removal. The decrease in removal was more pronounced at increased first-stage hydraulic loading rates as seen in Figure 23. It was also observed that increased hydraulic loadings coupled with increased influent SCOD concentrations had a less deleterious effect on SCOD removal. Again, the results suggest that increased hydraulic loadings had less impact in those RBC units where supplemental air was provided. Dupont and McKinney (40) investigated the relationship between hydraulic loading rate and percent BOD_5 removal. They indicated that there was a strong relationship between organic loading rates and removal rates, but the relationship between hydraulic loading rates and BOD_5 removal was not as statistically significant. Data obtained by other investigators (15, 31, 111) also support the results of Dupont and McKinney (40).

Ammonia nitrogen removal

The RBC system at this plant was designed only for carbonaceous substrate removal since there were no effluent ammonia nitrogen

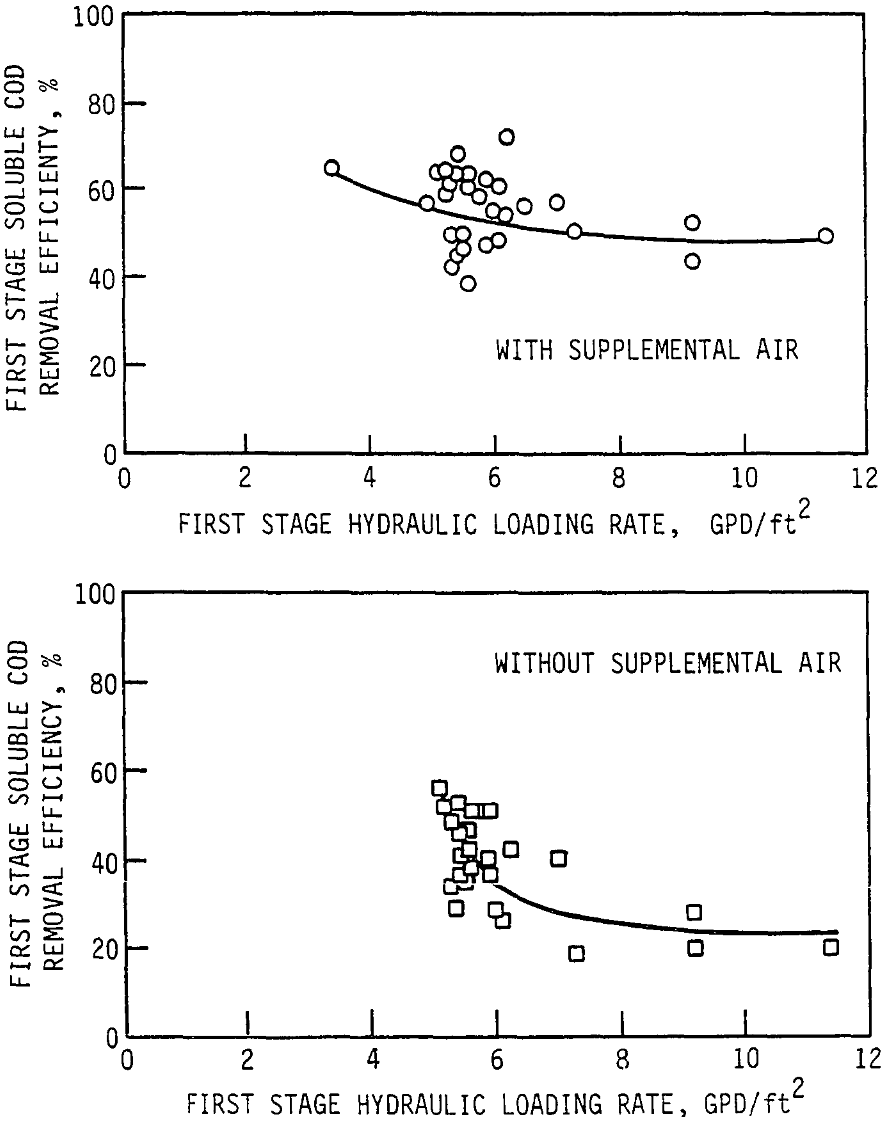
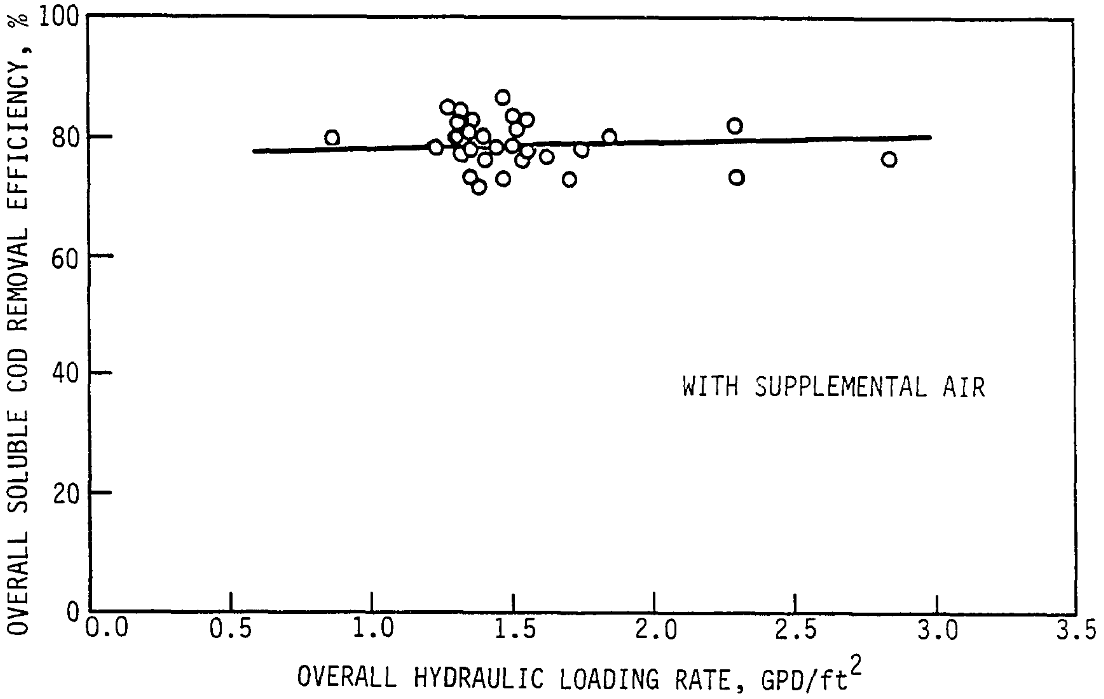


Figure 23. Percent soluble COD removal vs first-stage hydraulic loading rate during the Phase I study



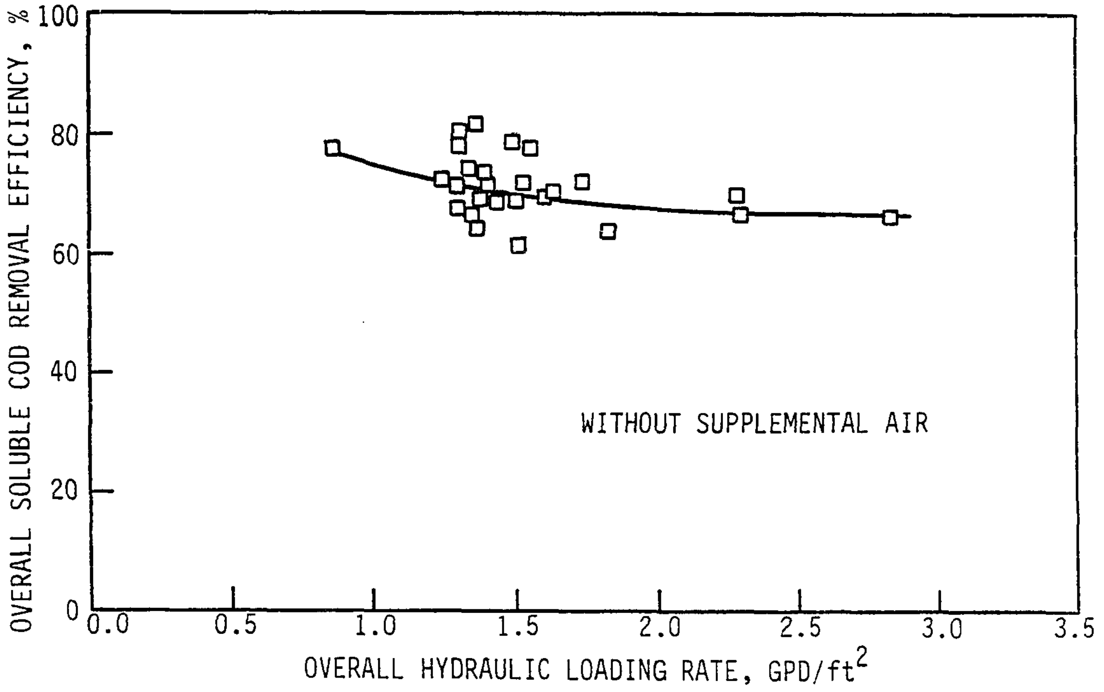


Figure 24. Percent soluble COD removal vs overall hydraulic loading rate during the Phase I study

requirements. However, the effluent ammonia nitrogen levels were monitored in each stage to determine the nitrification rates achieved with and without the supplemental air. The ammonia nitrogen concentrations in the primary effluent to the RBC units were shown earlier in Tables 3 and 4. These tables indicate that the mean influent ammonia nitrogen values varied between 22 and 25 mg/L.

Figures 25 and 26 show the relationship between stage effluent ammonia nitrogen concentrations and the corresponding percent removal under low and high organic loadings. The results in these figures indicate that effluent ammonia nitrogen concentrations decreased as the stage number increased. At lower loadings, the ammonia nitrogen removal with supplemental aeration was approximately 18 percent in the first stage and dropped to 8 percent in the second stage. Subsequently, the removal in the last two stages increased to 50 percent. This removal pattern suggests that most of the nitrification took place in the last two stages. Pano and Middlebrooks (92) also observed similar ammonia nitrogen removal patterns.

In the RBC units operated with supplemental aeration, the nitrification rate increased as the aeration startup acclimation period increased at the beginning of the Phase I study. In the first week after the installation of aeration equipment, the nitrification was insignificant, but it slowly increased in the second and third weeks, reaching a maximum of 95 percent removal at the end of the fifth week. Tables 13 and 14 show the summary of stage ammonia nitrogen concentrations and removal efficiencies. The results in Table 14 indicate

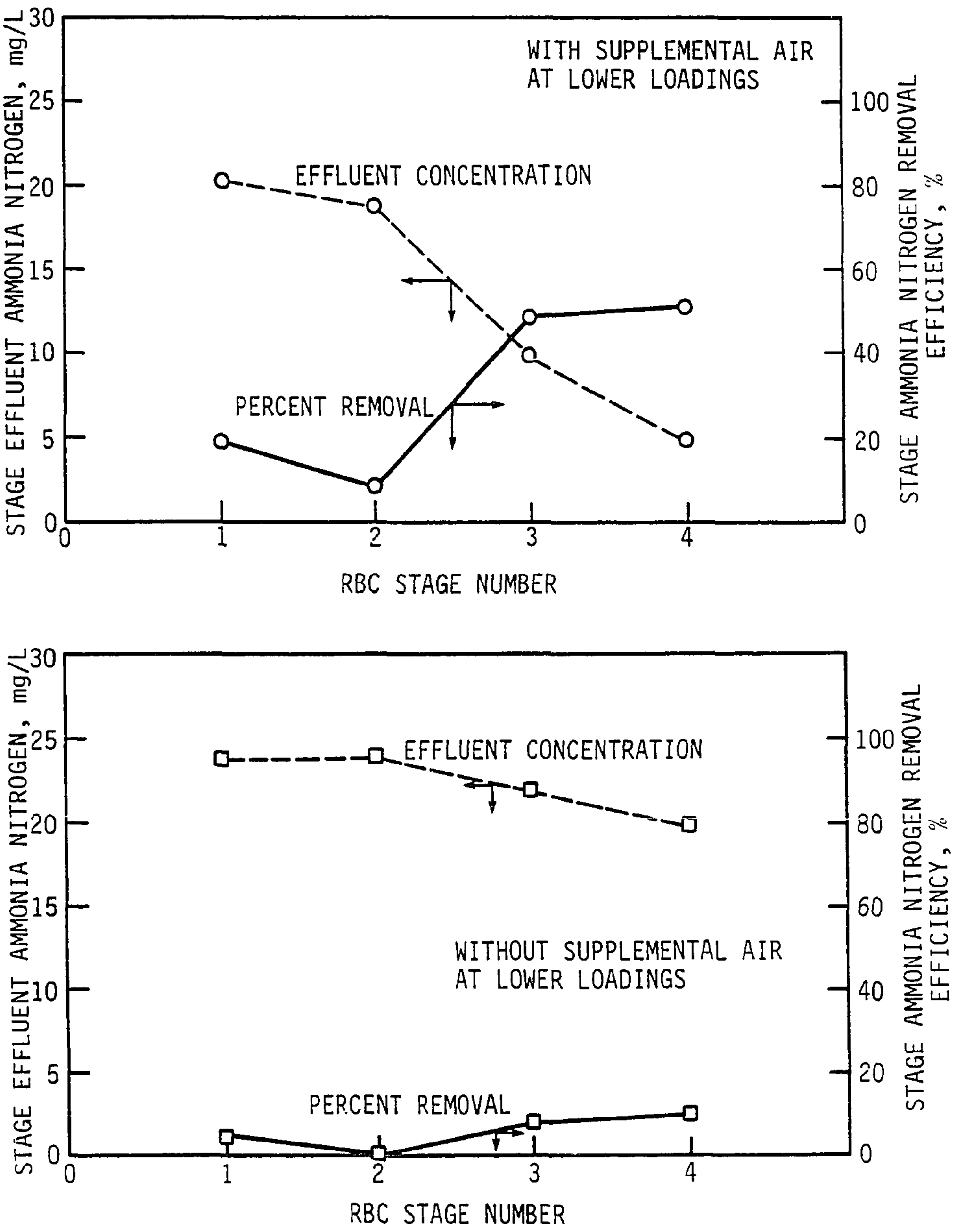
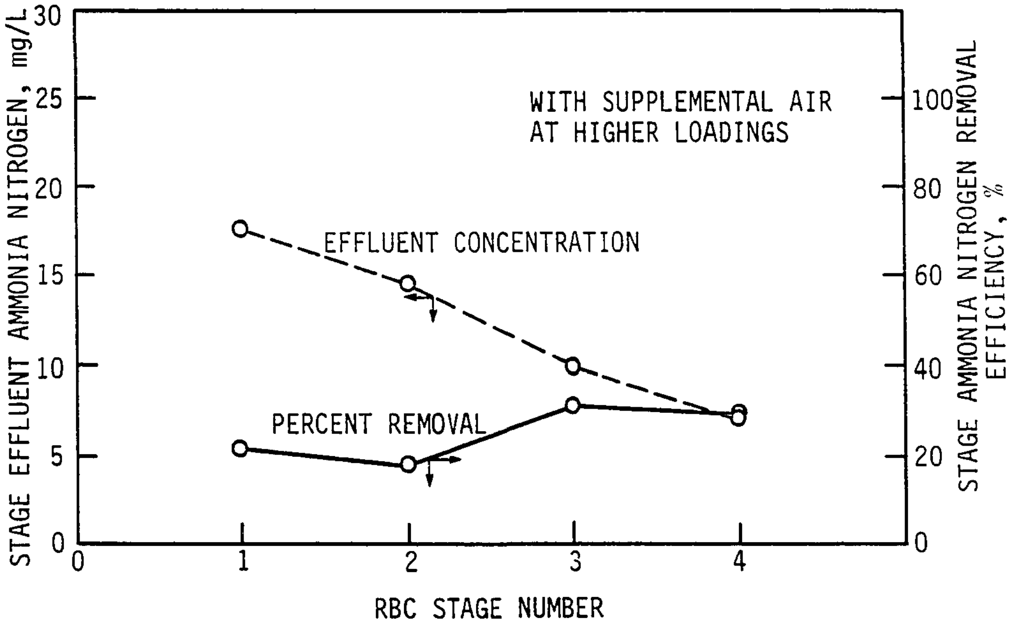


Figure 25. Stage effluent ammonia nitrogen concentration and removal efficiency profile at lower loadings during the Phase I study



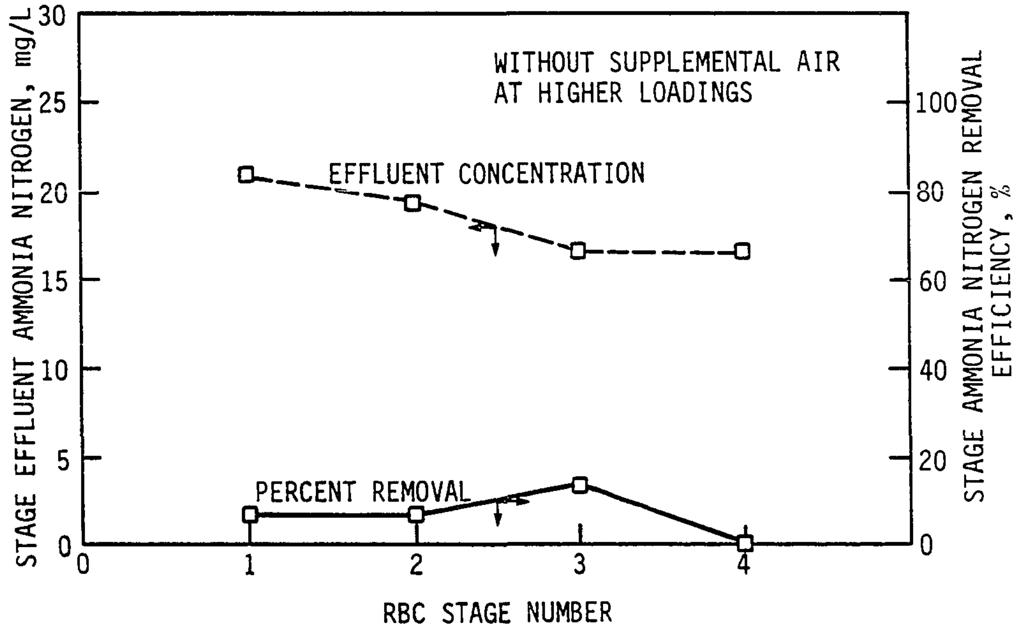


Figure 26. Stage effluent ammonia nitrogen concentration and removal efficiency profile at higher loadings during the Phase I study

that the overall ammonia nitrogen removal averaged 80.6 percent at low organic loadings with supplemental air. At the lower loadings, the carbon substrate was limiting after the first stage, this combined with the high dissolved oxygen concentrations enhanced nitrification in the north RBC units.

Nitrification in the absence of supplemental aeration was insignificant. Borchardt et al. (21) indicated that a minimum dissolved oxygen level of 3.5 mg/L was necessary to achieve nitrification in the first three stages. Their study was conducted to investigate trickling filter effluent nitrification using a four-stage RBC system. However, a minimum dissolved oxygen level of 2 mg/L is more often quoted as being necessary for nitrification. On the south (control) RBC units, the dissolved oxygen levels remained less than 1 mg/L most of the time. The little ammonia nitrogen removal that was observed in the control units could be due to ammonia stripping and assimilation. It has been reported (13) that, in combined carbon oxidation-nitrification RBC systems, up to 10 to 20 percent of incoming unoxidized nitrogen is utilized in the early stages to satisfy the cell growth requirements of the predominant heterotrophic population. Most of the nitrogen removal in the south units could be due to such assimilation. However, in the supplemental aeration units, the disappearance of ammonia nitrogen in the third and fourth stages was mainly due to ammonia conversion to nitrate rather than to heterotrophic metabolism. On an average, 1 mg/L of ammonia nitrogen was used in biomass synthesis when soluble COD of 39 mg/L was removed (120).

Table 13. Summary of stage ammonia nitrogen concentrations (mg/L) observed during the Phase I study

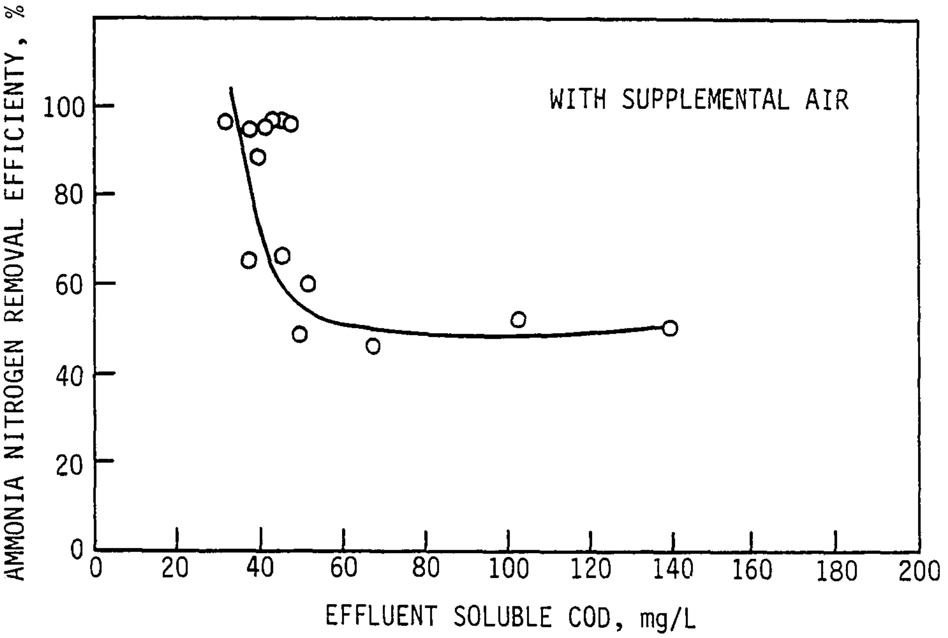
	With Supplemental Air						Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Stage 1	20.3	13-35	7.38	17.5	10-21	3.93	23.7	13-39	7.39	20.8	17-24	2.36
Stage 2	18.7	10-33	7.60	14.4	7-18	4.00	23.8	14-40	7.54	19.4	15-24	2.90
Stage 3	9.7	1-21	7.54	9.94	3-15	4.66	21.9	12-36	7.14	16.7	13.5-19	2.22
Stage 4	4.8	0.8-17	6.28	7.05	0.8-13	5.18	19.8	11-36	7.55	16.6	15-18	1.41

Table 14. Summary of ammonia nitrogen removal efficiencies (%) during the Phase I study

Stage	With Supplemental Air At Lower Loadings	With Supplemental Air At Higher Loadings	Without Supplemental Air At Lower Loadings	Without Supplemental Air At Higher Loadings
Stage 1	18.1	27.4	4.4	6.7
Stage 2	7.9	17.7	0.0	6.7
Stage 3	48.1	31.0	8.0	13.9
Stage 4	50.5	29.1	9.6	0.6
Overall	80.6	68.4	20.2	25.6

In general, the ammonia nitrogen concentrations in the control units fluctuated. Mostly, the concentrations increased in the first two stages. Analysis of other nitrogen parameters and the subsequent completion of a nitrogen balance indicated that volatilization of organic nitrogen and cell lysis contributed to the increased ammonia nitrogen levels. This means that the actual ammonia nitrogen removals in the RBC units receiving supplemental aeration are higher than indicated because the unaccounted for ammonia nitrogen due to volatilization was also oxidized in the process. Denitrification of nitrified ammonia nitrogen was also observed in the south RBC units, particularly at high organic loadings, when the dissolved oxygen levels were very low. Such observations were also made by others.

At increased organic loadings, ammonia nitrification was reduced even with supplemental air. This can be observed in Figure 26 and Table 14. The overall ammonia nitrogen removal with supplemental air was 68.4 percent. Again, the increased ammonia removals in the control units could be due to assimilation as the carbon substrate was not limiting in these stages because of high organic loadings. Figure 27 shows the ammonia nitrogen removal dependency on effluent soluble COD concentration. With supplemental air, ammonia nitrogen removal efficiency decreases as the effluent COD concentration increased above 50 mg/L and after that efficiency remained constant at higher COD concentrations. In the absence of supplemental air, the ammonia nitrogen removal efficiency remained constant at 25 percent irrespective of the effluent COD concentration. This could be due to two factors; at lower



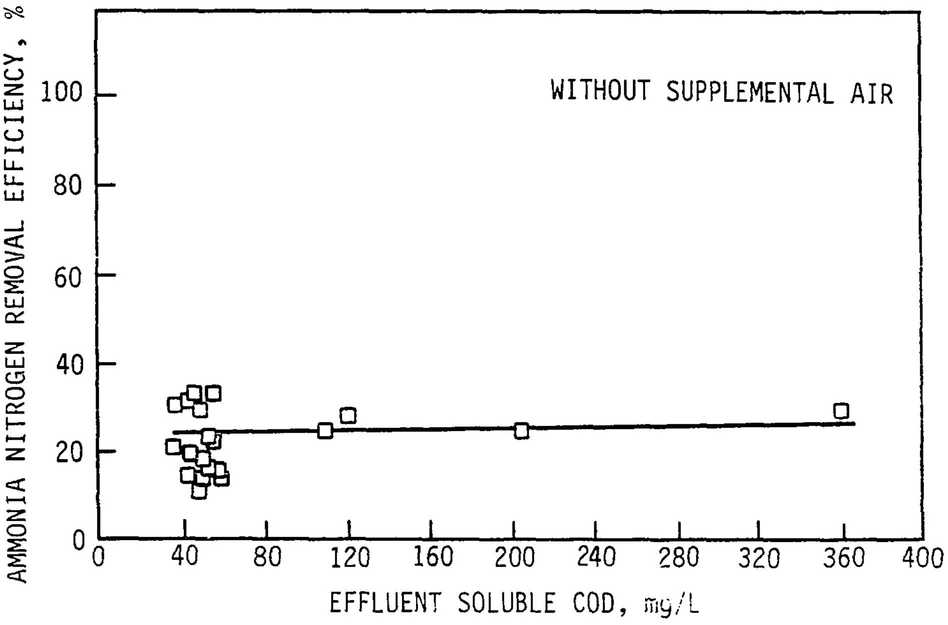


Figure 27. Percent ammonia nitrogen removal vs effluent soluble COD during the Phase I study

COD concentrations, oxygen was limiting and at higher concentrations, the intrusion of carbon substrate into the subsequent stages along with simultaneous oxygen limitation inhibited the growth of nitrifiers. It has been reported that, in the RBC process, the organic concentration transition point where nitrification is generally observed is approximately 15 mg/L of stage soluble BOD_5 or 30 mg/L of total BOD_5 (14, 142, 143).

The ammonia nitrogen removal rate as a function of the ammonia nitrogen loading rate is shown in Figure 28. Such relationships have been used extensively in the literature for investigation of RBC nitrification. The results and pattern of curves in Figure 28 suggest that, during nitrification, the kinetics followed approximately a zero order model. The approximate linear relationship observed in Figures 25 and 26 for stage ammonia nitrogen concentrations also support this contention. The rate of ammonia nitrification within an RBC stage is reported to follow zero to first order kinetics (8, 10, 62, 85, 107). It is reported (9) that, in full-scale RBC units, first order removal of ammonia nitrogen is observed at concentrations below 5 mg/L. At ammonia nitrogen concentrations above 5 mg/L, the removal is claimed to be zero order. Also, it has been reported that the maximum zero order removal rate was 0.3 lb NH_3-N/day/1000 sq ft above an ammonia nitrogen concentration of 5 mg/L (9).

The results in Figure 28 indicate that the maximum ammonia nitrogen removal rate with supplemental aeration was approximately 0.29 lb NH_3-N/day/1000 sq ft. However, the maximum zero order removal rate

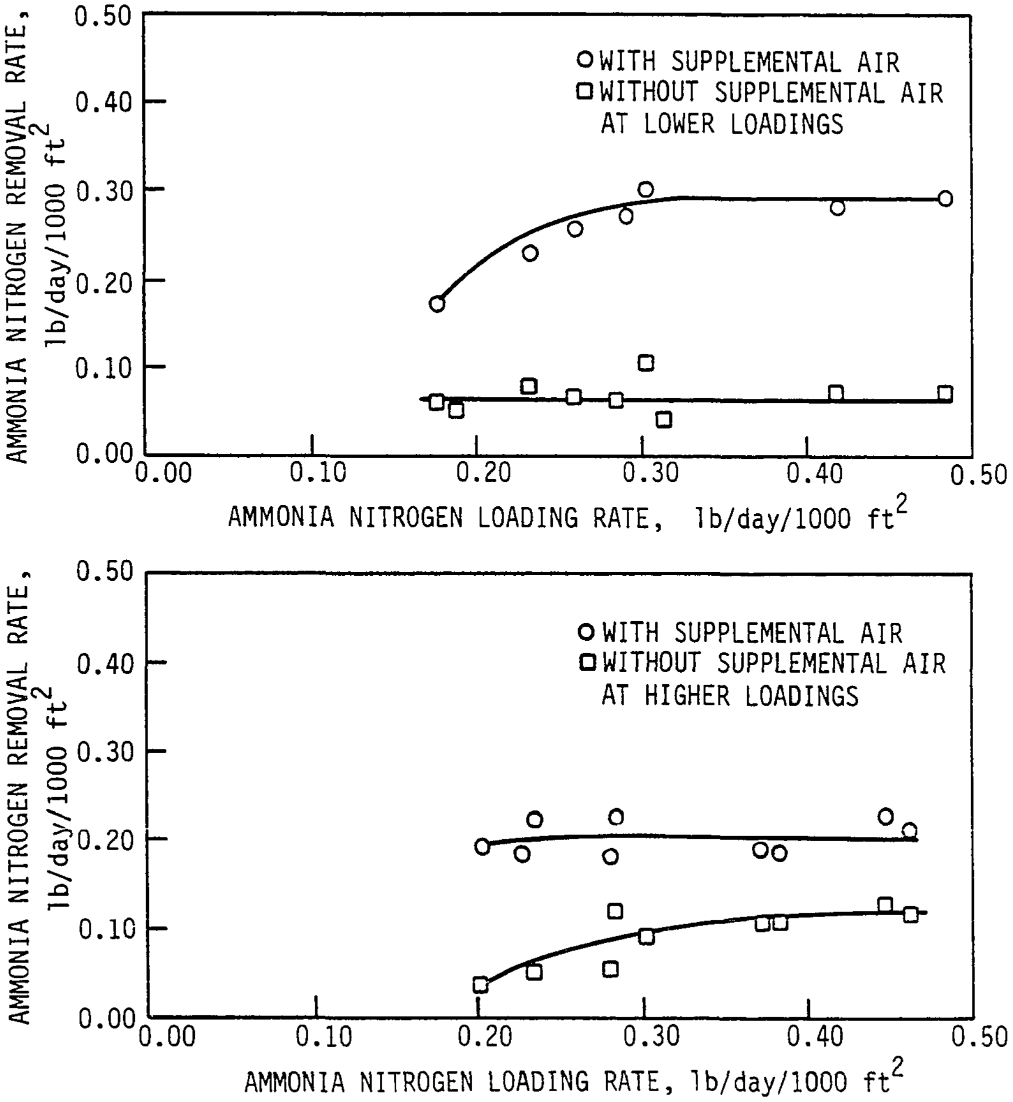


Figure 28. Overall ammonia nitrogen loading and removal rates during the Phase I study

without the supplemental air was only 0.065 lb NH_3-N/day/1000 sq ft due to oxygen limitations. At higher organic loadings, the removal rate with air decreased to 0.20 lb NH_3-N/day/1000 sq ft. In the absence of supplemental air, the ammonia nitrogen removal rate increased somewhat with increased organic loading rates as shown in Figure 27. However, this could be due to increased assimilation at the higher organic loadings.

Figure 29 shows the relationship between ammonia nitrogen removal efficiency and the overall hydraulic loading rate. An increased hydraulic loading rate had a significant impact on ammonia nitrogen removal efficiency in the north RBC units where supplemental air was provided. As hydraulic loading rates increased from 1.25 to 2.5 gpd/sq ft, there was a significant reduction in the ammonia nitrogen removal efficiency. Other investigators (143) also observed that increased hydraulic loading rate had a more pronounced effect on nitrogen removal than it did on the organic carbon removal. Increased hydraulic loading rates did not affect the ammonia nitrogen removal in the south RBC units due to oxygen-limiting conditions which kept ammonia nitrogen removal low anyway. However, the increased hydraulic loading rates enhanced the dissolved oxygen concentrations to a certain degree in the south control units.

In addition to the level of dissolved oxygen, ammonia nitrification depends on other environmental conditions such as wastewater temperature and pH. Figure 30 shows the pH profiles observed during the Phase I study. During both low and high organic loadings and both with and

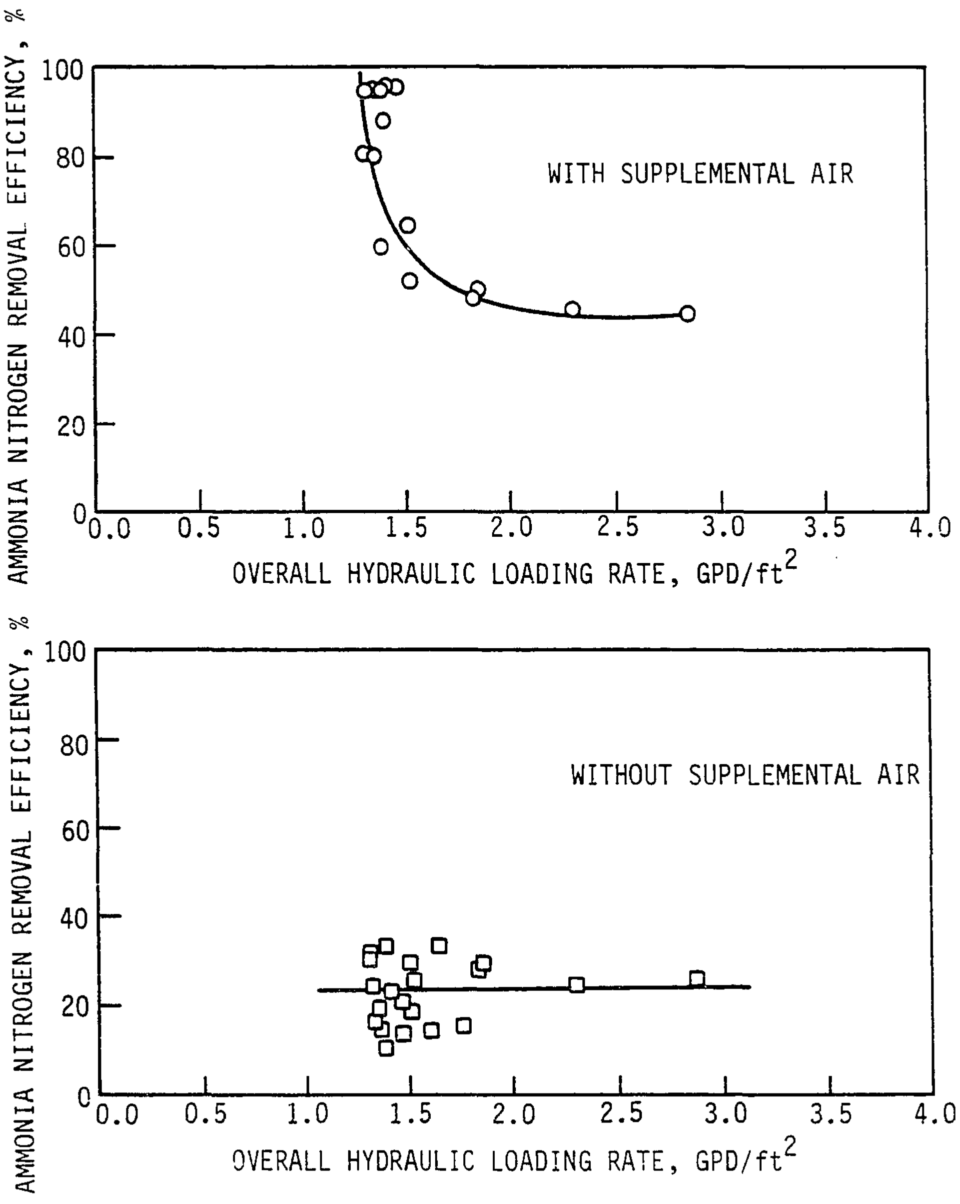


Figure 29. Ammonia nitrogen removal efficiency vs overall hydraulic loading rate during the Phase I study

without supplemental aeration, the pH values remained between 7 and 8. The pH values increased slightly as the wastewater passed through the stages, reaching a maximum value in the fourth stage. Also, the pH values were somewhat higher with supplemental aeration. Table 15 is a summary of the pH values measured in each stage. Theoretically, alkalinity destruction in the nitrification process is 7.14 mg (as $CaCO_3$)/mg of ammonia nitrogen oxidized. Total alkalinity of the incoming wastewater was always above 350 mg/L (as $CaCO_3$). Groundwater is the source of water supply in this city.

Figure 31 shows the percent soluble COD and ammonia nitrogen removed as a function of wastewater temperature. The data indicate that wastewater temperature had no effect on the percent removals since the wastewater temperature was always above 69°F. Antonie (10) reported that temperatures between 55°F to 85°F had no effect on the BOD_5 and ammonia nitrogen removals, but that the removals decreased at temperatures below 55°F.

Suspended solids and attached biomass characteristics

The importance of mixed liquor suspended solids in the activated sludge process has been well-documented. The higher the solids concentration, the higher the substrate removal rates. Kincannon and Groves (70) indicated that mixed liquor suspended solids in the RBC process should not be disregarded completely as these solids play an important role in substrate removal, particularly under low hydraulic loadings.

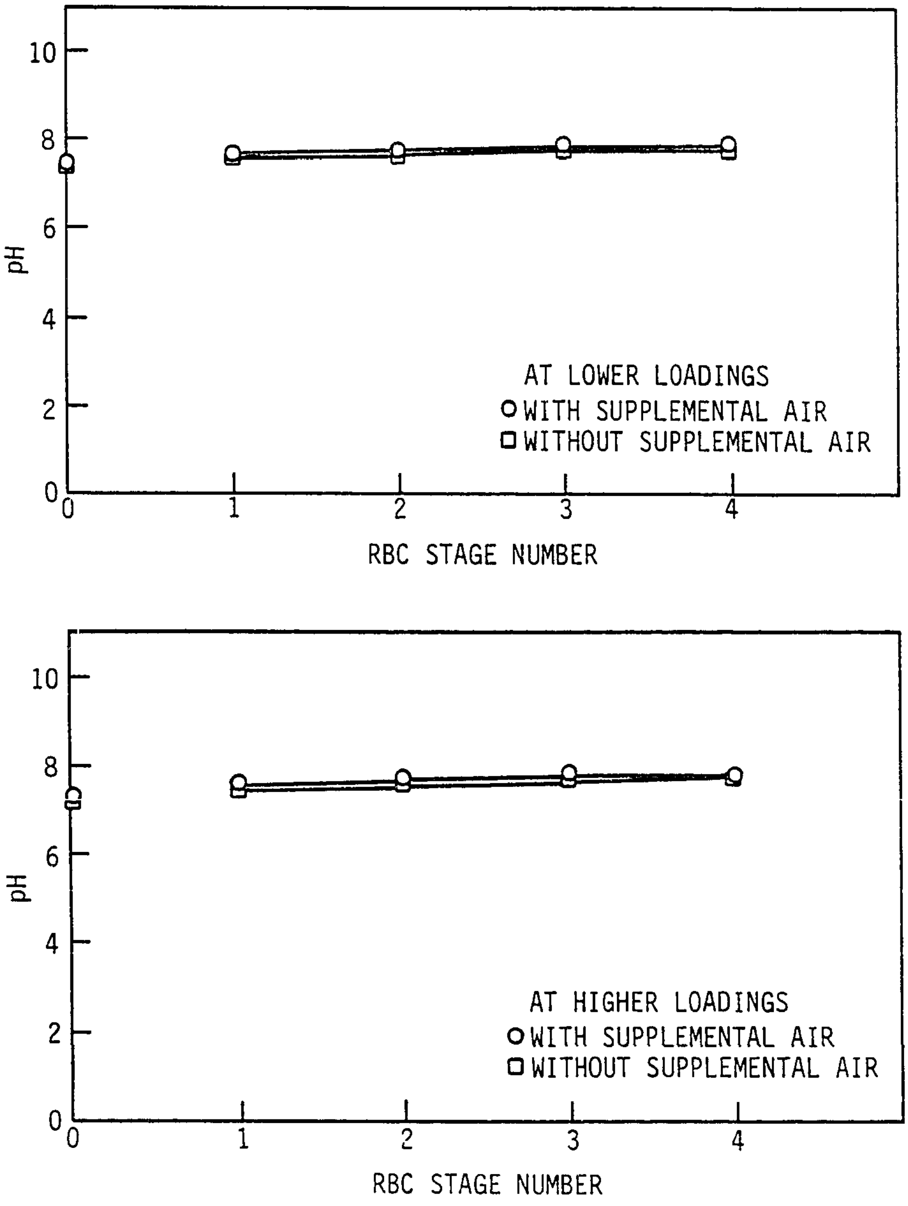


Figure 30. pH profile during the Phase I study

Table 15. Summary of pH values measured during the Phase I study

	With Supplemental Air						Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Stage 1	7.63	7.50-7.80	0.07	7.54	7.1-7.7	0.20	7.57	7.40-7.70	0.08	7.46	7.0-7.8	0.20
Stage 2	7.72	7.60-7.80	0.06	7.68	7.4-7.8	0.14	7.62	7.5-7.9	0.11	7.54	7.1-7.7	0.20
Stage 3	7.83	7.5-8.0	0.10	7.77	7.4-8.0	0.16	7.71	7.6-7.8	0.07	7.67	7.3-7.9	0.17
Stage 4	7.83	7.4-8.0	0.12	7.78	7.3-8.0	0.21	7.67	7.6-8.0	0.08	7.76	7.4-8.0	0.15

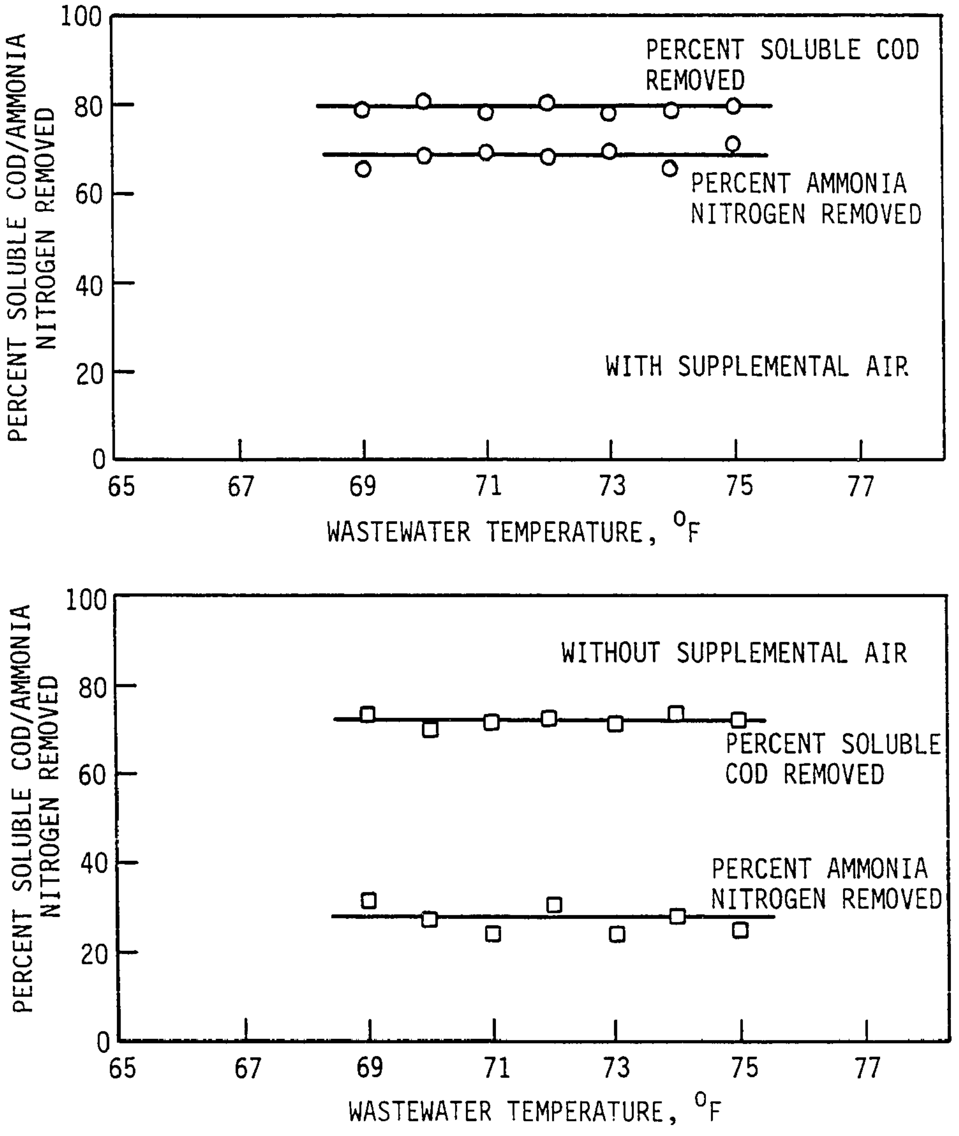


Figure 31. Percent SCOD/ammonia nitrogen removal vs temperature during the Phase I study

At lower hydraulic loadings, the hydraulic detention times increase allowing the suspended solids to remain in contact with the substrate for a longer time. This situation allows the suspended solids to play an active role in substrate removal in addition to that effected by the RBC fixed-film biomass. However, in this study the mixed liquor suspended solids played an important role at both high and low hydraulic loadings because of the significantly higher solids concentrations observed in the stages with supplemental aeration. The activity of these solids increased further because of the high mixed-liquor dissolved oxygen concentrations in the presence of the supplemental air.

Figures 32 and 33 show the measured total and volatile suspended solids profile, respectively, during the Phase I study. Generally, the suspended solids concentration decreased as the wastewater passed through the stages except in stage 3. At lower loadings, the mean influent suspended solids increased with supplemental aeration from approximately 105 mg/L to 327 mg/L in Stage 1. A similar level of increase was observed at higher loadings, but the influent suspended solids were higher due to reduced treatment at the dairy plant. The data in Table 16 indicate that mixed liquor suspended solids in stage 1 with supplemental aeration were as high as 694 mg/L at lower loadings. However, without the supplemental air the mean first-stage solids concentration remained less than 200 mg/L and the maximum never exceeded more than 350 mg/L. The higher, first-stage suspended solids were due to increased first-stage SCOD removals observed with the supplemental air.

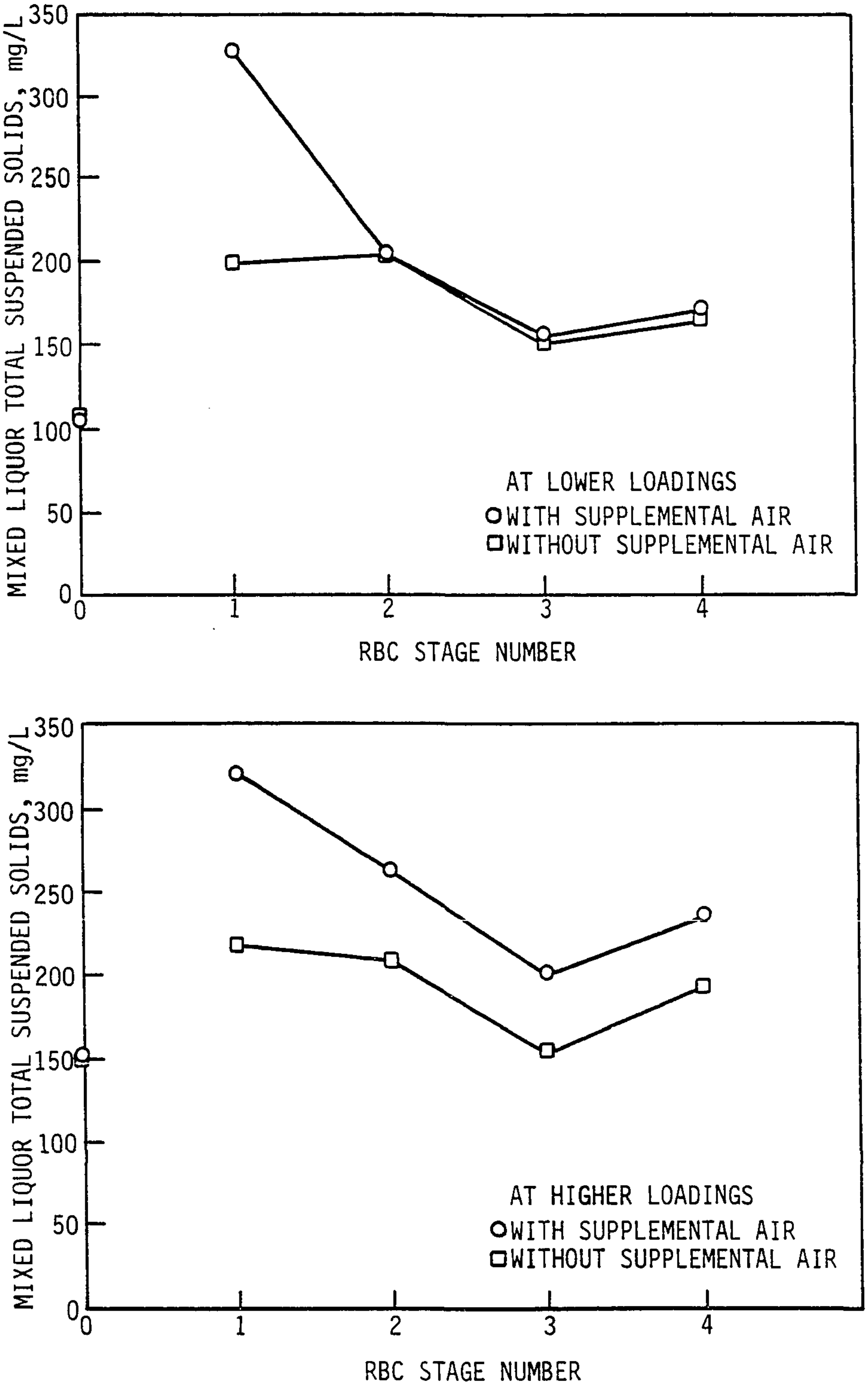


Figure 32. Total suspended solids profile during the Phase I study

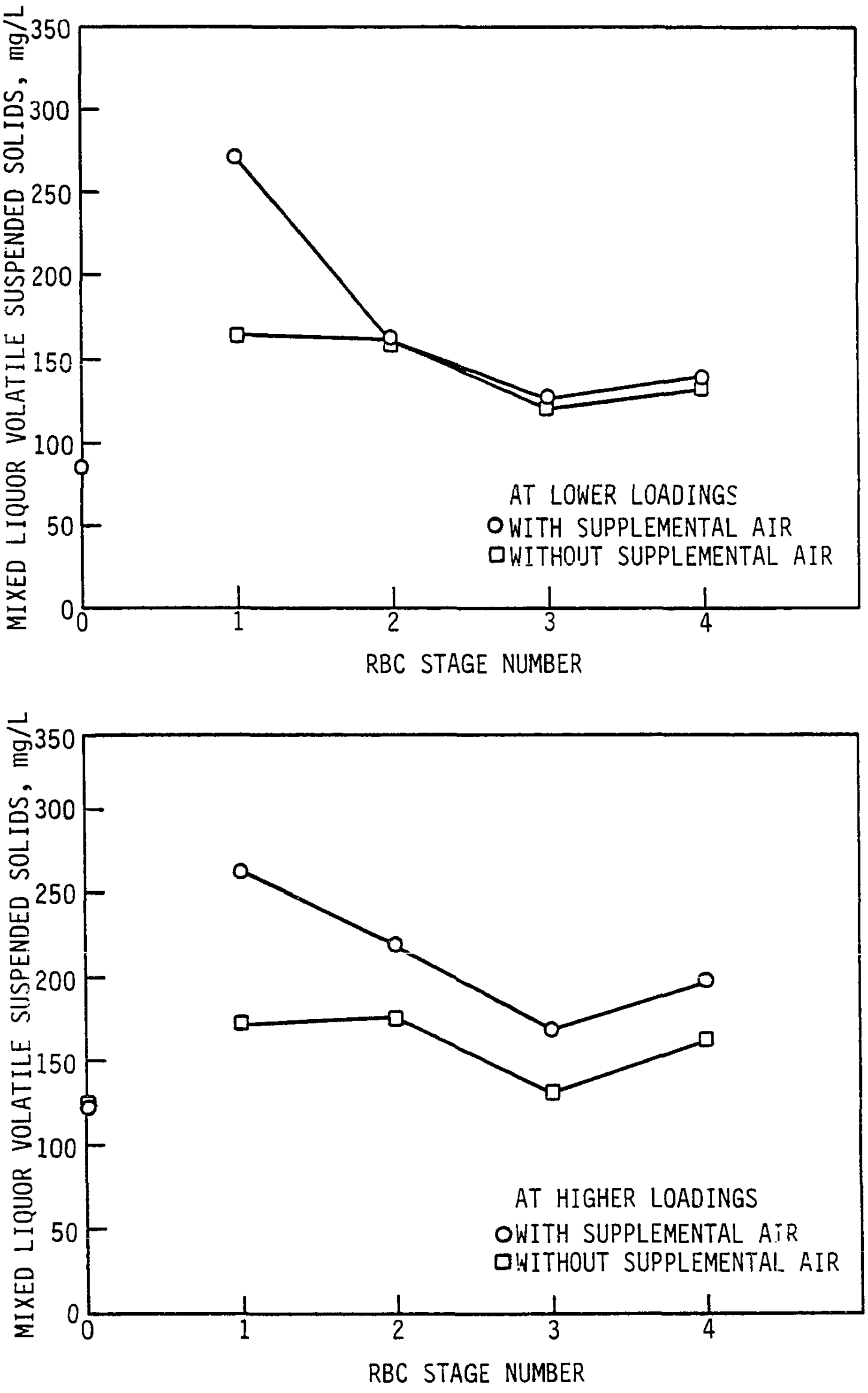


Figure 33. Volatile suspended solids profile during the Phase I study

Table 16. Stage total suspended solids (mg/L) observed during the Phase I study

	With Supplemental Air						Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Stage 1	327.2	72-694	183.7	321.6	178-826	213	197.9	76-350	70.8	217.4	113-298	75.4
Stage 2	203.6	92-436	71.3	263.6	184-464	97.7	204.3	103-330	76.2	208.3	102-358	96.6
Stage 3	155.0	84-250	51.7	201.2	112-544	122.6	151.3	108-226	64.9	154.2	98-195	33.0
Stage 4	171.3	86-340	77.6	236.8	96-610	146.4	165.0	61-274	55.9	193.9	100-432	89.6

The mixed-liquor suspended solids at lower loadings decreased in subsequent stages and remained approximately the same with and without supplemental air. Significant reduction in volatile suspended solids from stage 2 to stage 4, as shown in Figure 33, was due to stabilization in the later stages. At lower organic loading rates and higher temperatures, less organic substrate was available in these later stages. Most of the substrate was consumed in the first stage so these later stages stabilized the volatile biomass that was produced in the preceding stages. Table 17 summarizes the volatile suspended solids data observed during the Phase I study.

At higher loadings, the first-stage, mean mixed-liquor suspended solids concentration was approximately the same as was observed at lower loadings with supplemental air. However, the maximum concentration was as high as 826 mg/L. At higher organic loading rates, the volatile biomass stabilization in the later stages was not as significant as was observed at lower organic loading rates because of the availability of enough organic substrate in the subsequent stages. The volatile fraction of the mixed liquor suspended solids was approximately 80 percent, and was a little higher in the stages where supplemental air was not provided.

An important factor in biological wastewater treatment is the apparent sludge production. Table 18 shows a summary of the sludge production based on soluble COD removal, that is, pounds of sludge produced per pound of SCOD removed. At lower organic loading rates

Table 17. Stage volatile suspended solids (mg/L) observed during the Phase I study

	With Supplemental Air						Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Stage 1	271.0	52-576	153.9	263.0	146-669	169.4	165.6	48-308	62.0	172.4	78-244	57.2
Stage 2	160.8	76-294	45.2	218.9	151-367	76.9	161.3	94-261	55.5	175.5	80-304	82.1
Stage 3	126.3	70-190	40.6	169.2	78-468	107.1	120.0	70-172	51.5	131.2	75-172	40.9
Stage 4	139.6	70-302	60.2	197.8	88-512	119.5	132.2	51-219	43.4	163.3	85-354	75.2

the sludge production in stage 1 was approximately double with supplemental air as it was without the air. Again, this is because of the higher growth rates and higher SCOD removals with supplemental air. At higher organic loading rates, stage 1 sludge production was higher than that obtained without the air but significantly lower than that observed at lower loadings. With supplemental air, the mean SCOD removal efficiencies were 55.7 percent and 39.9 percent at low and high organic loading rates, respectively. This difference in removal efficiencies could explain the lower sludge production at higher loadings. The numbers in the parentheses in Table 18 indicate volatile sludge production.

The mean overall sludge production at lower loadings was 0.516 and 0.483 lb SS/lb SCOD removed with and without the supplemental air, respectively. At higher organic loading rates, the sludge production was 0.510 lb SS/lb SCOD removed with supplemental air and 0.547 without the air. These results suggest that the overall sludge production rates remained approximately the same under various loadings and operational modes. The little increase in overall sludge production at higher organic loadings in the absence of air was probably due to lower decay rates. Pano and Middlebrooks (92) reported mean sludge production rates of 0.550, 0.430 and 0.429 lb SS/lb SCOD removed at 5°C, 15°C and 20°C, respectively. The sludge production was based on pound of SS produced per pound of SCOD removed. Antonie (10) observed sludge production values of 0.5 to 0.6 based on pound of SS per pound of BOD_5 removed.

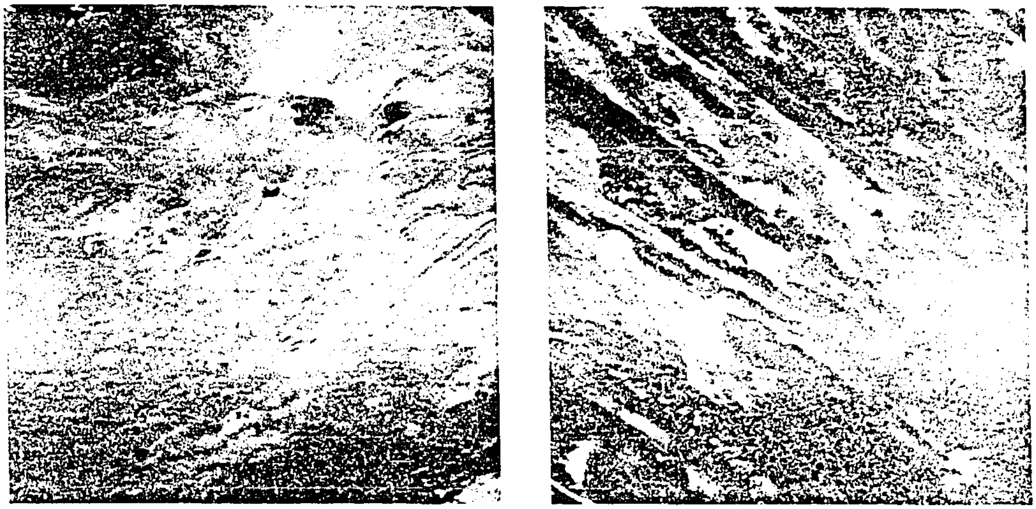
Table 18. Summary of sludge production based on soluble COD removal (lb SS/lb SCOD) during the Phase I study

Stage	With Supplemental Air At Lower Loadings	With Supplemental Air At Higher Loadings	Without Supplemental Air At Lower Loadings	Without Supplemental Air At Higher Loadings
Stage 1	2.404	1.004	1.259	0.835
	(2.033)[a]	(0.810)	(1.119)	(0.594)
Overall	0.516	0.510	0.483	0.547
	(0.440)	(0.430)	(0.395)	(0.482)

[a] Numbers in the parentheses indicate volatile sludge production.

The fixed-film biomass characteristics were noted regularly in both the south and north trains. The south RBC units where supplemental air was not provided had a heavy thick biomass and Beggiatoa growth was predominant in all stages. Figure 34 shows the attached biomass observed in the south train. It is clear from the pictures in Figure 34 that Beggiatoa (whitish) growth was predominant in all stages, particularly at higher organic loadings. Beggaitoa organisms, which use reduced sulfur as an energy source, compete with other heterotrophic organisms in the aerobic environment resulting in deterioration of process efficiency. It has been reported that these organisms become predominant whenever the incoming wastewater dissolved oxygen concentrations are low or when the loading to the first stage exceeds more than 2.5 lb $SBOD_5$/day/1000 sq ft (29, 121, 131).

In the RBC units receiving supplemental air, the fixed-film biomass in the first two stages was thin and grayish in color and, in the last two stages, the color changed to a brownish-red tan indicating growth of nitrifiers. The thinner biofilms have higher removal rates because they permit increased mass diffusion of substrate and oxygen within the biofilms. During the Phase I study, the mean biofilm thickness in stage 1 was 0.055 and 0.076 inch with and without the supplemental air, respectively. Without the supplemental air, the biofilm thickness as high as 0.110 inch was observed in stage 1 at higher organic loadings. The biofilm thickness in the fourth stage was 0.013 inch with supplemental air and 0.019 inch without the air. Hynek and Chou (64) related the first-stage biomass thickness to soluble BOD_5 removal. They



a. Stage 1

b. Stage 2

c. Stage 3

d. Stage 4

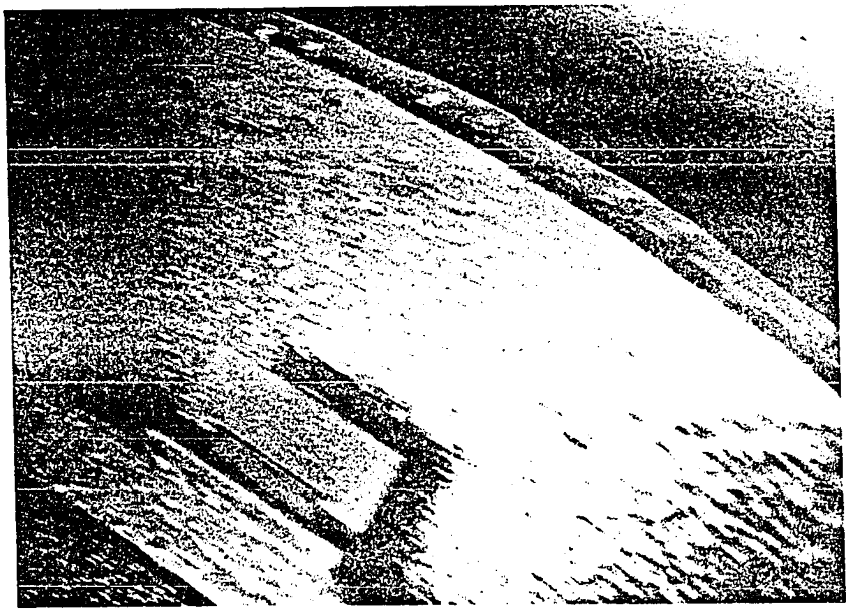
Figure 34. Attached biomass characteristics observed in RBC control units during the Phase I study

observed a soluble BOD_5 removal of 21 percent with a first-stage biofilm thickness of 0.110 inch. Generally, they observed that the BOD_5 removal decreased as the biofilm thickness increased.

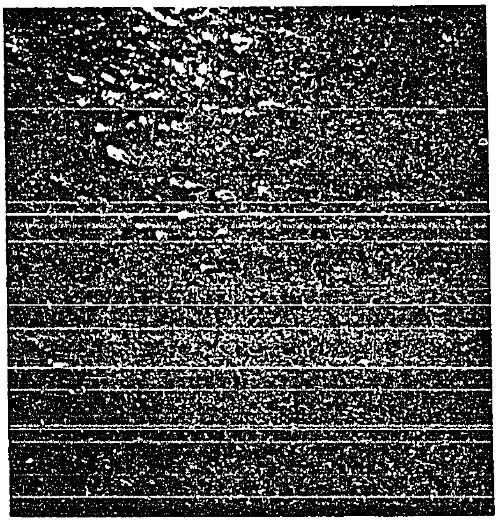
Figure 35 shows the first and the fourth-stage biomass characteristics in the presence of supplemental air in the north RBC units. At very high organic loading rates, the first stage of the north RBC train developed white patches indicating Beggiatoa growth, but these patches disappeared when the load to the first stage was decreased. At these very high organic loading rates, the brownish color nitrifying organisms in the third and to some extent in the fourth stage also disappeared because of the carbon substrate intrusion. However, the brownish color nitrifiers came back when the loadings were reduced. The fixed-film biomass characteristics observed during the Phase I study suggest that Beggiatoa growth can be eliminated completely and thinner active biomass can be established with the use of supplemental air, thereby enhancing substrate removal rates due to the increased mass diffusion of substrate and oxygen within the active biomass.

Performance During Phase II

During the Phase II study, the combined effectiveness of supplemental aeration and use of an enlarged first stage was investigated in the north RBC train. The south RBC train, also with an enlarged first stage, was used without supplemental aeration as a control to compare the results. Data obtained during the Phase I and Phase II studies are considered as four sets of results:



a. Stage 1



b. Stage 4

Figure 35. Attached biomass characteristics observed in RBC units receiving supplemental air during the Phase I study

performance with supplemental air; performance without supplemental air; performance with supplemental air and an enlarged first stage; and performance with an enlarged first stage only. In the discussions to follow, the results obtained from the Phase II study will be compared with the results obtained during the Phase I study. Phase II performance will be evaluated in the same way as was done in Phase I, that is, in terms of wastewater characteristics, kinetics, dissolved oxygen, SCOD removal, ammonia nitrogen removal, and suspended solids and attached biomass characteristics.

Wastewater characteristics

The influent wastewater characteristics during the Phase II study did not vary much from those observed during Phase I except for the SCOD concentration. Tables 19 and 20 list the influent wastewater characteristics observed during the Phase II study. At lower organic loadings, the RBC mean influent soluble COD was 239 mg/L and varied between 130 to 300 mg/L. During the Phase I study, the RBC mean influent soluble COD at lower loadings was 164 mg/L. This is lower than that observed in the Phase II study. At higher loadings, the influent soluble COD concentrations in the Phase II study were lower than those observed in the Phase I study. This was because of lower waste production at the dairy plant. The influent ammonia nitrogen concentrations were approximately the same in both phases; the mean values in

Table 19. RBC influent wastewater characteristics at lower loadings during the Phase II study

Parameter	Mean	Range	Standard Deviation
Flow, mgd	0.786	0.573-1.20	0.161
Soluble COD, mg/L	239.2	130-300	50.4
Ammonia-N, mg/L	22.1	20.5-26	2.1
SS-mg/L	182.0	100-332	55.2
VSS-mg/L	133.6	85-249	41.2
DO-mg/L	1.00	0.60-1.30	0.22
pH	7.17	7.00-7.35	0.09
Temperature, °F	68.5	66-70	1.50

Table 20. RBC influent wastewater characteristics at higher loadings during the Phase II study

Parameter	Mean	Range	Standard Deviation
Flow, mgd	0.706	0.407-0.935	0.138
Soluble COD; mg/L	362.5	270-540	76.4
Ammonia-N, mg/L	20.4	15.5-25.0	3.5
SS-mg/L	207.6	146-348	52.9
VSS-mg/L	159.5	109.5-233.2	33.6
DO-mg/L	1.02	0.90-1.30	0.12
pH	7.06	6.8-7.2	0.10
Temperature, °F	66.9	63-70	2.10

Phase II were in the range of 20 mg/L. Again, the higher suspended solids at higher organic loadings are due to reduced wastewater pretreatment at the dairy plant.

Mean influent dissolved oxygen concentrations at both the low and the high organic loadings remained at 1 mg/L. At lower loadings, the influent dissolved oxygen concentrations in Phase II were somewhat lower than those observed in Phase I but this could be due to observed higher influent COD concentrations in Phase II. The influent mean pH values in Phase II were above 7 and the standard deviation was approximately 0.10 pH unit. Phase II wastewater temperatures were lower than in Phase I but not sufficiently lower to affect the process efficiency. The wastewater temperatures varied between 66 and 70°F at lower loadings; at higher organic loadings, they varied from 63 to 70°F. During Phase I, the wastewater temperature was always above 70°F.

Kinetics

Kinetic models for zero order, first order and second order substrate removal were described earlier. In the Phase II study, after monitoring the stage soluble COD concentrations, an attempt was made to fit the obtained mean data into various kinetic models. Figures 36, 37 and 38 show the plots for first-order, zero-order and second-order kinetics, respectively.

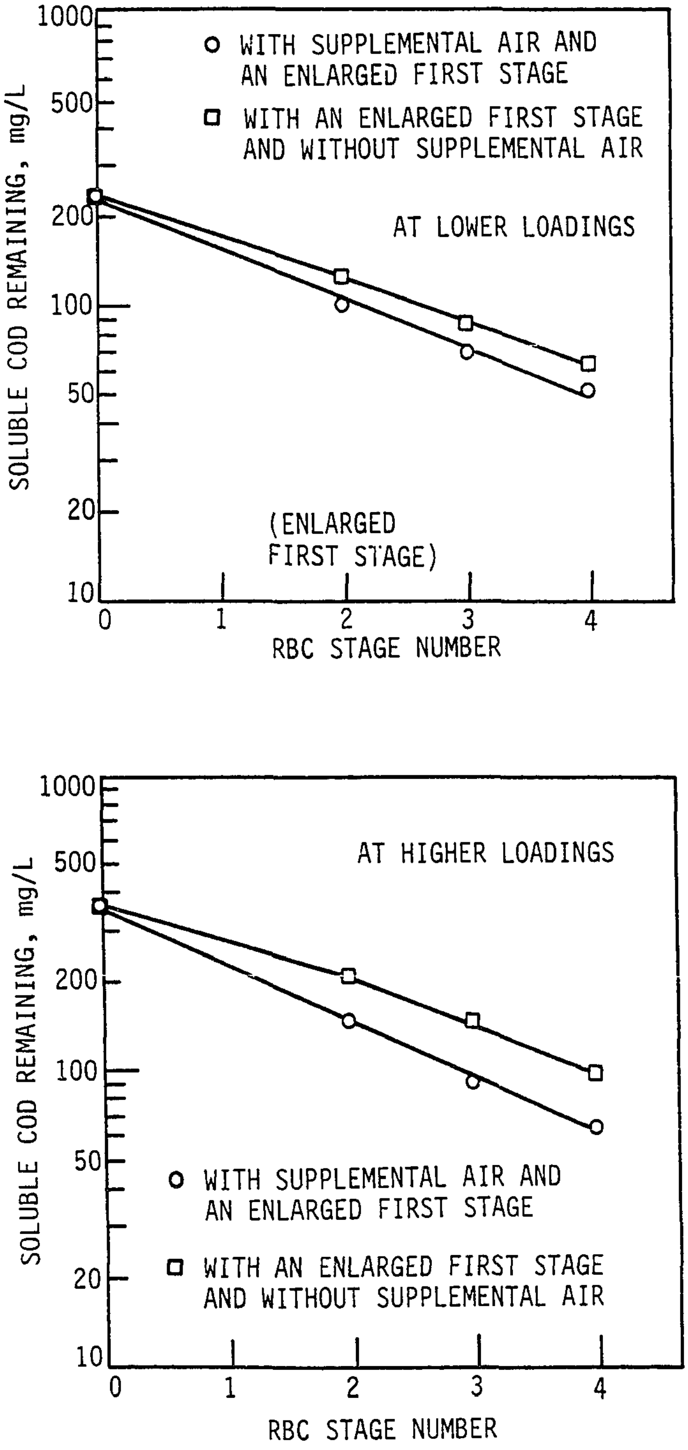


Figure 36. Log soluble COD remaining vs stage for first order kinetics during the Phase II study

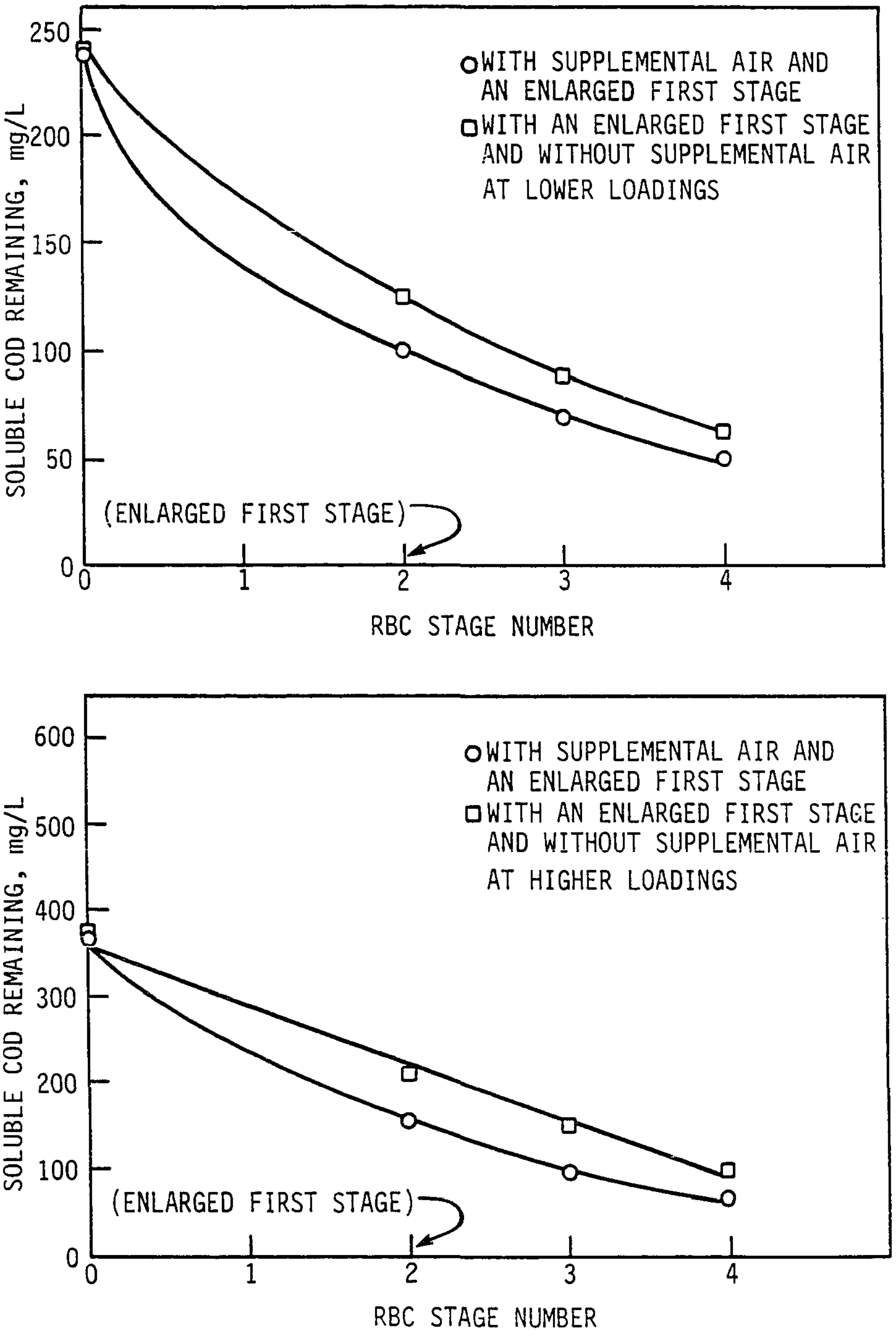


Figure 37. Soluble COD remaining vs stage for zero order kinetics during the Phase II study

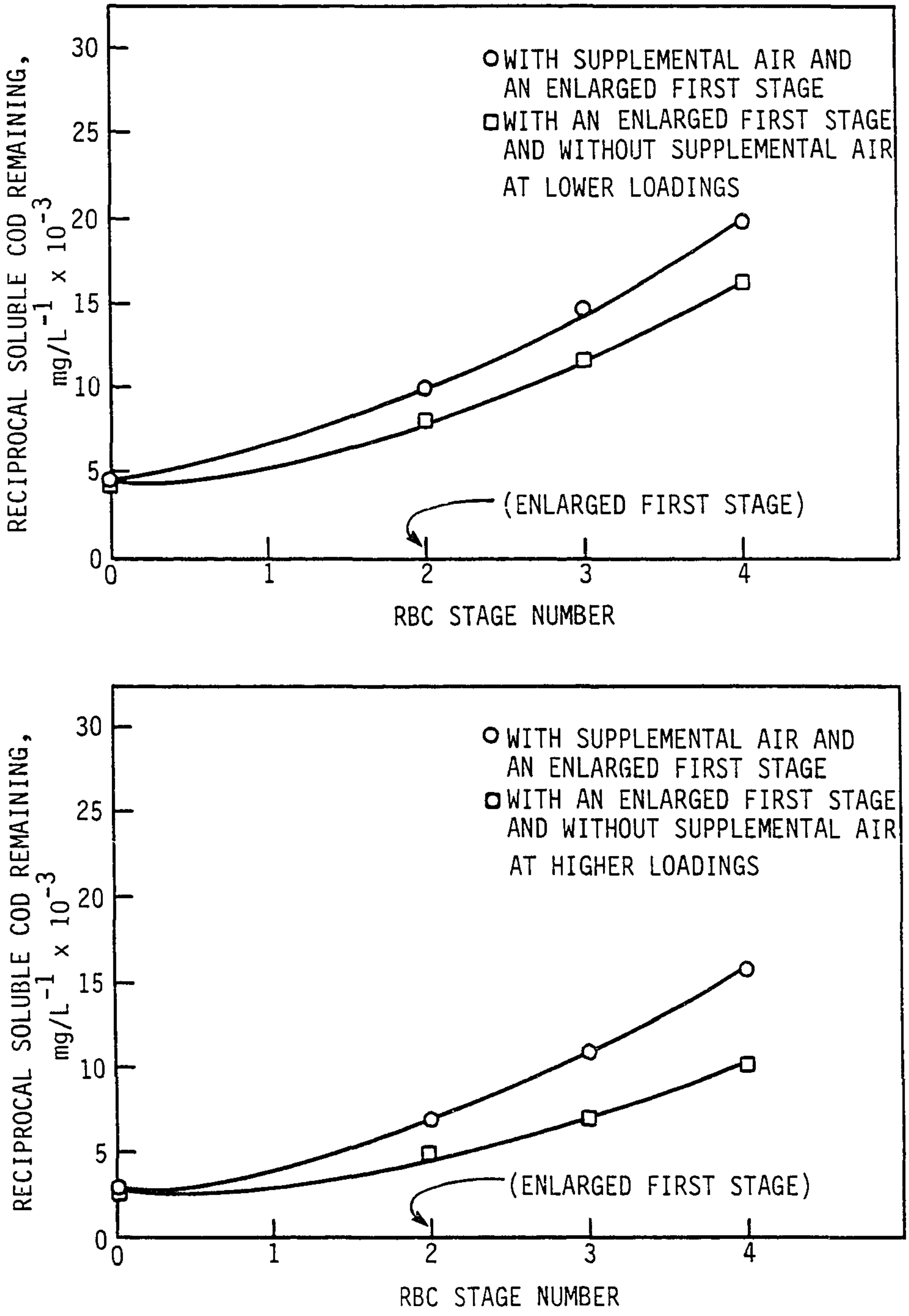


Figure 38. Reciprocal of soluble COD remaining vs stage for second order kinetics during the Phase II study

It can be seen from these plots that the data from both the south and the north RBC units fit a first-order model at lower organic loadings. In the Phase I study, first order kinetics were observed only in the units where supplemental air was provided and second order kinetics were observed without the supplemental air. At lower loadings, the influent soluble COD concentrations in Phase II were higher than those observed in Phase I. However, the observed first-order kinetics without the air were due to the enlarged first stage that divided the incoming load more evenly among the first two stages rather than on the first stage itself. Also, the mixed-liquor dissolved-oxygen levels increased to a certain extent because of the reduced load on the enlarged first-stage. The mixed-liquor dissolved-oxygen concentrations will be discussed further in the subsequent section. However, the slopes of these linear relationships showing first-order kinetics are different, as seen in Figure 36, suggesting that steeper slope with supplemental air indicates higher substrate removal.

Figure 37 shows that under higher organic loadings, zero-order kinetics were observed with the enlarged first stage without supplemental aeration. However, the north RBC units with supplemental air and an enlarged first stage indicate first-order substrate removal, as observed in Figure 36. Similar kinetics were observed in the Phase I study at higher organic loadings with and without the supplemental air. In the Phase II study, the zero-order kinetics observed in the absence of air at higher organic loadings suggest that baffle removal to create an enlarged first stage to lower the organic load was not sufficient to overcome the oxygen limitation problem. In the north RBC units, this oxygen limitation at higher loadings was eliminated with the use of the supplemental air.

The results in this study suggest that supplemental air in the initial RBC stages, where the organic loadings are high, is essential to overcome potential oxygen limitations at both low and high organic loading rates. The use of an enlarged first stage is helpful to some extent at lower organic loading rates, but, at higher loading rates, the use of an enlarged first stage only will not be enough to overcome oxygen limitation problems.

Dissolved oxygen

The mixed-liquor dissolved oxygen concentration in the Phase II study generally increased as the wastewater passed through the stages. Similar phenomena were observed in the Phase I study. Figure 39 shows the mixed-liquor dissolved oxygen profile observed during Phase II. At lower organic loading rates, the measured dissolved oxygen levels without supplemental air were approximately the same in both phases. However, the influent soluble COD concentrations were higher in Phase II, which indicated that creating an enlarged first stage did help to increase the dissolved oxygen concentration to some extent. With supplemental air and an enlarged first stage, the mixed-liquor dissolved oxygen concentrations at lower loadings were somewhat lower in the later stages than those observed with the supplemental air alone in Phase I. Again, this could be due to higher influent soluble COD

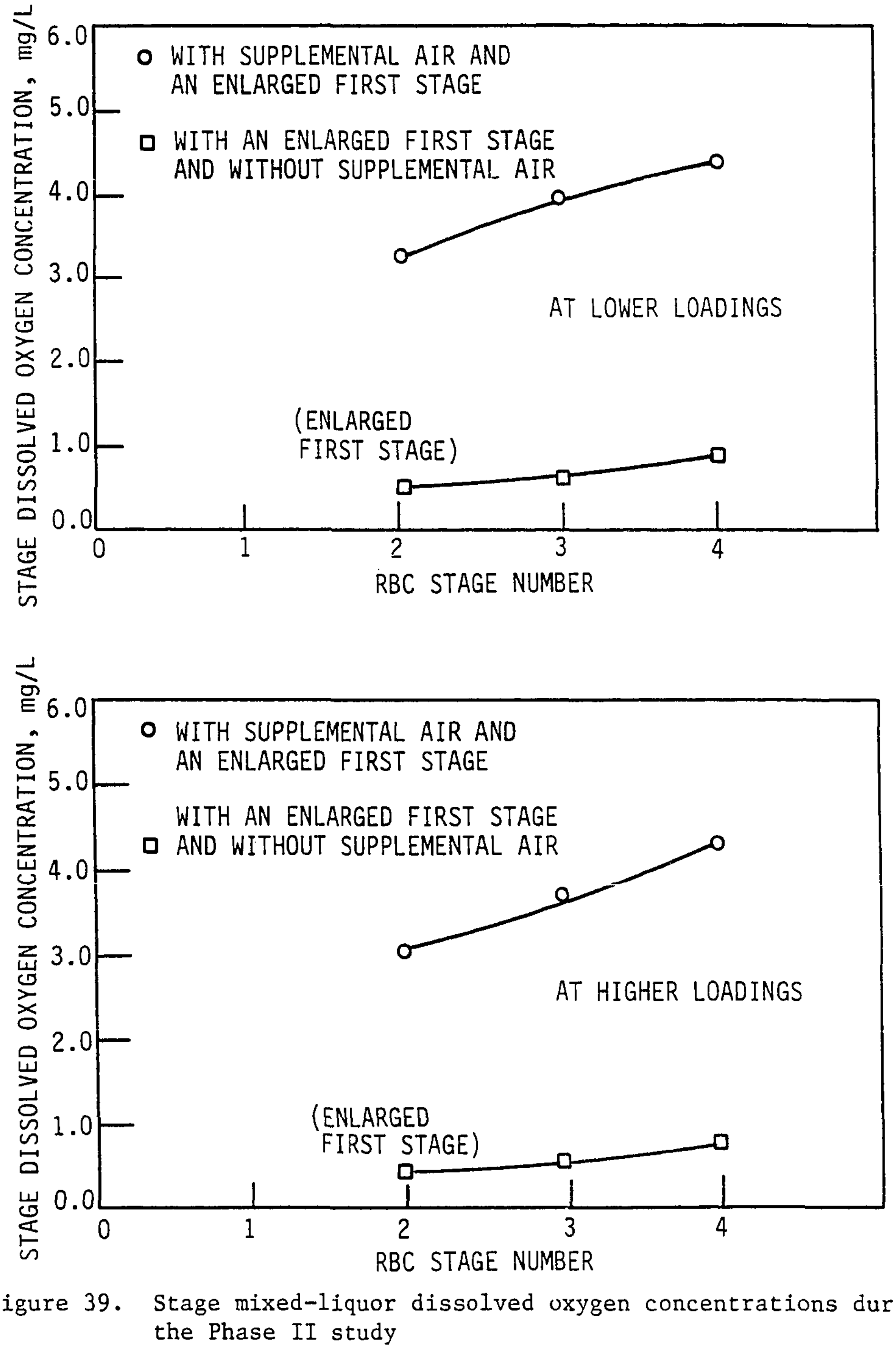


Figure 39. Stage mixed-liquor dissolved oxygen concentrations during the Phase II study

concentrations in the Phase II study. Creation of an enlarged first stage in the south RBC train reduced Beggiatoa growth to a certain degree, but such growths were still present in all stages. Table 21 lists the mixed-liquor dissolved oxygen concentrations recorded during the Phase II study.

At higher organic loading rates, the mixed-liquor dissolved oxygen levels in the Phase II study were higher than those observed in the Phase I study. This could be due to an enlarged first stage that reduced the organic loading to the first stage. With supplemental air and an enlarged first stage, the dissolved oxygen in the first, third and fourth stages were 3.05, 3.69 and 4.30 mg/L, respectively. During the Phase I study, with supplemental air alone, the dissolved oxygen levels were 1.48, 2.86 and 4.03 mg/L, respectively, in first, third and fourth stages as shown in Figure 11. Higher dissolved oxygen levels with an enlarged first stage suggest that RBC step feeding would be helpful to overcome oxygen-limiting conditions at higher loadings.

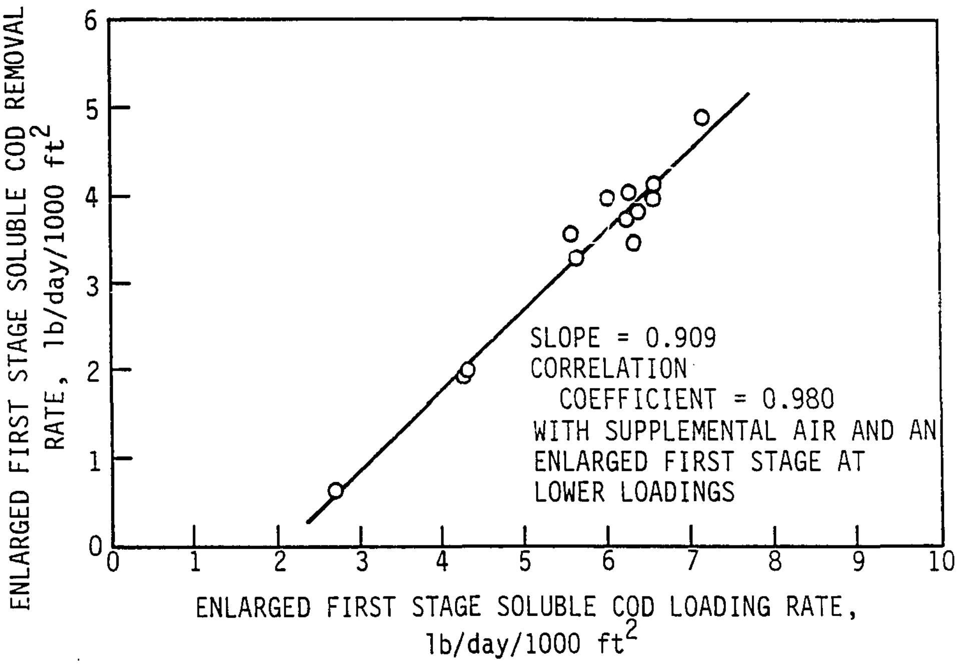
Soluble COD removal

In this section soluble COD removal at low and high organic loading rates will be discussed separately, as was done in discussion of the Phase I study results. Figure 40 shows the relationship between the enlarged first-stage applied SCOD load and its removal at lower organic loadings. It can be seen that linear relationships were observed both with and without the supplemental air and the correlation coefficients were high. However, the soluble COD removal rates were higher

Table 21. Summary of stage dissolved oxygen concentrations (mg/L) in the Phase II study

	With an Enlarged First Stage and With Supplemental Air						With an Enlarged First Stage and Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Enlarged[a] Stage 1	3.26	2.0-4.2	6.43	3.05	1.95-4.0	0.74	0.52	0.30-1.15	0.23	0.41	0.30-0.70	0.14
Stage 3	3.95	2.3-4.7	0.72	3.69	1.8-4.6	0.89	0.66	0.30-1.50	0.30	0.54	0.40-0.90	0.22
Stage 4	4.42	2.3-5.3	0.80	4.30	2.7-6.0	1.00	0.92	0.70-1.70	0.28	0.75	0.30-1.10	0.25

[a] Stage 1 and 2 combined.



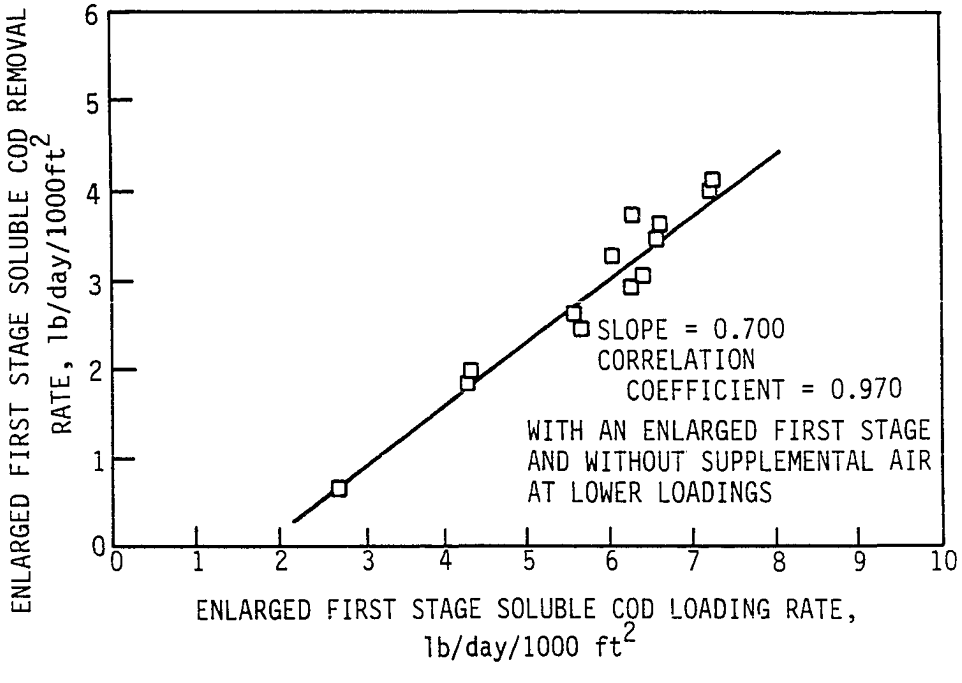


Figure 40. Enlarged first-stage soluble COD removal vs loading at lower loadings during the Phase II study

with supplemental air due to the higher available dissolved oxygen levels in the various stages. The slopes of these linear relationships were 0.909 and 0.700 with and without the supplemental air, respectively. The steeper slope observed with supplemental air indicates higher removal rates. Table 22 summarizes the soluble COD removal rate data observed at lower organic loadings. At a loading rate of 3 lb SCOD/day/1000 sq ft, the removal rates were approximately the same with and without supplemental air. However, the removal rates increased in the presence of air as the organic load increased. At a maximum loading rate of 7.5 lb SCOD/day/1000 sq ft, the removal rate with supplemental air was 4.93 lb SCOD/day/1000 sq ft, whereas, without the air, the removal rate was only 4.07 lb SCOD/day/1000 sq ft.

The overall organic loadings removal relationships were once again linear with high correlation coefficients, as shown in Figure 41. The curve slope was 0.989 with supplemental air and 0.900 without supplemental air. The overall soluble COD removal rates shown in Table 23 suggest that there was not much difference in removal rates with and without the air. Similar observations were made at lower organic loading rates during the Phase I study. This is due to existence of substrate limiting conditions after the first stage, as most of the SCOD removal takes place in the enlarged first stage. It was indicated earlier that the SCOD removal kinetics at lower organic loadings were first order both with and without the supplemental air.

Table 22. Enlarged first stage soluble COD removal rates at lower loadings during the Phase II study

	With an Enlarged First Stage and With Supplemental Air		With an Enlarged First Stage and Without Supplemental Air	
Soluble COD Loading Rate lb /day/1000 ft^2	Soluble COD Removal Rate lb /day/1000 ft^2	Percent Removal	Soluble COD Removal Rate lb /day/1000 ft^2	Percent Removal
3.0	0.85	28.3	0.87	29.0
3.5	1.30	37.1	1.25	35.7
4.0	1.75	43.8	1.60	40.0
4.5	2.22	49.3	1.95	43.3
5.0	2.67	53.4	2.30	46.0
5.5	3.13	56.9	2.65	48.2
6.0	3.57	59.5	3.00	50.0
6.5	4.00	61.5	3.35	51.5
7.0	4.47	63.9	3.70	52.9
7.5	4.93	65.7	4.07	54.3

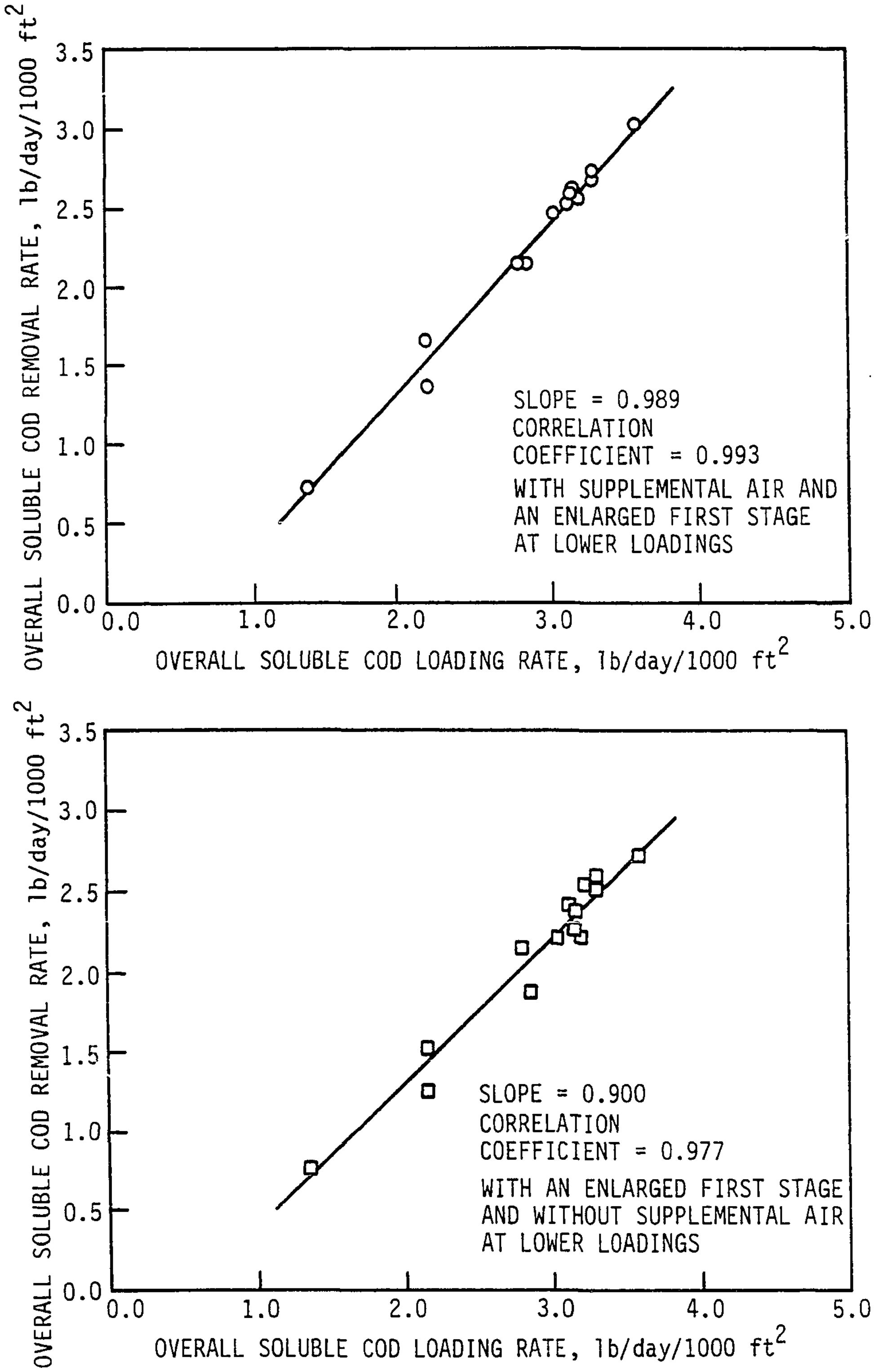


Figure 41. Overall soluble COD removal vs loading at lower loadings during the Phase II study

Table 23. Overall soluble COD removal rates at lower loadings during the Phase II study

	With An Enlarged First Stage and With Supplemental Air		With an Enlarged First Stage and Without Supplemental Air	
Soluble COD Loading Rate lb /day/1000 ft^2	Soluble COD Removal Rate lb /day/1000 ft^2	Percent Removal	Soluble COD Removal Rate lb /day/1000 ft^2	Percent Removal
1.25	0.60	48.0	0.62	49.6
1.50	0.85	56.7	0.85	56.7
1.75	1.11	63.4	1.08	61.7
2.00	1.37	68.5	1.30	65.0
2.25	1.62	72.0	1.53	68.0
2.50	1.88	75.2	1.77	70.8
2.75	2.13	77.5	1.98	72.0
3.00	2.39	79.7	2.21	73.7
3.25	2.65	81.5	2.44	75.1
3.50	2.90	82.9	2.67	76.3
3.75	3.16	84.3	2.90	77.3

Table 24 is a summary of stage soluble COD concentrations measured during Phase II. Earlier, in Figures 15 and 16, relationships were established between influent and effluent SCOD and $SBOD_5$.

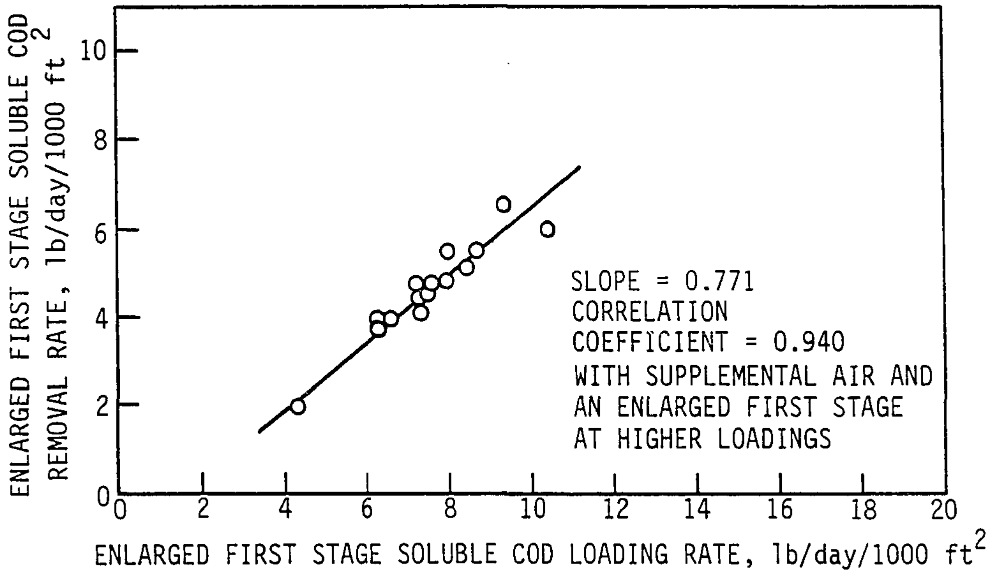
Enlarged first stage soluble COD removal rates were found to be higher with supplemental air at both the higher and lower organic loading rates. Figure 42 shows the relationship between the enlarged first stage soluble COD loading and removal at the higher organic loadings. The relationships were linear with and without the air. It is important to recognize that, without the baffle removal, the organic load in the first stage could have been double the observed load in the enlarged first stage. The baffle removal allows the incoming organic load to be distributed evenly to the first two stages. For example, a load of 10 lb SCOD/day/1000 sq ft in the enlarged first stage is equal to a load of 20 lb SCOD/day/1000 sq ft in the first stage without the baffle removal.

The linear relationship in Figure 42 also indicates that the slope with supplemental air was significantly higher than without the air, indicating higher COD removal rates with air. Table 25 shows the enlarged first stage soluble COD removal rates with and without the supplemental air at higher organic loadings. The results in this table suggest that as the organic loading increased, the SCOD removal rate in the absence of air decreased. Without the supplemental air, percent removal remained the same above a loading rate of 5 lb SCOD/day/1000 sq ft suggesting oxygen limitation at increased loadings. However, with air, the percent removal increased as the organic loading

Table 24. Summary of stage soluble COD concentrations (mg/L) observed during the Phase II study

	With an Enlarged First Stage and With Supplemental Air						With an Enlarged First Stage and Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D.	Mean	Range	S.D.	Mean	Range	S.D.
Enlarged[a] Stage 1	99.8	71.5-135	19.8	148.8	91-240	50.6	124.5	70.5-165	24.9	203.7	130-340	58.6
Stage 3	68.0	56-88	9.8	91.6	54-128	23.2	86.7	50-114	16.6	146.1	84-300	69.2
Stage 4	51.0	42-60	5.1	63.7	48-86	13.5	61.9	50-76	7.2	97.8	60-219	47.6

[a] Stage 1 and 2 combined.



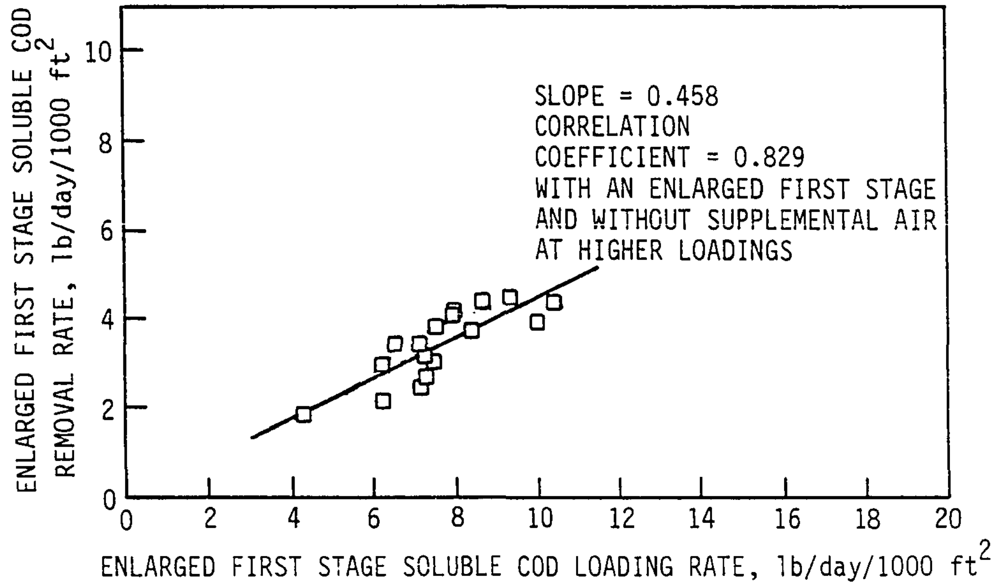


Figure 42. Enlarged first-stage soluble COD removal vs loading at higher loadings during the Phase II study

Table 25. Enlarged first stage soluble COD removal rates at higher loadings during the Phase II study

	With an Enlarged First Stage and With Supplemental Air		With an Enlarged First Stage and Without Supplemental Air	
Soluble COD Loading Rate lb /day/1000 ft^2	Soluble COD Removal Rate lb /day/1000 ft^2	Percent Removal	Soluble COD Removal Rate lb /day/1000 ft^2	Percent Removal
4.5	2.25	50.0	2.00	55.6
5.0	2.63	52.6	2.20	56.0
5.5	3.00	54.5	2.45	55.5
6.0	3.40	56.7	2.65	55.8
6.5	3.77	58.0	2.90	55.4
7.0	4.15	59.3	3.15	55.0
7.5	4.55	60.7	3.35	55.3
8.0	4.92	61.5	3.60	55.0
8.5	5.30	62.4	3.80	55.3
9.0	5.68	63.1	4.05	55.0
9.5	6.06	63.8	4.25	55.3
10.0	6.45	64.5	4.50	55.0
10.5	6.83	65.0	4.75	54.8

increased. At a maximum organic loading rate of 10.5 lb SCOD/day/1000 sq ft, the removal rate with supplemental air was 6.83 lb SCOD/day/1000 sq ft and in the absence of air, it was only 4.75 lb SCOD/day/1000 sq ft. The higher dissolved oxygen levels and the Beggiatoa-free growth contributed to increased SCOD removal in the units receiving supplemental air. The Beggiatoa growth in the south RBC units was reduced somewhat in the first stage because of baffle removal; however, it was still present in all stages at the higher organic loading rates. Without the air, zero-order kinetics were observed at higher organic loadings; whereas, the kinetics were first-order with supplemental air. These Phase II results suggest that use of supplemental air is essential at higher organic loadings even with an enlarged first stage. An enlarged first stage is helpful to reduce the organic load on the first stage but still is not adequate to overcome the oxygen-limitations.

Figure 43 and Table 26 show the observed overall soluble COD removal rates with and without the supplemental air at higher organic loadings. As can be seen, the relationships were linear and the correlation coefficients were high. The slopes with and without the air were 0.858 and 0.701, respectively. The overall SCOD removal rates in Table 26 indicate that at initial loading of 2 lb SCOD/day/1000 sq ft, the removal rates and percent removals were approximately the same for both with and without the supplemental air. However, as the loading rate increased, the SCOD removal rate and percent removal decreased without the supplemental aeration. With supplemental air, the SCOD removal rates and percent removals increased as the loading increased.

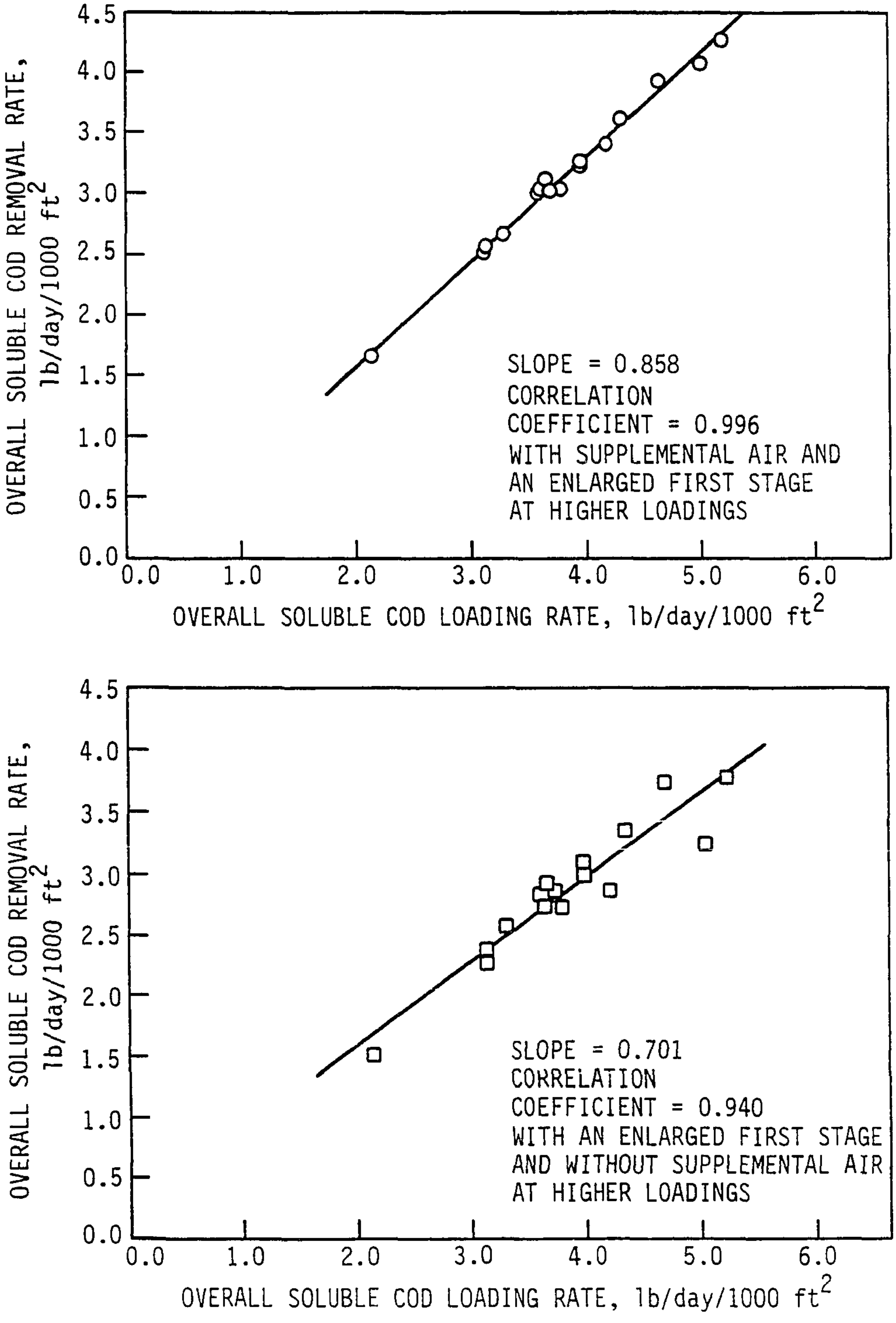


Figure 43. Overall soluble COD removal vs loading at higher loadings during the Phase II study

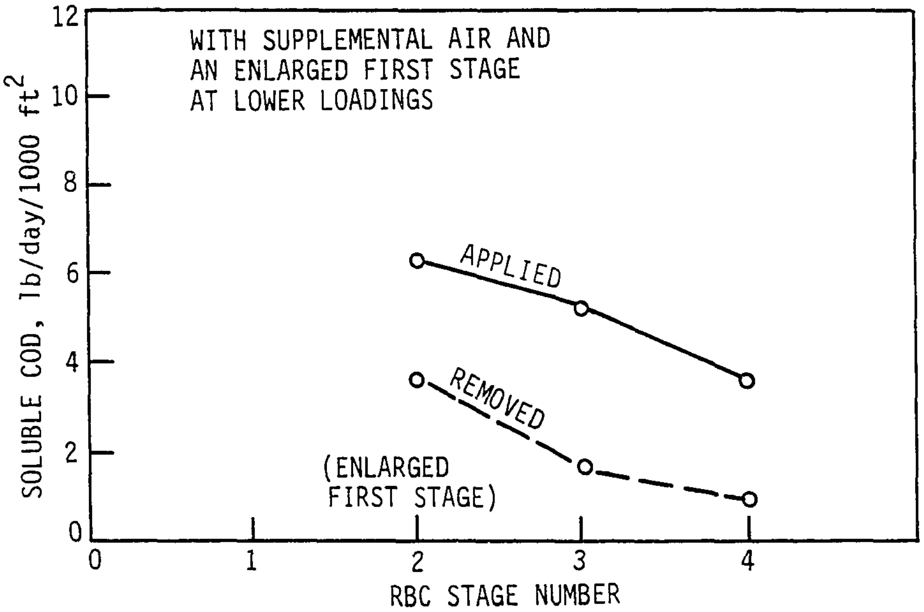
Table 26. Overall soluble COD removal rates at higher loadings during the Phase II study

	With An Enlarged First Stage and With Supplemental Air		With an Enlarged First Stage and Without Supplemental Air	
Soluble COD Loading Rate lb /day/1000 ft^2	Soluble COD Removal Rate lb /day/1000 ft^2	Percent Removal	Soluble COD Removal Rate lb /day/1000 ft^2	Percent Removal
2.0	1.60	80.0	1.60	80.0
2.5	2.00	80.0	1.94	78.0
3.0	2.43	81.0	2.30	76.7
3.5	2.85	81.4	2.65	75.7
4.0	3.28	82.0	3.00	75.0
4.5	3.72	82.7	3.35	74.4
5.0	4.15	83.0	3.70	74.0
5.5	4.58	83.3	4.05	73.6

A comparions of overall SCOD removal rates observed during the Phase I and Phase II studies suggest that, at higher organic loading rates, SCOD removal rates were higher with an enlarged first stage (stage 1 and 2 combined) than with four separate stages. This comparison further substantiates that step feeding in RBC systems would be helpful when operated at higher organic loading rates.

Figures 44 and 45 show the stage SCOD loading and removal profile in the Phase II study at lower and higher loadings, respectively. Table 27 summarizes the stage soluble COD loading and removal data observed during the Phase II study. Figure 44 indicates that at an enlarged first stage loading of 6.27 lb SCOD/day/1000 sq ft, the removal rate with supplemental air was 3.66 lb SCOD/day/1000 sq ft, whereas the removal rate was only 3.01 lb SCOD/day/1000 sq ft without the air. Table 28 contains a summary of soluble COD removal efficiencies observed during the Phase II study. This table shows that enlarged first stage efficiencies at lower organic loadings were 58.3 and 47.9 percent, respectively, with and without the air. A comparison of overall COD removal efficiencies at lower organic loadings in Phase I (Table 12) and Phase II (Table 28) suggest that the soluble COD removal efficiencies were somewhat higher with an enlarged first stage.

Figure 44 shows an increased loading on the third stage in the absence of supplemental air. This is due to the fact that the enlarged first stage effluent organic load is divided by the media area of the third stage alone, whereas the load to the enlarged first stage is divided by the media area of the normal first two stages.



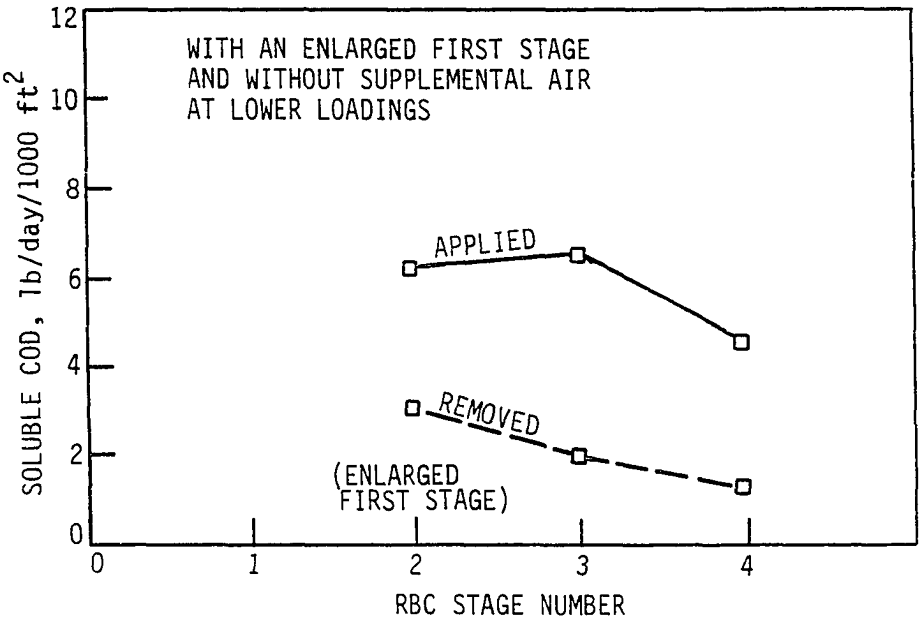
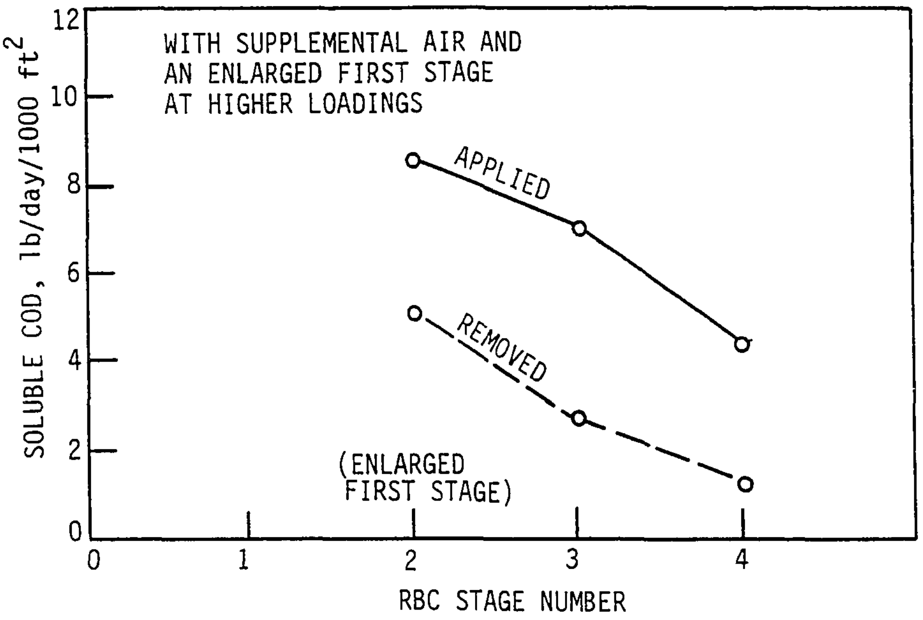


Figure 44. Stage soluble COD loadings and removal profile at lower loadings during the Phase II study



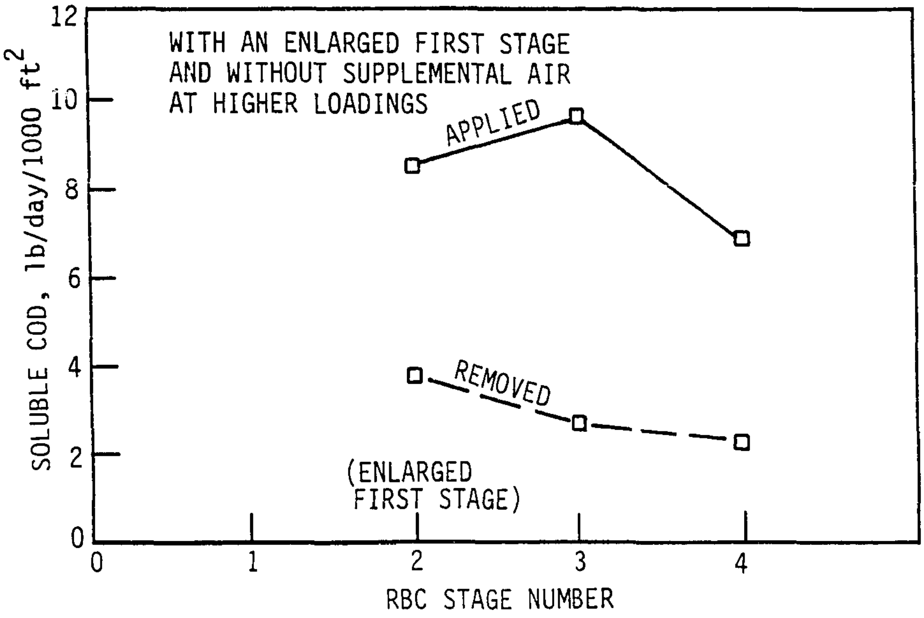


Figure 45. Stage soluble COD loadings and removal profile at higher loadings during the Phase II study

Table 27. Stage soluble COD loadings and removal rates during the Phase II study

	With an Enlarged First Stage and With Supplemental Air				With an Enlarged First Stage Without Supplemental Air			
	At Lower Loadings		At Higher Loadings		At Lower Loadings		At Higher Loadings	
Stage	SCOD Applied lb /day/1000 ft^2	SCOD Removed lb /day/1000 ft^2	SCOD Applied lb /day/1000 ft^2	SCOD Removed lb /day/1000 ft^2	SCOD Applied lb. /day/1000 ft^2	SCOD Removed lb /day/1000 ft^2	SCOD Applied lb /day/1000 ft^2	SCOD Removed lb /day/1000 ft^2
Enlarged[a] Stage 1	6.27	3.66	8.54	5.04	6.27	3.01	8.54	3.74
Stage 3	5.23	1.67	7.01	2.69	6.53	1.98	9.60	2.71
Stage 4	3.56	0.89	4.31	1.31	4.55	1.30	6.88	2.28

[a] Stage 1 and 2 combined

Table 28. Summary of soluble COD removal efficiencies (%) during the Phase II study

	With an Enlarged First Stage and With Supplemental Air		With an Enlarged First Stage and Without Supplemental Air	
Stage	At Lower Loadings	At Higher Loadings	At Lower Loadings	At Higher Loadings
Enlarged[a] Stage 1	58.3	59.0	47.9	43.8
Stage 3	31.9	38.4	30.4	28.3
Stage 4	25.0	30.5	28.6	33.1
Overall	78.7	82.4	74.1	73.0

[a] Stage 1 and 2 combined.

As explained earlier, the organic load to the first stage without the baffle removal would have been double the observed load in the enlarged first stage. These phenomena were not observed in the units with supplemental air due to the higher removal rates in the enlarged first stage which subsequently reduced the load to the third stage. A similar loading pattern was observed in Figure 45 under the higher organic loading rates.

Again, at higher organic loading rates, the soluble COD removal rates were higher with supplemental air. This can be seen in Figure 45. The soluble COD removal efficiencies data in Table 28 indicate that the enlarged first stage and the overall soluble COD removal efficiencies with the supplemental air were 59 and 82.4 percent, respectively, at higher organic loadings. However, without the air, the enlarged first stage and overall soluble COD removal efficiencies were only 43.8 and 73 percent, respectively.

Oxygen uptake rates measured during the Phase II study were also a little higher than those observed in the Phase I study. The oxygen uptake rate was a maximum in the enlarged first stage and declined in subsequent stages as the organic loading decreased. Comparison of Phase I and Phase II overall soluble COD removal efficiencies observed at higher organic loadings suggests that soluble COD removal efficiencies were higher with an enlarged first stage. This comparison further suggests that the step feeding would be useful at higher organic loading rates. It must be recognized that an enlarged first stage (or step feeding) will be helpful to overcome initial overloading problems; however, the use of supplemental aeration is essential to overcome oxygen and diffusion limitations and also to achieve Beggiato-free growth on the media.

Figures 46 and 47 show the relationship between the organic loading rates and the percent of soluble COD removed. The soluble COD removal efficiencies did not decline drastically as the organic load increased. This was particularly true when removal is expressed as a function of overall organic loading rates as in Figure 47. However, the removal efficiencies were observed to be higher with supplemental air and an enlarged first stage than with an enlarged first stage only. During the Phase I study, it was observed (Figure 21) that as the first stage organic loading increased the soluble COD removal efficiency decreased. This pattern of decreasing soluble COD removal efficiencies was more pronounced in the units where supplemental air was not provided. In the Phase II study, however, the increased organic loading effect on soluble COD removal efficiency was significantly reduced, particularly in the enlarged first stage because of the reduced loading in the first two stages due to baffle removal. The lower organic loadings in the initial stages also increased both the stage and overall soluble COD removal efficiencies.

It was discussed earlier that several existing RBC manufacturers design RBC systems based on empirical relationships developed between the percent soluble COD removal and the hydraulic loading rate. It was observed in Phase I, and also by several other investigators (15, 31, 40, 111), that statistically the relationship between percent

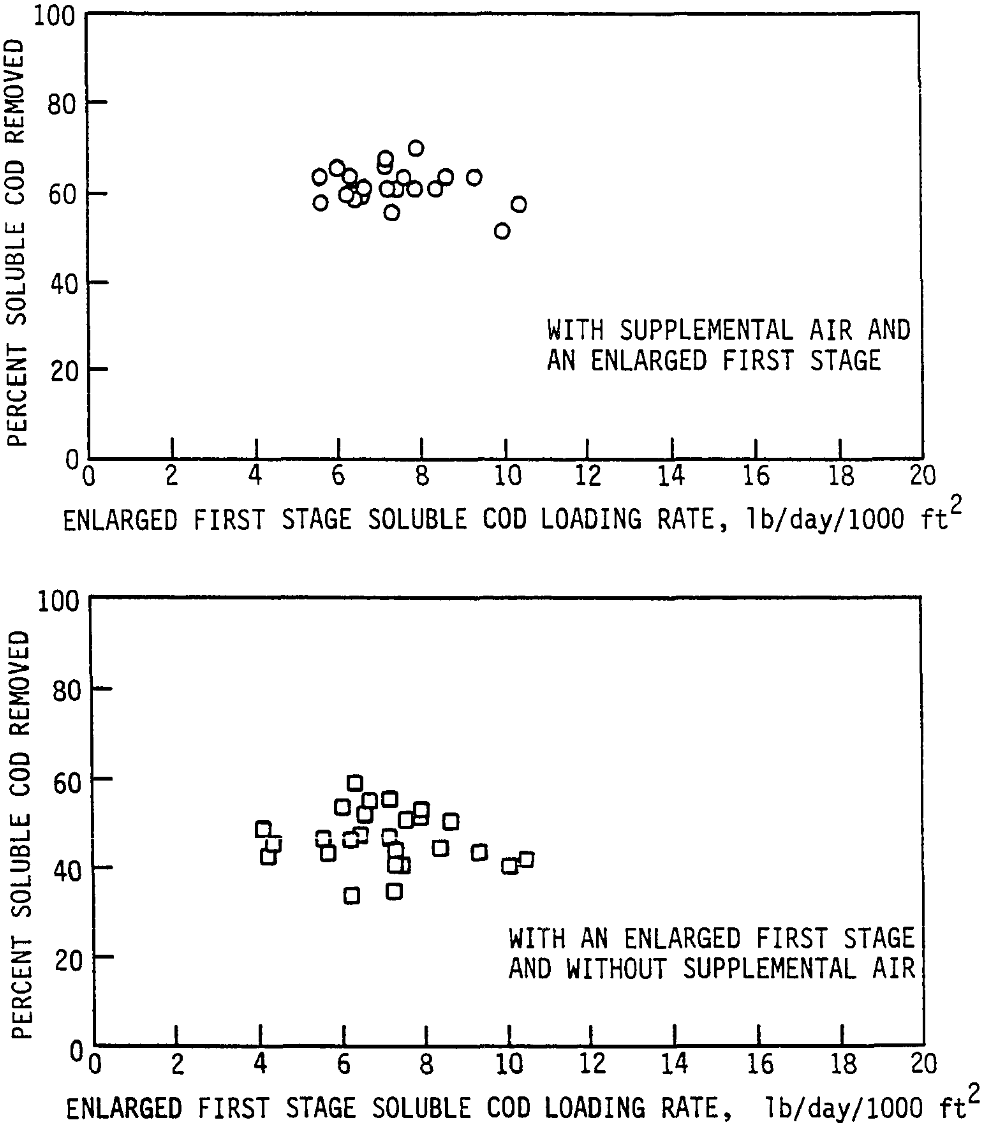


Figure 46. Percent soluble COD removal vs first-stage loading during the Phase II study

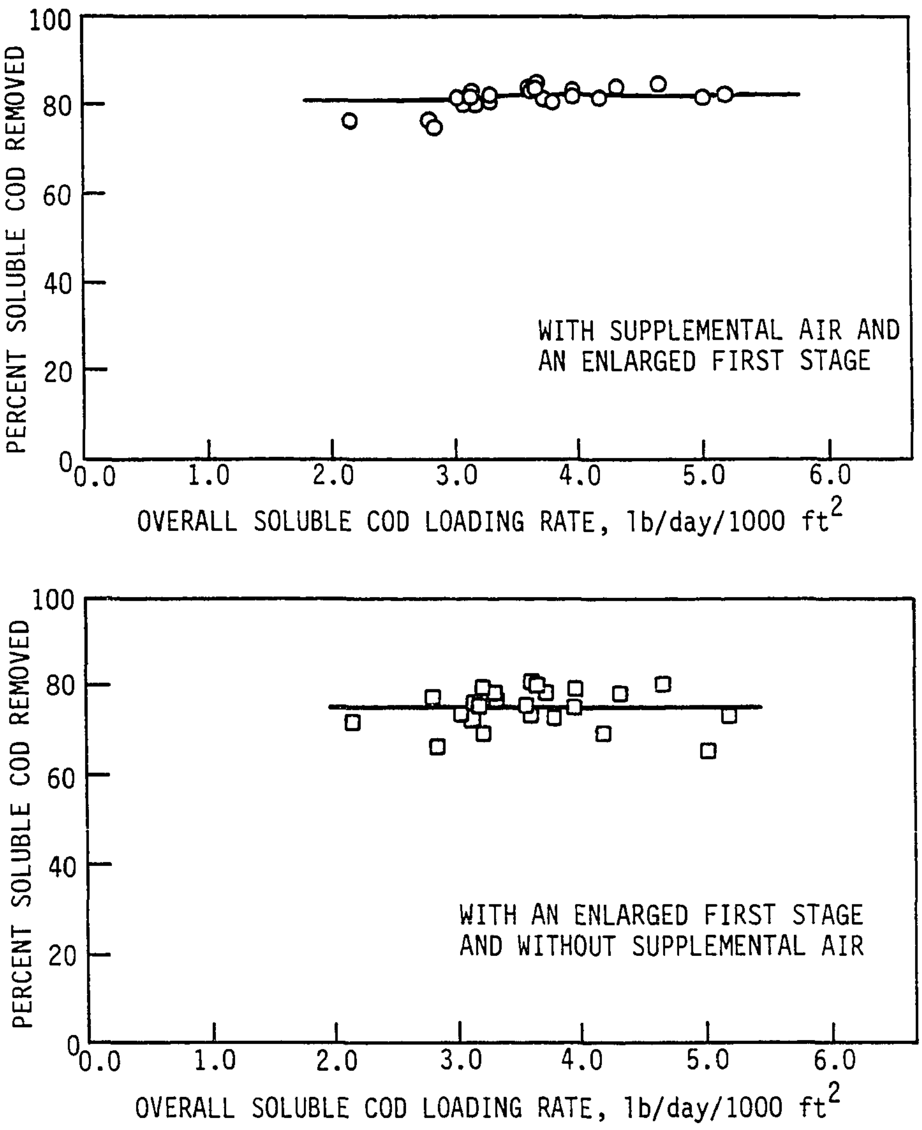
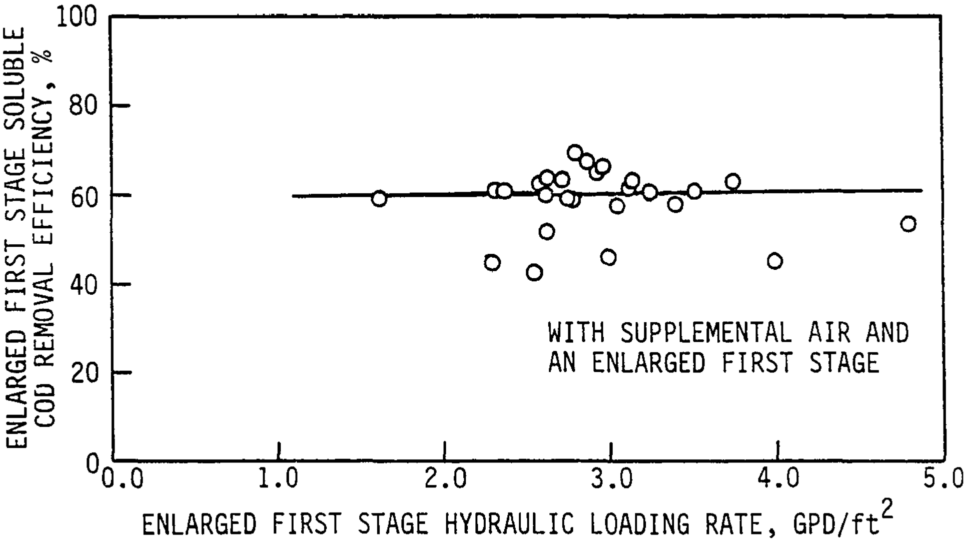


Figure 47. Percent soluble COD removal vs overall loading during the Phase II study

soluble COD removal and hydraulic loading rate is not significant. Figures 48 and 49 show the relationship between percent soluble COD removal and hydraulic loading rates. The observed relationship in Figure 48 suggests that increasing hydraulic loading rates in the enlarged first stage had little impact on the soluble COD removal efficiency. The impact of increasing the hydraulic loading rates on first-stage soluble COD removal was a little more pronounced in Phase I. However, in Phase II the impact was dampened due to the enlarged first stage. It was also observed in Phase II that the increased hydraulic loadings combined with increased COD concentrations had less impact on percent COD removal efficiency.

Ammonia nitrogen removal

The Maquoketa plant had no effluent ammonia nitrogen limits and was designed to meet only standard secondary effluent limits of 30 mg/L BOD_5 and 30 mg/L SS. However, stage effluent ammonia nitrogen concentrations were monitored to evalute the effect of an enlarged first stage and supplemental aeration on ammonia nitrification. Figures 50 and 51 show the effluent ammonia nitrogen concentration from each stage and the percent removal profiles at low and high organic loadings, respectively. Table 29 contains a summary of ammonia nitrogen concentrations in the RBC stage effluents observed during Phase II. It was observed that nitrification was significantly reduced in Phase II at both lower and higher organic loading rates because of the enlarged first stage. It is well recognized in activated sludge process



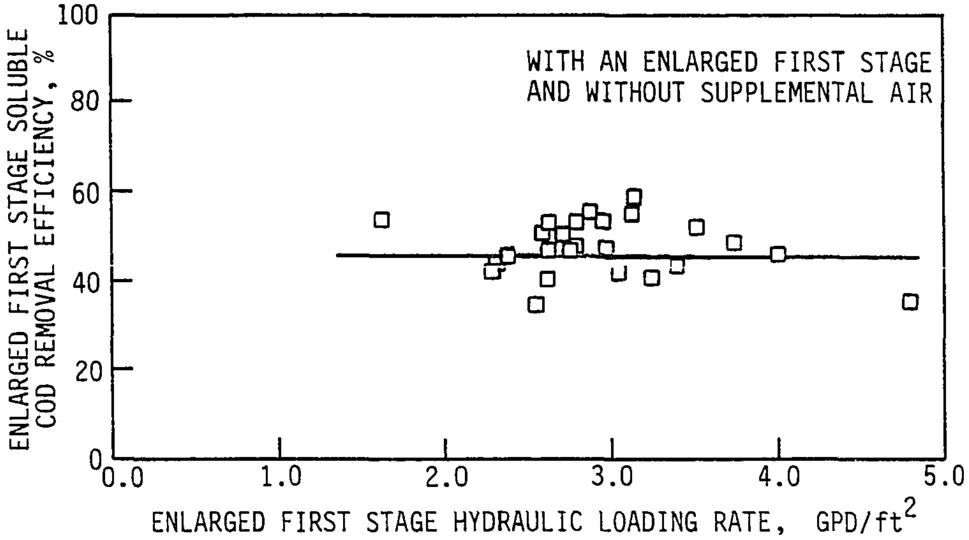


Figure 48. Percent soluble COD removal vs enlarged first-stage hydraulic loading rate during the Phase II study

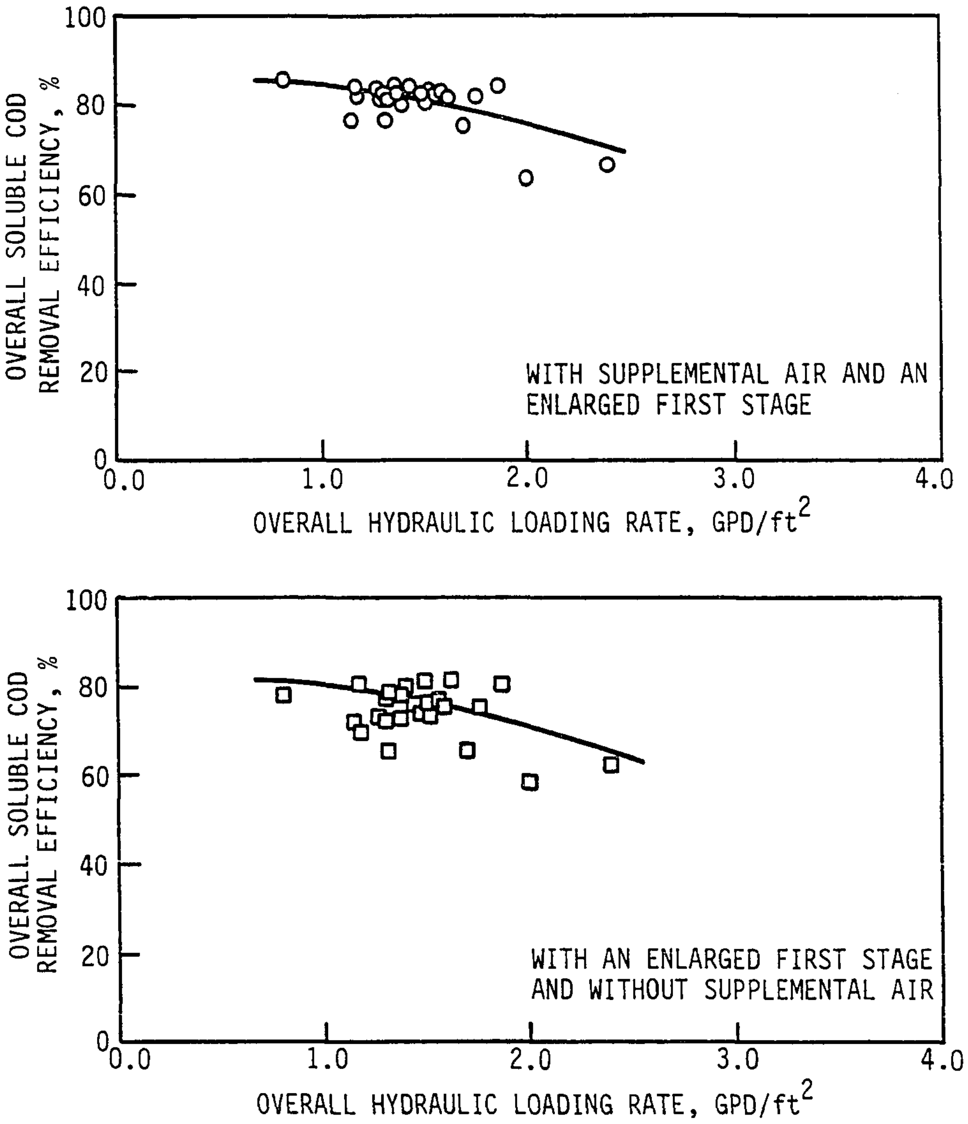


Figure 49. Percent soluble COD removal vs overall hydraulic loading rate during the Phase II study

design that a plug-flow operating mode achieves better nitrification than a single, complete-mix system.

In Phase I, most of the soluble COD removal took place in stage 1 because of the higher dissolved oxygen levels in the presence of supplemental air. In the subsequent stages, the $SBOD_5$ concentrations were low enough to initiate nitrification and most of the nitrification took place in the third and the fourth stages, particularly at the lower organic loading rates. However, in Phase II the intrusion of carbonaceous substrate from the enlarged first stage into the subsequent stages inhibited nitrifying organism growth since heterotrophs compete and become predominant in the presence of carbon sources. The increased ammonia nitrogen removal in the fourth stage, as observed in Figures 50 and 51 with supplemental air suggests that nitrification was initiated in the fourth stage but never reached the maximum observed in Phase I.

The fixed-film biomass characteristics observed in Phase II also indicated that the brownish red-tan growth in the third stage disappeared slowly over a period of time after the removal of baffles between the first and second stages. The fourth stage media had brownish-red bacteria growths, but it was significantly less than that observed in Phase I. Phase I results indicated that the maximum ammonia nitrogen removal took place in the third and fourth stages. Table 30 summarizes the ammonia nitrogen removals observed in the Phase II study.

Without the supplemental air, the ammonia nitrogen removals were approximately the same both in Phase I (Table 14) and Phase II (Table 30).

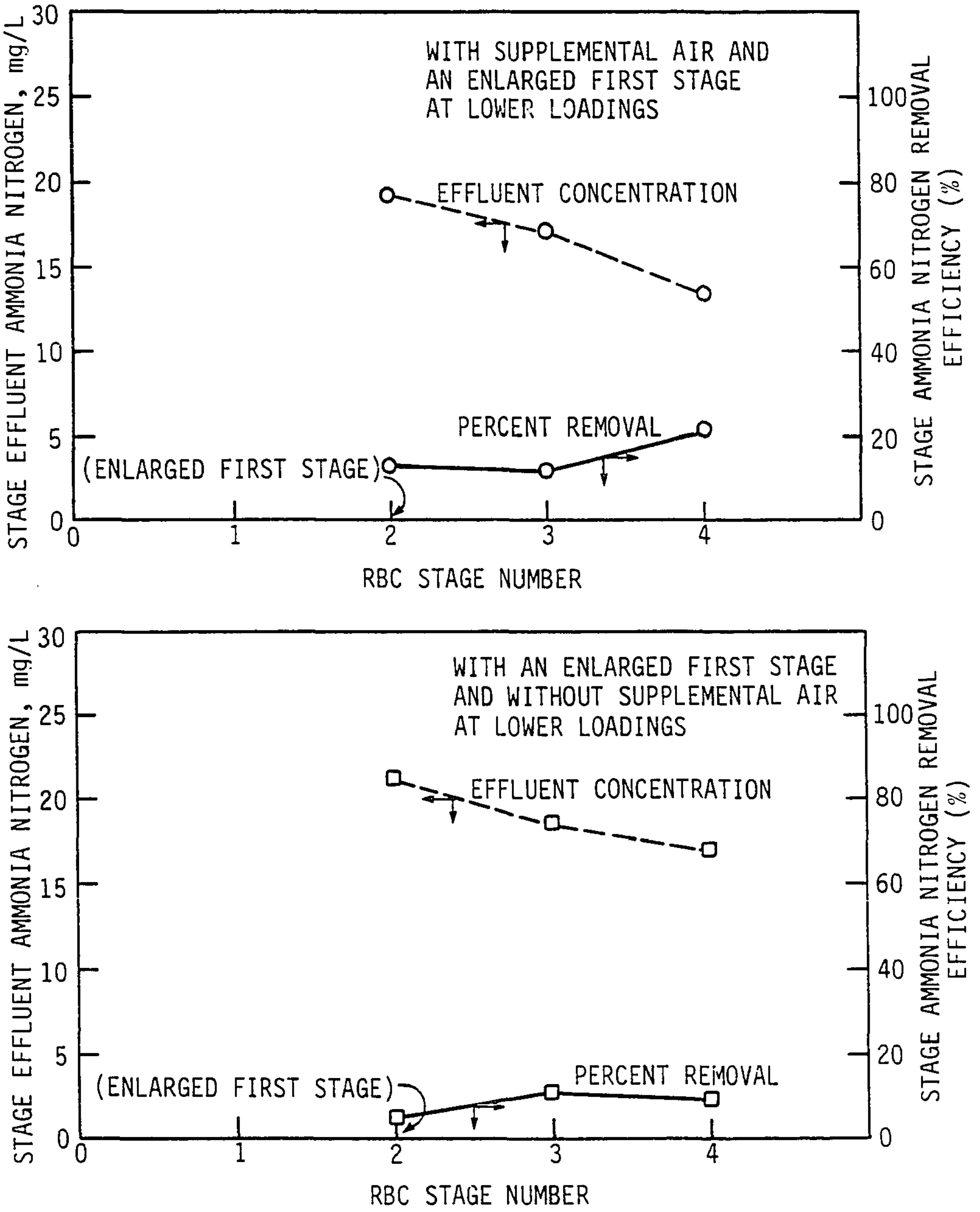
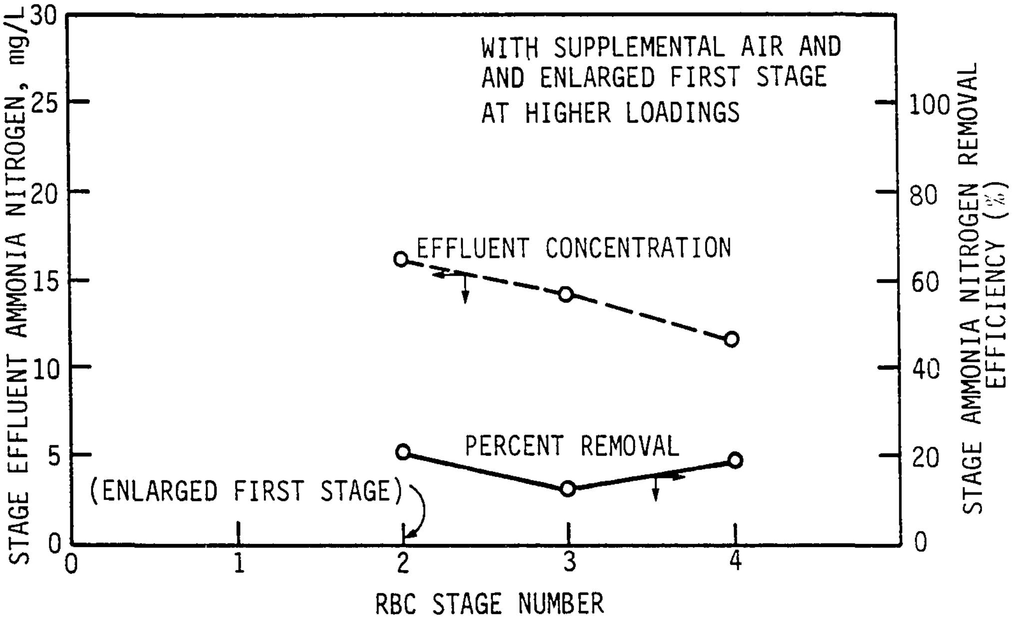


Figure 50. Stage effluent ammonia nitrogen concentration and removal efficiency profile at lower loadings during the Phase II study



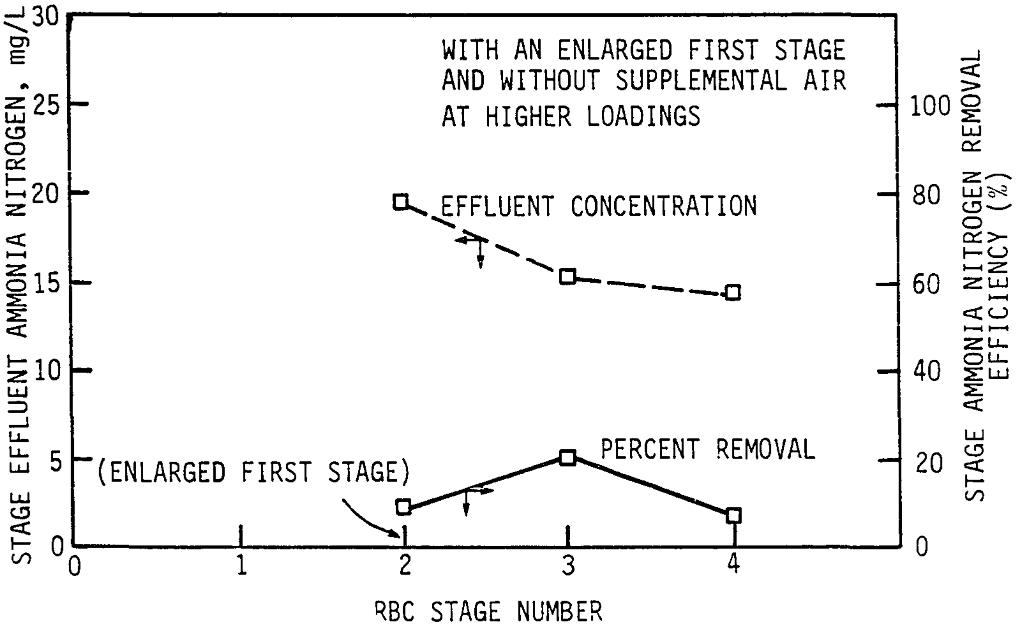


Figure 51. Stage effluent ammonia nitrogen concentration and removal efficiency profile at higher loadings during the Phase II study

Table 29. Summary of stage ammonia nitrogen concentrations (mg/L) during the Phase II study

	With an Enlarged First Stage and With Supplemental Air						With an Enlarged First Stage and Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Enlarged[a] Stage 1	19.0	16-24.8	2.60	16.2	9.3-23.5	4.64	21.2	18-26.5	2.98	18.7	11.5-25.5	4.10
Stage 3	17.0	14-20	1.60	14.2	9.2-18.0	3.22	18.5	16-24	2.93	15.4	9.8-22.0	4.00
Stage 4	13.4	9.5-17.5	2.46	11.6	7.4-15.5	2.55	16.8	15-19	1.75	14.3	9.2-20.0	3.37

[a] Stage 1 and 2 combined.

Most of the ammonia nitrogen removal in units without the supplemental air was due to assimilation and some removal could be attributed to air-stripping. It is reported that approximately 10 to 20 percent of the incoming ammonia nitrogen removal is used in the biosynthesis of heterotrophs. The increased ammonia nitrogen removal in the beginning stages, as observed in Figure 51, could be due to increased assimilation under the higher organic loadings. Without supplemental air, the dissolved oxygen levels in the south control RBC units were less than 1 mg/L. A minimum dissolved oxygen level of 2 mg/L or more is often quoted in the literature as being required for ammonia nitrification.

Figure 52 shows the relationship between the percentage of ammonia nitrogen removal and the effluent soluble COD. As can be seen, with supplemental air the ammonia nitrogen efficiency tended to decrease as the effluent soluble COD increased. Such phenomena has been observed by others (14, 79). The heterotrophic organisms compete with the nitrifiers and predominate on the media in the presence of carbon substrate. In the absence of air, the ammonia nitrogen removal efficiency remained the same irrespective of the effluent soluble COD concentrations. This is the case since most of the ammonia nitrogen removal in the units not receiving supplemental air is due to assimilation and the fact that oxygen was limiting in all the stages. Similar observations were made in Phase I with and without the supplemental air.

Figure 53 shows the ammonia nitrogen removal as a function of loading. The curves in Figure 53 suggest that ammonia nitrogen

Table 30. Summary of ammonia nitrogen removal efficiencies (%) during the Phase II study

Stage	With an Enlarged First Stage and With Supplemental Air		With an Enlarged First Stage and Without Supplemental Air	
	At Lower Loadings	At Higher Loadings	At Lower Loadings	At Higher Loadings
Enlarged Stage 1[a]	14.1	20.6	4.1	8.3
Stage 3	10.5	12.3	12.7	17.6
Stage 4	21.2	18.3	9.2	7.1
Overall	39.4	43.1	24.0	29.9

[a] Stage 1 and 2 combined.

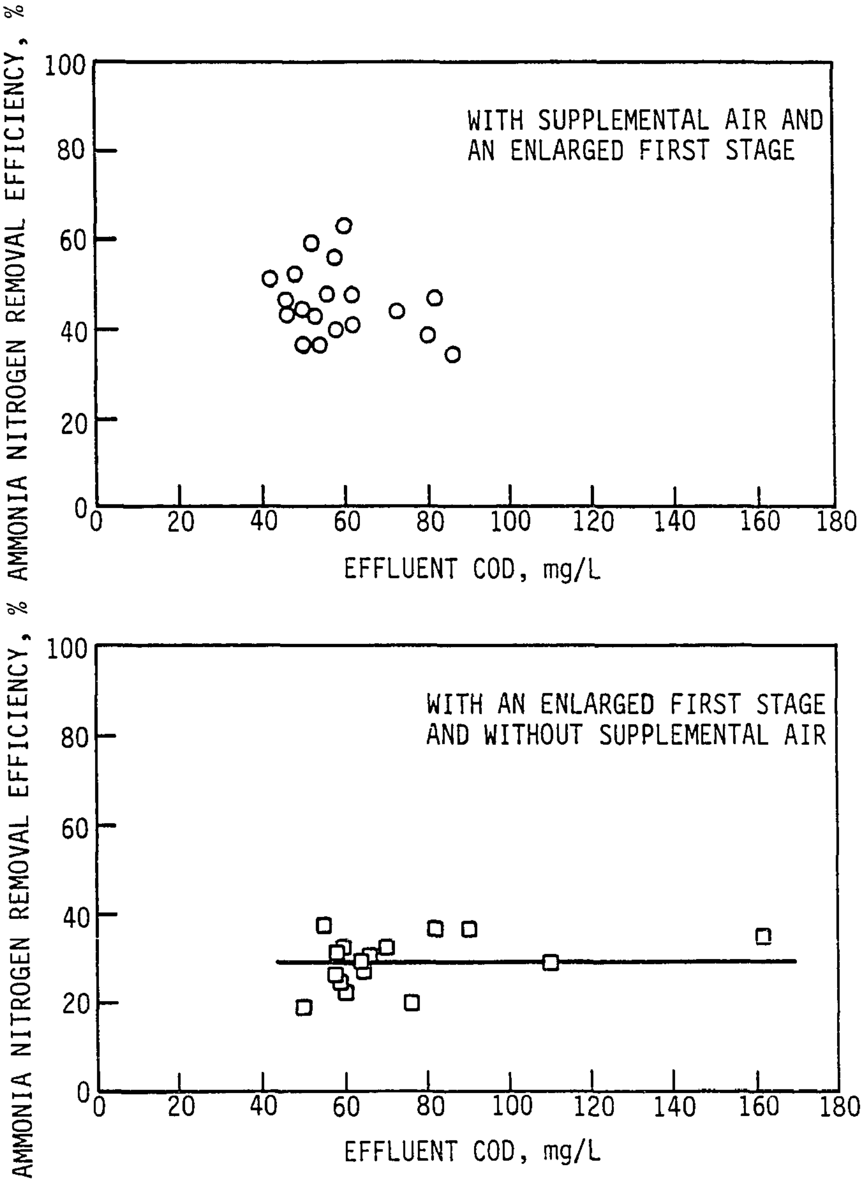
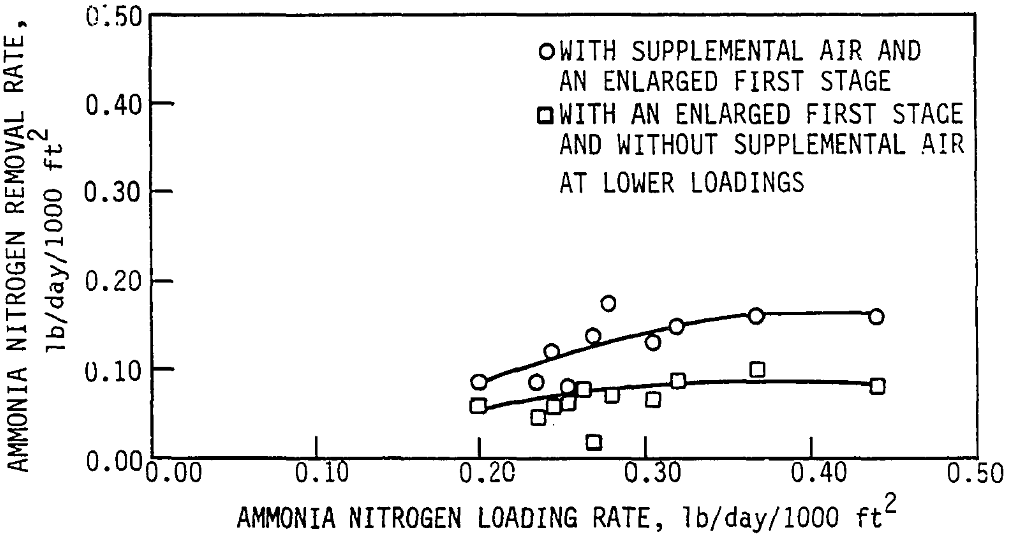


Figure 52. Percent ammonia nitrogen removal vs effluent soluble COD during the Phase II study

removal was zero-order both with and without supplemental air. Stage ammonia nitrogen concentrations indicated in Figures 50 and 51 also show an approximate linear relationship. This further indicates that zero-order kinetics were responsible for ammonia nitrogen removal in the Phase II study. Similar zero-order kinetic removal of ammonia nitrogen was observed in the Phase I study. It is reported that ammonia nitrogen removal follows zero to first-order kinetics depending upon the concentration. Antonie (9) indicated that the ammonia nitrogen removal is zero-order at an ammonia nitrogen concentration above 5 mg/L and first order below this concentration. With supplemental air, the maximum ammonia nitrogen removal rate at both lower and higher organic loading rates was approximately 0.165 lb/day/1000 sq ft. In the absence of air, the maximum removal rate was 0.10 lb NH_3-N/day/1000 sq ft. In full-scale RBC units, maximum removal rates of 0.30 lb NH_3-N/day/1000 sq ft have been reported (9). In the Phase I study, a maximum removal rate of 0.29 lb NH_3-N/day/1000 sq ft has been observed at lower organic loadings in the presence of supplemental air.

Appropriate environmental conditions such as wastewater temperature, pH and dissolved oxygen are important for ammonia nitrification. Figure 55 shows the pH profiles observed during the Phase II study. Wastewater pH values always remained above 7 and increased a little as the wastewater passed through the stages. The influent wastewater pH value was approximately 7. Table 31 summarizes the measured pH data and suggests that the pH values were somewhat higher with supplemental air. A similar observation was also made in the Phase I study



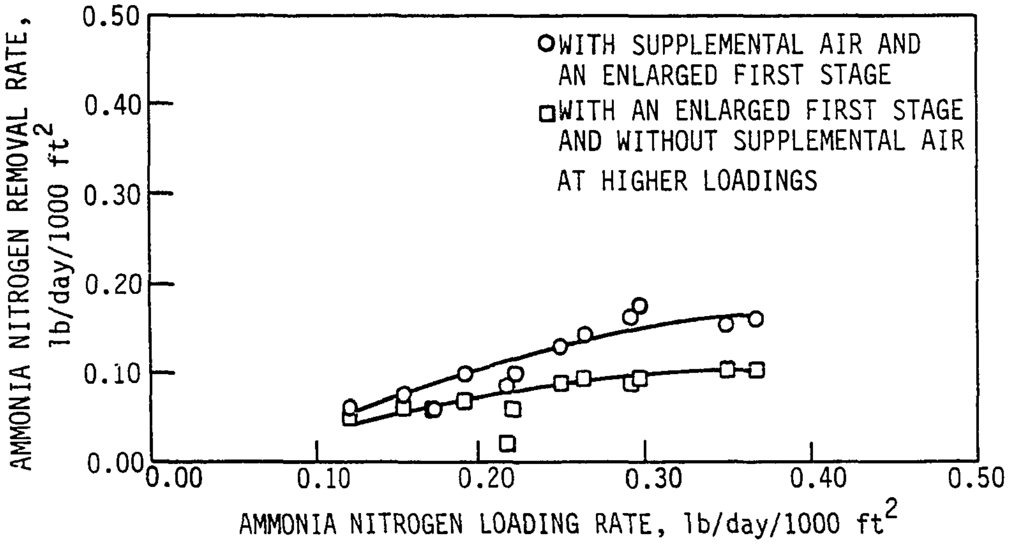


Figure 53. Overall ammonia nitrogen loading and removal rates during the Phase II study

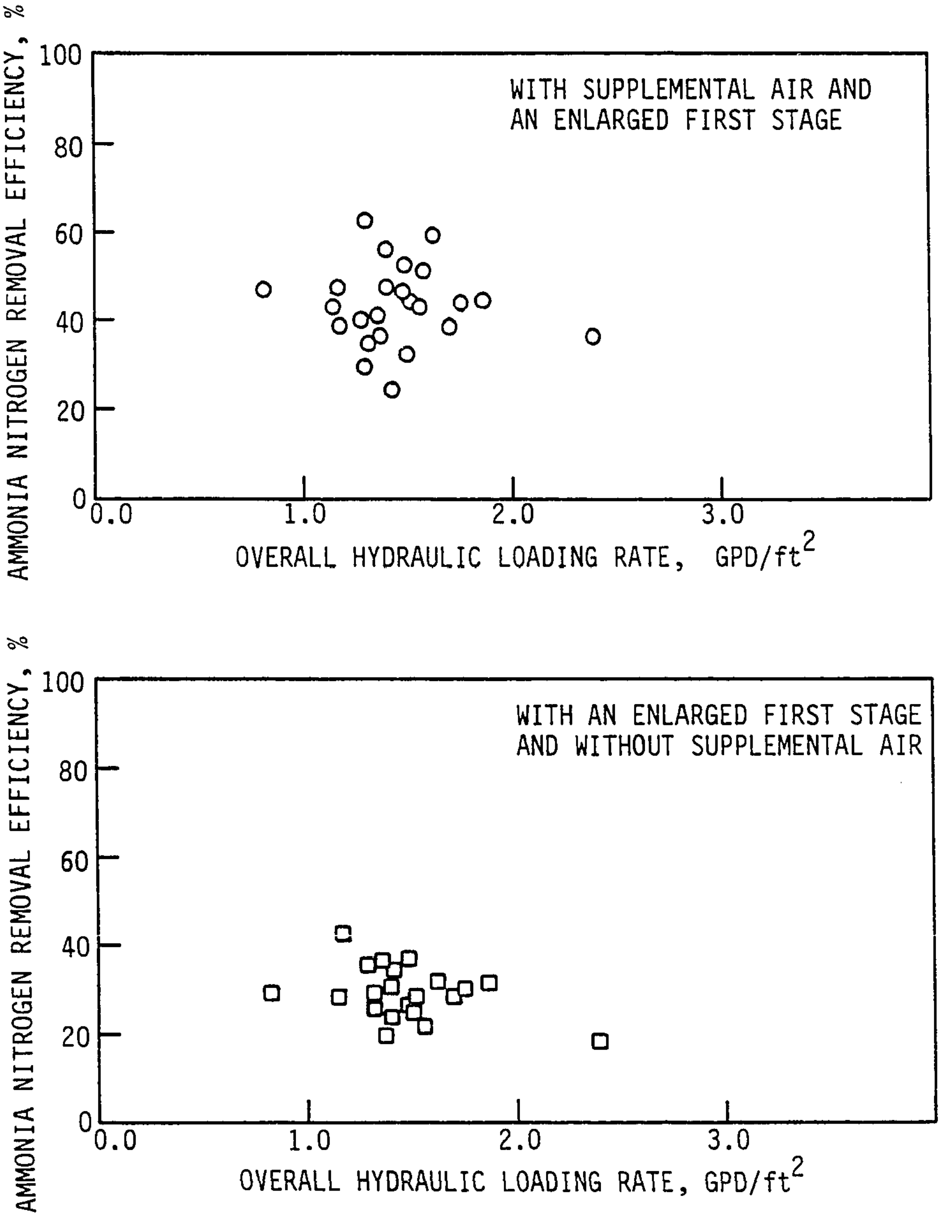


Figure 54. Ammonia nitrogen removal efficiency vs overall hydraulic loading rate during the Phase II study

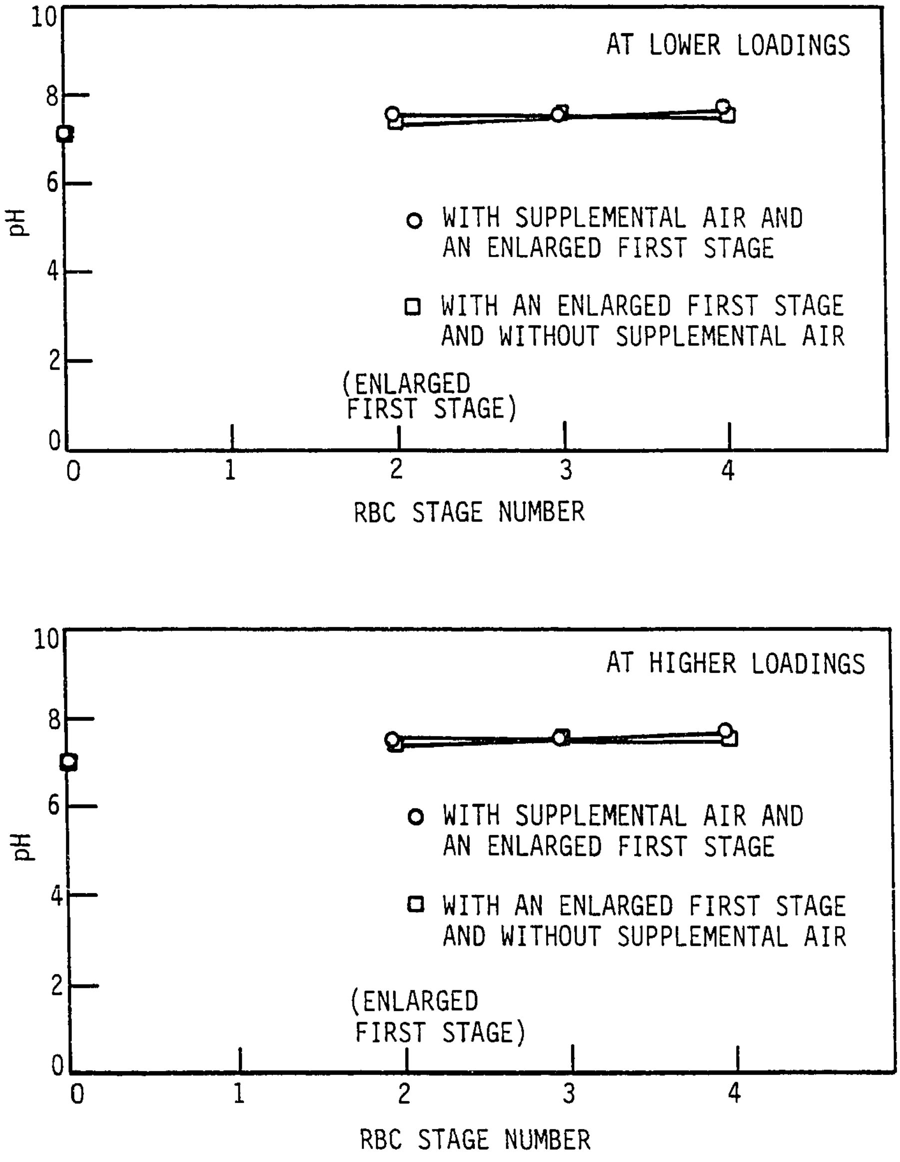


Figure 55. pH profile during the Phase II study

Table 31. Summary of pH values measured during the Phase II study

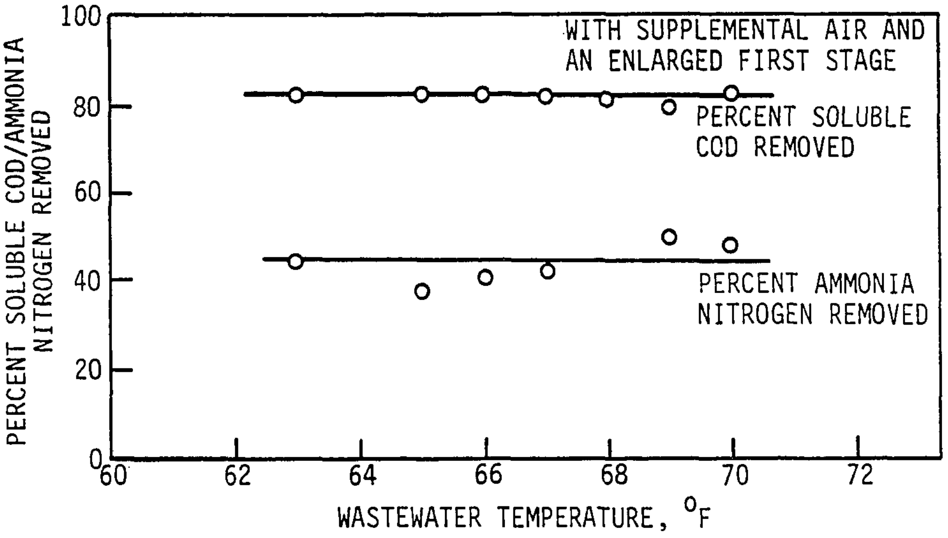
	With an Enlarged First Stage and With Supplemental Air						With an Enlarged First Stage and Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Enlarged[a] Stage 1	7.57	7.40-7.75	0.09	7.48	7.27-7.75	0.15	7.50	7.35-7.65	0.12	7.41	7.20-7.60	0.14
Stage 3	7.58	7.50-7.65	0.06	7.52	7.35-7.65	0.08	7.58	7.40-7.75	0.09	7.54	7.30-7.65	0.11
Stage 4	7.71	7.60-7.80	0.08	7.69	7.5 -7.90	0.10	7.62	7.40-7.75	0.10	7.62	7.50-7.70	0.07

[a] Stage 1 and 2 combined.

(Table 15). Figure 56 shows the soluble COD/NH_3-N removal as a function of wastewater temperature. Wastewater temperatures in the Phase II study varied between 63 and 70°F. The results in Figure 56 suggest that temperatures as low as 63°F had no effect on removal of either soluble COD or ammonia nitrogen. Antonie (10) indicated that soluble COD and ammonia nitrogen removals by RBC units are affected only by wastewater temperatures below 55°F. In Phase I and Phase II, the wastewater temperature ranged from 63 to 76°F and had no effect on removals of soluble COD and ammonia nitrogen.

Suspended solids and attached biomass characteristics

Earlier discussion of Phase I results indicated that mixed-liquor suspended solids play an important role, along with fixed-film biomass, in substrate removal, particularly at high dissolved oxygen concentrations. Figures 57 and 58 show the total and volatile suspended solids profile observed in the Phase II study. As can be seen in these figures, the mixed liquor suspended solids were always higher with supplemental air, except from the fourth stage, in which the solids increased without the air, particularly at lower organic loadings.



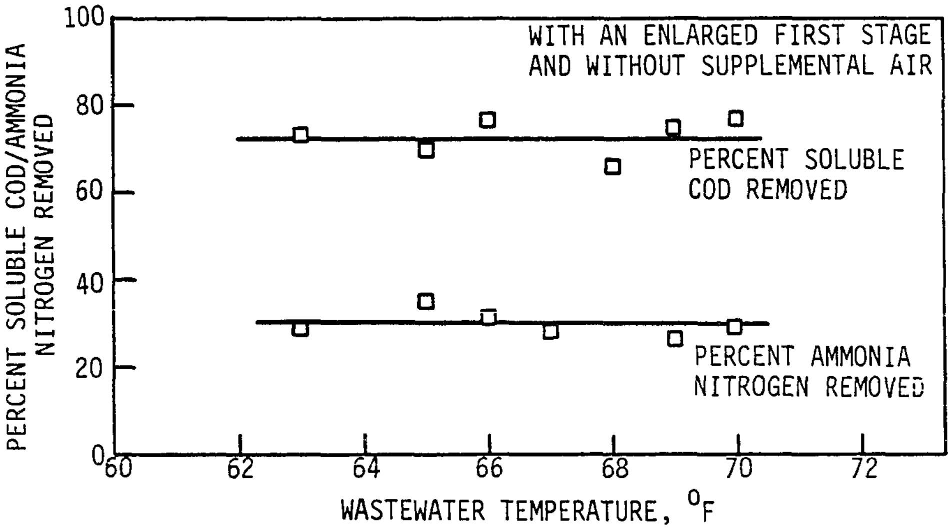
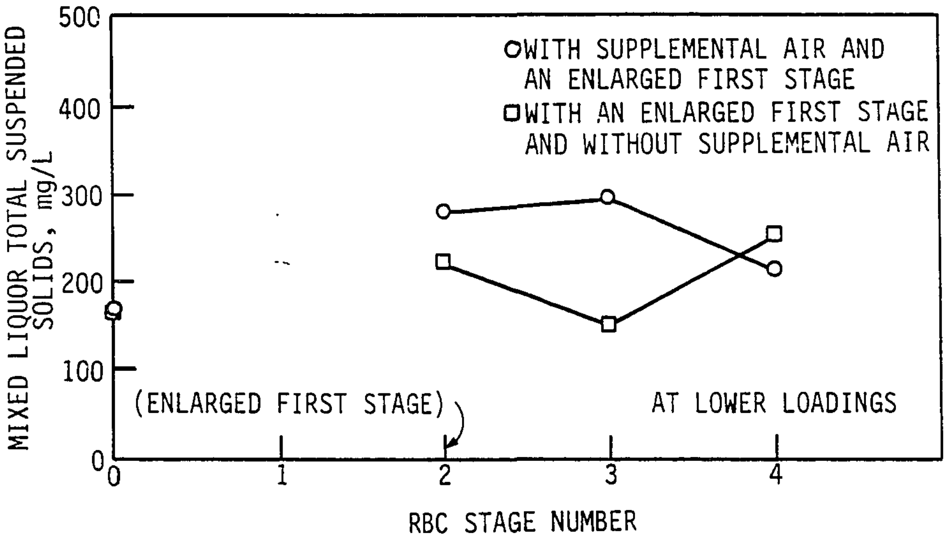


Figure 56. Percent SCOD/ammonia nitrogen removal vs temperature during the Phase II study

Phase I study results also indicated that the solids decreased from the first stage onwards but eventually increased in the fourth stage. However, in both the phases, the mixed-liquor suspended solids were generally higher with supplemental air.

Tables 32 and 33 summarize the total and the volatile suspended solids data observed in the Phase II study. The results indicate that, with supplemental air, the suspended solids in Phase II did not decrease rapidly in subsequent stages as was observed in the Phase I study except in the fourth stage. This is probably due to the enlarged first stage and the intrusion of substrate to the third stage. The Phase I study results (Table 16) suggest that first-stage mixed-liquor suspended solids were substantially higher than those observed when using an enlarged first stage. Again, this is because of the enlarged first stage equalization effect. In Phase II, the incoming load was equally distributed to the first two stages when the baffle was removed between these stages. Because of the lower loadings and the equalization effect, solids production in the enlarged first stage also remained low. The decreased suspended solids in the fourth stage operated with supplemental aeration could be due to solids stabilization as the substrate concentrations were low in this stage. With supplemental air, the enlarged first stage mixed-liquor suspended solids were observed to be as high as 438 and 574 mg/L at lower and higher organic loadings, respectively. However, these numbers are lower than those that were reported in stage 1 of the Phase I study.



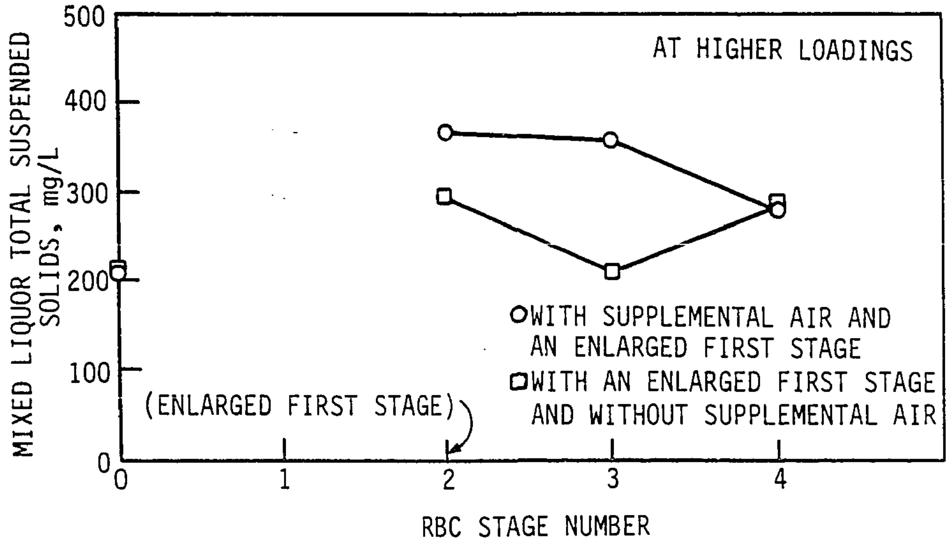


Figure 57. Total suspended solids profile during the Phase II study

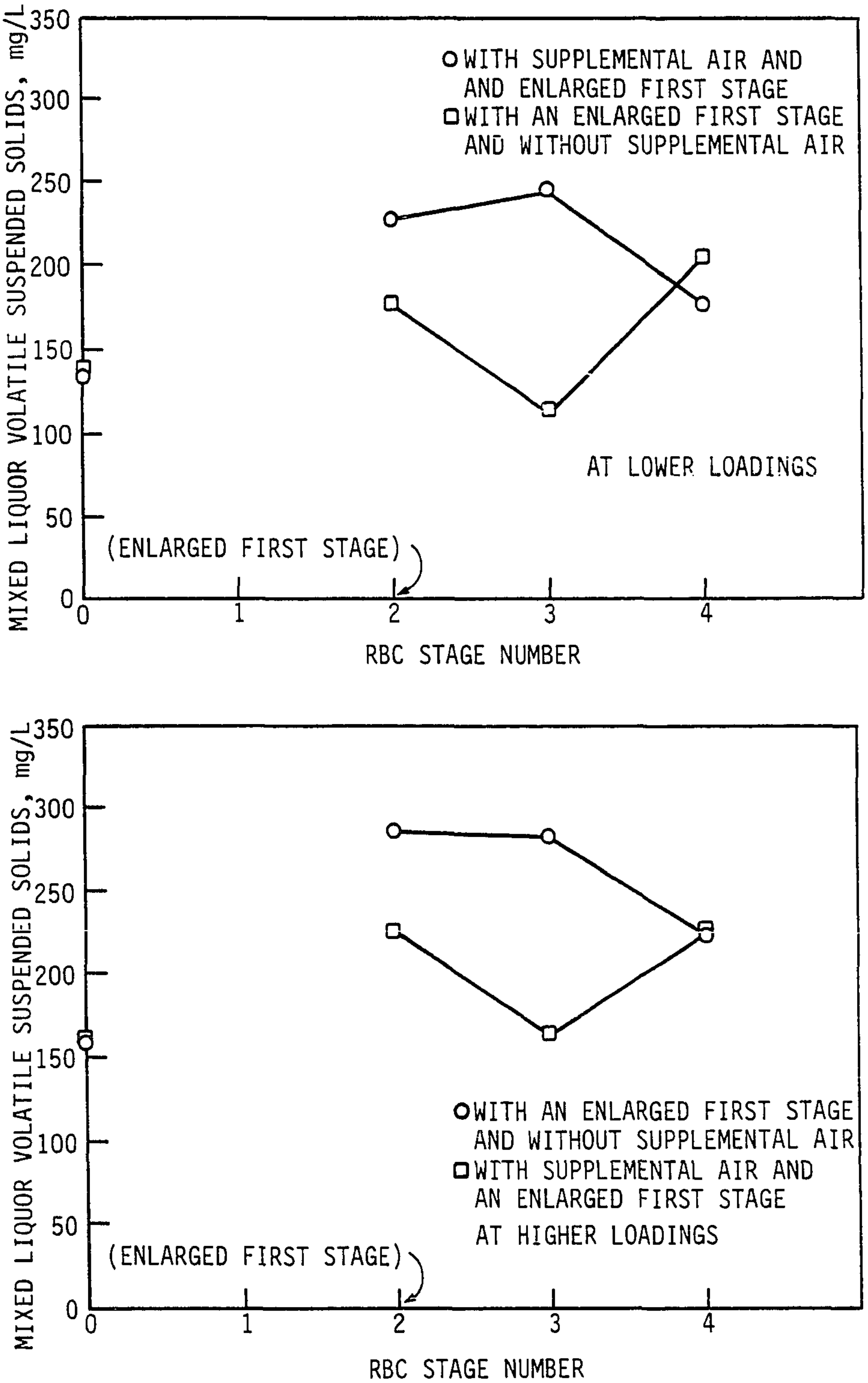


Figure 58. Volatile suspended solids profile during the Phase II study

Table 32. Stage total suspended solids (mg/L) observed during the Phase II study

	With an Enlarged First Stage and With Supplemental Air						With an Enlarged First Stage and Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Enlarged[a] Stage 1	279.1	161-438	69.1	365.9	175-574	127.7	220.3	51-454	108.6	293.2	166-416	83.1
Stage 3	293.8	177-362	67.1	356.9	242-560	90.8	147.0	95-216	62.3	210.5	130-290	87.3
Stage 4	213.0	124-293	47.0	279.3	161-386	59.9	250.7	140-292	43.0	285.6	184-368	57.0

[a] Stage 1 and 2 combined.

Table 33. Stage volatile suspended solids (mg/L) observed during the Phase II study

	With an Enlarged First Stage and With Supplemental Air						With an Enlarged First Stage and Without Supplemental Air					
	At Lower Loadings			At Higher Loadings			At Lower Loadings			At Higher Loadings		
Stage	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D	Mean	Range	S.D
Enlarged [a] Stage 1	225.7	144-346	55.3	280.3	134-422	86.8	181.6	44-345	81.9	223.2	129-295	58.2
Stage 3	245.3	143-301	60.5	280.7	203-437	68.0	109.5	73-156	42.1	163.2	98-226	70.8
Stage 4	177.4	100-258	46.4	222.0	142-303	45.5	202.7	116-250	35.9	223.0	142-290	45.9

[a] Stage 1 and 2 combined.

Table 34 is a summary of Phase II sludge production. A comparison of the Phase I (Table 18) and Phase II (Table 34) results suggest that sludge production in Phase II was substantially lower than that observed in Phase I, particularly overall sludge production with supplemental air. Three factors contributed to the lower sludge production in Phase II: the influent suspended solids levels were generally higher than those observed in Phase I; the sludge production in the enlarged first stage was lower due to the organic load equalization effect; and lastly, with supplemental air, the solids decreased in the fourth stage whereas an increase was observed in Phase I. According to Monod kinetics (84), the growth rate increases as long as the substrate concentration increases, eventually reaching a maximum growth rate at which the substrate becomes saturating. In Phase II, the growth rates were reduced because of the enlarged first-stage equalization effects. Overall sludge production rates between 0.4 to 0.6 (lb SS/lb SCOD) have been reported by other investigators (10, 92). Phase II sludge production results suggest that the RBC systems using an enlarged first stage can expect lower sludge production along with lower costs for sludge stabilization and disposal.

The fixed-film biomass characteristics in Phase II did not change much from that observed in Phase I, except for the Beggiatoa growth which was not as significant in the enlarged first stage as was observed in Phase I without the supplemental air. Also, the white patches in stage 1 that were observed in Phase I at very high organic loadings with the supplemental air did not appear again in Phase II.

Table 34. Summary of sludge production based on soluble COD removal (lb SS/lb SCOD) during the Phase II study

	With an Enlarged First Stage and With Supplemental Air		With an Enlarged First Stage and Without Supplemental Air	
Stage	At Lower Loadings	At Higher Loadings	At Lower Loadings	At Higher Loadings
Enlarged Stage 1	0.697	0.741	0.334	0.539
	(0.661) [a]	(0.565)	(0.418)	(0.401)
Overall	0.265	0.240	0.388	0.295
	(0.233)	(0.209)	(0.390)	(0.240)

[a] Numbers in the parentheses indicate volatile sludge production.

This could be due to the enlarged first stage which reduced the organic loads to the initial stage. The Beggiatoa growth in the non-supplemental air units was present in all stages; however, it was not as predominant as observed earlier in Phase I. The biomass thickness in the first and the fourth stages was 0.076 and 0.032 inch, respectively, in the absence of supplemental air. The biomass thickness with the supplemental air was thinner and was observed to be 0.066 and 0.022 inch in the first and the fourth stages, respectively.

A comparison of the biomass thickness results with supplemental aeration from Phase I and Phase II studies suggests that the thicknesses were somewhat higher in Phase II, both in stage 1 and stage 4. Since the increase in thickness is significantly less, it is hard to arrive at some reasoning, except for the fourth-stage biomass thickness, which could have increased due to the reduced nitrification and increased intrusion of substrate into the later stages from the enlarged first stage. Actually, the biofilm thickness in stage 1 of the Phase II study should have gone down from what was observed in Phase I because of the reduced load in the initial stages, as a result of using the enlarged first stage. Without the supplemental air, the first stage biomass thickness remained at 0.076 inch in both phases. It was observed in the units receiving supplemental aeration in Phase II that the brownish-red biomass in the third and fourth stages present in Phase I disappeared slowly after the baffle removal but did not disappear completely in the fourth stage. Phase I and Phase II biomass characteristics indicate that thinner biofilms can be achieved with the use of supplemental air which could enhance the mass diffusion of substrate and oxygen into the biomass. The Beggiatoa growth can also be eliminated completely from the media with supplemental air and use of an enlarged first stage.

CONCLUSIONS AND RECOMMENDATIONS

Based on the experimental results in this study, the following conclusions can be made:

1. Given the same amount of media, it is possible to achieve higher organic loadings and removal rates when RBC units are provided with supplemental aeration. Regardless of the organic loading rates, units receiving supplemental aeration demonstrate remarkable performance and ability to adapt to differing organic loading rates.
2. Much of the soluble COD is removed in the first stage and the soluble COD removal efficiencies with supplemental air are considerably higher than those observed in the absence of air, particularly at higher organic loading rates. The maximum first stage soluble COD removal rate with supplemental air was 13 lb SCOD/day/1000 sq ft and, without the air, the removal rate was 5.6 lb SCOD/day/1000 sq ft.
3. With supplemental air, the dissolved oxygen levels increased stage by stage to a final value as high as 5.23 mg/L and always remained above 1 mg/L. Dissolved oxygen limitations were not observed with the use of supplemental air. Dissolved oxygen levels in the stages without the supplemental air remained less than 1 mg/L and oxygen-limiting conditions were observed, particularly at high organic loading rates. Dissolved oxygen levels as low as 0.2 mg/L were observed in the beginning stages without use of supplemental aeration.

4. The relationship between the organic loading and removal was statistically significant and these relationships can be used to design RBC systems. At lower organic loadings, the relationships were linear, and at higher loadings the relationships became curvilinear and started to level off indicating oxygen-limiting conditions prevailed.
5. Dissolved oxygen levels in the beginning stages increased significantly when the RBC units were operated with supplemental air and an enlarged first stage. Without the air, the dissolved oxygen levels increased to a certain extent with an enlarged first stage, but were still less than 1 mg/L. The oxygen-uptake rates were higher during operation with supplemental air.
6. The overall soluble COD removal efficiencies were higher in RBC units with supplemental air but were significantly higher at the higher organic loading rates. The overall soluble COD removal rate with air was 8.8 lb SCOD/day/1000 sq ft and without the air it was only 5.1 lb SCOD/day/1000 sq ft.
7. The use of an enlarged first stage by removal of the baffle between the first and second stages reduced the organic loadings in the initial stages and increased the soluble COD removal efficiencies. Removal rates obtained from RBC units supplied with supplemental air and an enlarged first stage were comparatively higher than with an enlarged first stage only. The enlarged first stage soluble COD removal rate with supplemental air was 6.83 lb SCOD/day/1000 sq ft

and in the absence of air the removal rate was only 4.35 lb SCOD/day/1000 sq ft.

8. Carbonaceous substrate removal kinetics with supplemental air and use of an enlarged first stage were found to follow first-order kinetics both at lower and higher organic loadings. Without the supplemental air, the removal of substrate followed second-order kinetics at lower organic loadings and zero-order kinetics at higher loadings. With an enlarged first stage only, the removal of substrate followed first-order kinetics at lower loadings and zero-order kinetics at higher loadings.
9. With supplemental aeration, RBC removal efficiency for ammonia nitrogen was 80.6 percent at lower loadings and 68.4 percent higher loadings. Ammonia nitrogen removal efficiencies as high as 95 percent were observed at lower organic loadings. This RBC plant was designed to meet only secondary effluent limits. Most of the ammonia nitrogen was removed in the third and fourth stages. Without use of supplemental air, ammonia nitrogen removal was insignificant and was mainly due to assimilation of ammonia nitrogen for cell synthesis.
10. The ammonia nitrogen removal efficiencies deteriorated when the RBC units were operated with supplemental air and an enlarged first stage, suggesting preference for plug-flow operation. In the absence of supplemental aeration, ammonia nitrogen removals remained approximately the same with and without an enlarged first stage.

11. Hydraulic loading rate was not a satisfactory indicator of RBC performance. The correlation between hydraulic loading and soluble COD removal was not satisfactory.
12. The mixed-liquor suspended solids were significantly higher in all stages of RBC units operated with supplemental aeration. In the presence of high dissolved oxygen levels, these solids formed a suspended-growth system within the fixed-film system and played an important role in substrate removal. At lower loadings, the maximum mixed liquor suspended solids were 694 mg/L and at higher loadings the solids were as high as 826 mg/L.
13. Thinner biofilms were observed on RBC units supplied with supplemental air which enhanced the mass diffusion of substrate and oxygen into the active biomass.
14. With supplemental air, Beggiatoa growth disappeared completely in all RBC stages. With an enlarged first stage, Beggiatoa growth was reduced to a certain extent but was still present in all the stages.
15. Sludge production from RBC units operated with supplemental aeration was considerably higher in the first stage but the overall sludge production approximately remained the same with and without the supplemental air. The sludge production decreased significantly in the RBC system operated with an enlarged first stage.
16. In this study temperatures as low as 63°F had no impact on soluble COD or ammonia nitrogen removal.

17. It is recommended that supplemental aeration be provided in all future RBC systems and that the system design be based on total organic loading relationships rather than current vendor-supplied empirical relationships. Operational flexibilities such as the ability to operate with step feeding or to remove baffles between stages should be provided to improve RBC performance.
18. When supplemental air is provided, the first stage design loading can be increased up to 25 lb SCOD/day/1000 sq ft without any oxygen limitation and the overall design loading can be varied between 3 to 10 lb SCOD/day/1000 sq ft (Table 10) depending upon the desired removal efficiency. A minimum dissolved oxygen level of 1 mg/L should be maintained in the first stage to prevent oxygen limitation and to maintain Beggiatoa-free growth. Temperature correction should be taken into consideration in the standard way for wastewaters having temperatures of less than 63°F.
19. Due to the higher substrate removal rates, considerable cost savings can be achieved in design and construction just by providing supplemental aeration facilities and removable baffles between stages to permit a reduction in the first-stage loading rate.

FUTURE RESEARCH

The following topics are recommended for future study at a full-scale plant:

1. To optimize air use, intermittent use of supplemental aeration and its impact on RBC performance should be investigated at various organic loading rates.
2. Instead of depending only on use of an enlarged first stage to distribute load to RBC units, the best split ratios for step feeding should be studied under various operating conditions in a plant equipped to permit step feeding.
3. There are several RBC media designs that are available on the market other than that used in this study. The effects of these different media designs on dissolved oxygen levels and RBC performance need to be studied.
4. Recirculation of RBC effluent and its effect on stage dissolved oxygen levels and RBC performance need to be investigated.
5. Media biomass sloughing and its settling and stabilization properties need to be studied.

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APPENDIX:

RBC DESIGN PROBLEM

This appendix will discuss a typical RBC design for treating combined domestic and industrial wastewater in a town with a population of 10,000. The RBC design for this plant will be based on the total organic loading curves developed in this study.

The RBC influent wastewater characteristics in this town are as follows:

Flow = 1 mgd

Soluble BOD_5 = 200 mg/L

Suspended solids = 150 mg/L

Ammonia nitrogen = 25 mg/L

Wastewater temperature = 65°F

pH = 7.5

All other nutrients are present in sufficient quantities in the wastewater to fulfill the nutritional requirements.

Since the best correlation for RBC process performance is with soluble BOD_5, let's assume for design convenience that the relationships between the soluble BOD_5 and soluble COD are as shown in Figures 15 and 16.

The effluent limits for this plant are standard secondary and the plant is required to produce an effluent of 30 mg/L total BOD_5 (15 mg/L soluble BOD_5) and 30 mg/L suspended solids.

From Figure 15, an RBC influent soluble BOD_5 of 200 mg/L is approximately equal to a soluble COD of 350 mg/L. Similarly, an effluent soluble BOD_5 of 15 mg/L is equal to a soluble COD of 78 mg/L (Figure 16).

The required soluble COD removal efficiency in the RBC system to meet effluent limits is

$$= \frac{(350 - 78)\ \text{mg/L}}{350\ \text{mg/L}} \times 100 = 78\%$$

An overall RBC removal efficiency of 80% can be achieved with supplemental air at an overall loading rate of 9-11 lb SCOD/day/1000 sq ft. (Figure 17 and Table 10.)

Based on a loading rate of 9 lb SCOD/day/1000 sq ft, the total RBC media required at this plant is

$$= \frac{[(350 - 78\ \text{mg/L})\ (1\ \text{mgd})\ (8.34)]}{9\ \text{lb/day/1000 sq ft}}\ \text{lb/day}$$

$$= \frac{2269\ \text{lb/day}}{9\ \text{lb/day/1000 sq ft}}$$

= 252,111 sq ft.

With supplemental aeration, the first-stage loading can be increased up to 25 lb SCOD/day/1000 sq ft (Figure 14) without an oxygen limitation. Therefore, the media required for the first-stage is

$$= \frac{2269\ \text{lb/day}}{25\ \text{lb/day/1000 sq ft}}$$

= 90,760 sq ft.

Since most of the RBC manufacturers provide a minimum media of 100,000 sq ft in each stage, therefore, this plant should be provided with three stages. All operational flexibilities should be taken into consideration in the design of this RBC plant.