CONTINUOUS FIXED FILM BIOLOGICAL NITRIFICATION AND DENITRIFICATION OF WASTEWATER

By

Richard W. Wilson, B.Sc.

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AUTHOR : Richard W. Wilson, B.Sc. (Queen's University)

SUPERVISOR : Dr. K.L. Murphy

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ABSTRACT:

This work examines the feasibility of continuous biological nitrification and denitrification for nitrogen removal from municipal wastewater. Pilot plant studies were conducted using a rotating biological contactor (RBC) for nitrification and upflow packed columns for denitrification. Of primary interest were the effects of temperature on the systems.

It was found that an Arrhenius model adequately described nitrification rates measured over a range of temperatures from 7°C to 25°C. Direct comparison of the Arrhenius Activation Energies determined for the RBC and a two stage activated sludge system with intermediate clarification showed that nitrification in the RBC was less temperature sensitive than in the activated sludge process. At 10°C, roughly 20 mg/hr·m^2 (0.10 lb/day·1000 ft^2) of ammonia as nitrogen was removed from the system.

The rate of denitrification in the packed column reactors displayed great variability. The temperature dependency of the data could not be characterized by an Arrhenius model or any other simple relationship. Although significant nitrate removal was observed at all temperatures between 5°C and 25°C, severe short circuiting due to solids accumulation tended to limit minimum nitrate effluent concentrations to 1 or 2 mg NO_3-N/ℓ.

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INTRODUCTION

For almost two hundred years, nitrogen and its compounds have been of great interest to scientists in many different fields. Only during the past twenty to thirty years, however, has man developed a full awareness of the effects and behaviour of nitrogenous materials in aquatic environments. For the first fifty years of this century, the field of pollution and environmental control dealt almost exclusively with three goals. These goals were to treat municipal sewage by eliminating suspended matter, to remove carbonaceous substances which exerted a 5 day biochemical oxygen demand (BOD) and to reduce the numbers of pathogenic organisms. Then, in the early 1950's, the environmental pressures caused by massive industrialization and changes in agricultural practices in Europe and North America finally caused a major expansion of the historical concepts of pollution assessment and abatement. Phenomena such as eutrophication, toxicity along with noise, air and thermal pollution were recognized as having significant environmental impact. Today, there is general acknowledgement that nitrogen in many of its different forms can be a major pollutant. In fact, roughly fifty percent of the states in the U.S. now have established some form of nitrogen control standards (Barth and Smith, 1973).

The major problem areas associated with nitrogenous compounds include:

1. high oxygen demand exerted by ammonia present in sewage and agricultural drainage,
2. eutrophication of lakes resulting from nitrogen excesses,
3. NH_3 toxicity to fish,
4. greatly increased chlorine requirements and contact time due to ammonia present in normal secondary effluents, and
5. NO_3 toxicity in drinking water.

Although technically there are many processes capable of removing nitrogen from wastewater, biological nitrification-denitrification is currently preferred for the treatment of municipal sewage. This is essentially a two-step process. The major portion of the nitrogen entering treatment plants is in the ammonia form. Although urea is present in large quantities in human waste, it hydrolizes rapidly to ammonia. Most of the remaining nitrogen is contained in organic compounds but these release ammonia as a result of their decomposition by heterotrophic bacteria which are present in the organic removal stage of standard activated sludge plants. In the first stage of biological nitrification/denitrification, autotrophic bacteria oxidize the ammonia present to nitrate. In the

second stage, heterotrophic bacteria in the absence of oxygen are able to utilize the nitrates present in two ways. In assimilatory denitrification, nitrate is reduced to ammonia which is then used for cell synthesis. Nitrogen removal from the system in this case is accomplished by sludge wasting. Dissimilatory denitrification involves the use of nitrate by the bacteria as a hydrogen acceptor during the redox reactions associated with cell metabolism. The nitrate is reduced to elemental nitrogen which is released to the atmosphere as a gas.

For the nitrification/denitrification process to be applicable to cold climates, it must be demonstrated that relatively efficient removals of ammonia and nitrate nitrogen can be obtained at operating temperatures approaching 5°C. This research program was designed to evaluate the effects of temperature on fixed film nitrification and denitrification reactors.

A rotating biological contactor or RBC was employed in parallel with an activated sludge plant for the nitrification study. Essentially, the RBC system consists of plastic media, which is about 45% submerged in a trough-like tank, rotated on a horizontal shaft. Biological growth becomes attached to the plastic media and is alternately contacted with air and wastewater as the shaft is slowly turned. Raw waste enters at one end of the tank and treated waste leaves at the other end. Under suitable conditions, populations of both heterotrophic organic carbon consuming

bacteria and autotrophic nitrifiers can be established within the biomass.

Eight foot (2.44 m) high and 12 inch (30.5 cm) diameter upflow packed columns were used for the denitrification study. Two identical columns were constructed each of which was packed with a different size of similar plastic media. Nitrified secondary effluent was fed to the units and this created conditions such that heterotrophic denitrifying bacteria could become established on the surface of the packing. These were run in parallel with a stirred tank denitrification reactor.

A summary of the main objectives of this research is as follows:

1. to investigate the effects of temperature on the operating efficiencies of fixed film nitrification and denitrification systems,

2. to directly compare the temperature sensitivities of nitrification in an RBC and nitrification in a two-stage activated sludge nitrification system with intermediate clarification,

3. to directly compare the temperature sensitivity of columnar denitrification and denitrification in a suspended growth stirred tank reactor, and

4. to supplement existing knowledge concerning the effect of available packing surface area on the rate of denitrification.

LITERATURE REVIEW

Nitrogen, Its Presence and Role in the Biosphere

Nitrogen is an essential element in living matter. It forms the bulk of atmospheric gases and because of its seven available valence states, it is found in hundreds of different compounds, both organic and inorganic, that exhibit widely varying chemical and physical properties. It is for these reasons that many people consider nitrogen as the most interesting of all elements. Nitrogen is very closely associated with life itself for it is only in the biosphere that the element is found in any significant quantity and in so many different forms.

A summary of the numerous types of nitrogen compounds that are present in nature is depicted in Figure 1. Many authors have previously discussed the physical, chemical and biochemical factors which account for the dynamic distribution of these compounds in our environment. Of key importance in these discussions of the "Nitrogen Cycle" has been the role of the aquatic environment. Natural processes provide for the continuous addition and removal of nitrogen compounds from the earth's water bodies. Animal wastes and dead plant matter contribute large quantities of ammonia and organic nitrogen to rivers and lakes. Certain forms of aquatic organisms, notably blue-green algae, fix atmospheric nitrogen directly into organic forms. Nitrates and nitrites

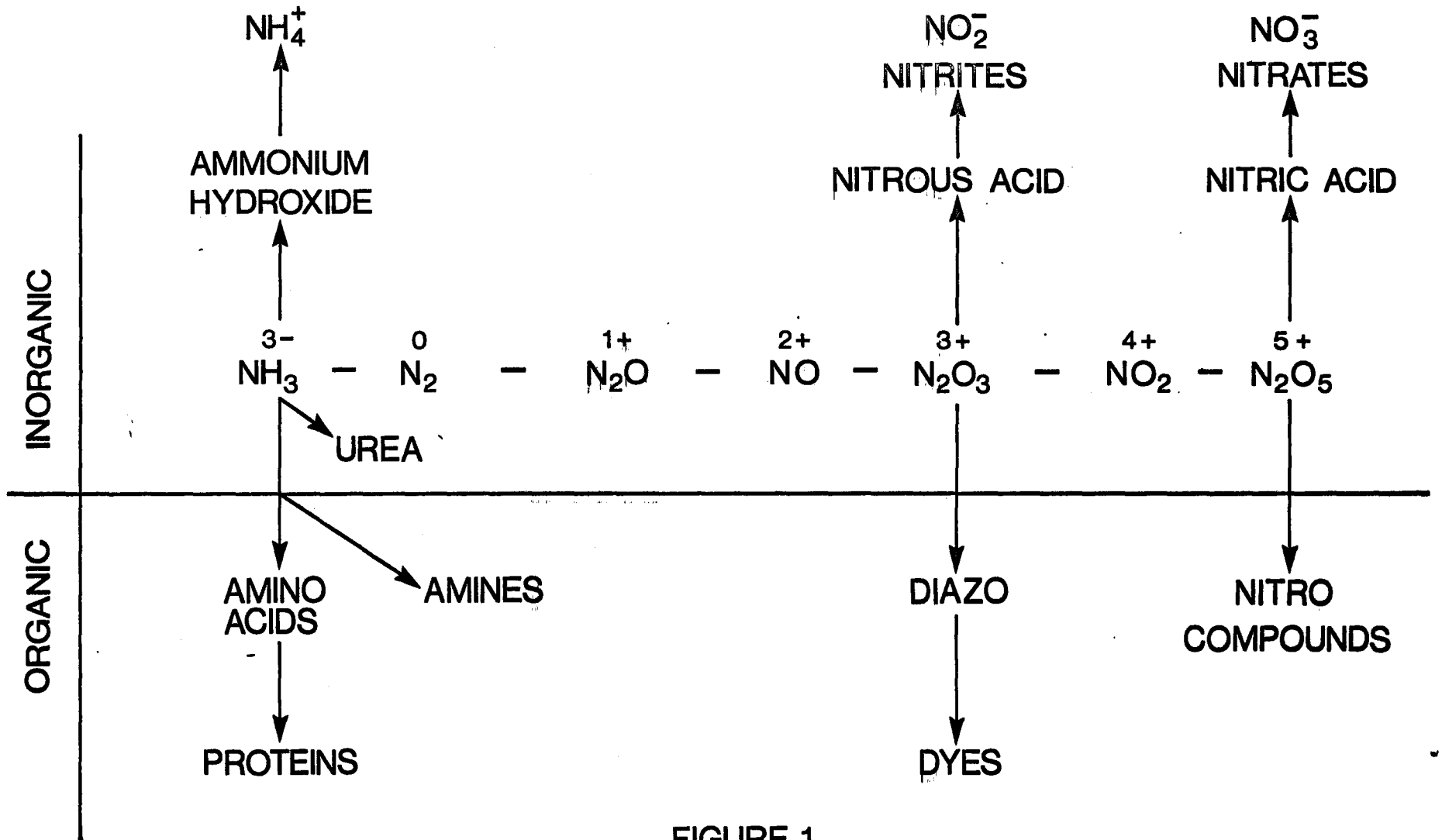


FIGURE 1

THE PRESENCE OF NITROGEN IN IT'S SEVEN VALENCE STATES (McCARTY 1973)

are formed in nature by electrical discharges in the atmosphere as well as through the actions of certain plant related bacteria. These oxidized nitrogen forms also find their way into rivers and lakes through direct precipitation or transport in the ground water. Limnologists and marine biologists point out that the synthesis of organic nitrogen compounds from inorganic ammonia occurs almost exclusively as a result of growth and reproduction of aquatic and marine plants and micro-organisms. Practically all higher forms of plant and animal life derive their organic nitrogen directly or indirectly from these micro-organisms. Bacterial denitrification of nitrates and nitrites to gaseous nitrogen, evaporation of free ammonia or other volatile nitrogen species and settling of non-readily degradable nitrogenous organic residues are all processes by which nitrogen can leave the hydrosphere. These latter processes tend to permit the establishment of an equilibrium between the nitrogen entering and the nitrogen leaving the world's rivers, lakes and oceans.

Justification for Controlling Nitrogenous Wastes

Through recent decades, man's activities have had a greater and greater effect on nitrogen equilibria. For example, Ferguson (1968) estimated that in the U.S., man was directly or indirectly responsible for 46 to 79 percent of the total quantity of nitrogen entering waterways.

Municipal sewage, runoff from feedlots and other animal producing land, and runoff from farmland that utilizes ammonia and nitrate fertilizer account for the bulk of this nitrogen contribution. Nor is this extra nitrogen load distributed evenly throughout the environment. Feedlot runoff and municipal sewage effluent provide a relatively finite number of point sources of concentrated nitrogen. An average total nitrogen concentration of close to 40 mg/l as N quoted by the American Chemical Society (1969) for secondary municipal effluents is many times higher than normal levels found in receiving waters. It is not surprising then that a number of serious problems specifically related to excess nitrogen availability have been recognized and have aroused genuine concern within recent years.

1. EUTROPHICATION. The process of eutrophication can be defined as an acceleration of the biological productivity of a body of water due to an increased availability of essential nutrients. This tends to hasten the natural aging process of a lake by increasing the quantity of settleable material which then provides a more rapid filling of the basin through sedimentation. The lake eventually becomes extinct. Today, anything that shortens the life of a body of water or interferes with its use and enjoyment is socially unacceptable. For instance, one characteristic of many eutrophicated bodies of

water is the formation of nuisance amounts of algae. This can create clogging of water purification equipment, it can necessitate costly pretreatment of water for industrial use and generally will reduce the aesthetic quality of recreational areas. Anoxic zones in lakes can also be caused as a result of eutrophication. This occurs when dead algae and other micro-organisms accumulate so rapidly that dissolved oxygen is used up during the decay process faster than it can be replenished. This brings about reductions or shifts in fish populations.

The concept of nutrient limitation allows an insight into the causes of eutrophic conditions within a lake. In the early nineteenth century, the eminent German scientist, Justus von Liebig, first proposed the idea of the limiting or growth-determining nutrient in his Law of the Minimum. A contemporary statement of this law as it affects eutrophication has been presented by Gibson (1971). Briefly, Gibson proposed that a factor is not limiting growth if, when it is increased in concentration, no effect on growth is observed. It is now generally agreed that either phosphorus, nitrogen, or carbon are the nutrients which are most likely to be in limiting concentrations for growth of aquatic phytoplankton. Also, since these elements are required in far greater quantities than other

essential nutrients, it would seem that the availability of these would be the easiest to regulate. Some studies have indicated that carbon may limit eutrophication in soft water areas (Kerr, 1970). Massey (1971) pointed out that the majority of nutrient limitation studies conducted indicate phosphorus to be the growth limiting factor. As a result of this evidence, many people believe that nitrogen removal from wastewater will have no beneficial effects. However, a few studies such as that of Shapiro (1965) have shown that in certain areas where phosphate levels are relatively high, nitrogen can indeed be limiting growth. Massey also cited a study by Yoshimura in 1932 where it was shown that phosphorus was limiting at one time of year and nitrogen at another time. Therefore, there are at least a number of specific cases in which nitrogen removal from effluents would seem to be justified. Still some people argue that effective nitrogen controls would not be possible through treatment of wastewater, particularly because some aquatic species, notably blue-green algae, are known to be able to fix atmospheric nitrogen. This attitude infers that nitrogen can never be limiting. An argument of this nature however, is not valid because nitrogen fixation requires a fairly intensive outlay of energy, and nitrogen fixers that can utilize more

readily available nitrogen sources will undoubtedly grow more quickly than those which are forced to fix all of their required nitrogen from the atmosphere.

2. OXYGEN SAG. It has long been recognized that ammonia present in wastewater can be oxidized to nitrate by nitrifying bacteria with the consumption of 4.57 parts of oxygen for every part of ammonia nitrogen changed to nitrate. Nitrifying bacteria however, have a long generation time and historically, it was considered inefficient to design treatment plants to provide for ammonia oxidation. It was also thought that the rate of nitrate formation in receiving waters could be sufficiently slow so as to avoid any significant oxygen sags. Two recent studies cited by Sawyer (1973) indicate that this is not necessarily the case and that significant oxygen sags can be caused by ammonia oxidation, especially in slow shallow rivers. This is a very important discovery since there is generally about 20 mg/l of ammonia as N in effluents from conventional secondary treatment plants and this represents an oxygen demand approaching 100 mg/l.

3. NH_3 TOXICITY. Even very low levels of free molecular ammonia are known to be toxic to fish. The harmful effects of ammonia on fish are related chiefly to the pH value and the temperature value due to the fact

that only the un-ionized fraction of ammonia is more toxic. This un-ionized portion increases with rising pH value, and with rising temperature. Some research has indicated that free ammonia becomes more toxic as temperature is decreased from 10°C. (European Inland Fisheries Advisory Commission Working Party on Water Quality Criteria for European Freshwater Fish, 1973). In this range, therefore, the effect of increasing toxicity with decreasing temperature tends to cancel the effect of the decrease in the percentage of un-ionized ammonia.

Laboratory experiments of relatively short duration have demonstrated that the lethal concentration of ammonia (un-ionized) for a variety of fish species lies in the range 0.2-2.0 mg NH_3/l, with trout being the most sensitive and carp being the most resistant. Although concentrations of un-ionized ammonia below 0.2 mg NH_3/l may not kill a significant proportion of a fish population, significant tissue damage has been observed with prolonged exposure at concentrations lower than 0.025 mg NH_3/l. Concentrations of total ammonia which contain this amount of the un-ionized portion vary from 19.6 mg/l (pH 7.0, 5°C) to 0.12 mg/l (pH 8.5, 30°C).

4. NO_3 TOXICITY. High nitrate levels in water consumed both by infants and by ruminant livestock are known to have toxic effects. The stomachs of both reduce nitrate to nitrite which in infants causes methemoglobinemia (blue babies). The Ontario Ministry of the Environment has assigned a limit of 10 mg/l as N for nitrate in drinking water. Although most water sources at present contain substantially less than this quantity of nitrate, the situation could change should areas that reuse the same water several times not adopt nitrogen removal regulations. A case in point would be sections of Minnesota and Manitoba that rely on the Red River for water. By the time the river empties into Lake Winnipeg, the water has been used several times by man. Nitrate levels from farm runoff and sewage effluents could conceivably reach hazardous levels. The munitions industry is another example in which high effluent nitrate concentrations in the wastewaters could cause problems if suitable treatment is not employed.

5. Cl_2 DEMAND FOR DISINFECTION. The quantity of chlorine required for water purification and sewage effluent disinfection to produce a free chlorine residual varies directly with the concentration of ammonia as well as other reduced materials in the water. Before a free chlorine residual appears, all of the

ammonia is oxidized to free nitrogen gas and nitrogen trichloride in a series of reactions. It takes roughly 3.8 parts of chlorine to oxidize one part of ammonia nitrogen. If large ammonia concentrations are present when the disinfection step is reached in a treatment plant, large quantities of costly chlorine will be required. From economic considerations, it may make sense to remove ammonia from sewage if disinfection is a requirement.

BIOLOGICAL NITRIFICATION/DENITRIFICATION THEORY

Nitrification

Nitrification is the process by which micro-organisms oxidize ammonia to nitrite and then to nitrate as a means of providing energy for growth and other metabolic functions. Painter (1970) mentioned that research to date has identified two main genera of autotrophic bacteria which are known to oxidize ammonia to nitrite, namely, Nitrosomonas and Nitrosococcus. Two other genera, Nitrobacter and Nitrocystis, have been shown capable of forming nitrate from nitrite. Although Painter (1970) also mentioned that a large number of heterotrophic bacteria have been identified as nitrifiers, heterotrophic nitrification appears to be much less important than autotrophic nitrification. Many of the heterotrophic species have been found in soil samples only and it is not known whether they could also adapt to the environment of an activated sludge treatment plant. Autotrophic

nitrifying bacteria are probably much more efficient than heterotrophic forms in ammonia conversion because all of the energy used by these organisms is derived from the energy liberated during ammonia oxidation. Heterotrophs obtain only part of their energy requirements from nitrification, the major portion coming from organic substrate oxidation. Therefore, in discussing nitrification, only nitrifying autotrophs will be considered.

The processes of bacterial ammonia oxidation can be represented by the following equations:

$$NH_4^+ + 3/2\ O_2 \xrightarrow{\text{Nitrosomonas}} NO_2^- + 2H^+ + H_2O \qquad (1)$$

$$NO_2^- + 1/2\ O_2 \xrightarrow{\text{Nitrobacter}} NO_3^- \qquad (2)$$

McCarty (1970) suggested $C_5H_7O_2N$ as an acceptable empirical cell formula for nitrifying bacteria. As a result, the assimilation reaction can be represented as:

$$5CO_2 + NH_4^+ + 2H_2O \rightarrow C_5H_7O_2N + 5O_2 + H^+ \qquad (3)$$

By using reported values of actual cell yields the following overall mass balances combining nitrification and assimilation were proposed by Haug and McCarty (1971).

$$\underline{\text{Nitrosomonas}} \quad 55\ NH_4^+ + 5CO_2 + 76\ O_2 \longrightarrow$$

$$C_5H_7O_2N + 54\ NO_2^- + 52H_2O + 109H^+ \qquad (4)$$

$$\underline{\text{Nitrobacter}} \quad 400\ NO_2^- + 5CO_2 + NH_4^+ + 195\ O_2 + 2H_2O$$

$$\longrightarrow C_5H_7O_2N + 400\ NO_3^- + H^+ \qquad (5)$$

It is significant to note that on the basis of equations (4) and (5), 20 mg of ammonia nitrogen would produce only 3 mg of Nitrosomonas and roughly 0.5 mg of Nitrobacter. These yields are much lower than normally observed with heterotrophic aerobes. Also, the hydrogen ions formed during nitrification combine with bicarbonate and carbonate ions in solution to produce carbon dioxide and water. This decreases alkalinity by 7.2 mg as $CaCO_3$ for every 1 mg ammonia nitrogen oxidized. Since the water in a number of areas in North America has a natural alkalinity less than 100 mg/l as $CaCO_3$, there may not always be sufficient natural buffering capacity in wastewater to permit the use of biological nitrification.

Stoichiometrically equation (1) and equation (2) show that 4.57 mg of oxygen are required to oxidize 1.0 mg of ammonia to nitrate. When the contribution of the carbon dioxide used in assimilation is taken into consideration, this value is reduced to 3.9 mg of oxygen.

Oxidation of ammonia provides less energy than the oxidation of most organic substrates used by heterotrophic bacteria. Because of this, a large amount of ammonia must be converted to supply sufficient energy for the assimilation of one bacterial cell. This is the reason for the low cell yield exhibited by nitrifying bacteria. Another facet of

nitrifiers is their long generation time. As a result of this,relatively long sludge residence times are necessary to allow the establishment of nitrifying populations in biological systems. In mixed cultures, the presence of high concentrations of organic substrates tends to reduce the percentage of nitrifiers because of competition from the more rapidly generating heterotrophs.

Denitrification

Denitrification can be accomplished in two distinct ways by micro-organisms. First of all, assimilative nitrate reduction can be defined as the overall process whereby nitrate-N is reduced to ammonia with the subsequent formation of nitrogenous cell constituents. Secondly, dissimilative nitrate reduction or respiration is the process in which nitrate is used as the terminal hydrogen acceptor instead of molecular oxygen during the oxidation of organic substrates. This results in the reduction of the oxidation state of the nitrogen from plus three in the nitrate form to zero as liberated gaseous nitrogen.

A wide variety of common facultative bacteria are known to accomplish denitrification. Examples reported by Delwiche (1956) include Pseudomonas sp, Bacillus sp, Micrococcus sp, Achromobacter sp and Spirillum sp. The reason why such a large number of bacteria are able to utilize nitrate respiration as well as oxygen respiration is that the same series of reversible enzymatic reactions

employed in transferring electrons from organic substrates to molecular oxygen is also used when electrons are transferred to nitrate. This specific enzymatic pathway is called the electron transport chain. Only a different terminal enzyme, nitrate reductase, is required for nitrate respiration and this is formed by the bacteria in an oxygen free environment. Therefore, it is generally agreed that denitrification cannot occur in the presence of oxygen. Although some workers (Myers, 1955; Schmidt, 1962) have reported the occurrence of denitrification under aerobic conditions, this could have been caused by bacteria acting in anaerobic regions within flocs.

Denitrifying bacteria can oxidize the same range of organic substances through nitrate respiration as through oxygen respiration with the exception of compounds such as aromatics which require oxygenases. These enzymes can only be manufactured in the presence of oxygen. Research conducted by McCarty (1969) has shown that methanol is an effective and economical substrate for denitrification. Using the same technique described for deriving the overall mass balance for nitrification McCarty (1973) presented a mass balance for denitrificatiion using methanol as substrate. The equations involved are shown in Figure 2 together with a scheme for the pathways that nitrate follows, including the intermediate compounds involved, during both assimilative and dissimilative denitrification. Painter (1970) concluded that the basic system represented in part

FIGURE 2

A. MASS BALANCE FOR OVERALL DENITRIFICATION

(McCarty 1973)

Energy Generating Reactions

Step 1

$$NO_3^- + 1/3\ CH_3OH \longrightarrow NO_2^- + 1/3\ CO_2 + 2/3\ H_2O$$

Step 2

$$NO_2^- + 1/2\ CH_3OH \longrightarrow 1/2\ N_2 + 1/2\ CO_2 + 1/2\ H_2O + OH^-$$

Overall

$$NO_3^- + 5/6\ CH_3OH \longrightarrow 1/2\ N_2 + 5/6\ CO_2 + 7/6\ H_2O + OH^-$$

Assimilation

$$NO_3^- + 9/2\ CH_3OH + 1/3\ CO_2 + H^+ \longrightarrow C_5H_7O_2N + \frac{19}{3}\ H_2O$$

Overall Balance (Assimilation + Dissimilation)

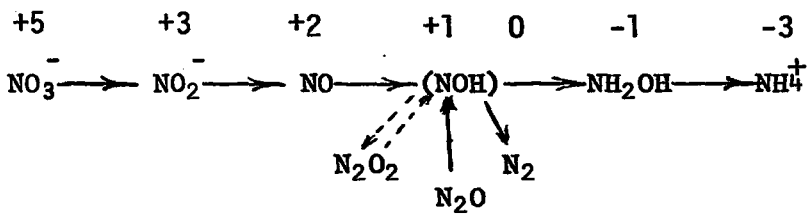
$$NO_3^- + 1.08\ CH_3OH + H^+ \longrightarrow$$

$$.065C_5H_7O_2N + .47\ N_2 + .76\ CO_2 + 2.44\ H_2O$$

B. ASSIMILATION AND DISSIMILATION PATHWAYS AND INTERMEDIATES

(Painter 1970)

Redox State of N



----- Non Enzymatic

_____ Enzymatic

B of figure 2, which was first proposed by Fewson and Nicholas (1961), although not completely confirmed, is most likely correct.

On the basis of the overall denitrification balance of Figure 2, it can be seen that the reduction of 20 mg of NO_3-N would require 50 mg of CH_3OH or 0.94 mg of methanol as carbon per mg of NO_3-N. The 20 mg of NO_3-N would also result in the production of 10.5 mg of biomass that would contain 0.84 mg or about 6 percent of the total nitrogen removed. To facilitate estimation of methanol requirements and sludge production in a normal denitrifying reactor, McCarty (1973) presents the following formulae:

Methanol Requirements

$$C_m = 2.47\ NO_3\text{-}N + 1.53\ NO_2\text{-}N + 0.87\ D.O. \qquad (6)$$

Biomass Production

$$C_B = 0.53\ NO_3\text{-}N + 0.32\ NO_2\text{-}N + 0.19\ D.O. \qquad (7)$$

where: C_m is the required methanol in mg/l,

C_B is the biomass production in mg/l,

NO_3-N is the nitrate nitrogen in mg/l,

NO_2-N is the nitrite nitrogen in mg/l, and

D.O. is the dissolved oxygen concentration entering the system in the feed in mg/l.

These expressions are basically derived from research on actual methanol consumption conducted by McCarty (1969). Other research is also cited as confirming McCarty's work

(Smith et al, 1972; Stensel, Loehr and Lawrence, 1973).

Finally, it should also be noted that hydrogen ions are consumed during denitrification at a rate of 3.0 mg of alkalinity as $CaCO_3$ per mg of NO_3-N. This will partially compensate for the alkalinity removed during nitrification.

KINETICS AND REACTION RATES

Basic Kinetics

Many researchers have investigated the kinetics of nitrification and denitrification during the last ten to fifteen years. To date, the Monod kinetic model has been used most often to describe experimental data.

$$R = \frac{\mu S}{K_s + S} \tag{8}$$

where:

R = mass of substrate removed per mass of biological solids per unit time,

S = substrate concentration in the system (NO_3-N for denitrification, NH_4^+ -N for nitrification),

μ = rate constant corresponding to the maximum substrate removal rate,

K_s = half reaction constant defined as the concentration of substrate at which the rate of substrate removal is half of the maximum possible.

Recent discussions of the literature by Sutton on nitrification kinetics (1974) and denitrification kinetics (1973) indicate that for mixed culture activated sludge

systems,the rates of ammonia and nitrate removal can generally be approximated by a simpler model which is zero order with respect to substrate concentration. This conclusion is largely based on the fact that the Monod K_s values derived by many researchers for nitrification and denitrification are in the 0.2 mg/l to 2.0 mg/l range. Therefore, under most practical reaction conditions, the effect of K_s becomes insignificant and the Monod model reduces directly to a "zero order" expression with respect to substrate concentration. In at least one case (Requa and Schroeder, 1973) the "zero order" approximation has been shown as valid for a fixed film denitrification reactor as well. Nevertheless, the rates of substrate diffusion into and out of biological films may play a much more important role in determining the apparent rate of reaction for fixed film processes than for dispersed growth processes. Therefore, in the absence of more data, care must be taken in adopting "zero order" kinetics for nitrification and denitrification in non-dispersed growth systems.

Effects of Carbon Concentration on Denitrification

Although there is general agreement that the dissolved carbon concentration influences the rate of denitrification, Dawson and Murphy (1972) have shown that as the carbon to nitrate ratio is increased, an increase in the unit denitrification rate occurs only until the theoretical carbon to nitrate ratio predicted for nitrate

reduction and organism growth is reached. Consequently, in operating a denitrifying reactor, to avoid rate limitations due to carbon availability, it is only necessary to assure that a stoichiometric quantity of carbon substrate is present.

Oxygen Limitation in Nitrification

Painter (1970) quoted work by Schoberl and Engel (1964) which showed that oxygen did not become limiting for ammonia oxidation by Nitrosomonas until a concentration of 0.9 mg/l was reached. For mixed culture systems, Johnson and Schroepfer (1964) mentioned that 0.5 mg/l was found by Downing and Bagley (1961) to be the limiting dissolved oxygen level for nitrification. Somewhat higher limiting oxygen concentrations have been reported for nitrite oxidations by Nitrobacter but this is of less practical interest for sewage treatment since ammonia oxidation to either nitrite or nitrate is equally acceptable if denitrification is to follow.

pH Effects

Nitrification and denitrification have been reported to operate in the broad range of pH between 5.0 and 10.0. Generally, optimum conditions for nitrification have been found to exist between pH 8.0 and 9.0. Denitrification seems to proceed best at the slightly higher hydrogen ion concentrations associated with pH values of 7.0 to 8.0.

Significant, however, is the fact that much of the work conducted in the past was with pure cultures and usually little or no consideration was given to the effects of long term acclimation.

Temperature Effects

For many reactions, both chemical and biochemical, the rate expression can be written as the product of a temperature dependent term and a basic kinetic term, or:

$$\text{Rate} = \text{func (temperature)} \cdot \text{func (basic kinetics)} \quad (9)$$

Consequently, in biological sewage treatment design, knowledge of kinetics alone is insufficient as most treatment facilities experience annual temperature fluctuations.

All micro-organisms exhibit the same basic temperature versus activity relationship. At low temperatures, reaction rates are low. Rates increase more and more quickly as the temperature is raised until a maximum is reached. Usually the optimum temperature range for a specific species is quite narrow. As temperature is raised beyond the optimum the activity of the micro-organisms falls off quickly and continues to decrease until all activity ceases. This rapid deterioration is thought to be caused by temperature inhibition of the manufacture of certain key enzymes which are essential in catalyzing specific cell reactions. Although all bacteria follow this general temperature-activity relation, the optimum temperatures of the various genera vary significantly. Definitions are not

precise but the following three groups of bacteria; psychrophilic, mesophilic and thermophilic, can be defined as having optimum growth rates under 20 degrees C, between 20 and 50 degrees C and over 50 degrees C respectively. Nitrifying bacteria and the chief denitrifying bacteria are mesophilic with peak activities generally between 25 and 35 degrees. Therefore, for all temperature conditions of normal raw sewage (5 to 25 degrees C in cold and temperature climates) nitrification should exhibit increasing reaction rates with increasing temperature.

An empirical relationship commonly employed to describe the effect of temperature on simple chemical systems and on the increasing activity phase of biochemical reactions was suggested by Arrhenius in 1889 (Laidler, 1965).

$$K = Ae^{-E/RT} \qquad (10)$$

where:

K is the reaction velocity,

A is a constant (frequency factor),

E is the activation energy (cal/gm mole),

R is the gas constant (1.987 cal/gm mole ^{o}K), and

T is the absolute temperature (^{o}K).

It is important to understand that the activation energy E increases as the temperature sensitivity of a given system increases. Therefore, a reaction rate which is shown to fit the Arrhenius expression varies more with changing temperature if its energy of activation is 20,000 cal/gm

mole that if it were 2000 cal/gm mole. Systems that tend to minimize temperature sensitivities are less susceptable to large fluctuations in operating efficiency as the temperature changes and are therefore preferred.

In the analysis of rate data, several rearrangements of the basic Arrhenius equation have been used during the past. These include:

$$K_T = K_o \, \theta^{(T-T_o)} \quad \text{Streeter and Phelps, (1925)}$$

$$K_T = K_o \, e^{\theta'(T-T_o)} \quad \text{McCarty, (1973)}$$

$$Q_{10} = \frac{K_T}{K_{T-10}} \quad \text{Fair, Geyer, and Okun, (1968)}$$

where:

K_T is the reaction rate at temperature T,

K_o is the reaction rate at temperature T_o,

K_{T-10} is the reaction rate at temperature T-10,

Q_{10} is a measure of the increase in reaction rate caused by a 10 degree rise in operating temperatures, and

θ is the thermal coefficient (related to the activation energy).

A summary of temperature coefficients as calculated by Sutton (1973) for published denitrification data is given in Table 1. Table 2 provides a similar tabulation of nitrification coefficients. It is worth noting that in the case of both nitrification and denitrification the average Q_{10} values are slightly greater than 2.0. This is compatible

Table 1

Temperature Coefficients For Denitrification

(Data from Sutton, 1973)

REFERENCE	SYSTEM	TEMPERATURE RANGE ^{o}C	$K=Ae^{-E/RT}$ E	$K_T=K_{20}e^{\theta'(T-20)}$ θ'	$K_T=K_{20}^{\theta(T-20)}$ θ	Q_{10} VALUES
Dawson (1971) Lab Scale	Batch P. Denitrificans	3-27 10-20	16,800	0.11 0.10	1.12 1.10	3.0
Stensel (1971) Lab Scale	Batch Activated Sludge SRT=2 days	15-25	10,000	0.06	1.06	1.74
	Continuous Activated Sludge	10-20	19,500	0.12	1.13	3.3
	Continuous Activated Sludge	20-30				-0.5
Mulbarger et al, (1971) Pilot Plant	Activated Sludge SRT=7.6 days	10-20	19,000	0.14	1.15	3.3
Johnson, Vania (1971) Pilot Plant	Activated Sludge	10-20				2
Wuhrmann, Mechsner (1965) Lab Scale	Batch Activated Sludge	10-20				2.6
Sutton (1973) Pilot Plant	Continuous + Batch Activated Sludge					
	1. SRT=3 days	5-25	15,300	0.089	1.093	~2.4
	2. SRT=6 days	5-25	15,900	0.093	1.097	~2.4
	Continuous Packed Columns	5-25	11,090	0.067	1.07	~2.0

Table 2

Temperature Coefficients For Nitrification

REFERENCES	SYSTEM	TEMPERATURE RANGE ^{o}C	$K=Ae^{-E/RT}$ E	$K_T=K_{20}e^{\theta'(T-20)}$ θ'	$K_T=K_{20}^{\theta(T-20)}$ θ	Q_{10} VALUES
Blue Plains Data Jan.72 - Sept.73 Cited by Brown and Caldwell (1974)	Batch Activated Sludge	16-27	12,200	0.074	1.08	2.1
Mulbarger (1971)	Batch Activated Sludge	8-23	10,800	0.065	1.07	1.9
Pretorius (1974)	Continuous Rotating Biological Contactor	5-30	3,654	0.02	1.02	1.25
Downing et al (1964)	Activated Sludge	5-15	20,400	0.12	1.13	3.3

with the general rule of thumb that a ten degree C temperature rise for a biological system will double the reaction rate. Of specific interest in the nitrification results is the very low Q_{10} reported by Pretorius (1974) for his RBC apparatus. Although, it may well be that nitrification in an RBC exhibits some difference in temperature sensitivity compared to nitrification in the activated sludge process, the activation energy found by Pretorius is nevertheless very much smaller than any value previously quoted in the literature. In fact, Pretorius ' Q_{10} value of 1.25 is almost identical to the Q_{10} value of 1.30 reported by Kehrberger et al (1964) for diffusion limited glucose utilization in a BOD bottle. Diffusional limitations on the transport of oxygen or substrate may well have had a major effect on the nitrification rates observed by Pretorius since his disc rotational speed was set to give a tip velocity of only 29 ft/min (8.8 m/min). This is barely half the value recommended by Antonie (1970) for optimum nitrification. The literature quoted in Table 1 and Table 2 also shows that significant nitrification and denitrification can occur at temperatures as low as 5 to 10 degrees C. This furnishes important support for the idea that biological nitrogen removal is viable in cold climates.

Fixed Film versus Dispersed Growth

There are basic environmental differences between

organisms in dispersed growth reactors and those which form stable films on solid surfaces such as those in packed columns and RBC's. Probably the most significant difference between these two types of systems involves the percentage of active organism surface area in direct contact with the nutrient rich liquid phase. In kinetic studies of dispersed systems, the simplifying assumption that all active organisms have equal contact opportunity with nutrients is usually understood. This assumption however, can never be made for fixed film systems as nutrient and oxygen concentration gradients through the film directly affect contact opportunities. It is, therefore, logical to speculate that diffusion of oxygen, nutrients and metabolic wastes between a film's surface and the interior plays an important role in determining overall substrate removal rates. In fact, both Torpey (1972) and Pretorius (1974) have shown that nitrification rates increase significantly in rotating biological contactors when oxygen enriched or pure oxygen atmospheres are used instead of air. This would suggest that the higher driving force for oxygen diffusion between the atmosphere and the biological film produces higher rates of mass transport and hence, increased rates of nitrification. Similar behaviour has not been observed for high oxygen concentrations in dispersed growth systems. Figure 3 and Figure 4 show many of the diffusional processes which could be of importance in film nitrification and denitrification.

FIGURE 3

DIFFUSION PROCESSES IN FIXED FILM NITRIFICATION

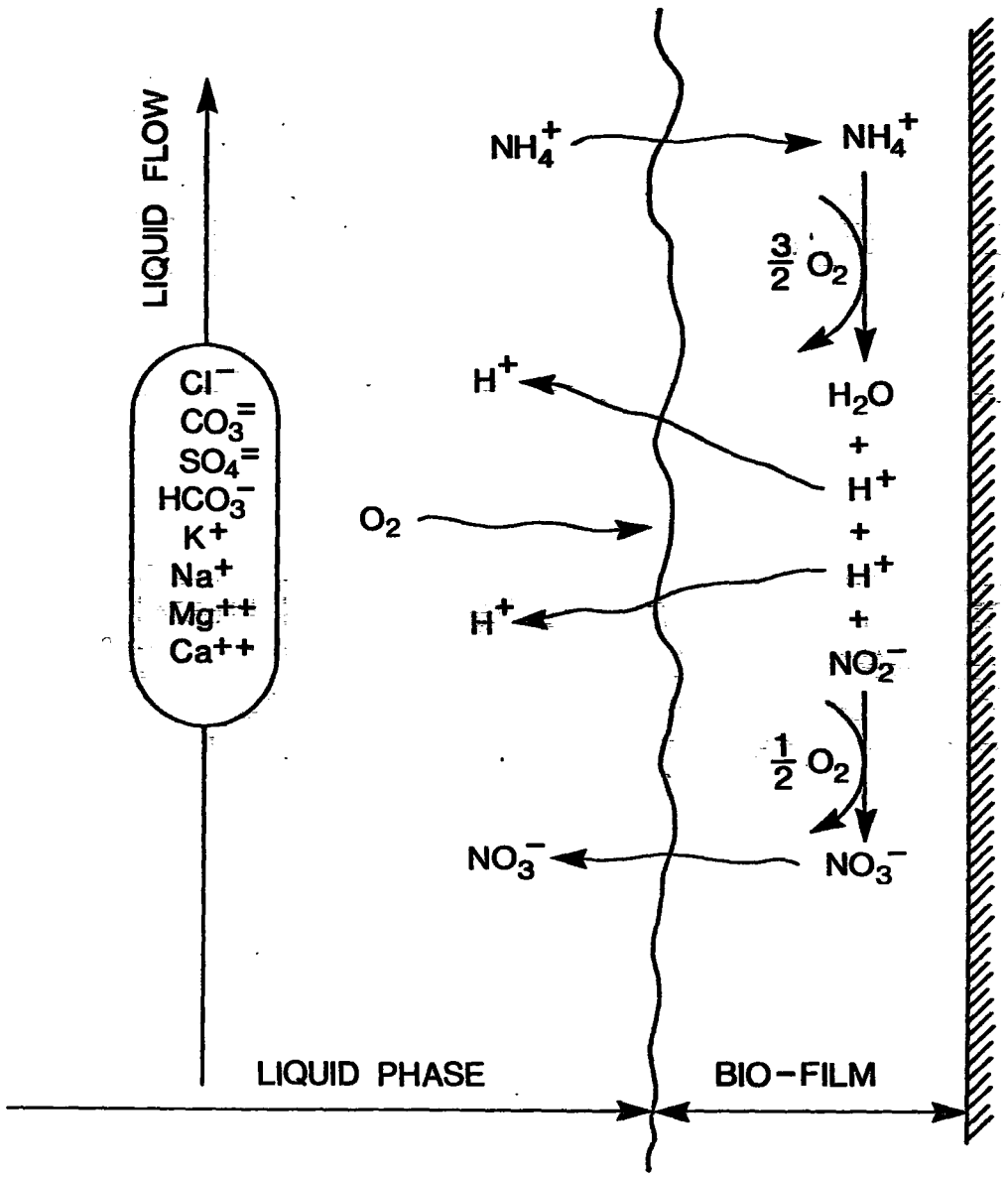
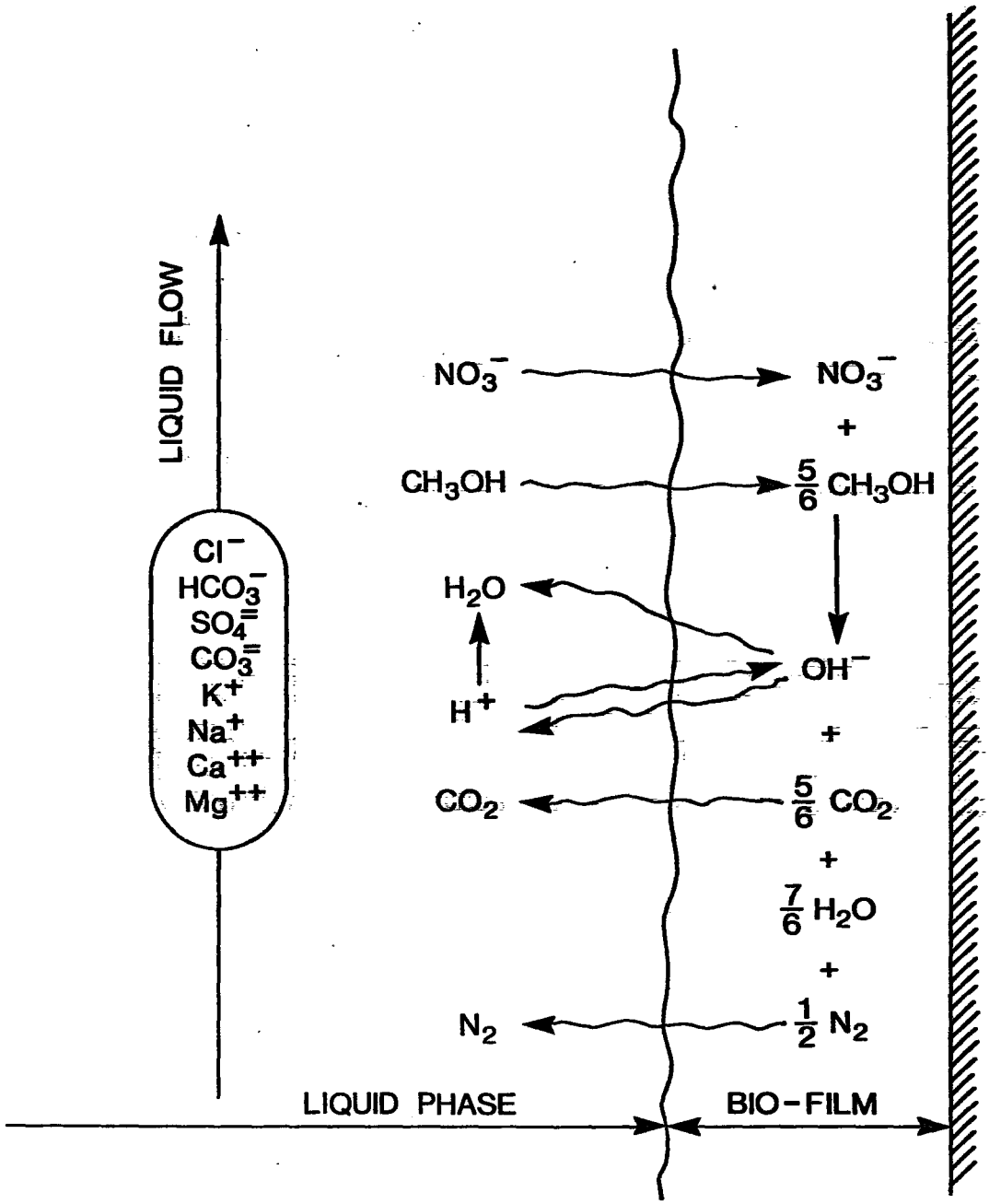


FIGURE 4

DIFFUSION PROCESSES IN FIXED FILM DENITRIFICATION

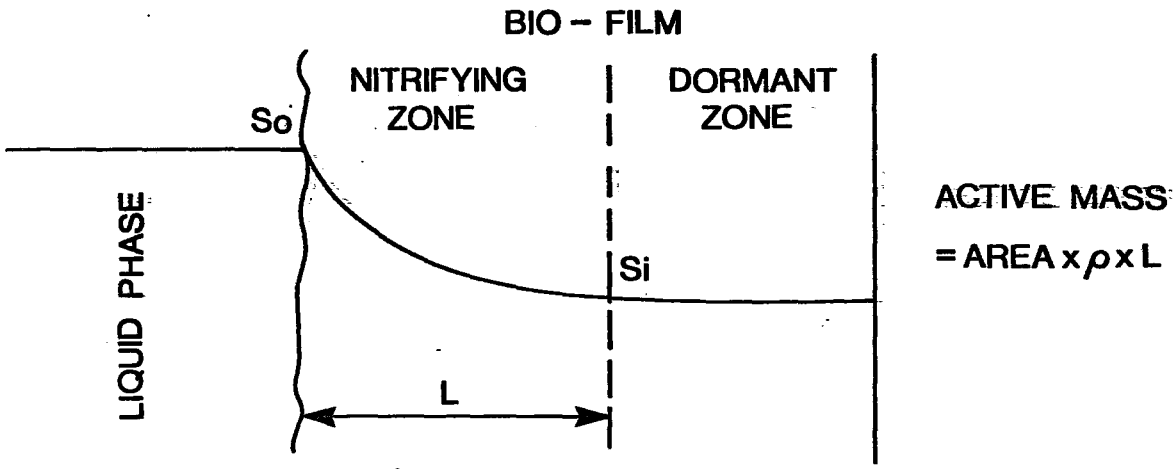


Several authors (Grieves, 1972, Haug and McCarty, 1971) have included the effects of substrate diffusion successfully into mathematical models for nitrification in biological films. In the case of the model presented by Haug and McCarty, it was predicted that fixed film nitrification was less temperature sensitive than the usual dispersed growth process. The basis for this argument came from the assumption that certain portions within a film can remain inactive in ammonia oxidation for extended periods of time while still remaining viable. At each temperature, a characteristic substrate gradient would be established within the film. The depth of the gradient would be dependent upon the diffusive flux of substrate into the film from the liquid phase and the degree of biological activity at that temperature. Theoretically, an active mass of micro-organisms could then be determined by multiplying the total film surface area by the film density and then by the depth of the substrate gradient into the film. As the temperature of the system is decreased, biological activity reduces rapidly. There is also a slight reduction in diffusive flux; however, diffusive transport does not decrease as rapidly with falling temperature as biological activity. This provides for deeper penetration of the NH_4^+ and O_2 gradients into the film (see Figure 5) at low temperatures. Consequently, even though the ammonia removal per mass of organisms per time decreases as the temperature is lowered, the mass of active nitrifiers increases because significant ammonia concentrations reach deeper into the film. These two phenomena

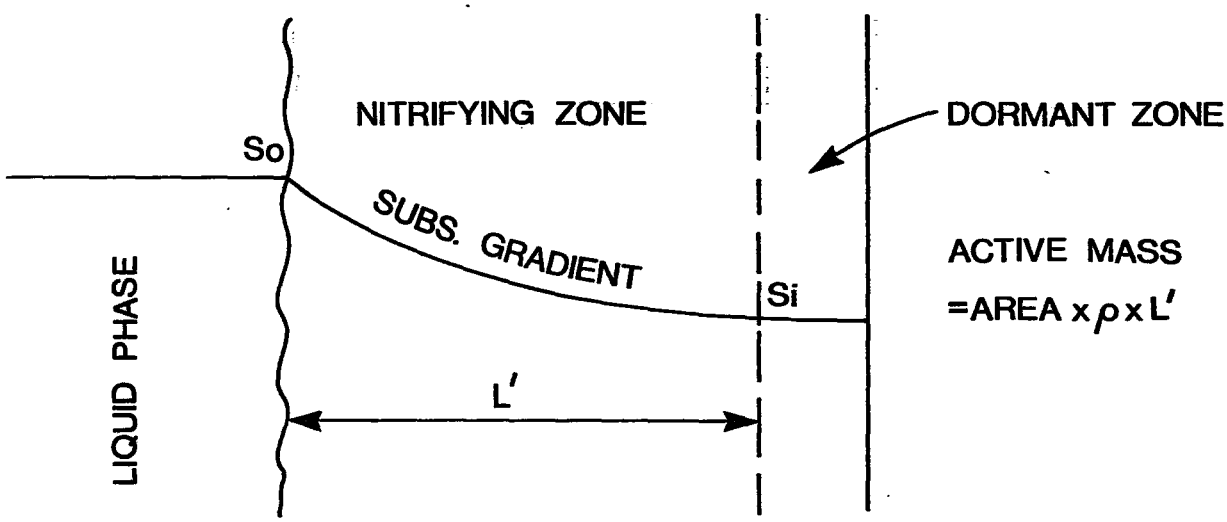
FIGURE 5

TEMPERATURE SENSITIVITY OF FIXED FILM REACTORS

HIGH TEMPERATURE



LOW TEMPERATURE



So = INITIAL SUBSTRATE CONCENTRATION IN LIQUID

Si = CONC. OF SUBSTRATE (APPROX = 0) WHERE NITRIFICATION CEASES

would tend to cancel one another resulting in a slower change in ammonia removal rate with temperature than in dispersed phase systems. This model can also be generalized to include such things as denitrification and BOD removal. In some systems, the oxygen gradient may be limiting the "active mass" rather than the substrate gradient. Pretorius (1974) with his Q_{10} value of 1.25 provides some support to this theory of reduced temperature sensitivity for fixed film systems. As was previously discussed, however, unnecessary diffusion limitations may be partially or entirely responsible for the very low temperature sensitivity found for his system.

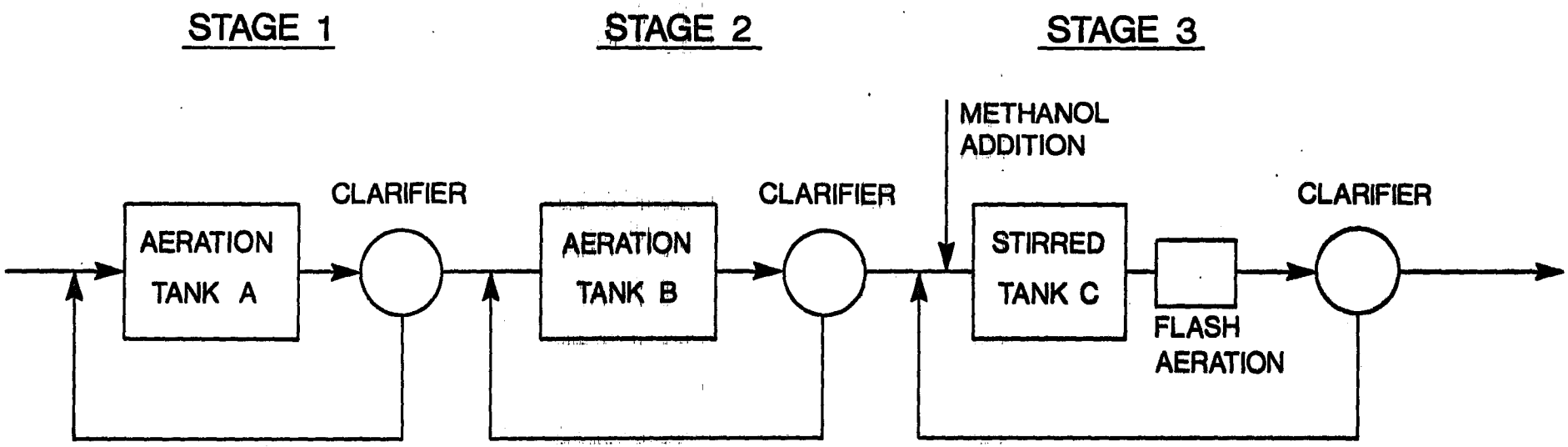
TYPES OF REACTORS

Activated Sludge

Many different modifications of the basic activated sludge process have been made in an attempt to provide stable and efficient biological nitrogen removal. Mulbarger (1971), who investigated a number of process alternatives, obtained the most consistent and dependable performance using the three stage sludge system with methanol (Figure 6). The first stage consists of an aeration tank and clarifier operated at a relatively short average solids retention time. Its main function is to provide BOD_5 removal. A second aeration tank and clarifier are then operated at a much larger sludge age to allow sufficient time for the slow growing nitrifiers to become established. Nitrified secondary effluent then enters

FIGURE 6

THREE STAGE FLOW SCHEME FOR NITROGEN REMOVAL (MULBARGER, 1971)



TANK A : BOD REMOVAL

TANK B : NITRIFICATION

TANK C : DENITRIFICATION

FLASH AERATION : NITROGEN STRIPPING PLUS RESIDUAL METHANOL REMOVAL

the stirred denitrification tank in the third stage. Since most organic carbon has been removed in the first two stages, methanol is added to the system to provide substrate for the denitrifiers. A small flash aeration tank after the stirred tank serves to remove any residual amounts of methanol and strips any nitrogen gas from the bacterial floc. This provides an effluent with a low residual oxygen demand and tends to prevent rising sludge problems in the final clarifier.

Although the three stage sludge system is known to function well, it tends to be costly. Therefore, research into other means of biological nitrification and denitrification has been prompted by a desire to find less expensive and simpler processes which still allow efficient removals.

The Rotating Biological Contactor (RBC)

The RBC consists of a series of closely spaced discs anchored to a shaft which is supported just above the surface of the waste in a semicircular bottomed rectangular tank. The shaft rotates with a velocity generally between 2 and 6 rpm (peripheral velocity about 60 ft/min), thus alternately exposing the biological slime growing on the disc surfaces to the waste and then to the atmosphere. The motion of the discs through the liquid promotes good mixing and efficient nutrient contact and transport from the waste into the slime. Borchardt (1971) calculated for one of his RBC units treating municipal wastes that the amount of volatile solids contained in the attached films would have been equivalent to an acti-

vated sludge tank containing 40,000 to 60,000 mg/ℓ of suspended volatile solids. This may account partially for the high efficiencies reported for these systems.

The rotating disc process grew from the development of the trickling filter. According to Steels (1974), the basic concept that slimes present on solid media in contact with sewage and air could aid in the overall efficiency of treatment had its origins from work conducted by Travis in England and the U.S. at the turn of the century. Also, Steels (1974) mentioned that the first rotating cylindrical filter was designed and built by Weigard circa 1900. This consisted of a wooden cylinder with slatted walls that was filled with brushwood, partially submerged in the waste and slowly rotated. The design was supposedly inspired by the desire to reduce treatment power consumption. Although this system worked satisfactorily, as a roughing process, problems were encountered with sludge accumulation in the filter resulting in short circuiting and the development of anaerobic zones.

In 1929, Buswell reported the invention of the "Biologic Wheel" by A.J. Maltby (Grieves, 1972). The basic design consisted of a series of paddle wheels with 12 or more steel blades per wheel which were rotated by sewage flow. Treatment results were good for detention times of 4 to 6 hours. No commercial applications for this were reported.

The RBC acquired its present form as a result of considerable research initiated by Hans Hartmann and Franz Popel at the Technical University of Stuttgart in 1955 (EPS

Report, 1973). The first commercial installation of a modern RBC plant was made in 1959. Today hundreds of plants are in operation primarily in Western Europe. One of the most important design features of RBC development during the past fifteen years has been the replacement of asbestos with plastic for disc construction. This has greatly reduced the weight and aided the manageability of the shafts. Power requirements have also been reduced significantly due to the lighter plastic media.

The main advantages which have been quoted widely for the RBC compared to standard activated sludge treatment are as follows.

1. The RBC has a simple design which allows easy installation in any location and a minimum of operator control and maintenance.

2. Only a small amount of energy is required to rotate the shaft of the RBC providing excellent BOD and ammonia removal efficiencies per kilowatt hour.

3. Overloading the system will not cause solids washout and plant failure.

4. It is thought that shock loadings of adverse pH and toxic materials have less effect on the fixed film of the RBC than in the"dispersed"bacteria in activated sludge.

5. Because protective hoods are generally required over each RBC, potential odour problems could be easily controlled.

Largely due to the advantages listed above, North American interest in the RBC has been gaining rapidly during the past four to five years. Nevertheless, there are still

relatively few commercially installed units on this side of the Atlantic. It is expected that the economy to be realized in constructing an RBC unit over a conventional activated sludge plant would be best achieved in small to medium sized plants. In the larger activated sludge plants, a great deal of added volume can be obtained with only a modest amount of additional concrete. Costs are much more linear with respect to sewage volumes with RBC treatment.

Considerable experience has been gained in the treatment of municipal sewage by RBC reactors. The three most important operating parameters are detention time, disc surface area and temperature.

A pilot study by Torpey et al (1972) using municipal wastewater showed that 30 minutes of contact time was generally sufficient for up to 90 percent BOD removal. This produced effluent BOD's in the 15 mg/ℓ range. For treatment beyond this point, much longer residence times were necessary. Data presented by Antonie (1970) indicated that ammonia removal to an effluent concentration of 2.0 mg/ℓ NH_4^+-N or less can be achieved in systems with hydraulic loadings of about 1 U.S. gal/ft^2/day (40 l/m^2/day). In Antonie's systems, this would mean hydraulic detention times of roughly 90 minutes or surface loadings between 0.15 and 0.20 #NH_4^+-N/1000 ft^2·day (0.3-0.4 mg NH_4^+-N/m^2·hr). Lue-Hing et al (1974) successfully operated a pilot scale RBC at detention times of 1.5 to 12.0 days to produce essentially complete nitrification in a high ammonia content lagoon supernatant

(740-830 mg NH_4^+-N/l).

Since the amount of biological film increases in direct proportion to the disc area, most RBC systems are designed to provide the maximum surface practical.

To date little comprehensive data are readily available concerning the effect of temperature on RBC operation. No direct comparison between the RBC and activated sludge temperature sensitivities has been published. The work that is presently available shows the predictable result that BOD and ammonia removal rates decline with decreasing temperature, but these rate decreases are not usually quantified. The major exception here is the work of Pretorius (1974) which has already been discussed.

Currently, there are two differing opinions concerning the effect of ammonia concentration on the rate of nitrification in the RBC for municipal wastewater. Torpey (1972) concluded that nitrification was zero order with respect to ammonia concentration. On the other hand, Antonie (1974 A) proposed that ammonia does exert a concentration effect although this effect is not specifically first order. Although Antonie's use of results from five separate RBC pilot plants provides a wider range of data than was cited by Torpey, it did not negate Torpey's findings. Also, each of Antonie's pilot units was divided into four equal sized compartments and it is inferred from his article that Antonie made the assumption that the hydraulic nature of each RBC was equivalent to four ideal stirred tanks in

series. This assumption may not have been valid since there was no mention that the assumption was substantiated by tracer analysis. Therefore, the apparent kinetics of ammonia removal is still uncertain.

Anaerobic Filters

The anaerobic filter offers an alternative to stirred tank denitrification. Here stationary media is submerged and organisms which become attached to the media affect nitrate reduction in the presence of a carbon source. As with the RBC, a large mass of micro-organisms can be supported within the reactor without experiencing the problem of washout due to overloading. Logically, packed beds that are designed and operated to give long hydraulic detention and maximum contact area between bacteria and sewage would exhibit the highest nitrate removals. This infers that a balance must be made between large voidage and high surface area per cubic foot when choosing the best filter media.

A number of investigations of packed bed denitrification have been carried out since the original work of Bringmann and Kühn in the early 1960's. However, to date, few general design criteria have been established for this form of treatment. The systems that have been studied so far can be classified into two broad categories, small media systems (less than 1 inch nominal diameter packing) and larger media systems (packing diameters equal to or greater than 1 inch).

With the small packing, although nitrate removals appear to be efficient, rapid solids accumulation causes large pressure drops and necessitates frequent backwashing. English (1974), in his recent work with simultaneous COD polishing and denitrification in a 0.3 MGD (US) activated carbon plant, found that, even with backwashing twice daily, first stage head losses averaged 30 to 50 psi (2.1 to 3.5 kg/sq cm). High and variable operating pressures create operating complexities and added equipment costs for processes. Back-wash disposal also becomes an increasing problem.

In the larger packing category,head losses have not been a problem. Unfortunately, removal efficiencies also tend to be much lower based on empty bed residence. It is thought that packings such as very large aggregate (2 inches) and Dow Surf-pac (a special synthetic trickling filter media) have too much void volume and insufficient surface area to allow the build-up of a large mass of active denitrifiers (Jones,1971). Although English (1974) includes in his report a rough cost estimate for providing denitrification for a 10 MGD(US) plant, it is not stated whether this would be more economical than the much simpler stirred tank process.

A novel approach to packed bed denitrification has recently been reported by Jeris and Flood (1974). Their system involves passing nitrified secondary effluent through a sand filled column at a rate sufficiently high to expand the bed. Preliminary results have shown almost complete

removal of roughly 20 mg/ℓ nitrate nitrogen with an empty bed detention time as low as 7.2 minutes. To date, no mention has been made of the nature and degree of operating problems for this system. A process such as this, however, may eventually become attractive should the results of extended continuous operation show no decline in removal efficiency and no solids accumulation and pressure drop problems.

Relatively little work on denitrification by submerged filters has included study of temperature on removal rates. Investigations by Sutton (1973) over a temperature range of 5 to 25 degrees C. and using 0.5 inch and 0.375 inch Berl Saddle packing produced nitrate reduction rates which fit the Arrhenius temperature dependency model. Here an activation energy of 11,090 cal/mole was reported. This was slightly lower than activation energies found by Sutton for stirred tank systems. In the same study, by comparing rates obtained with the two different packings, it was shown that packing surface area was directly related to nitrate removal efficiency. Important however, is the fact that between the two packings evaluated there was only a 25 per cent difference in surface area per unit volume. This probably increased the likelihood of correlation. Sutton also found that backwashing was required for his systems once in every four or five days caused by slow but persistent increases in head loss.

Recently Riemer (1974) has experimented with two

13 ft. (4.0 m) PVC columns, one packed with crushed granite (2-5 mm) and the other with quartz pebbles (2-5 mm), over a temperature range of 9 to 19 degrees C. Removal rates for nitrate were found to fit the following retardant type kinetic model:

$$\frac{C_o - C}{C_o} = 1 - e^{-r\left(\frac{V}{Q\,C_o}\right)} \qquad (11)$$

where: C = NO_3-N concentration,

C_o = NO_3-N concentration in the feed,

r = removal rate of NO_3-N,

V = empty bed volume, and

Q = flow rate.

The Arrhenius model was also adequate in describing the rate versus temperature dependency of Riemer's systems. Resulting activation energies fell between 13,700 and 22,000 cal/mole (Q_{10}'s from 2.3 to 3.8). These compare closely to the values for stirred tank systems (Table 1).

It is significant to mention that neither of the above authors has accounted for deterioration in column efficiencies due to solids accumulation and changing hydraulic detention time in the column at the time of each run for rate calculations. Up to the present, all rates in column denitrification studies have been determined using empty bed residence or the theoretical packed bed residence (e.g. no growth on packing). This does not adequately

reflect the changing nature of column operation. The changes in actual residence times for submerged filters operated continuously for extended periods of time can be easily followed by conducting periodic tracer studies.

EQUIPMENT AND PROCEDURES

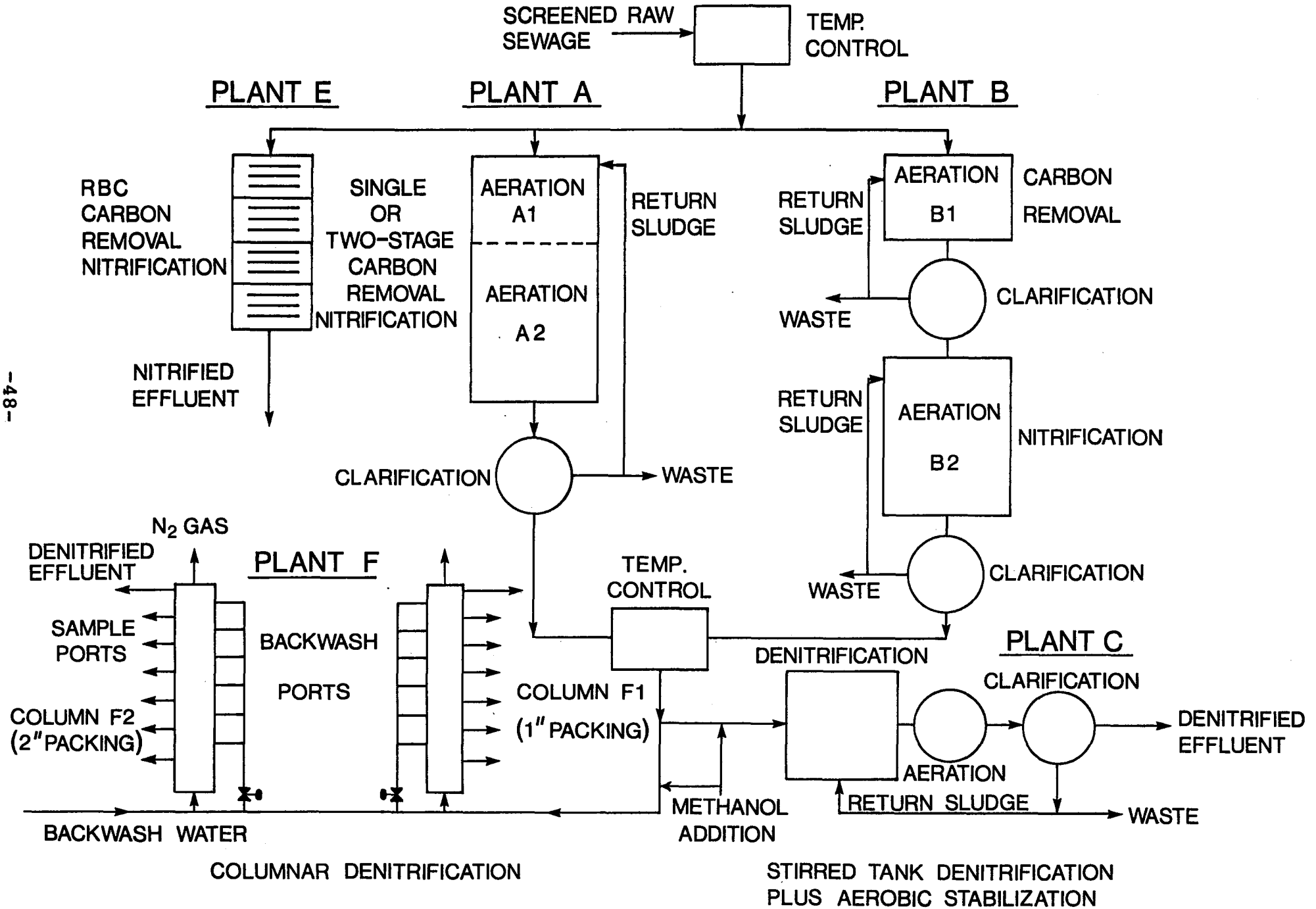
Pilot Plant Setup and Reactor Specifications

The equipment used for this research is part of a larger 7200 IGPD (32.7 m^3/day) capacity pilot plant facility located at the Canada Centre for Inland Waters in Burlington, Ontario and which was constructed specifically for the study of biological nitrogen removal. Figure 7 provides a schematic diagram of the entire nitrification/denitrification plant. Screened raw wastewater is received from the Burlington Skyway Water Pollution Control Plant and enters a temperature controller unit. The wastewater can then be fed simultaneously to three separate nitrifying reactors; two different activated sludge systems and the RBC. Nitrified secondary effluent from Reactors A and B enters a second temperature controller from which the two different denitrifying systems are fed. Of primary concern in this study was the operation of the rotating biological contactor (RBC) and the packed columns.

The RBC used for the nitrification part of this work was an Autotrol Bio-Surf 1.5 ft (0.5 meter)Pilot Plant, Serial No. 7407. Feed was introduced at the head of the unit by a rotating scoop device and flow was parallel to the central shaft through a series of four separate compartments. A total of thirty-six discs provided 250 sq. ft (23.2 m^2) of

FIGURE 7

FULL NITRIFICATION DENITRIFICATION PILOT PLANT FLOW DIAGRAM

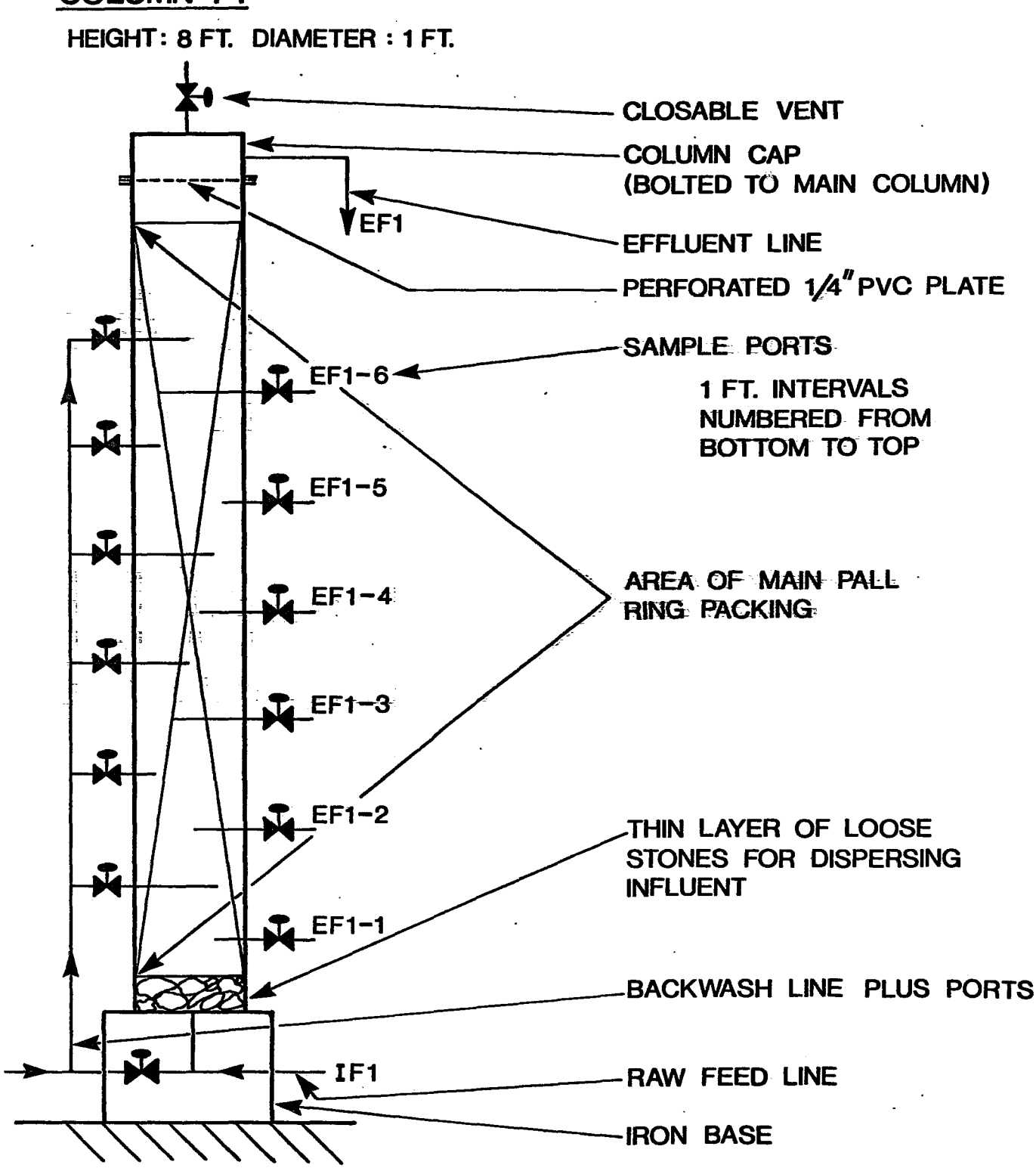


surface area. Rotation of the discs was fixed at 13 rpm which resulted in a disc tip velocity of 1.1 ft/sec (0.34 m/sec). Hydraulic loadings of approximately 0.18 IGPM (0.8 ℓ/min) and 0.35 IGPM (1.59 ℓ/min) were used during the course of the research. Although the measured liquid volume of the reactor varied a small amount depending on the hydraulic flow, the tank capacity was essentially 28.2 Imp gallons (128ℓ).

Variable speed positive displacement pumps delivered nitrified secondary effluent to the two upflow packed bed denitrification columns. Each column was an 8 ft (2.44 m) high PVC cylinder with a 12 inch (0.30 m) diameter. As is shown in Figure 8, a series of six equally spaced sample ports and six backwash inlets were located vertically on separate sides of the columns. All of the backwash inlets were connected to a line which could be fitted to the end of a garden hose when backwashing was required. Two pressure gauges were mounted on each column to allow detection of any pressure gradients formed due to media plugging by micro-organisms. Column F1 was packed using 5 cubic ft (0.15 cubic m) of 1 inch (2.54 cm) outer diameter and length Norton polypropylene Pall Rings. A similar volume of 2 inch (5.08 cm) rings was used in F2. This provided 315 sq. ft. (29.3 m^2) of packing surface area with roughly 90 percent void space in F1 and 155 sq. ft. (14.4 m^2) of packing surface with 92% void space in F2. The choice of Pall Rings as the packing media was influenced by the desire to have a high void fraction in the columns to help avoid development of large

FIGURE 8

PACKED BED DENITRIFICATION COLUMN F1 SCHEMATIC



pressure gradients during continuous operation while at the same time trying to maintain as large an available surface area as possible. Measured packed bed liquid volumes before growth were 34.8 Imp gal (158 ℓ) and 35.9 Imp gal (163 ℓ) for F1 and F2 respectively. A constant feed rate of 0.5 IGPM (2.27 ℓ/min) was applied to each column throughout the test programme. Therefore, the theoretical packed bed residence time was generally about 70 minutes for both F1 and F2.

Start-Up

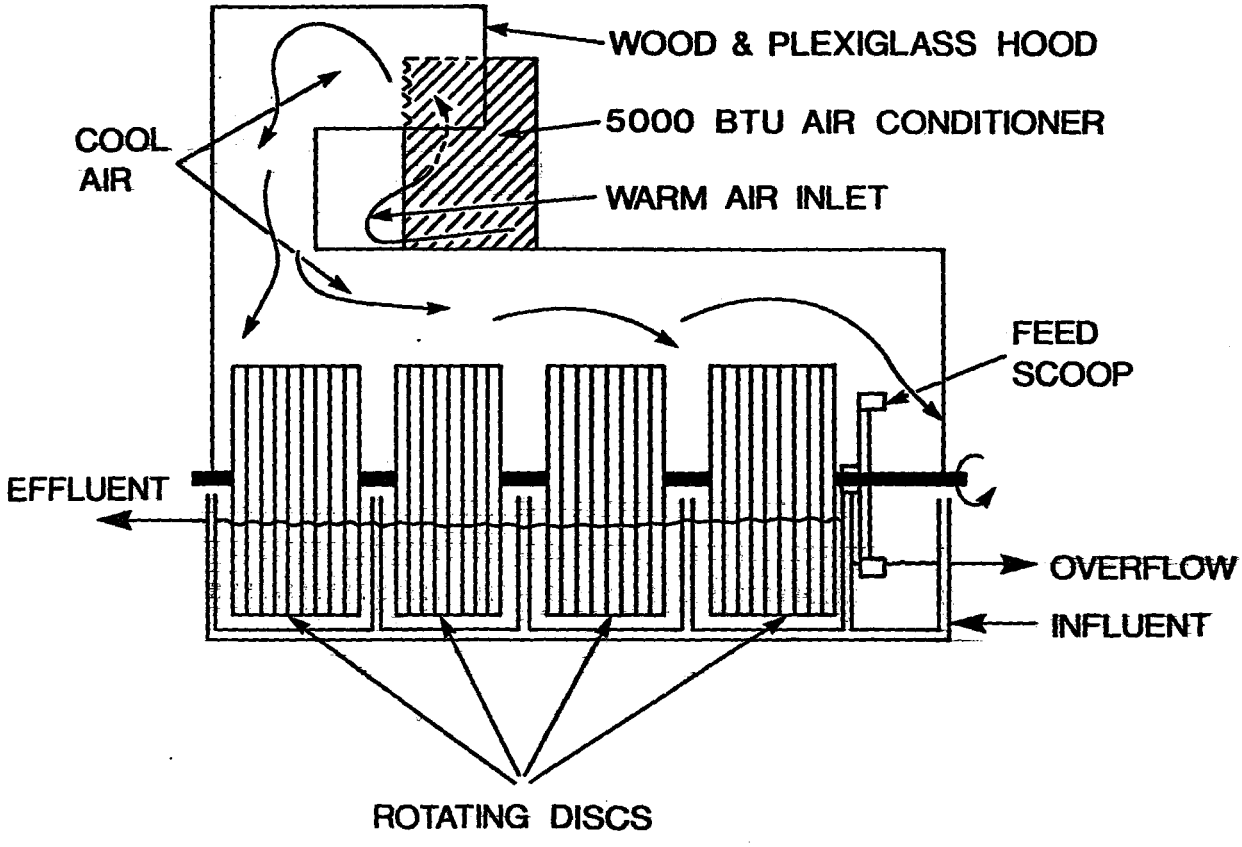
The RBC was started up two months prior to the initiation of the experimental programme. This permitted the early establishment of a stable biofilm on the disc surfaces. Three weeks before commencing the experimental runs, the feed rate to the unit was set at 0.18 IGPM (0.82 ℓ/min) providing low surface loading for nitrification. High heat transfer efficiency between the rotating discs and the surrounding air made it difficult to maintain low operating temperatures. Therefore, prior to the first run, the RBC was insulated with one half inch (1.27 cm) styrofoam on the sides and bottom and a specially designed hood containing a standard 5000 BTU (1260 kcal) air conditioner was installed over the discs. Figure 9 shows the final arrangement.

The two denitrifying columns were identical in design, the component parts of which were manufactured by private contractors. Assembly of the columns, packing and leak testing

FIGURE 9

ROTATING BIOLOGICAL CONTRACTOR

SCHEMATIC OF PLANT E



were all done just prior to start-up. Start-up procedure involved filling each reactor about one third full of actively denitrifying sludge from the clarifier underflow of Plant C. To this was added sufficient water to fill both columns and enough potassium nitrate and methanol solution to provide 35 mg/ℓ of NO_3-N and 50 mg/ℓ of methanol as carbon. Both units were then left to undergo a batch type action overnight after which time continuous feed rates of 0.25 IGPM (1.1 ℓ/min) of nitrified effluent from Plants A and B were started. Methanol was added continuously to this feed in sufficient quantity to maintain a minimum methanol as carbon to nitrate nitrogen ratio of 1:1. Two days later, the feed rates were increased to 0.5 IGPM. A spike of 20 mg/ℓ of NO_3-N plus extra methanol was instituted for two days a week after start-up to aid rapid development of denitrifying films especially on the upper sections of the packing. Visual observation of film development was not possible as the columns were not made of transparent material. Nevertheless, analysis of early effluent samples showed that significant denitrification was established very rapidly immediately following start-up. Because of the rapid acclimation, experimental runs started after two weeks of operation for F1 and after three weeks for F2. One half inch (1.27 cm) styrofoam insulation was also placed around the columns. This essentially eliminated any temperature gradients within the reactors.

Experimental Design

After acclimation, the effects of temperature on the rates of nitrification and denitrification in the RBC and the columns were investigated. A complete design over five levels of temperature from 5 degrees C to 25 degrees C and for one hydraulic loading was conducted with the denitrification reactors. The runs are listed in Table 3. By operating the two reactors under identical conditions of feed and temperature, it was possible to determine the effect of the packing surface area on the rate of denitrification.

It was intended to study nitrification in the RBC over two hydraulic loadings and the five temperature levels chosen for the denitrification work. Difficulties in attaining and maintaining the lower temperatures resulted in additional runs at other temperature levels. However, as can be seen from Table 3, almost the entire temperature range desired was covered and sufficient repeats were done to allow estimation of pure error. To avoid systematic unknown errors affecting the results, the runs for the RBC and the columns were randomized as much as was practical.

A series of dye tracer studies was also run on each of the three reactors to allow characterization of the hydraulic flow patterns throughout the duration of the study.

Operation of plants A,B, and C (see Figure 2) was supervised by different personnel in a separate project established to study nitrification and denitrification by activated sludge techniques. It was intended that data

Table No. 3

Experimental Design

RBC REACTOR				COLUMN REACTORS (F1 + F2)		
Temperature °C	Hydraulic Loading	Date	Run No.	Temperature °C	Date	Run No.
7	High	27/08	R16	5	29/06	C2
7	High	29/08	R17	5	05/07	C3
7	Low	12/07	R8	5	10/07	C4
7	Low	08/10	R20	5	01/10	C16
7	Low	10/10	R21	5	03/10	C17
10	Low	18/06	R1	10	29/08	C11
10(1	Low	20/06	R2	10	27/09	C15
10	Low	10/07	R7	15	20/06	C1
10	High	20/08	R14	15	18/07	C5
12	High	22/08	R15	15	20/08	C10
13.5	Low	05/07	R6	21	25/07	C6
15	Low	26/06	R3	21	06/08	C7
15	Low	28/06	R4	21	03/08	C8
15	Low	02/07	R5	21	15/08	C9
20(1	Low	25/07	R9	21	19/09	C14
20	Low	30/07	R10	25	06/09	C12
20	Low	08/08	R11	25	12/09	C13
20	High	15/08	R13	25	28/10	C18
21.5	High	13/08	R12	25	07/11	C19
25	Low	10/09	R18			
25	Low	12/09	R19			
25	Low	25/10	R22			
25	Low	06/11	R23			

(1 Only grab samples are available for R9 and R2.

generated from plants B and C be compared with results from the RBC and the columns. Specifically:

1. Plant B, operated as a two stage activated sludge plant to remove BOD and to carry on nitrification with a 7 day mean sludge age, provided rate data for comparison with the RBC results. Most of the runs used for comparison were conducted at the same time, using the same feed and operating temperature as the RBC runs.

2. Plant C provided similar comparative data for the denitrification reactors. A relatively constant high sludge age was maintained in C and runs were conducted in a similar range of temperatures and with similar feed as for F1 and F2.

Feed Characteristics

Plants A and B and the RBC were continuously fed with normal screened municipal wastewater. The median values observed for influent BOD_5, COD, suspended solids and TKN are tabulated below. Probability distributions of these parameters are given in Figures 10, 11, 12, and 13.

	Median Concentration (mg/ℓ)
Unfiltered BOD_5	120
Unfiltered COD	575
Suspended Solids	260
Filtered TKN	22

FIGURE 10

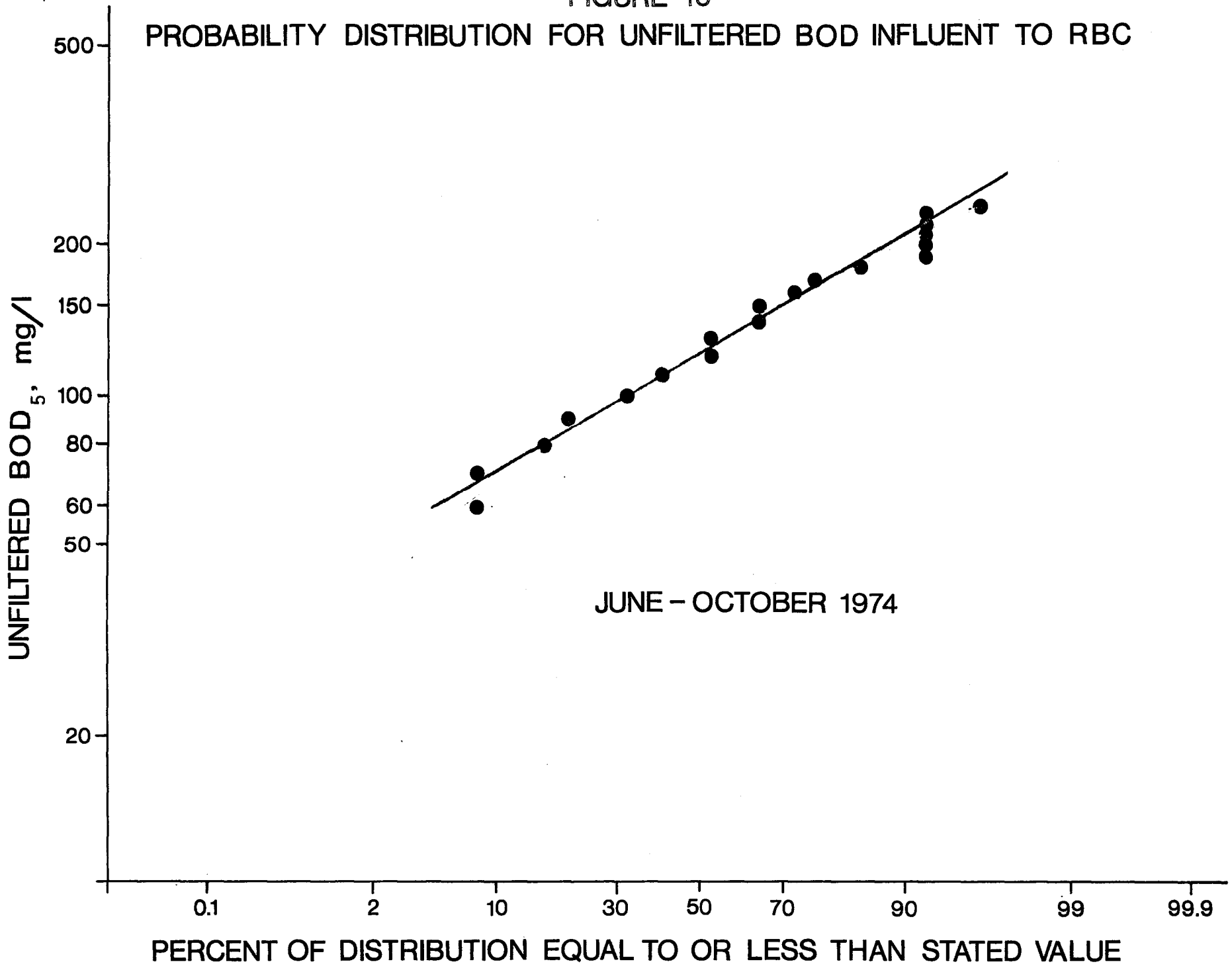

PROBABILITY DISTRIBUTION FOR UNFILTERED BOD INFLUENT TO RBC
500
200
150
100
80
60
50
20
UNFILTERED BOD5, mg/l
JUNE – OCTOBER 1974
0.1
2
10
30
50
70
90
99
99.9
PERCENT OF DISTRIBUTION EQUAL TO OR LESS THAN STATED VALUE

FIGURE 11

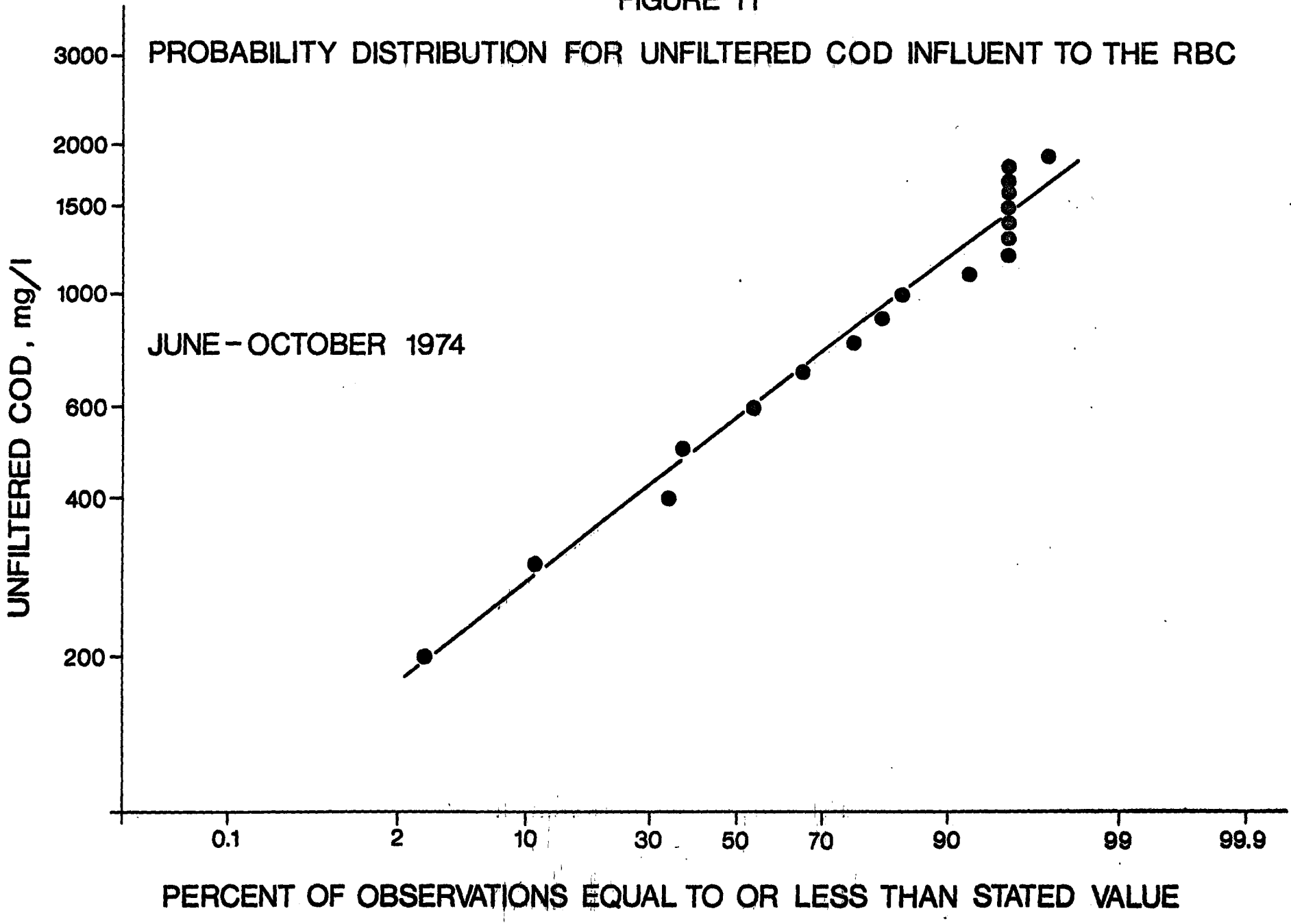

PROBABILITY DISTRIBUTION FOR UNFILTERED COD INFLUENT TO THE RBC
JUNE - OCTOBER 1974
UNFILTERED COD, mg/l
3000
2000
1500
1000
600
400
200
0.1
2
10
30
50
70
90
99
99.9
PERCENT OF OBSERVATIONS EQUAL TO OR LESS THAN STATED VALUE

FIGURE 12

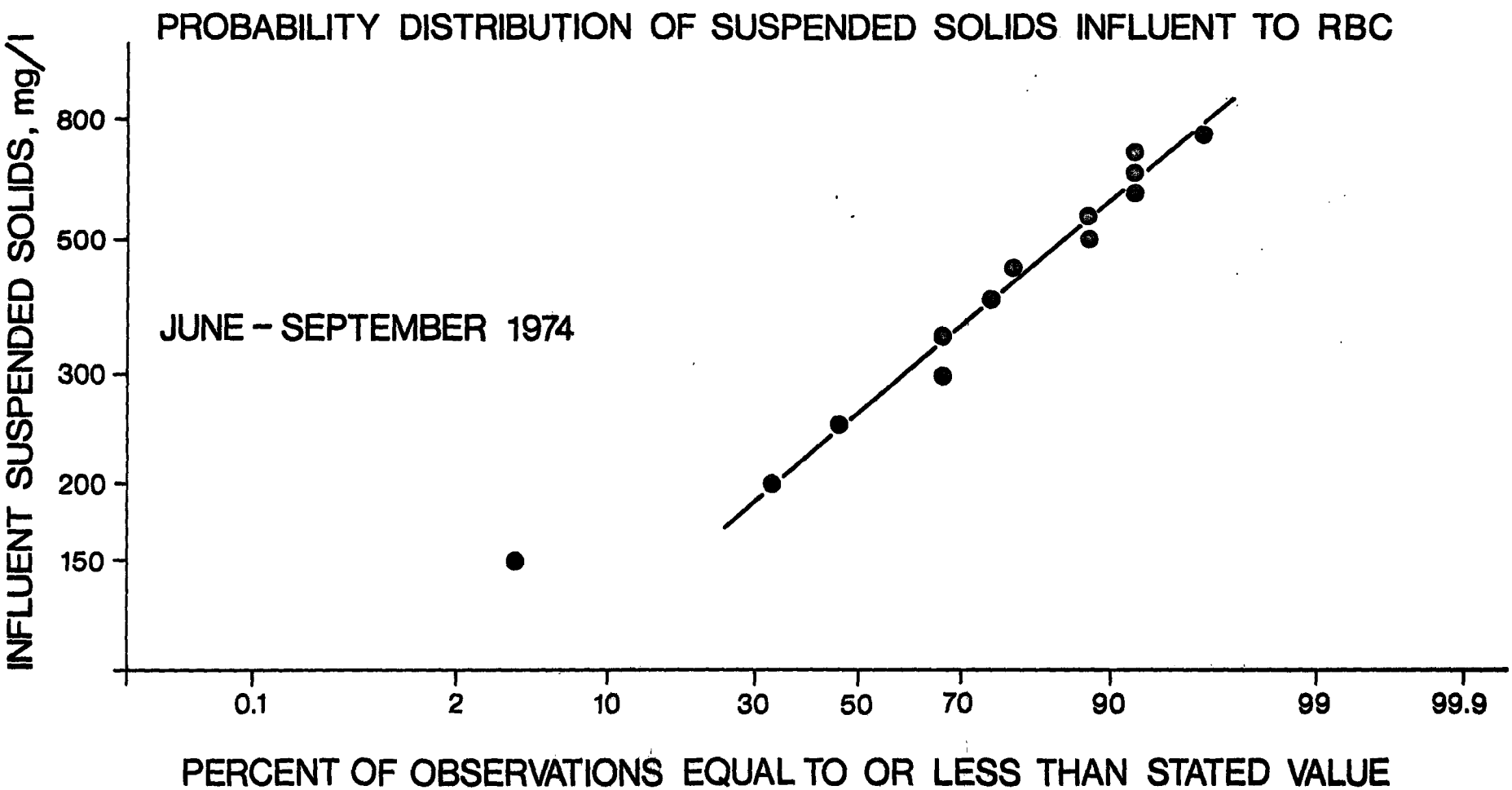
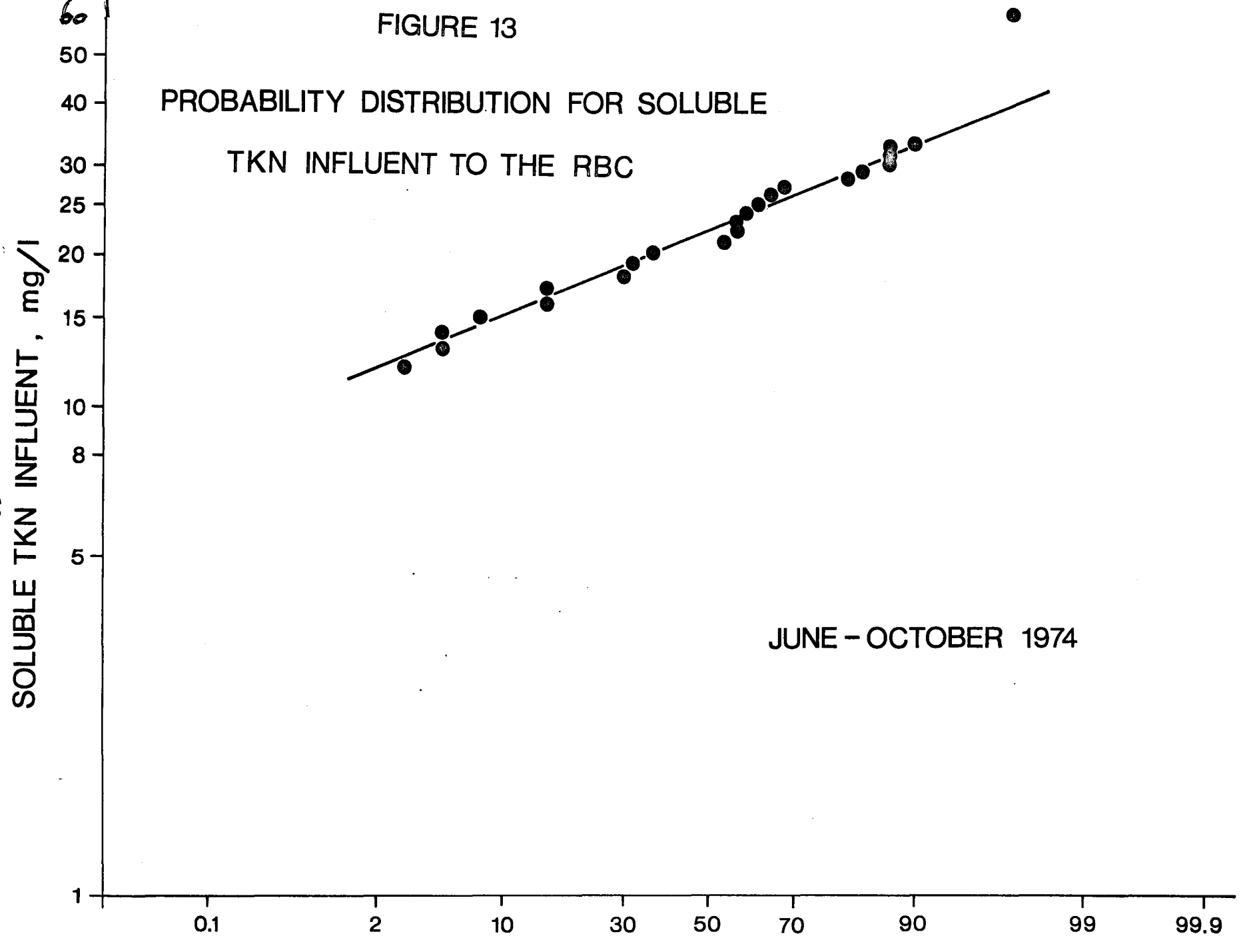

PROBABILITY DISTRIBUTION OF SUSPENDED SOLIDS INFLUENT TO RBC
INFLUENT SUSPENDED SOLIDS, mg/l
800
500
300
200
150
JUNE - SEPTEMBER 1974
0.1
2
10
30
50
70
90
99
99.9
PERCENT OF OBSERVATIONS EQUAL TO OR LESS THAN STATED VALUE

FIGURE 13

PROBABILITY DISTRIBUTION FOR SOLUBLE TKN INFLUENT TO THE RBC



Occasional upsets at the treatment plant supplying the wastewater resulted in the appearance of mixed liquor activated sludge in the pilot plant's feed for short periods of time. This, of course, caused dramatic increases in influent suspended solids. Normally, as soon as such a problem was noticed the feed was turned off and the pilot plants were run on recycle until the feed problems were solved. The distribution of TKN values of the wastewater shown in Figure 13 does not include the effects of ammonium chloride additions made to the feed on rate days. Ammonia spikes were often necessary during runs to provide residual ammonia in the effluents of Plants A and B.

The feed for the columns and Plant C can be classified as nitrified secondary effluent. Suspended solids and COD distributions are plotted in Figures 14 and 15. The median influent concentrations of unfiltered COD and suspended solids are 60 mg/ℓ and 34 mg/ℓ respectively. COD contributed as a result of methanol addition is not included in Figure 14. Combined nitrate and nitrite nitrogen concentrations varied over a wide range depending upon:

1. whether supplemental ammonia was being used for Plants A and B,
2. the degree of nitrification provided in Plant A and B at a given temperature, and
3. whether supplemental nitrate was being added directly to the second cooler.

FIGURE 14

PROBABILITY DISTRIBUTION OF UNFILTERED COD INFLUENT TO COLUMNS

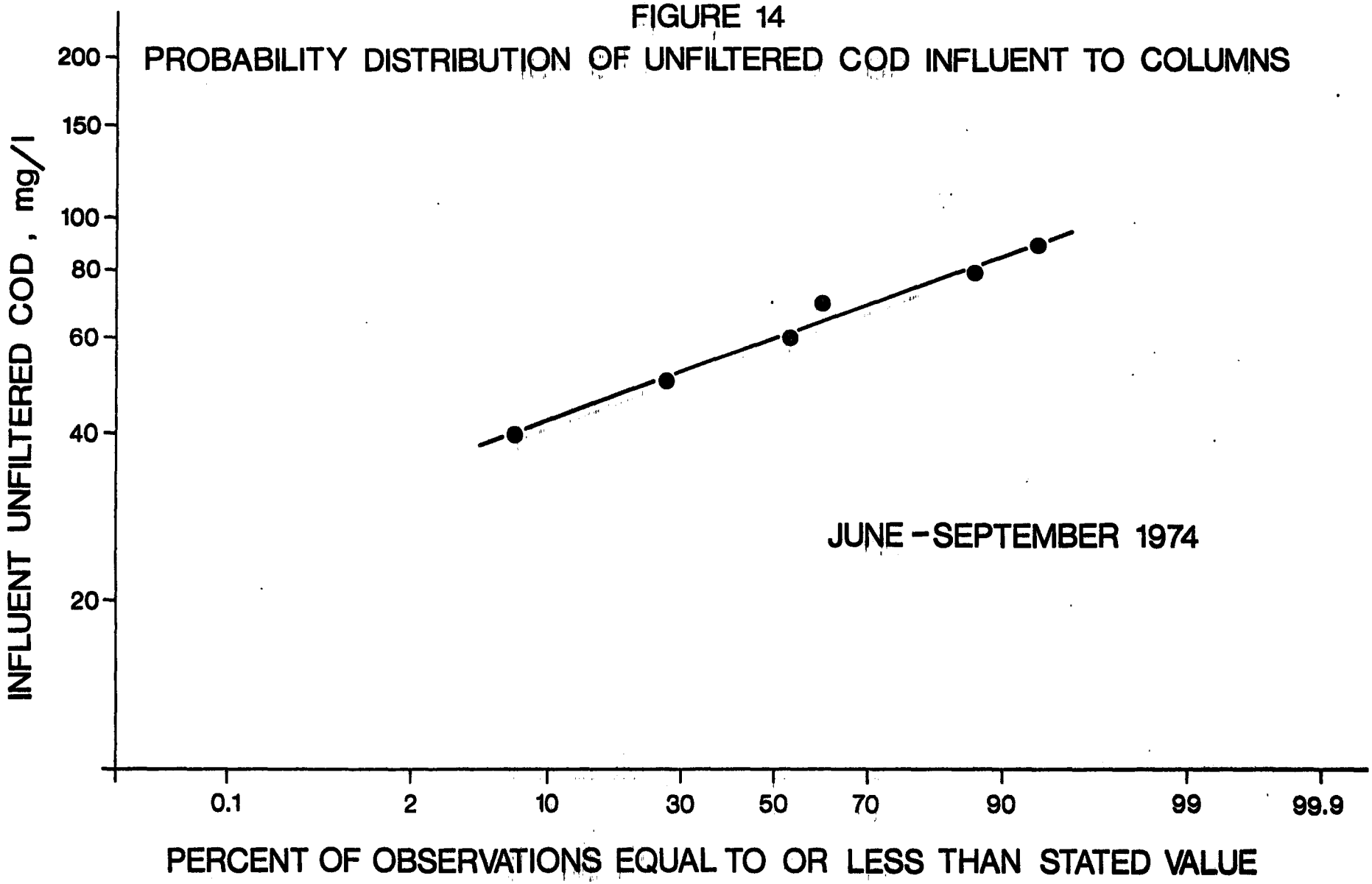
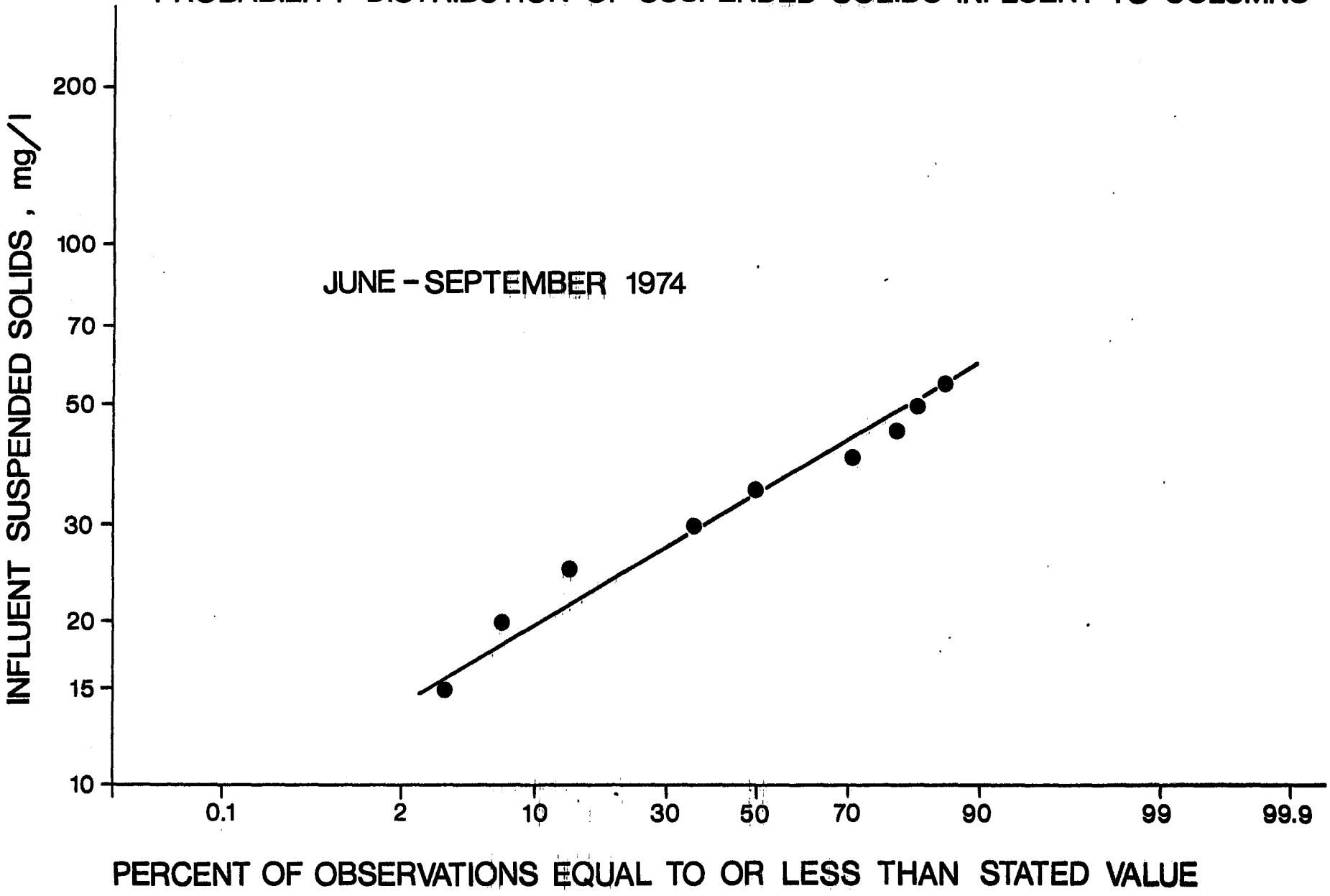


FIGURE 15

PROBABILITY DISTRIBUTION OF SUSPENDED SOLIDS INFLUENT TO COLUMNS



During rate determining days, the influent nitrate plus nitrite nitrogen concentration was generally in the 15 mg/ℓ to 45 mg/ℓ range with a median value of 28 mg/ℓ. In a few cases, concentrations exceeded this range.

RBC Operation and Sampling

Once the unit was started, very little maintenance was required to keep the RBC operating efficiently during the five month experimental period. No shut downs for cleaning purposes were necessary. Except for two brief periods when the rate of film sloughing noticeably exceeded the rate of growth, the RBC maintained a relatively thick smooth brown biomass on 90 to 100 percent of the visible disc area. Occasionally the feed scoop at the head of the unit was rinsed with a garden hose when it was noticed that the feed rate was decreasing due to biomass accumulation within the scoop channel. As was previously mentioned, some difficulty was encountered in adjusting the system temperature to the prescribed levels. Although the temperature of the feed could generally be set near the desired value, heat transfer occurring between the disc surfaces and the air often caused an unacceptable temperature rise through the system at the lower temperatures. The addition of the hood and air conditioner greatly reduced the problem as the air within the hood could normally be maintained between 10 and 15 degrees C, thus greatly reducing the heat transfer driving force. Temperatures within the nitrification unit were recorded daily. Other system and feed characteristics such as suspended solids,

alkalinity, pH, flow and dissolved oxygen were measured at varying intervals throughout the test period.

The experimental design was arranged such that two runs could be conducted each week. Run temperatures were set each Friday with a maximum of 10 degrees C change from the previous week. Allowing four days for acclimation, experimental runs were then made on Tuesdays and Thursdays. Refrigerated twenty-four hour composite samplers were used to collect effluent and raw feed at one hour intervals during each run. This was the same procedure followed for Plant B. Normally, one raw feed composite sample served as Plant A, Plant B and Plant E influent. The effluent and raw feed were then prepared for submission to the Analytical Section of the Wastewater Technology Centre for COD, BOD_5, TOC, TKN, NO_3-N, NO_2-N and NH_4^+ determinations. On Thursdays, a set of grab samples was also taken from each of the four RBC compartments as well as from the influent and effluent. Analysis of these samples provided information on the gradients within the RBC of the various nitrogen compounds present.

In many instances, ammonium chloride/carbonate or bicarbonate was mixed in with the wastewater in cooler No. 1 ahead of the RBC during rate days to assure that a TKN residual would remain in the effluent composite.

Denitrification Column Operation and Sampling

Day to day operation of the denitrification columns involved occasional monitoring of feed temperature, column pressure gradients, flow rates, pH and nitrate levels. No problem was encountered in maintaining desired temperatures. Methanol was continuously added to the feed line such that the minimum C:N ratio entering the system was 1:1.

An experimental run for the columns consisted of continuous operation of the reactors for one week at a constant temperature. Temperature changes between runs were usually made on Fridays with no more than a 10 degree C change being made in any given week. After six days of acclimation, grab samples were taken of the feed, from port 2, from port 4 and of the effluent of each column. These were prepared and either refrigerated or submitted immediately for COD, TOC, NO_3-N, NO_2-N, TKN and NH_4-N analyses. Some samples were frozen for future methanol determination. This procedure was similar to that followed for sampling and operating of Plant C.

Daily operating data and analytical results for the RBC as well as the columns are tabulated in Appendix A.

Sample Preparation and Analyses

Samples for TOC and methanol analysis were prepared by filtration through 0.45 micron Sartorius filters followed by acidification to approximately a pH of 2 with concentrated hydrochloric acid. Unfiltered TKN and COD samples were

acidified with concentrated sulphuric acid. Preparation of NO_3-N, NO_2-N, filtered TKN, NH_4-N and COD samples was accomplished by filtration through 0.45 micron Gelman glass fiber filters. All samples were stored at 5-10 degrees C in polyethylene bottles while awaiting analysis except for methanol and BOD samples which were frozen.

The specific analytical procedures utilized are listed and described in Appendix B.

RESULTS AND DISCUSSION

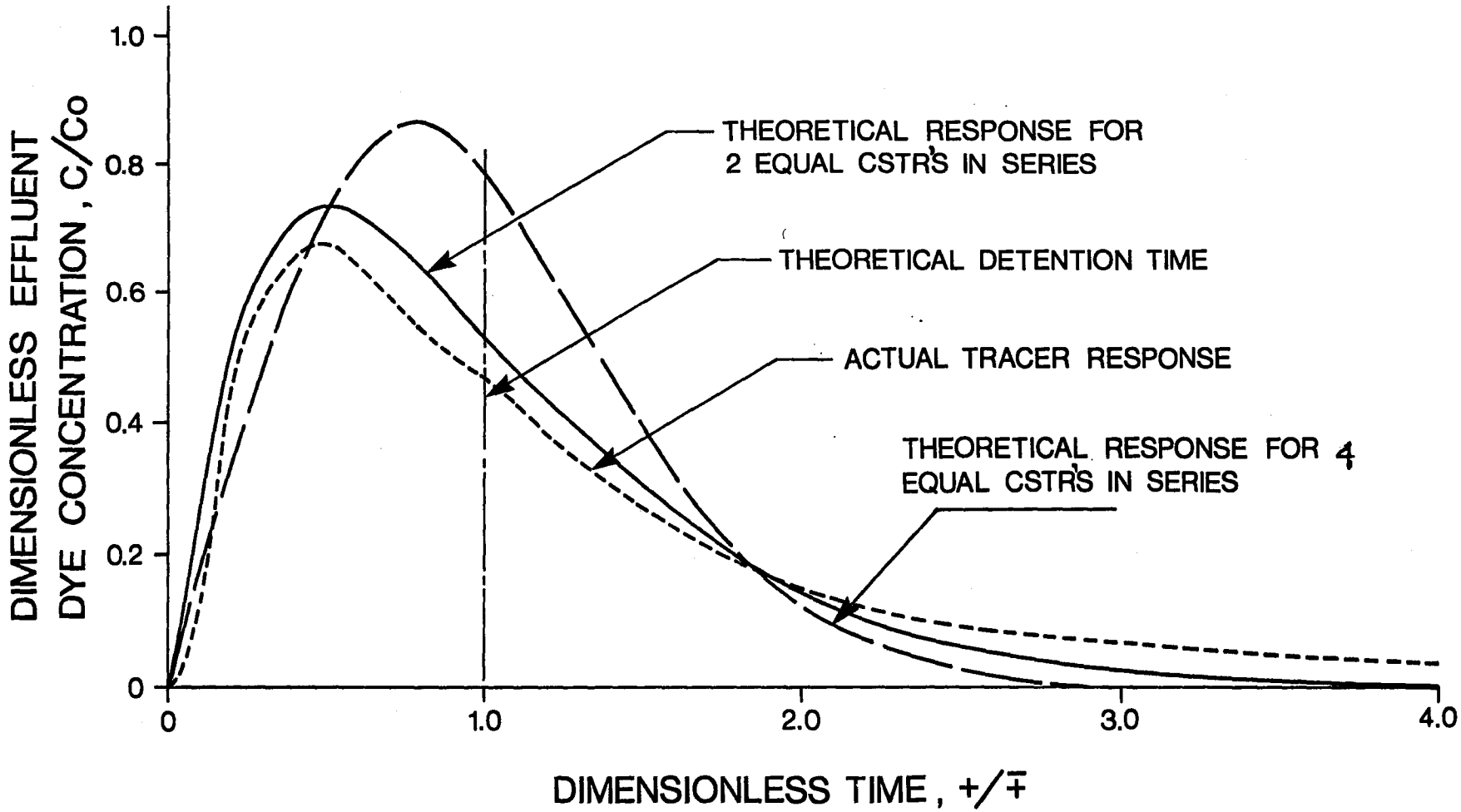
Nitrification

Hydraulic Characterization:

Two separate dye studies were conducted, one at each hydraulic loading used during the nitrification research. These studies involved the monitoring of reactor effluent dye concentration after a slug of Rhodamine WT dye had been added to the feed inlet. Both runs produced essentially identical response curves indicating that variation of the hydraulic detention in the RBC has no effect on the flow characteristics. Also, the fact that the mean dye residence time found in each study was the same as the theoretical residence time showed that there were no stagnant zones or dead spaces in the reactor. Attempts were made to fit a dispersion model (Timpany, 1966) and an equal tanks in series model (Levenspiel, 1967) to the experimental data. Physically, the RBC consisted of four compartments in series as was shown in Figure 9. Consequently, it was anticipated that the flow in the unit would be described adequately by a system of four consecutive equal stirred tanks (CSTR's). This was not the case. Figure 16 shows that the flow was in fact represented best by a 2 CSTR model. This indicates that significant backmixing was occurring between adjacent compartments in the RBC. It should be noted that in both cases, only 88 percent dye recovery was achieved. Absorption into the biological film in the reactor may account for the majority of this discrepancy.

FIGURE 16

RBC FLOW CHARACTERISTICS BY DYE TRACER ANALYSIS (PULSE INPUT)



A brief summary of the procedures used in conducting the dye studies and in analyzing the results is presented in Appendix F. Computer analysis was done with Programme #1 in Appendix C.

Nitrogen Balances:

In its simplest form, a nitrogen balance for the RBC can be expressed as a standard mass balance in the following manner.

NITROGEN ENTERING THE RBC	-	NITROGEN LEAVING THE RBC	=	NITROGEN ACCUMULATION

For this particular system, the major nitrogen forms which must be accounted for are:

1. soluble NO_3^-
2. soluble NO_2^-
3. soluble NH_4^+
4. nitrogen in soluble organic compounds
5. nitrogen in suspended organic solids
6. dissolved N_2

Unfortunately, there was no point in monitoring the levels of dissolved nitrogen gas in the influent and effluent of the RBC since there was no way in which the nitrogen entering and leaving the system via the atmosphere could be measured. Nevertheless, a balance on the remaining nitrogen forms should be possible as long as no organic fixation of

nitrogen gas occurs and none of the other nitrogen species is transformed to nitrogen gas. The latter would only occur in the event of biological denitrification. In that case, there would be an apparent net loss of nitrogen from the system. For each experimental run on the RBC for which 24 hour composite feed and effluent samples were available a tabulation was made of soluble NO_3^-, soluble NO_2^- and unfiltered TKN levels in the two streams. The TKN analyses account for the ammonia present as well as most of the nitrogen present in the soluble and suspended organic compounds. For the five months in which the RBC was operated, the amount of film on the disc surfaces seemed to remain relatively constant and there was no build-up of sludge at the bottom of the tank. Therefore, the average value for the accumulation term in the nitrogen mass balance is assumed to be zero. The balances for each run are shown in Table 4. It can be seen from the last column that in almost every run more nitrogen seemed to enter the system than leave it. In fact, an average of close to 7 mg N/ℓ or 15% of the total nitrogen entering is unaccounted for in the effluent. This can be explained most easily if denitrification was indeed taking place in the system particularly deep in the biofilm where oxygen deficient zones were likely to be present. The only other plausible explanation would be that the effluent composite sampler was undersampling suspended solids, particularly with respect to the large floc particles sloughed from the discs. A tabulation of the available composite

TABLE 4

ROTATING BIOLOGICAL CONTRACTOR

NITROGEN BALANCE TABULATION
FROM 24 HOUR COMPOSITE SAMPLE ANALYSES

A: TOTAL NITROGEN

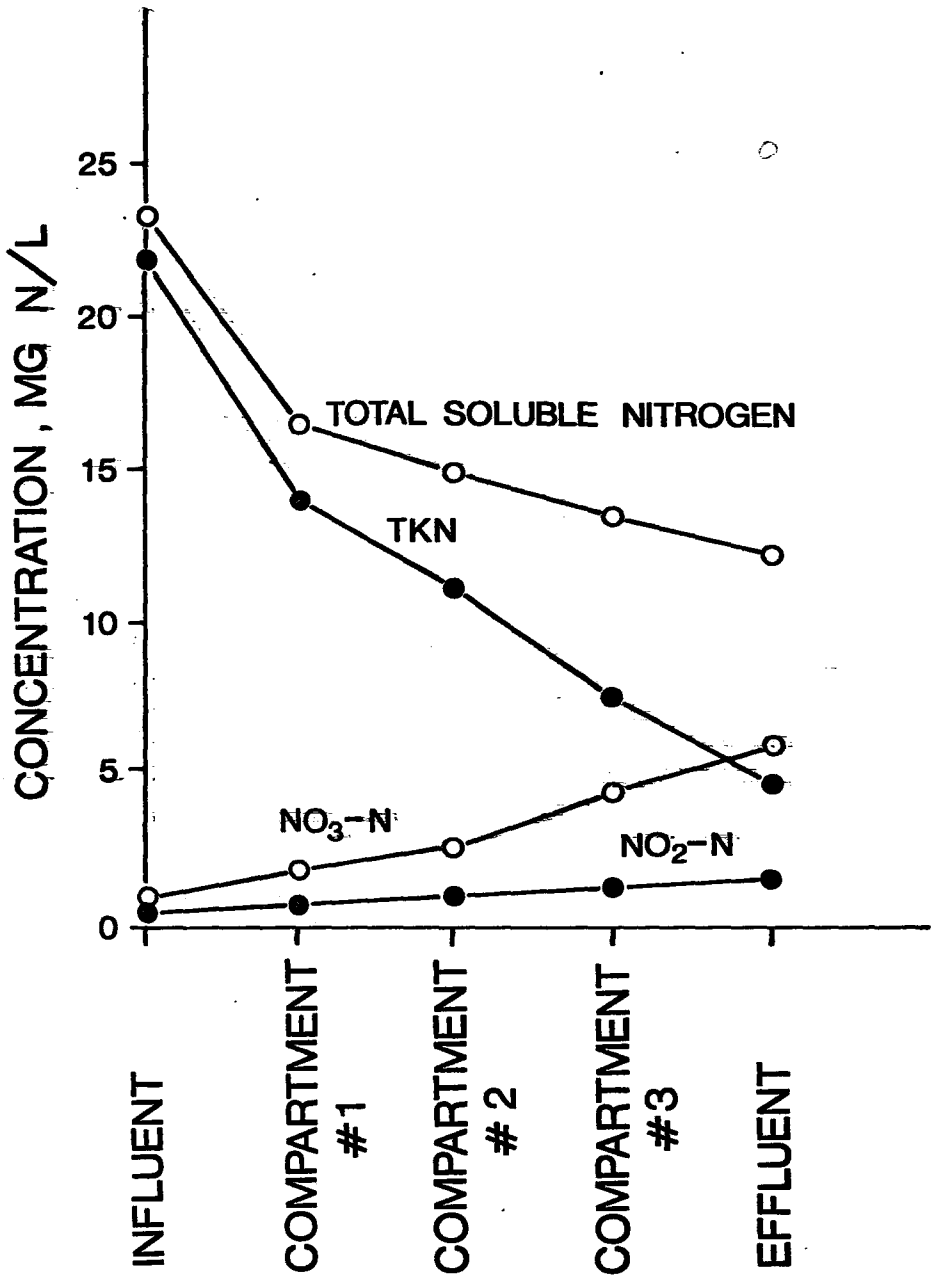
RUN	NITROGEN IN (mg/l)				NITROGEN OUT (mg/l)				DIFF (IN-OUT)
	TKN (UNFIL)	NO_3	NO_2	TOTAL	TKN (UNFIL)	NO_3	NO_2	TOTAL	
R1	26.8	0.5	0.1	27.4	15.3	8.0	1.0	24.3	3.1
R3	36.0	0.5	0.1	36.6	12.6	10.5	4.8	27.9	9.5
R4	43.3	3.0	0.0	46.3	19.6	7.5	5.0	32.1	14.2
R5	40.8	1.0	0.2	42.0	17.4	10.5	2.5	30.4	11.6
R6	43.1	0.3	0.1	43.7	32.5	8.0	1.0	41.5	2.2
R7	27.4	1.3	0.4	29.1	15.6	5.7	0.8	22.1	7.0
R8	27.6	0.2	0.1	27.9	18.9	3.5	0.6	23.0	4.9
R10	52.6	0.5	0.1	53.2	35.9	12.3	7.5	49.7	3.5
R11	65.9	0.7	0.2	66.8	49.6	9.5	1.3	60.4	6.4
R12	39.2	1.0	0.5	40.7	23.7	7.3	3.8	34.8	5.9
R13	46.2	0.7	0.2	47.1	33.8	5.3	3.0	42.1	5.0
R14	33.6	0.2	0.1	33.9	28.2	0.6	1.2	30.0	3.9
R15	49.3	1.8	0.1	51.2	48.1	0.7	0.7	49.5	1.7
R16	31.2	0.9	0.1	32.2	32.1	1.0	0.3	33.4	-1.2
R17	42.0	0.3	0.1	42.4	39.4	1.1	0.2	40.7	1.7
R18	62.3	0.1	0.8	63.2	52.7	1.3	2.4	56.4	6.8
R19	65.5	0.0	0.1	65.6	40.8	2.4	7.1	50.3	15.3
R20	69.6	0.0	0.4	70.0	36.3	11.0	1.0	48.3	21.7
R21	38.3	0.0	0.0	38.0	42.3	0.3	1.9	44.5	-6.5
R22	37.0	0.0	0.4	37.1	37.0	0.2	1.5	38.7	-1.6
R23	61.0	0.5	0.0	61.5	39.8	7.0	1.0	47.8	13.7
R24	72.9	0.7	0.0	73.6	41.2	10.3	2.9	54.4	19.2
				46.8				40.0	6.8
									15%

suspended solids data shows an average raw feed level of 303 mg/ℓ while the effluent level is only 293 mg/ℓ. Because of the large variations from day to day in solids levels, these two average values are not significantly different statistically. Nonetheless, it could be reasonably expected that the suspended solids level leaving a reactor such as the RBC would be somewhat higher than the level entering as solids are continuously sloughed from the discs adding to the suspended material already present. The quantity of additional solids would depend on the micro-organism yield from BOD_5 removal and nitrification. With an average soluble BOD_5 removal of roughly 30 mg/ℓ and nitrate plus nitrite formation of 10 mg/ℓ, a net production of 15 mg/ℓ of biomass could be easily rationalized. Theoretically, therefore, the effluent solids for the RBC might have been 25 mg/ℓ higher than what the actual data shows. This would explain perhaps 3 mg/ℓ of the 7 mg/ℓ nitrogen imbalance. A profile of the relative composition of soluble nitrogen in the RBC is presented in Figure 17.

To provide a rough comparison of the RBC operation to that of an activated sludge plant, several influent and effluent nitrogen tabulations were made on Plant B. Average results for eleven days operation of plant B, chosen randomly during the same operational period in which the RBC was run, show that an average of 8 percent of the measured influent nitrogen cannot be accounted for through effluent analysis. Balances for individual days ranged from a nitrogen gain of + 12 percent to a loss of 24 percent. Parameters included in the balance calculations were influent and effluent

FIGURE 17

PROFILE OF SOLUBLE NITROGEN COMPOUNDS IN THE RBC (GRAB SAMPLES TAKEN 25/7)



NO_3-N, NO_2-N and unfiltered TKN along with unfiltered TKN leaving the system through sludge wasting.

Alkalinity Consumption

From equation (4) in the literature review, it can be shown that 7.1 mg of alkalinity as $CaCO_3$ should be consumed for every mg of ammonia nitrogen utilized by nitrifying bacteria. This includes the nitrogen that is used in assimilation as well as the nitrogen which is oxidized. Equation (4) also shows a very low yield for nitrifiers, hence almost all of the ammonia is converted directly to nitrite and nitrate. The result is that 7.2 mg of alkalinity as $CaCO_3$ are consumed per mg of nitrate or nitrite nitrogen formed. When considering the actual amount of alkalinity consumed during the RBC operation, it must be remembered that other processes besides nitrification were occurring, specifically BOD_5 removal. The average removal of soluble BOD_5 from the system during the experimental period was estimated to be 30 mg/ℓ. Assuming a yield of 0.5, this would result in the production of 15 mg/ℓ of biomass. Between 1.5 and 2.0 mg/ℓ of this biomass would be nitrogen. The process of assimilation has no effect on alkalinity. Therefore, for this particular system, the ratio of alkalinity consumed per mg of ammonia nitrogen consumed should be less than 7.1. The actual ratio will vary depending upon the relative importance of BOD_5 removal in a given run.

These "consumption ratios" for alkalinity also

depend on whether or not denitrification is occurring simultaneously with nitrification. For instance, if in the RBC 2 mg of nitrate nitrogen are formed, the alkalinity consumed would be 14.4 mg. Assume then that of the 2 mg of nitrate nitrogen formed 1 mg is denitrified. From the overall balance in Figure 2 of the literature review, it can be determined that 3.6 mg of alkalinity as $CaCO_3$ will be reformed as a result of 1 mg of NO_3-N being denitrified. The net result is that for an apparent formation of 1 mg of NO_3-N a total of 10.8 mg of $CaCO_3$ (14.4 mg-3.6 mg) would be utilized. This shows that if nitrification and denitrification are both present in a biological system, the ratio of alkalinity used to NO_3-N + NO_2-N formed should be larger than 7.2. At the same time, the alkalinity to ammonia nitrogen ratio will decrease from 7.1 since in the preceding example 2 mg of NH_4^+-N were utilized to only 10.8 mg of alkalinity as $CaCO_3$. The ratio in this case is 5.4.

Table 5 lists alkalinity consumption data for 14 separate 24 hour composite samples from the RBC. The last values of the last two columns show that on the average 2.0 mg of alkalinity were removed from the RBC for every mg of NH_4^+-N removed and that 5.9 mg were removed for every mg of nitrite and nitrate nitrogen produced. The second value in particular is very unexpected as it was pointed out in the above discussion that the ratio of alkalinity as $CaCO_3$ to NO_3-N + NO_2-N should be equal to or greater than 7.2. No reasonable explanation for this result was

TABLE 5

ALKALINITY CONSUMPTION IN THE RBC

DATE	Δ SOL NH_4^+-N mg/l	Δ NO_2+NO_3-N mg/l	Δ ALKALINITY mg/l as $CaCO_3$	$\frac{\Delta \text{ ALKALINITY}}{\Delta\ NH_4^+\text{-N}}$	$\frac{\Delta \text{ ALKALINITY}}{\Delta\ NO_2+NO_3\text{-N}}$
06/09	10.0	2.8	13.7	1.4	4.9
10/09	23.2	9.4	35.7	1.5	3.8
12/09	28.0	10.7	69.4	2.5	6.5
16/09	20.0	6.0	43.9	2.2	7.3
17/09	15.0	7.2	36.2	2.4	5.0
18/09	11.4	5.9	34.1	3.0	5.8
19/09	15.0	3.6	22.4	1.5	6.2
24/09	12.0	3.2	18.3	1.5	5.7
25/09	18.0	5.5	34.2	1.9	6.2
26/09	17.0	30.1	23.4	1.4	.8
08/10	7.5	2.2	13.2	1.8	6.0
10/10	8.0	1.6	21.2	2.7	13.3
25/10	20.0	7.5	50.0	2.5	6.7
06/11	22.5	12.5	53.0	2.4	4.2
AVERAGE VALUES				2.0	5.9

found although the value of 5.9 mg $CaCO_3$ per mg NO_3-N found in this study is similar to the value of 6.1 reported by Mulbarger (1970) in his work with nitrifying activated sludge systems. Certainly this data does not support the hypothesis that denitrification was also present in the RBC.

Nitrification Rates

For the purposes of this work, the rate of nitrification was defined as the rate of soluble TKN removal from solution. Removal rates were calculated using a "zero order" kinetic model. First, however, it was necessary to demonstrate that the experimental data in fact displayed no TKN concentration dependency. Two different approaches were used to investigate this problem. First of all, nitrification rates were determined for each experimental run using a simple first order kinetic model coupled with a two equal tanks in series hydraulic model. The tracer studies have previously shown the hydraulic model to be adequate. Levenspiel (1967) gives the following mathematical expression for solution of first order reactions in tanks in series.

$$\frac{C_m}{C_o} = \left[\frac{1}{1+K\bar{t}_m}\right]^m \qquad (12)$$

where: C_o is the influent soluble TKN concentration into the first tank in mg/ℓ,

C_m is the TKN concentration in the m th tank in series in mg/ℓ,

$\bar{t}_m$ is the average detention time in each tank in hr,

m is the total number of tanks, and

K is the rate constant at a given temperature in hr^{-1}.

When m=2, this equation is rearranged in the following manner to allow the determination of the rate constant K.

$$K = \frac{1}{\bar{t}_2}\left[\left(\frac{C_o}{C_2}\right)^{\frac{1}{2}} - 1\right] \qquad (13)$$

If the effluent TKN concentration of the RBC is assumed to be the same as C_2, then the rate of nitrification can be calculated for the second hypothetical tank in the model where:

$$\text{Rate} = \frac{K \cdot C_2 \cdot V_{\frac{1}{2}}}{A_{\frac{1}{2}}} \qquad (14)$$

In this case $V_{\frac{1}{2}}$ and $A_{\frac{1}{2}}$ are one half of the total RBC volume and surface area respectively. This allows the removal rates to be expressed as mg TKN/hr m^2. The data calculated using the above technique is listed in Table 6. As can be seen from this table, the rates were then transformed into dimensionless quantities by taking all of the values at a given temperature and dividing each by the average rate for that temperature. A similar transformation was made of the soluble effluent TKN concentrations. The dimensionless rates were then plotted against the dimensionless concentrations in Figure 18. This form of presentation allows the comparison of rate versus concentration data with temperature effects blocked out. Logically, if TKN concentration did

TABLE 6

RBC DATA

CALCULATION OF DIMENSIONLESS RATES AND DIMENSIONLESS EFFLUENT TKN

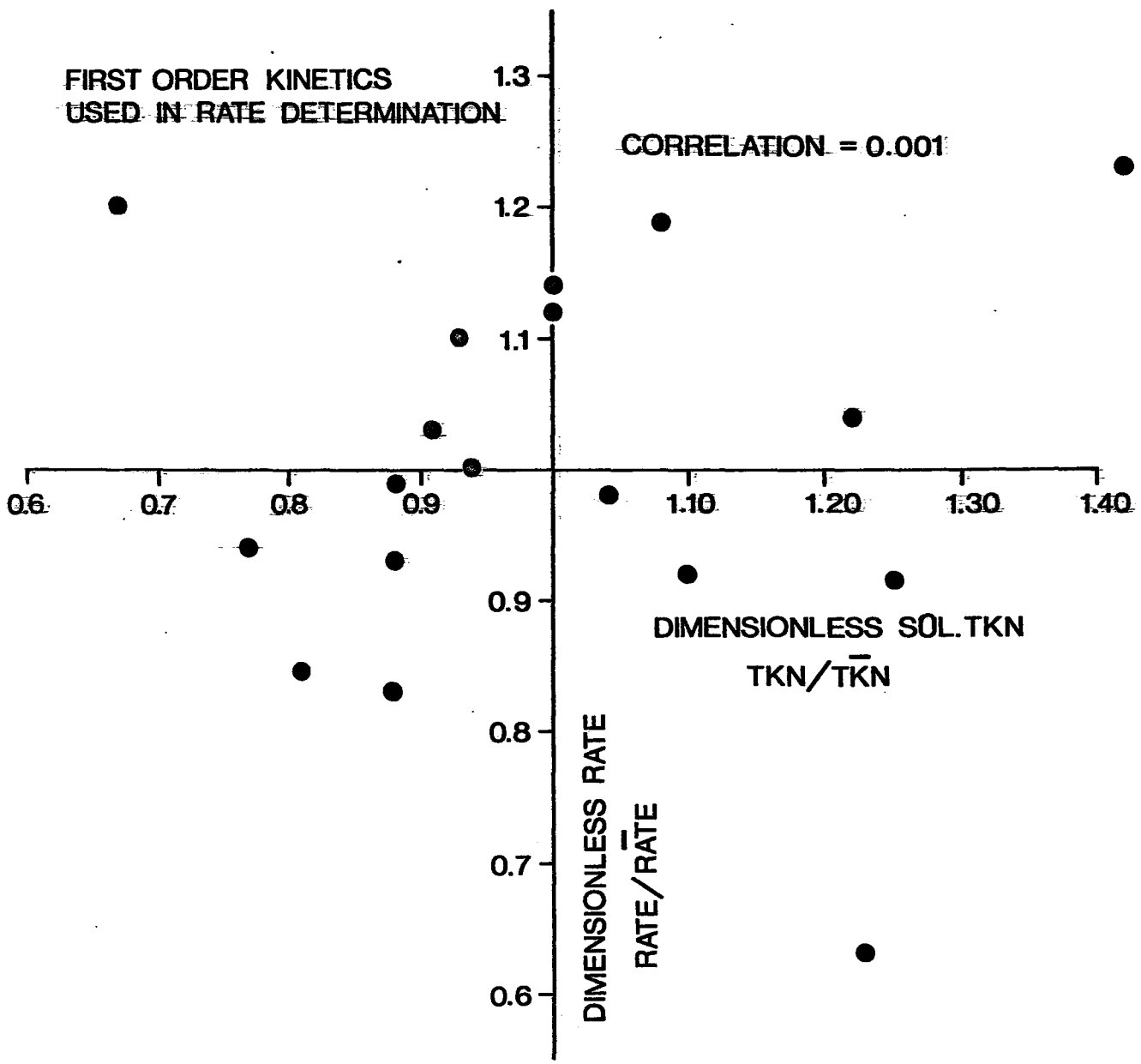
1ST ORDER MODEL

RUN	TEMPERATURE	EFFLUENT SOL. TKN		REMOVAL RATES	
	°C	mg/1	DIMENSIONLESS	mg/hr m^2	DIMENSIONLESS
R16	7	18.9	1.00	13.8	1.12
R17	7	23.3	1.23	7.7	.63
R8	7	12.7	.67	14.8	1.20
R20	7	20.8	1.10	11.3	.92
R21	7	18.9	1.00	14.1	1.14
AVERAGE		18.9	1.00	12.3	1.00
R1	10	10.4	.81	16.2	.84
R7	10	9.9	.77	18.2	.94
R14	10	18.2	1.42	23.8	1.23
AVERAGE		12.8	1.00	19.4	1.00
R3	15	12.5	.88	24.6	.93
R4	15	17.4	1.22	27.7	1.04
R5	15	13.1	.91	27.5	1.03
AVERAGE		14.3	1.00	26.6	1.00
R10	20	25.4	1.04	40.3	.98
R11	20	21.4	.88	34.4	.83
R13	20	26.3	1.08	49.5	1.19
AVERAGE		24.4	1.00	41.4	1.00
R18	25	25.5	.94	46.6	1.00
R19	25	25.0	.93	51.5	1.10
R22	25	23.7	.88	46.2	.99
R23	25	33.8	1.25	43.0	.92
AVERAGE		27.0	1.00	46.8	1.00

FIGURE 18

NITRIFICATION RATE VERSUS SOLUBLE TKN. ROTATING BIOLOGICAL CONTACTOR

PLOT OF: DIMENSIONLESS SOL. TKN REMOVAL RATE VERSUS DIMENSIONLESS TKN IN 2nd STAGE OF 2 CSTR'S IN SERIES



have an effect on the reaction rate, the higher rates in Figure 18 should be associated with the higher concentrations. This is not the case. From the scatter of the data, there is no reason to believe that any significant correlation exists between these two variables.

The second procedure used to investigate concentration effects was to repeat the above analysis using a "zero order" assumption for nitrification kinetics. If the overall removal is independent of TKN concentration, there is no need of a suitable hydraulic model of the reactor since conversion is only a function of detention time and surface area. The following expression was used to generate the rate data listed in Table 7.

$$\text{Rate} = K = \frac{(C_o - C) \cdot Q}{A} \qquad (15)$$

where:

C_o	= influent soluble TKN	mg/ℓ
C	= effluent soluble TKN	mg/ℓ
Q	= hydraulic loading	l/hr
A	= surface area of discs	m^2
K	= rate	mg/hr m^2

In order to ascertain if the calculated rate data varied with concentration, the values were plotted against influent concentrations in a dimensionless format. The resulting plot (Figure 19) shows the same behaviour as Figure 18. Therefore, once again there is no indication that concentration of soluble TKN influences nitrification in the RBC.

In light of the above, it was concluded that TKN

TABLE 7

RBC DATA

CALCULATION OF DIMENSIONLESS RATES AND DIMENSIONLESS INFLUENT TKN

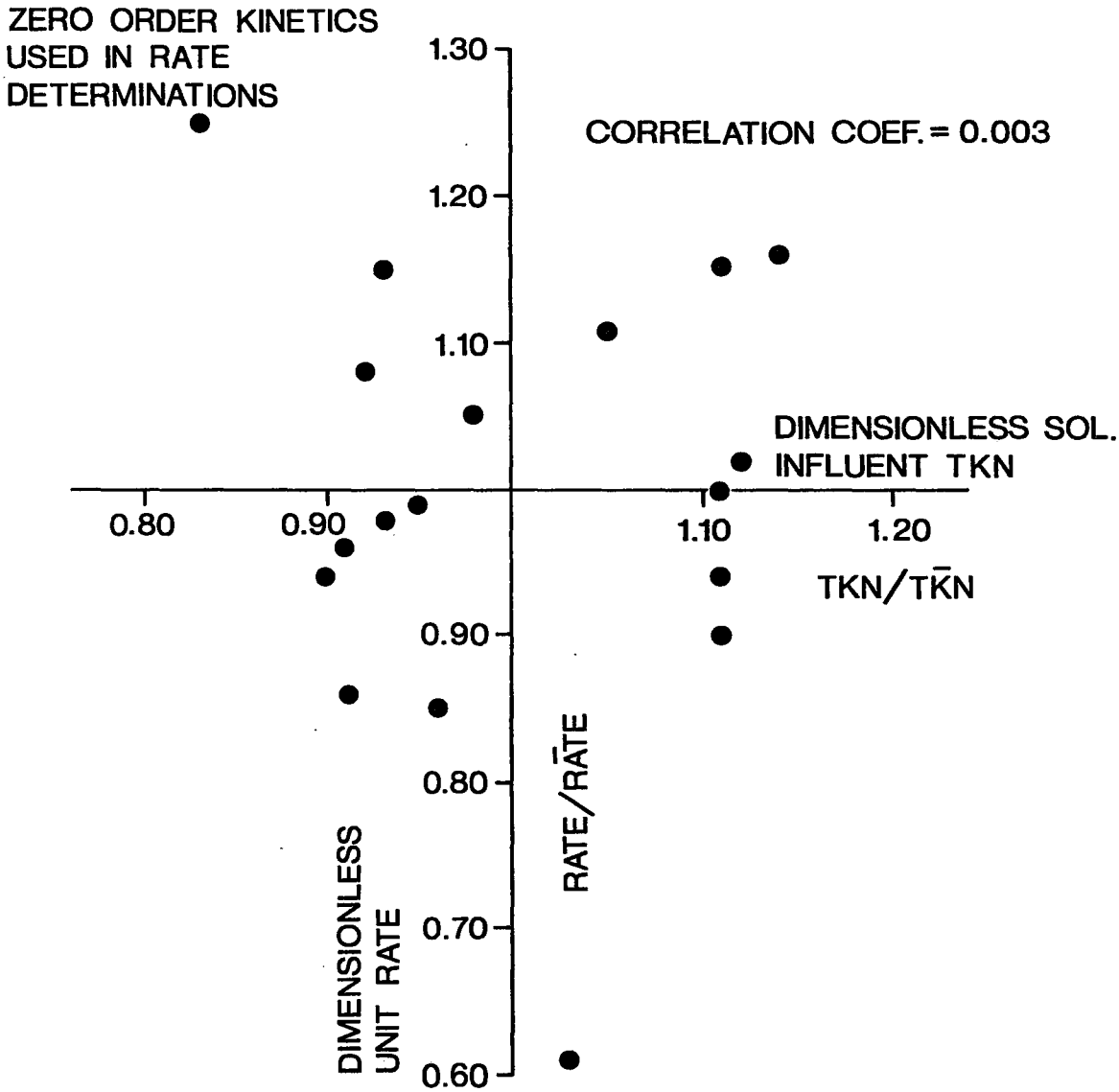
ZERO ORDER MODEL

RUN	TEMPERATURE °C	INFLUENT TKN mg/l	INFLUENT TKN DIMENSIONLESS	REMOVAL RATES mg/hr m^2	REMOVAL RATES DIMENSIONLESS
R16	7	22.7	.92	14.7	1.08
R17	7	25.4	1.03	8.3	.61
R8	7	20.6	.83	17.0	1.25
R20	7	27.5	1.11	12.1	.90
R21	7	27.5	1.11	15.7	1.15
AVERAGE VALUES		24.7	1.0	13.6	1.0
R1	10	19.4	.91	19.3	.86
R7	10	20.2	.95	22.1	.99
R14	10	24.3	1.14	26.0	1.16
AVERAGE VALUES		21.3	1.0	22.5	1.0
R3	15	26.6	.90	30.6	.94
R4	15	33.2	1.12	33.2	1.02
R5	15	28.9	.98	34.2	1.05
AVERAGE VALUES		29.6	1.0	32.6	1.0
R10	20	47.7	1.11	48.3	1.0
R11	20	41.1	.96	41.3	.85
R13	20	39.8	.93	55.5	1.15
AVERAGE VALUES		42.9	1.0	48.4	1.0
R18	25	48.7	.91	55.7	.96
R19	25	56.2	1.05	64.3	1.11
R22	25	49.5	.93	56.7	.98
R23	25	59.4	1.11	54.2	.94
AVERAGE VALUES		53.5	1.0	57.8	1.0

FIGURE 19

NITRIFICATION RATE VS. CONCENTRATION DEPENDENCY FOR THE ROTATING BIOLOGICAL CONTACTOR

PLOT OF : DIMENSIONLESS NITRIFICATION UNIT RATE VERSUS
DIMENSIONLESS INFLUENT TKN



removal in the RBC could be described satisfactorily by a "zero order" kinetic expression. This conclusion, of course, is only valid within the TKN concentration range studied. In this research, 10 mg/ℓ of filtered TKN was the lower concentration limit measured during rate days. Table 8 provides the nitrification rates calculated from the RBC data observed in this study.

Arrhenius Temperature Dependency

Of prime importance in this study was the effect of temperature on the rate of nitrification. Although using soluble TKN removal as a definition of nitrification is not technically accurate, it is appropriate for wastewater treatment since the main reason for promoting nitrification is to remove TKN. As was mentioned previously, the activation energy in the Arrhenius equation is a measure of the temperature sensitivity of a system. Using a log transformation, a linearized form of the Arrhenius equation was fitted to the RBC data. The linearized form of the model was developed from a reparameterized version of the original Arrhenius expression:

$$K = K^* \, e^{-E/R \, (\frac{1}{T} - \frac{1}{T_o})} \qquad (16)$$

where:

$$K^* = Ae^{-E/RT_o} \qquad (17)$$

T_o = median temperature in ^oK

TABLE 8

RUN	TEMPERATURE °C	NITRIFICATION RATE mg SOLUBLE TKN/m^2 hr
R16	7	14.7
R17	7	8.3
R8	7	17.0
R20	7	12.1
R21	7	15.7
R1	10	19.3
R7	10	22.1
R14	10	26.0
R15	12	15.2
R6	13.5	17.5
R3	15	30.6
R4	15	33.2
R5	15	34.2
R10	20	48.3
R11	20	41.3
R13	20	55.5
R12	21.5	65.8
R18	25	55.7
R19	25	64.3
R22	25	56.7
R23	25	54.2

Evaluation of K* and E in this reparameterized form minimizes the interaction between A and E which makes the standard Arrhenius equation a very difficult non-linear expression to fit (Himmelblau, 1970). The log transformation used for linearization produced the following simplified equation:

$$\ln K = -\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right) + \ln K^* \qquad (18)$$

or $$y = a\,x + b \qquad (19)$$

where: $y = \ln K$

$a = -E/R$

$b = \ln K^*$

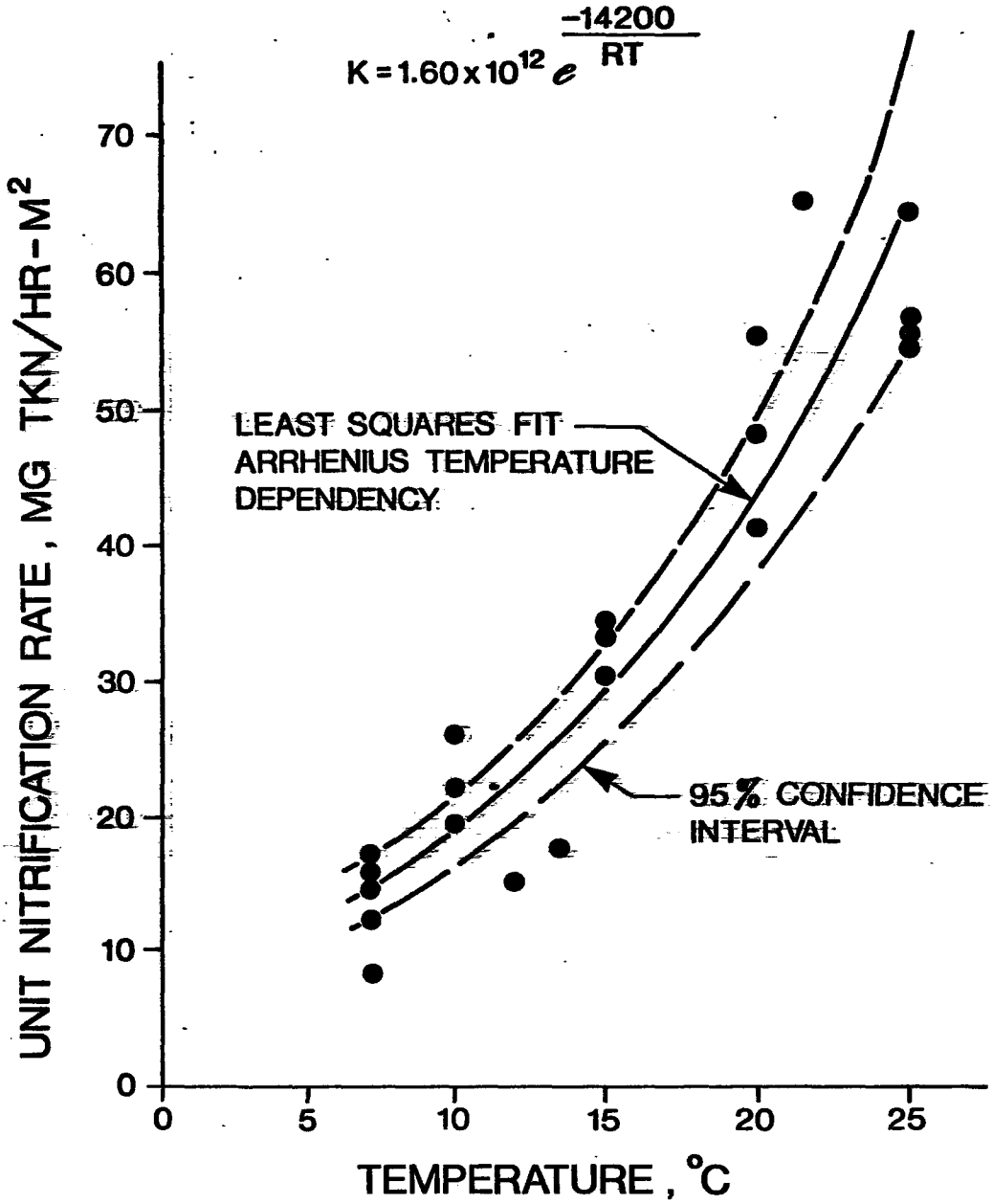
The results from this analysis for the RBC are shown in Figure 20. An F test at α=95% using the model and residual sums of squares along with the pure error estimate obtained from repeat runs indicated no lack of fit. Between 10°C and 20°C, the Q_{10} for this system was found to be 2.36.

A similar analysis was undertaken for data that was obtained from the two stage activated sludge process (Plant B). The results are directly comparable to those of the RBC because of the following:

1. The same raw feed was used for both plants.
2. The majority of the experimental runs for the two systems were conducted simultaneously and at similar temperatures.
3. Rate determinations were all based on 24 hour influent and effluent composite samples.

FIGURE 20

TEMPERATURE DEPENDENCY OF UNIT NITRIFICATION RATE. ROTATING BIOLOGICAL CONTACTOR



4. Only runs from plant B in which the sludge ages were between 6 and 8 days were used for comparison with the RBC.

Figure 21 shows the rates obtained for the activated sludge unit along with the fitted Arrhenius constants. Once again, analysis of variance showed no lack of fit. The Q_{10} for this system between 10°C and 20°C was found to be 3.42. A graphical comparison of the temperature sensitivities of the two nitrifying processes can be seen in Figure 22. The results show that the variation with temperature in the rate of nitrification is less in the RBC than in the two stage activated sludge plant. To a confidence level of 95% the RBC activation energy is smaller than that of the activated sludge system.

Before the nitrification results of this study are compared to the results of other nitrification research, it must be remembered that the RBC and Plant B provided simultaneous BOD removal and nitrification. Most pilot plant nitrification work published to date reports on the rate of nitrification observed for wastewaters which had already been treated for BOD removal. The nitrification rates observed in this research might well be expected to be somewhat lower than rates reported elsewhere simply because there was undoubtedly competion for space within the disc films between the nitrifying bacteria and the heterotrophs.

Several TKN removal rates for the RBC were calculated using the fitted Arrhenius expression. These are shown in

FIGURE 21

TEMPERATURE DEPENDENCY OF UNIT NITRIFICATION RATE

TWO STAGE ACTIVATED SLUDGE SYSTEM WITH INTERMEDIATE CLARIFICATION (7 DAY SLUDGE AGE)

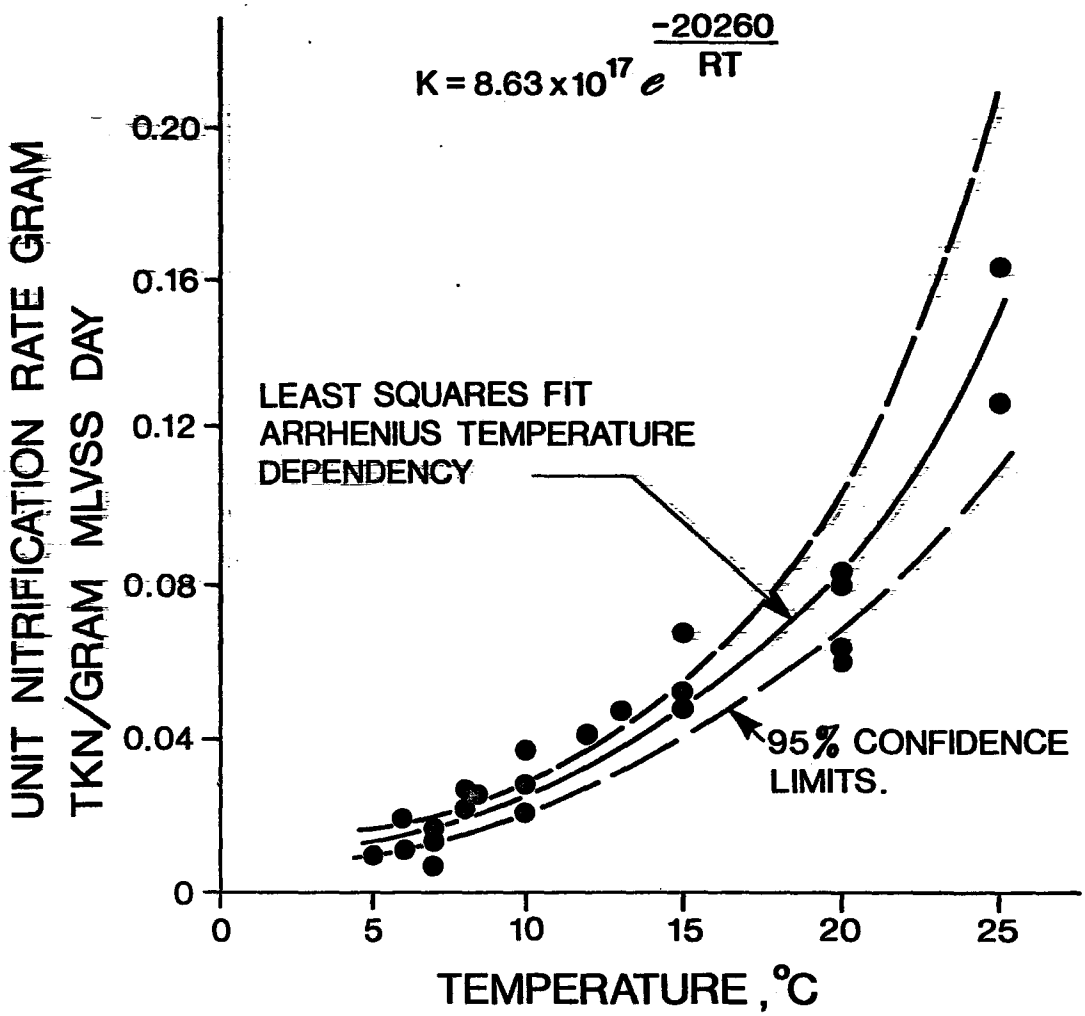


FIGURE 22

ACTIVATED SLUDGE VERSUS RBC NITRIFICATION TEMPERATURE DEPENDENCY

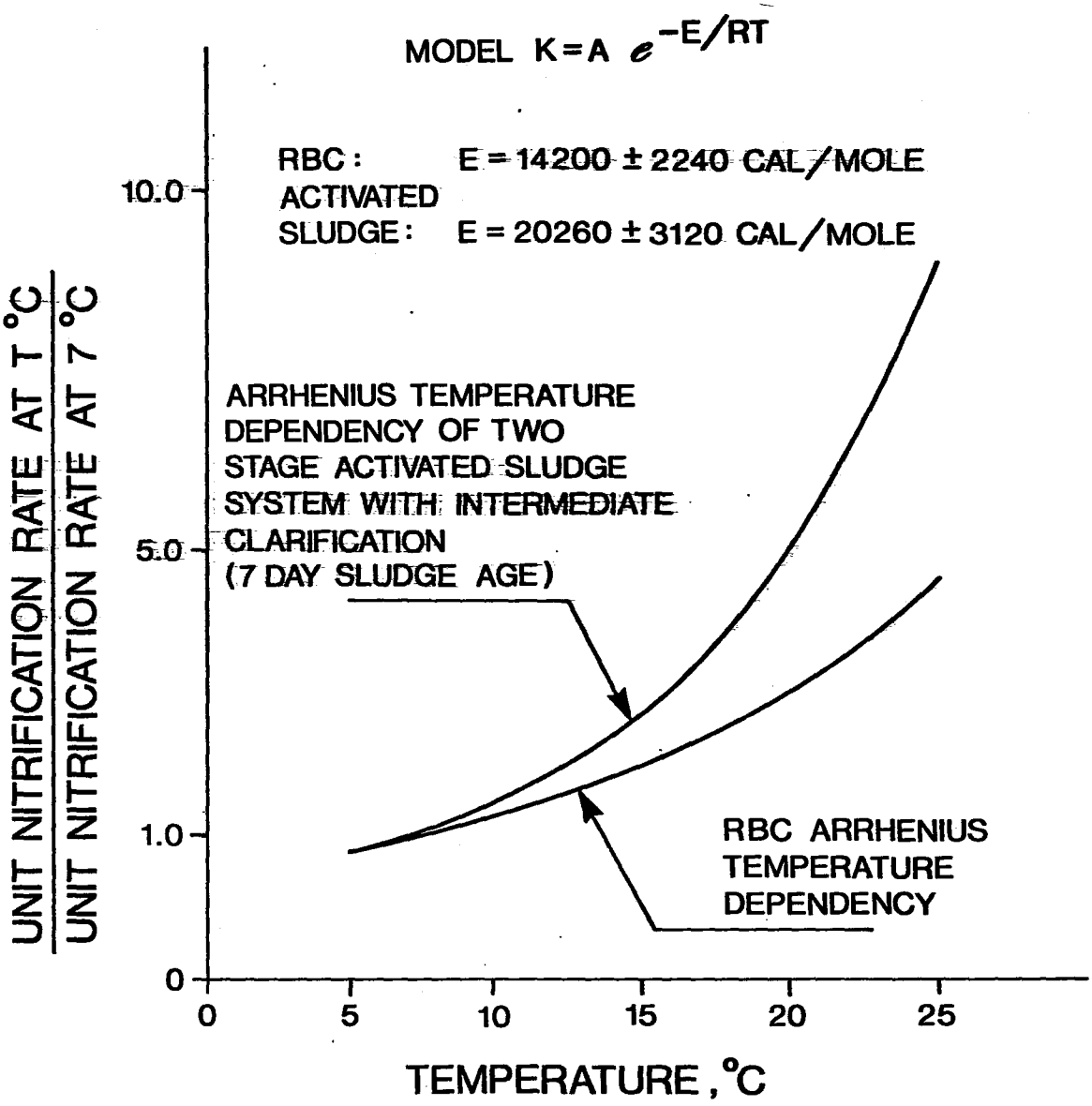


Table 9 along with similar rates calculated from data presented by other researchers. Results presented by Antonie (1974B) Torpey (1972) and Pretorius (1974) presumably represent the upper limit for nitrification rates since their research was conducted with wastewater which was previously treated for BOD. A review of the operating data which was cited by Ahlberg and Kwong (1974) for various municipal RBC plants tends to substantiate this since the higher ammonia removals generally seemed to occur in systems with low BOD loadings. Only a part of the data included in Ahlberg and Kwong's report is presented in Table 9.

Heat Transfer Characteristics

Early in the research programme, it was recognized that the RBC was an efficient heat transfer unit in that it was impossible to maintain operating temperatures below 10 to 15°C when the ambient air temperature was above 20°C. Insulation placed around the sides and on the bottom of the unit had no noticeable effect. Only after the hood and air conditioner were installed could the wastewater be kept at the lower temperatures. The heat transfer properties of RBC's are very important to understand when consideration is being given to their use in cold climates. Consequently, an attempt was made to determine an approximate heat transfer coefficient for the RBC using the following model:

$$Q = K \cdot A \cdot \Delta T \qquad (20)$$

TABLE 9

RBC NITRIFICATION RATES

WORK	TEMPERATURE °C	RATE mg/m²hr	RATE #/Day 1000 Ft²	NOTES
THIS STUDY	25	65.4	.32	1. Simultaneous BOD + TKN removal
	15	28.6	.14	
	7	14.0	.07	
PRETORIUS (1974)	25	66.7	.33	1. Treatment of secondary effluent
	15	54.6	.27	2. Disc peripheral velocity at 29 ft/min.
	10	47.9	.24	
TORPEY et al (1972)	16-26	68	.34	1. Most of the sewage BOD was removed in RBC units prior to the units in which nitrification was measured. 2. Nitrification defined as NO_3-N Formation
ANTONIE (1974)(B)	>15	a) 40	.20	1. Antonie proposes an NH_4^+ conc. dependency on the removal rate. a) effluent NH_4^+-N at 2.0 mg/l b) effluent NH_4^+-N at 10.0 " 2. Treatment of secondary effluent
		b) 120	.60	
* KAPPELROEDEK W.GERM.	-	24	.12	1. Simultaneous BOD + NH_4^+ removal 2. Disc peripheral velocity at 36 ft/min
* SPALT W.GERM.	-	24	.12	1. Simultaneous BOD + NH_4^+ removal 2. Disc peripheral velocity at 31 ft/min
* JAMAICA WPCP NEW YORK	-	18	.09	1. Simultaneous BOD + TKN removal 2. Disc peripheral velocity at 94 ft/min

* Rates calculated from data cited by Ahlberg and Kwong (1974).

where Q = heat flux into sewage kcal/hr

K = transfer coefficient kcal/m^2 hr ^oC

ΔT = difference between average sewage temperature and the ambient air temperature in ^oC

A = total disc surface area.

In the above expression, the heat flux was estimated by taking the difference between the influent and effluent wastewater temperature and multiplying this by the flow rate and the wastewater specific heat (1 kcal/kilogram/^oC). To determine the average driving force, air temperatures were recorded at three locations within the hood and liquid temperatures at four locations. These were then averaged. Since the proposed model does not include a term to account for the varying effects of evaporative cooling, the heat balances conducted on the RBC were only done when the air conditioner cooling unit was on. This tended to saturate the air above the discs in the RBC thus minimizing any driving force that would cause evaporation. Another factor affecting the efficiency of heat transfer is the speed of the rotating discs relative to the air. This was kept constant at all times since the rotation of the discs was always 13 rpm and the low speed fan of the air conditioner was always used. Nevertheless, it is probable that the forced convection of air in the hood from the fan caused transfer efficiency in the unit to be increased to a level somewhat higher than normal.

The results of twenty heat balances which met the conditions mentioned above are plotted in Figure 23. Linear regression analysis of the data shows a high correlation between the flux and driving force indicating that the model proposed has considerable merit. The constant term of -2.1 kcal/hr m^2 could be explained perhaps by small cooling effects caused by evaporation since it was unlikely that all evaporation was eliminated. The heat transfer coefficient calculated by regression was 2.1 kcal/m^2 hr ^oC. If this is a valid approximation of the actual heat transfer capabilities of such units, cold weather operation could conceivably result in severe icing problems. At the very least, sewage temperatures could be reduced to such low values that the efficiency of the biological process would be very small. This is particularly true if long detention times are used such as would be necessary for nitrification. Using the transfer coefficient calculated here and a similar RBC, it can be shown that an ambient temperature of 0^oF (-17.8^oC) would cool raw feed from 8.5^oC to the freezing point given a one hour detention time. Figure 24 is presented to indicate the expected drop in sewage temperatures per hour of hydraulic detention for various temperature driving forces. RBC's with similar volume to surface ratio's (in this case 5.5 1/m^2) could be expected to behave in a similar fashion.

Many Rotating Biological Contactors are presently in use with only hoods to protect the discs from the elements. Existing units, however, are generally located in areas that do not experience long periods of severe cold. The economics

FIGURE 23
HEAT TRANSFER COEFFICIENT FOR THE RBC

LINEAR REGRESSION FOR $Y = aX + b$

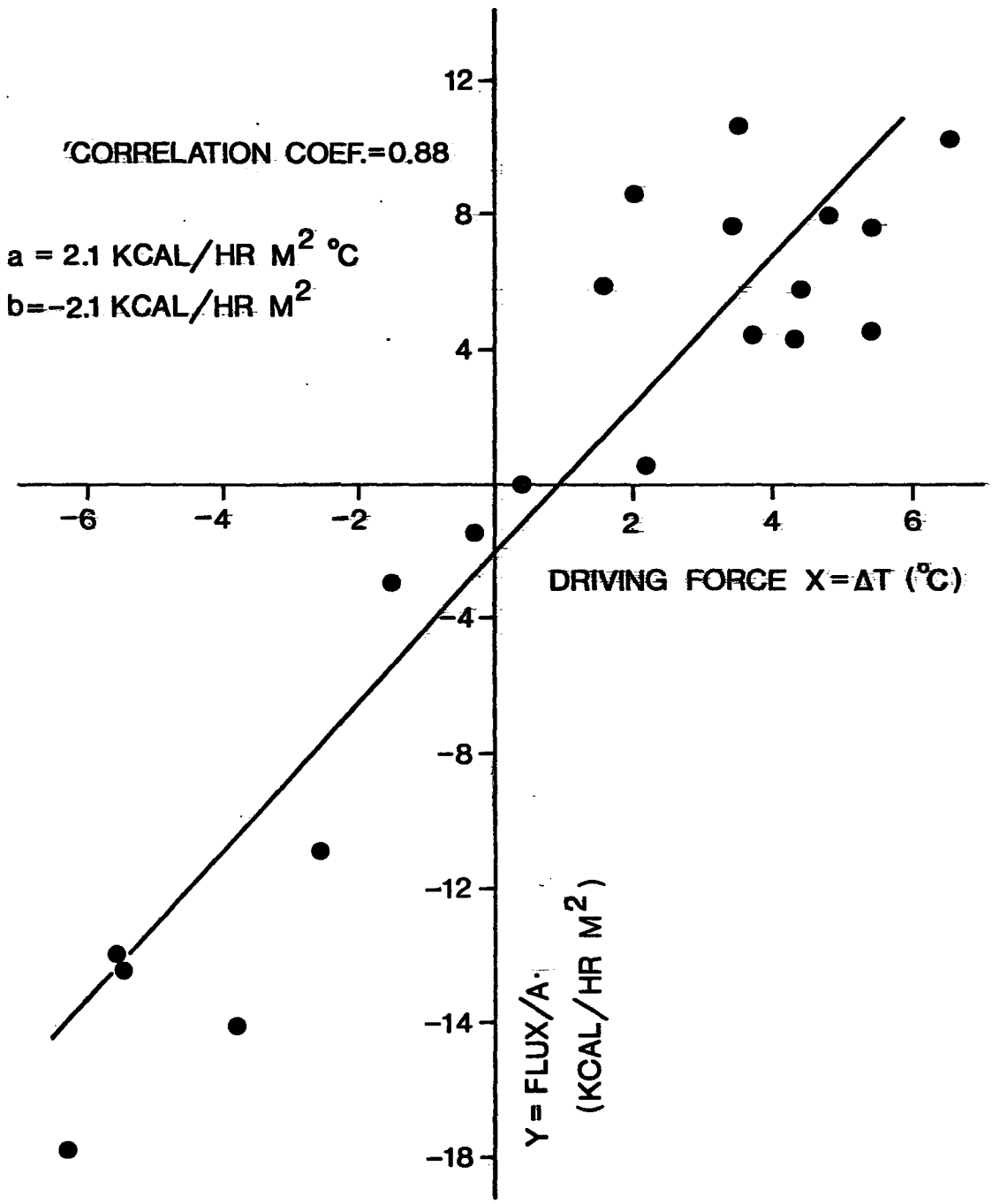
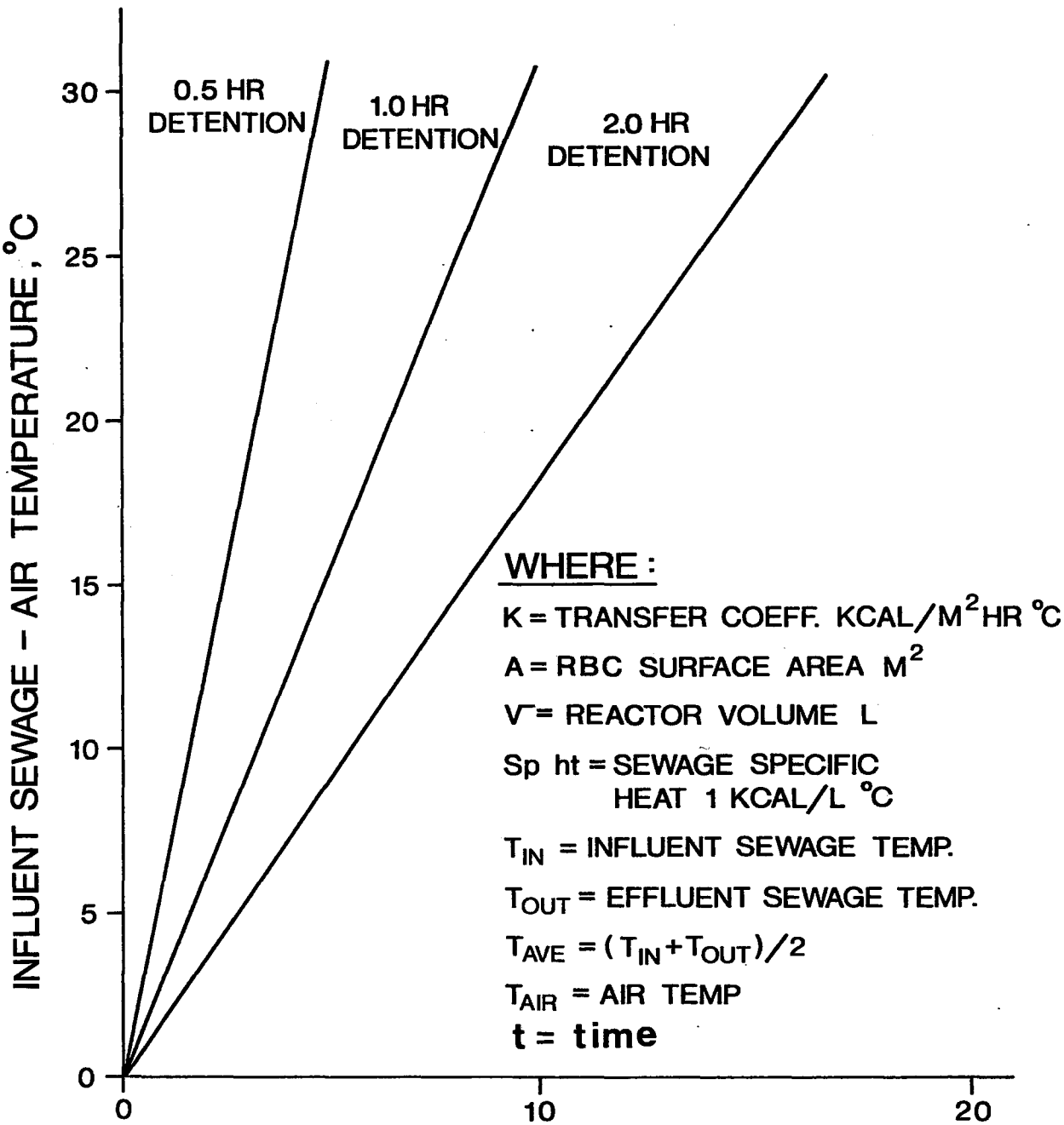


FIGURE 24
HEAT TRANSFER IN THE RBC

MODEL : $\bar{V} \cdot Sp\ ht \cdot (T_{IN} - T_{OUT}) = K \cdot A \cdot t \cdot (T_{AVE} - T_{AIR})$

(EVAPORATIVE COOLING NOT INCLUDED)



of RBC use compared to activated sludge treatment in such regions as western and northern Canada may be significantly hindered should it be necessary to provide semi-heated enclosures for this type of system during winter operation. Little published information is available on the heat losses experienced by the standard activated sludge process. Experience to date, however, has shown that this form of treatment can operate relatively efficiently in even the coldest of climates.

Rate and heat transfer calculations and methods of data analysis for this section are included in Appendix E. Computer programmes for calculating confidence limits and providing linear regression are shown in Appendix C.

Denitrification

Column Flow Characteristics:

A series of tracer studies was run on each of the packed columns in order to gain information on the degree of short circuiting, the changing nature of the flow pattern as a result of solids accumulation and the effects of backwashing. None of this information could be obtained from visual examination as the PVC used in the column construction was not transparent. Furthermore, solids buildup in the reactors were not characterized by increases in operating pressures. Pressure gauges located at two positions on each column never registered any greater value than could be accounted for by the static head. This continued over a six

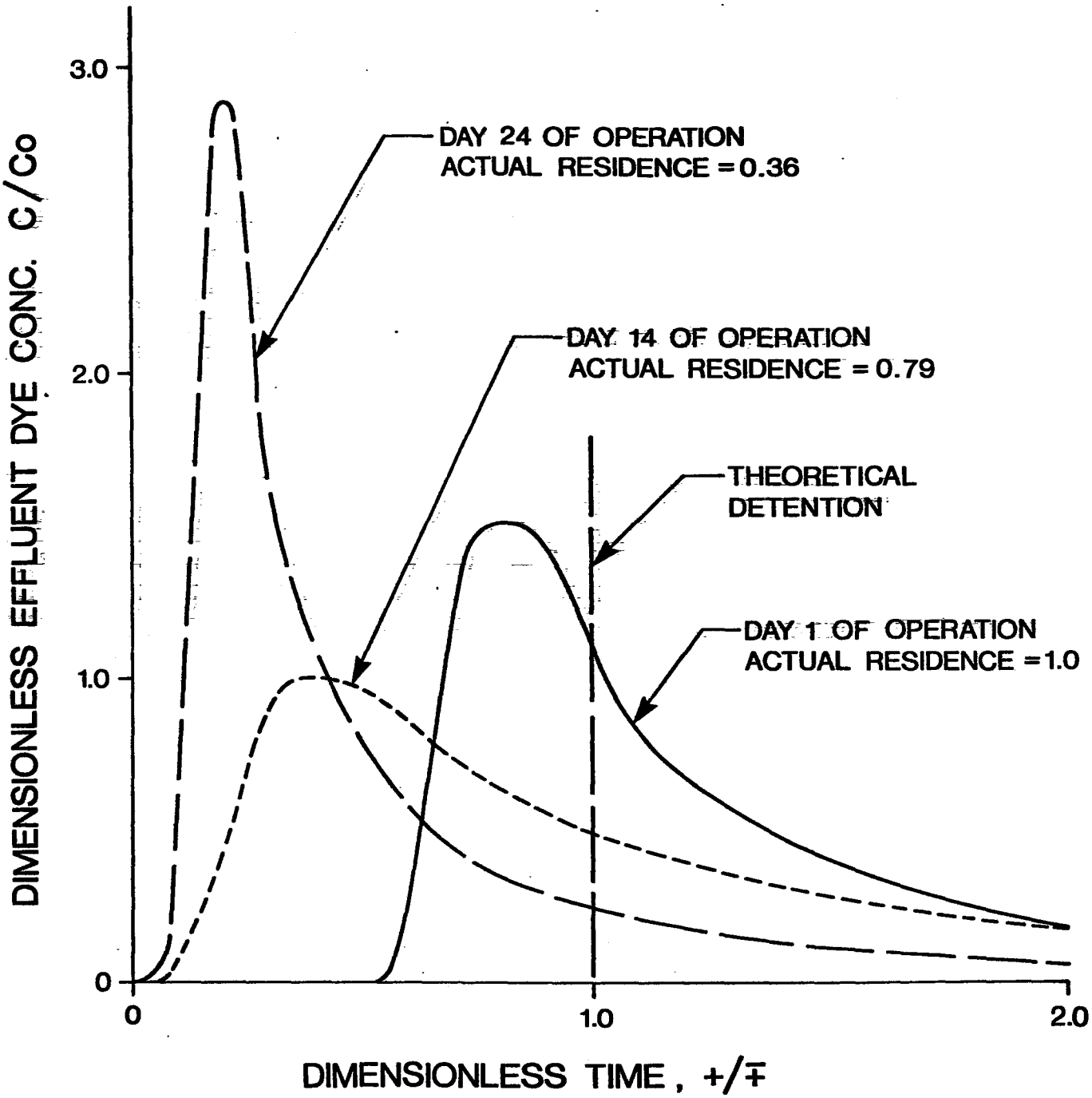
month operational period. Although the lack of pressure buildup was a definite operational advantage compared to the pressure problems recorded from other denitrification studies in which smaller packing media was used (English 1974, Sutton, 1973), it was difficult to determine when and if backwashing was required.

Figure 25 contains the results of three tracer studies run on column F1. During the first day of operation when growth on the packing was minimal the hydraulic pattern approached that of plug flow and little or no short circuiting was present. This rapidly changed as the 14th and 24th days of continuous operation were reached. Dye studies after one month of running revealed large stagnant zones. This is more typical of conventional rock media trickling filters. Therefore, not only does the average detention time in the column decrease but also the nature of the flow changes. This is bound to affect the efficiency of nitrate removal. Similar results were obtained from studies conducted on column F2.

After the first 73 days of uninterrupted running, dye studies indicated that stagnant zones accounted for about 65 percent of the volumes of each column. This meant that the average contact time between sewage and column packing was only 35 percent of the theoretical packed bed detention time (e.g. columns filled with packing but with no growth). At this point, backwashing was attempted. Tracer studies run subsequent to the backwashings showed that even high backwash

FIGURE 2.5

COLUMN F1 FLOW CHARACTERIZATION BY DYE TRACER ANALYSIS (PULSE INPUT) CHANGE IN FLOW WITH TIME



flows for extended periods of time had little effect on the time of the dye peak and in particular the amount of dead space. Figure 26 shows two tracer studies, one run before and the other run after backwashing. Even a rate of 13 Igal/ft^2 min (620 l/m^2 min) over a period of 16 hours had little effect. This would indicate that columns containing media similar to the 1 inch and 2 inch rings used in this study cannot be effectively backwashed without expanding the bed. Bed expansion for this type of media would require an impractical rate and quantity of backwash water.

Figure 27 shows the actual column detention times as estimated over the entire experimental program from the tracer response results. It would appear from the results of the last two studies that a final leveling off in actual detention time does not occur until about one tenth of the theoretical value is reached.

Appendix F describes the procedures used for and lists the results of the tracer studies.

Nitrogen Balances:

A series of nitrogen balances were attempted for each column by measuring NH_4-N, NO_2-N, NO_3-N, soluble and suspended organic nitrogen and dissolved plus gaseous N_2. Procedures followed and the results are in Appendix D. Averaging the data from four consecutive days in which balances were attempted for F2 indicated a net loss of 19 percent of the system's nitrogen between the influent and effluent. A

FIGURE 26

COLUMN F1 FLOW CHARACTERISTICS BY DYE TRACER ANALYSIS EFFECTS OF UPFLOW BACKWASHING

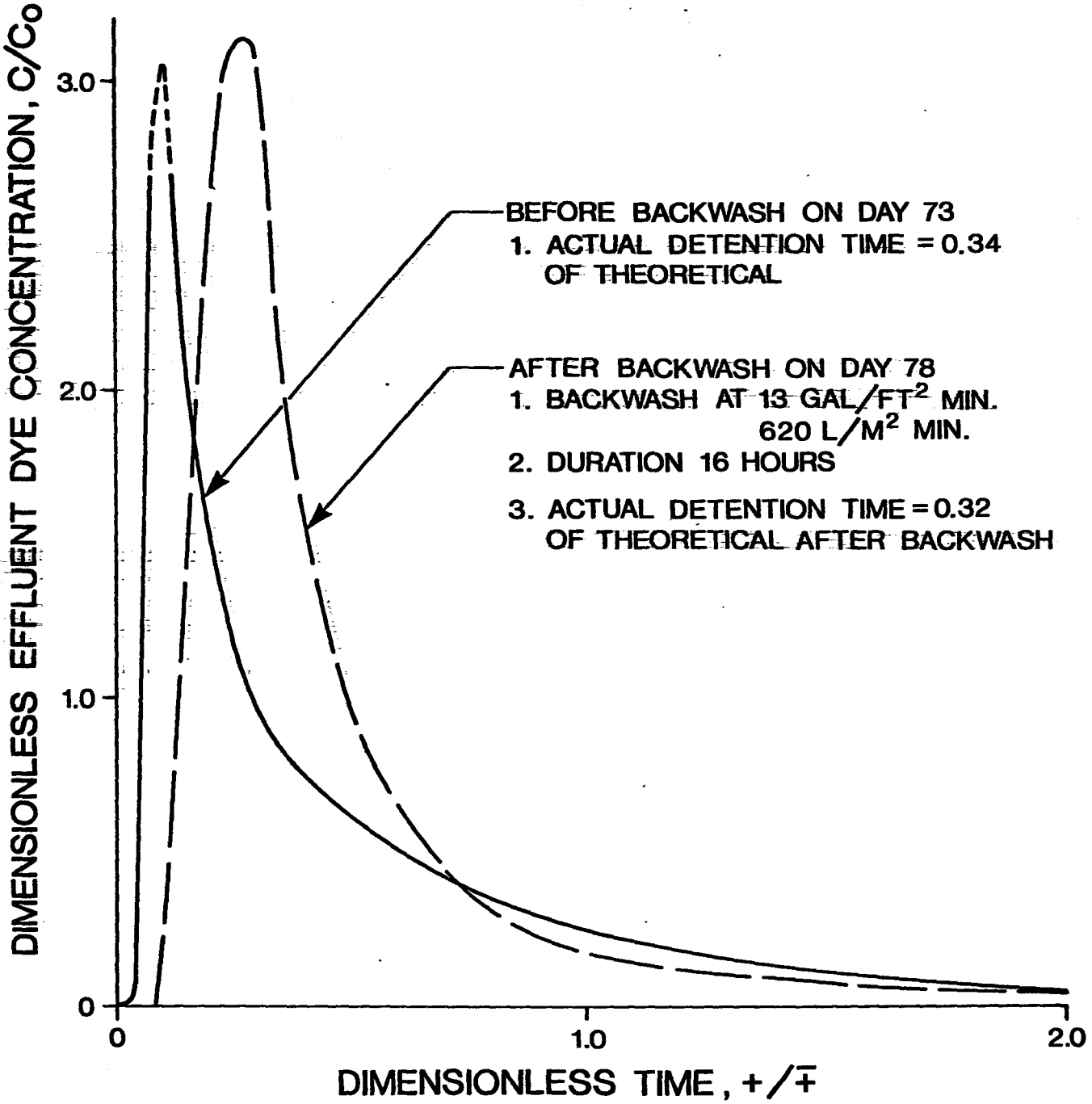
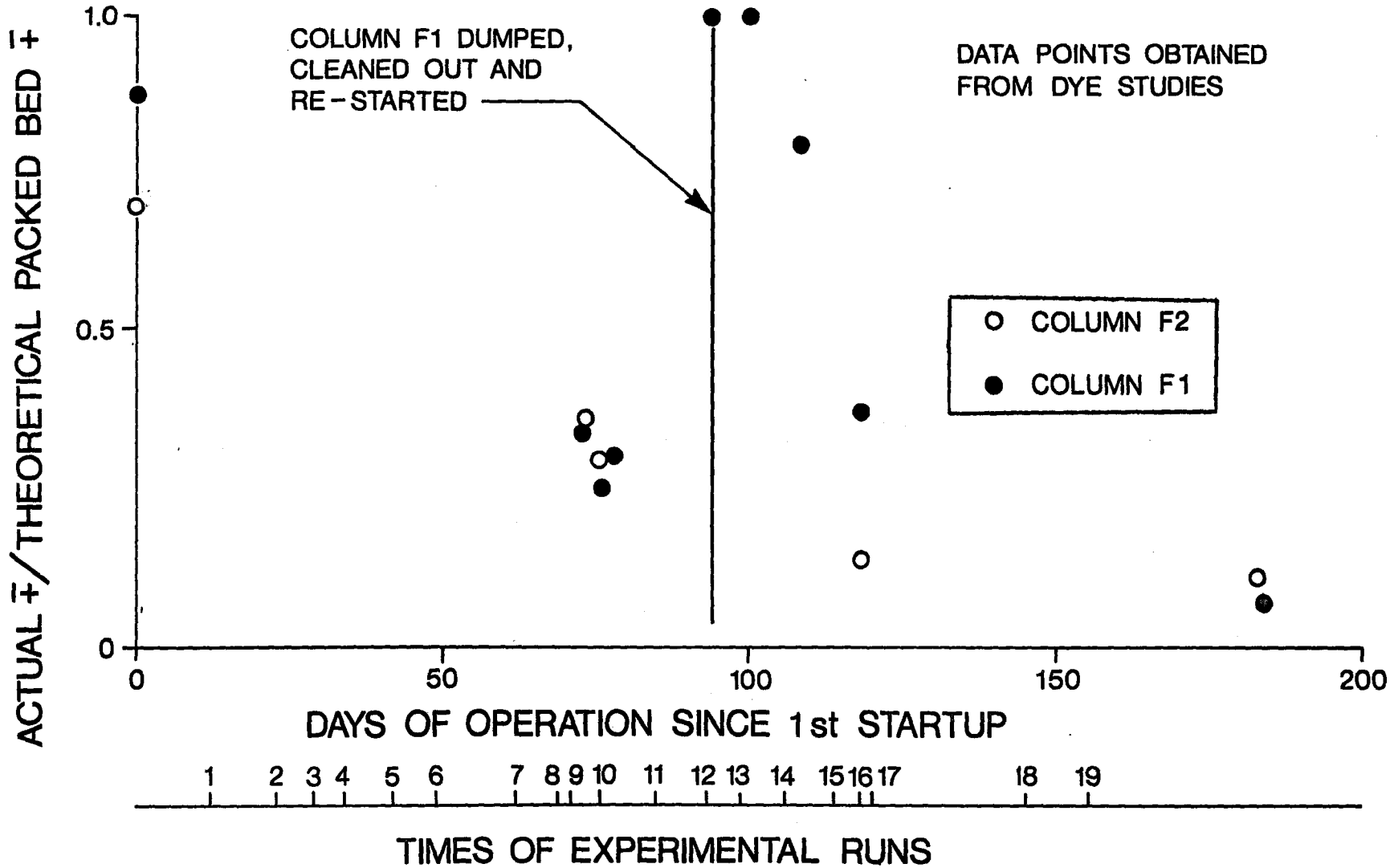


FIGURE 27

ACTUAL MEAN COLUMN RESIDENCE TIMES VERSUS DAYS FROM 1st STARTUP

RESIDENCE TIME EXPRESSED AS FRACTION OF THEORETICAL PACKED BED VALUE



similar averaging of three sets of data for F1 showed a loss of 15 percent. These values represent a loss of 6 to 7 mg/ℓ of nitrogen for the columns. Some of this apparent discrepancy between the nitrogen entering and leaving the columns can be explained by the accumulation of organic nitrogen in the system. A number of separate processes could have contributed to this buildup. These include:

1. production of bacteria through assimilatory denitrification,
2. production of methane bacteria from methanol (significant quantities of methane were found in all gas analyses conducted,
3. trapping of solids present in the feed, and
4. production of bacteria through aerobic respiration which was permitted by the presence of dissolved oxygen in the feed.

Calculations involving the theoretical accumulation of nitrogen through biomass production within the columns show that a maximum of 2 to 3 mg/ℓ of the previously mentioned nitrogen discrepancy could be accounted for. These calculations, however, do not include the possibility of luxury uptake of nitrogen by the micro-organisms as the standard empirical formula of $C_5H_7NO_2$ was employed. In addition, some experimental error was inevitable in conducting these balances, particularly in the determination of gas flows. It is possible that the error associated with the gas rate measurements was as high as 20 percent. This was largely due to the sporadic and widely varying nature of

gas evolution that was always observed even during reasonably steady state feed conditions. An error of this magnitude for any given balance could also account for roughly 3 mg/ℓ of nitrogen.

Sutton (1973) using a similar method for nitrogen balances for his packed bed denitrification columns obtained results which were not much different than those reported here. Sutton found that his best balances occurred when the column operating temperatures were low (5-10°C) at which time the quantity of nitrogen gas in the effluent represented only a couple percent of the total nitrogen present. The balances attempted by Sutton at 15°C and 25°C all indicated an apparent nitrogen loss of 10 to 15%. Under these conditions the evolved nitrogen gas was about 5 to 10% of the total nitrogen input. The balances attempted in the current study were done at 20°C and the gaseous nitrogen in the effluent represented on the average 20 to 30 percent of the nitrogen entering the reactors. It would appear then, that difficulty in conducting successful nitrogen balances on packed column reactors increases as the relative importance of the nitrogen gas evolved increases. Perhaps better methods of gas metering must be found before better results can be expected.

Nitrate and Nitrite Removal Rates:

The data from the denitrification experimental runs are plotted in Figures 28 through 33. Each graph shows the nitrate plus nitrite nitrogen profile through the columns for a given run. The analytical results which displayed erratic behaviour and showed no particular pattern have not been included in these figures. Of the data that does follow a recognizable profile most can be adequately described by a linear model. From a total of 34 separate runs, only two can be said to exhibit distinctly nonlinear behavior. Several other profiles were fitted with a constant slope although some indication of curvature could be inferred.

It would seem, therefore, that the apparent nitrate plus nitrite removal rate in the columns can be described by a model that is zero order with respect to concentration. The term "apparent rate" is used here to emphasize that the observed nitrate removals were influenced by the flow patterns within the columns as well as by the kinetic response of bacterial cells. In reactors such as packed columns, it is generally impractical to separate these two effects during data analysis. A large part of this difficulty is caused by the fact that columns are never in true steady state as solids are produced and retained continuously. Nor are the flows and solids levels homogenous within each unit as heavier biomass accumulations are usually found at lower levels.

For each run in which a constant removal rate was

FIGURE 28

$NO_3-N + NO_2-N$ CONCENTRATION VERSUS HEIGHT

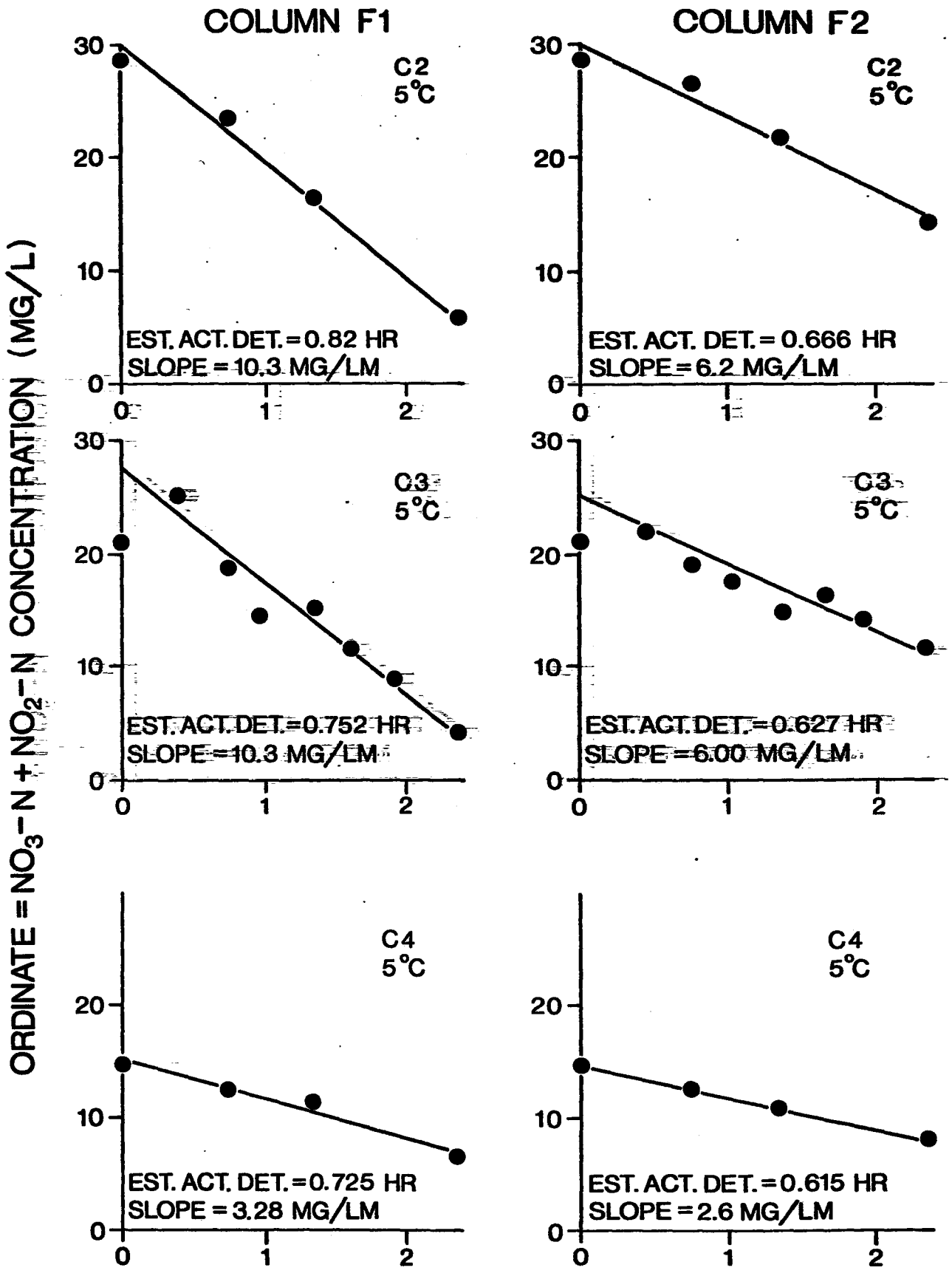


FIGURE 29

NO_3-N + NO_2-N CONCENTRATION VERSUS HEIGHT

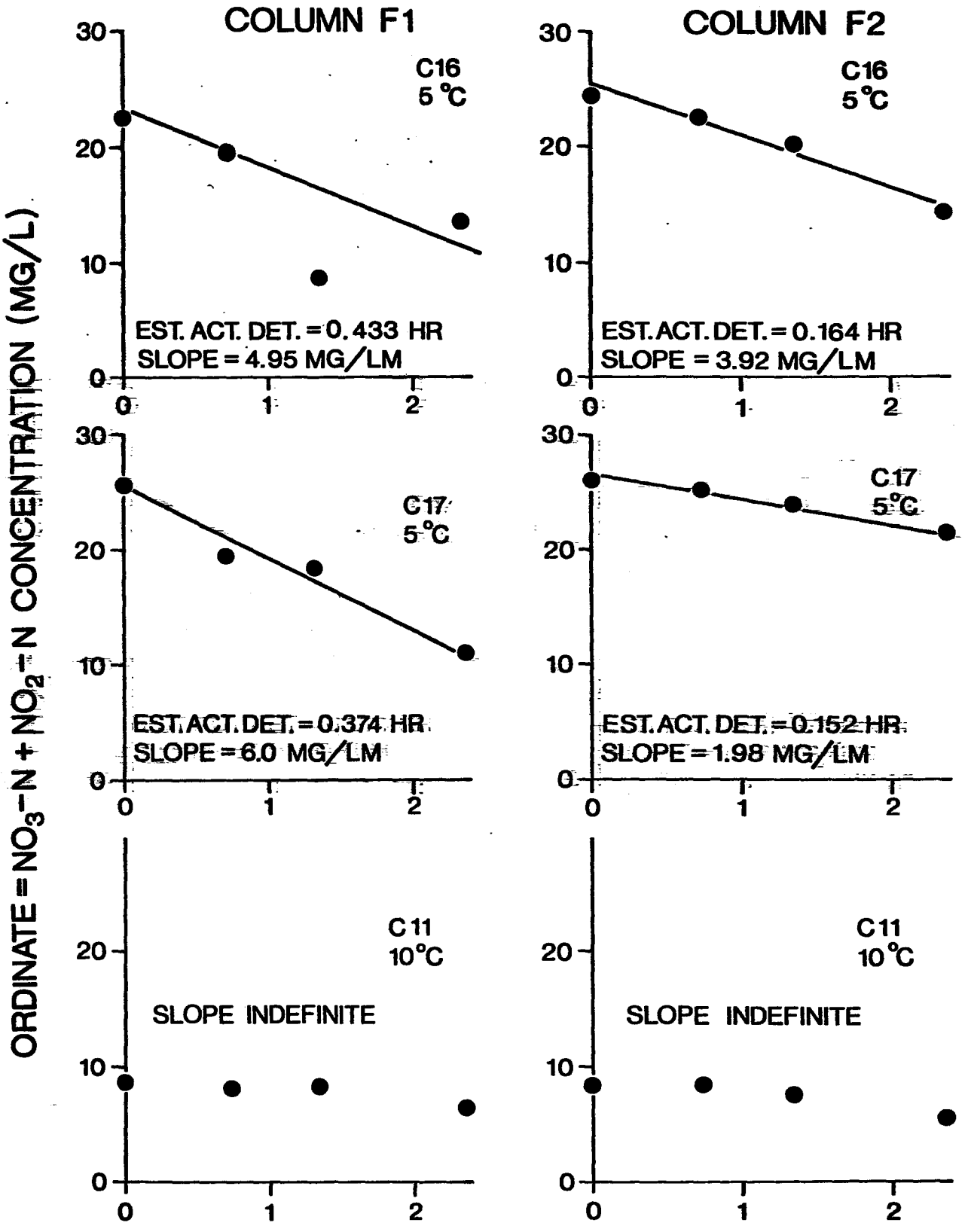


FIGURE 30

$NO_3-N + NO_2-N$ CONCENTRATION VERSUS HEIGHT

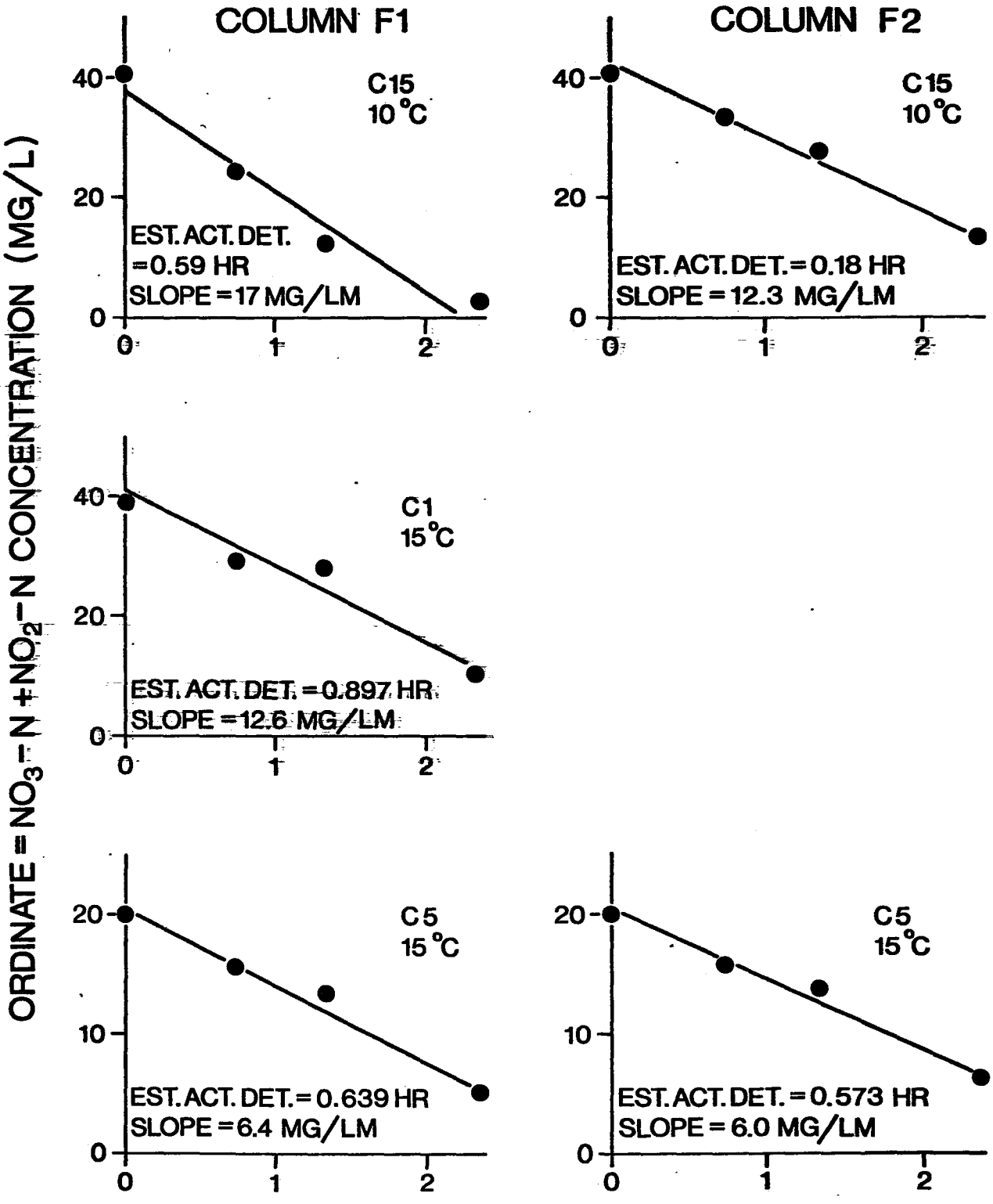


FIGURE 31

$NO_3-N + NO_2-N$ CONCENTRATION VERSUS HEIGHT

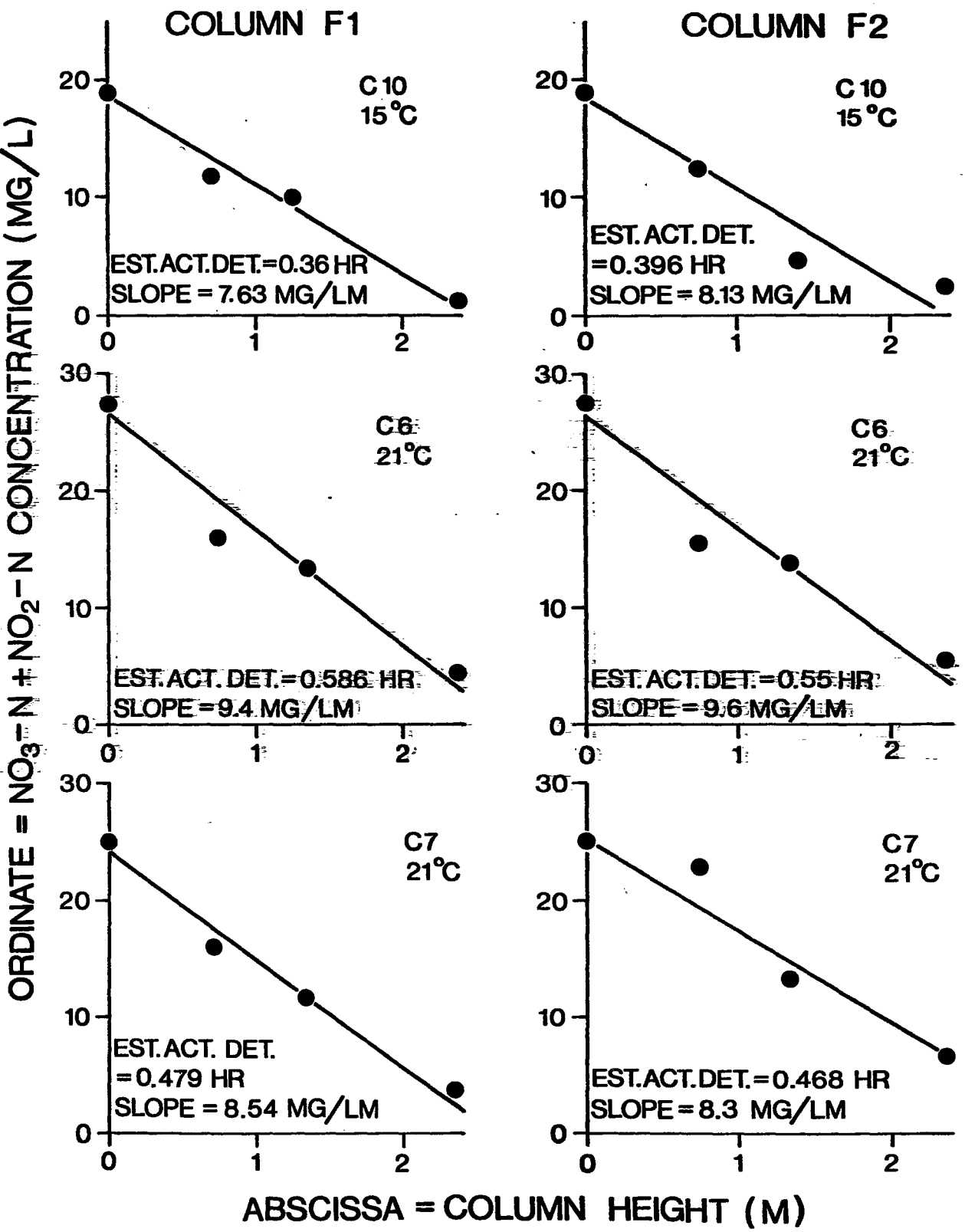


FIGURE 32

$NO_3-N + NO_2-N$ CONCENTRATION VERSUS HEIGHT

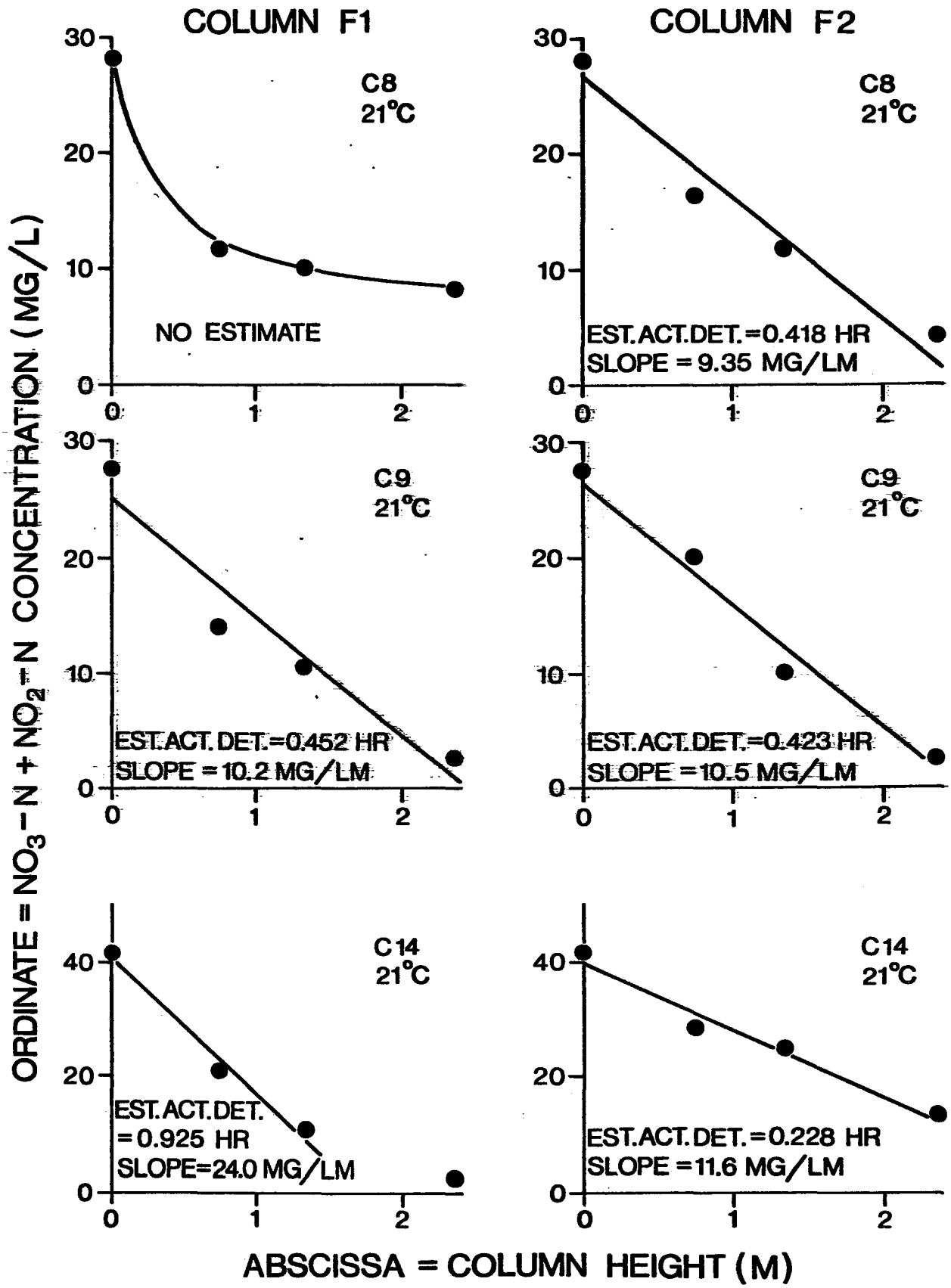
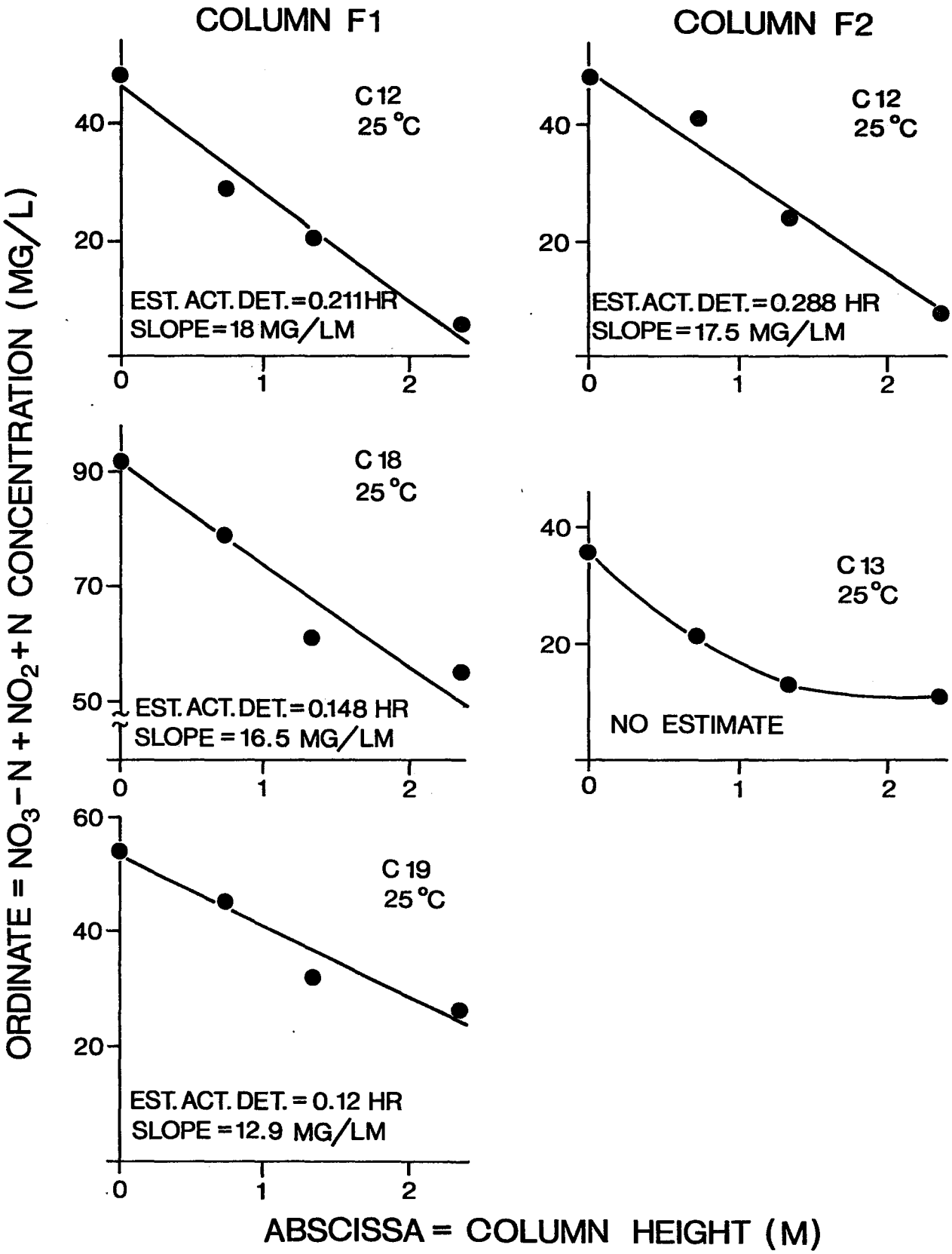


FIGURE 33

$NO_3-N + NO_2-N$ CONCENTRATION VERSUS HEIGHT



determined, an estimate was also made of the actual hydraulic detention time in the system. This was done with the aid of Figure 27. Given this information, denitrification rates were calculated and were expressed as mg NO_3-N + NO_2-N removed per liter of theoretical reactor void volume per hour of contact. These are listed in Table 10.

Effects of Packing Surface:

Both columns were started at the same time and in a similar manner. A common feed source was used to supply influent to the units at the same temperature and flow. Sampling for rate determinations was done simultaneously on each system. During the first 94 days of operation, before F1 was cleaned, the amount of "dead"space in the columns were roughly the same as can be seen from Figure 27. The size of packing media, therefore, constituted the only significant difference between the columns during this period. Results from ten paired runs conducted in this section of the research are listed in Table 11. The rates indicated come directly from the slopes of the respective plots in Figures 28 to 33 and these are expressed as mg NO_3-N + NO_2-N/l m. The ratio of the available surface area in Column F1 to that in Column F2 is 2:1. Consequently, the ratio of nitrate removal should also be 2:1 if the removal is directly proportional to the available packing area. This is not the case. In fact, most of the paired runs give ratios close to 1 indicating a complete lack of surface area dependency. Only the first two sets of runs seem to support the

TABLE 10. COLUMN DENITRIFICATION RATES:
NITRATE PLUS NITRITE NITROGEN REMOVED PER LITER OF REACTOR
VOID VOLUME PER HOUR

TEMPERATURE	RUN	RATE	
		F1	F2
		mg NO_3-N + NO_2-N/l·hr	mg NO_3-N + NO_2-N/l·hr
5°C	C2	29.5	22.0
	C3	32.5	22.0
	C4	10.5	10.0
	C16	27.0	61.0
	C17	38.0	28.5
10°C	C15	68.0	161
15°C	C1	33.0	
	C5	23.5	25.0
	C10	50.5	48.5
21°C	C6	39.0	39.0
	C7	42.0	41.8
	C8		52.8
	C9	53.0	58.5
	C14	57.0	120
25°C	C12	201	144
	C18	263	
	C19	254	

TABLE 11. EFFECTS OF PACKING SURFACE: RATES EXPRESSED AS NO_3-N + NO_2 -N REMOVED PER LITER OF VOID VOLUME PER HOUR

AVAILABLE SURFACE AREA: COLUMN F1 29.3 M^2
COLUMN F2 14.8 M^2

RUN	TEMPERATURE °C	NO_3-N + NO_2-N REMOVAL RATES		RATE F1 / RATE F2
		F1 mg/l·m	F2 mg/l·m	
C2	5	10.3	6.2	1.64
C3	5	10.3	6.00	1.72
C4	5	3.3	2.6	1.26
C5	15	6.4	6.0	1.07
C6	21	9.4	9.6	.98
C7	21	8.5	8.3	1.02
C9	21	10.2	10.5	.97
C10	15	7.4	8.1	.91
C12	25	18.0	17.5	1.03
	AVERAGE RATIO			1.17

variance = .091; df = 8; $t_{\nu,\alpha}$ = 1.86

confidence limits: $1.17 \pm .19$
(1 tailed t-test)

hypothesis that surface area is significant. It is possible that this may be the case when growth and solids accumulation in the columns is small. As has already been mentioned, however, even vigorous backwashing is unable to maintain this condition.

The nitrate plus nitrite removal rates in Table 11 do not include the effects of small differences in the actual hydraulic residence time between F1 and F2. Table 12 presents a similar analysis of the same data except that the denitrification rates were calculated from Table 10. Here the actual hydraulic detentions have been considered. Results using this procedure also indicate that for this system, surface area has little or no effect.

Temperature Effects

The denitrification rate data from Table 10 is plotted in Figure 34. Unfortunately, the large degree of variation in the data plus the presence of a few unexpectedly high removal rates makes it very difficult to draw definite conclusions concerning temperature sensitivity. The Arrhenius Model does not fit the data adequately. No explanation was found that could account for the very high denitrifying rates calculated for the columns at 10 degrees. The runs at 25 degrees, however, were done when the columns were more heavily plugged with solids. Since this means that the actual hydraulic detention times were small (between 10% and 20% of the theoretical value) even a relatively small change in nitrate concentration between the influent and effluent

TABLE 12. EFFECT OF PACKING SURFACE:

INCLUDING EFFECTS OF ACTUAL DETENTION TIME:

RATES EXPRESSED AS NO_3-N + NO_2-N REMOVAL PER LITER OF REACTOR VOID VOLUME PER HOUR

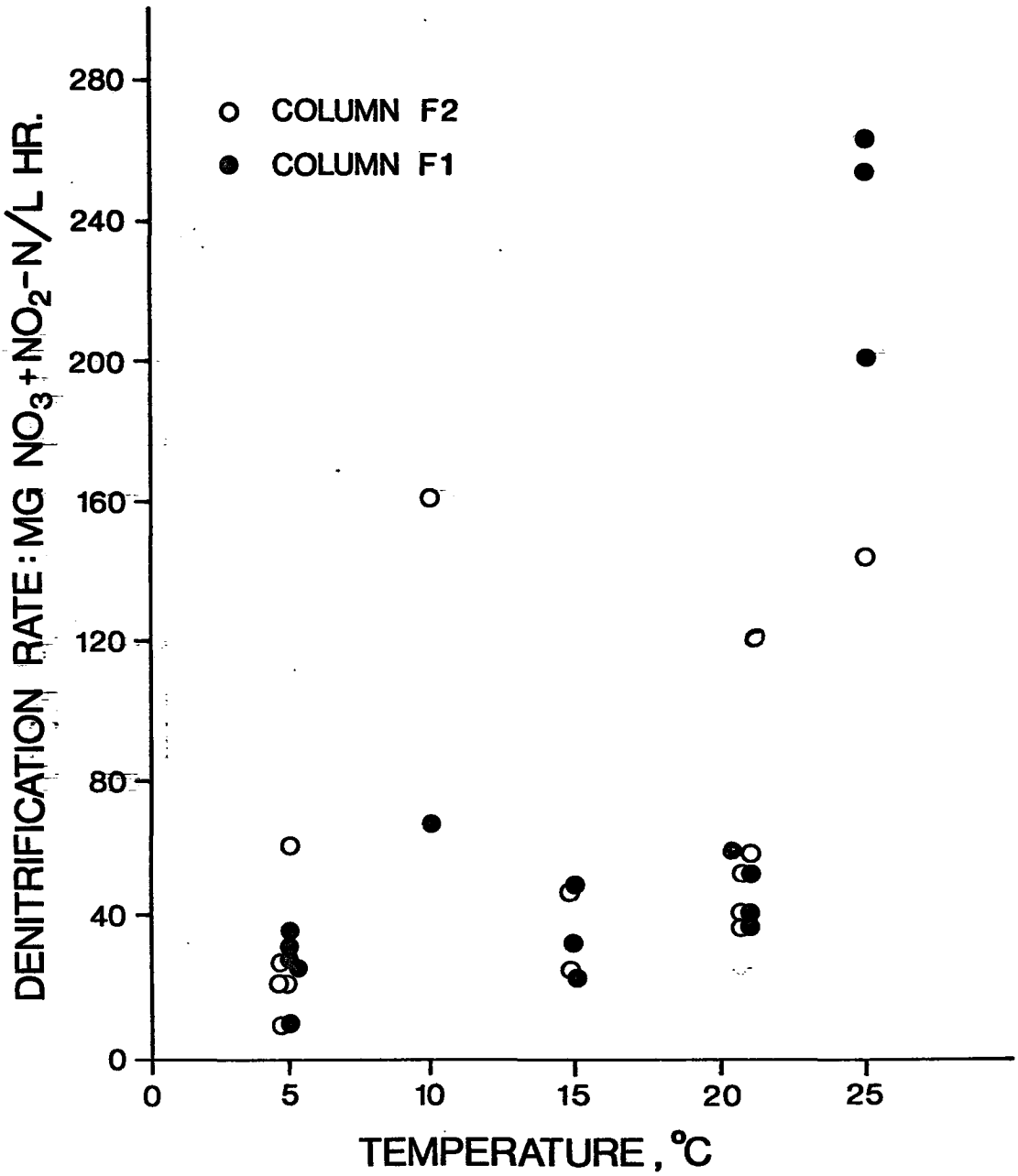
RUN	TEMPERATURE °C	NO_3-N + NO_2-N REMOVAL RATES		RATE F1 / RATE F2
		F1 mg/l·hr	F2 mg/l·hr	
C2	5	29.5	22.0	1.34
C3	5	32.5	22.0	1.48
C4	5	10.5	10.0	1.05
C5	15	23.5	25.0	.94
C6	21	39.0	39.0	1.00
C7	21	42.0	41.8	1.00
C9	21	53.0	58.5	.91
C10	15	50.5	48.5	1.04
C12	25	201	144	1.40
	AVERAGE			1.13

variance = .047; df - 8; $t_{\nu,\alpha} = 1.86$

confidence limits: $1.13 \pm .14$
(1 tailed t-test)

FIGURE 34

DENITRIFICATION RATE VERSUS TEMPERATURE. RATES BASED ON ACTUAL LIQUID DETENTION TIME

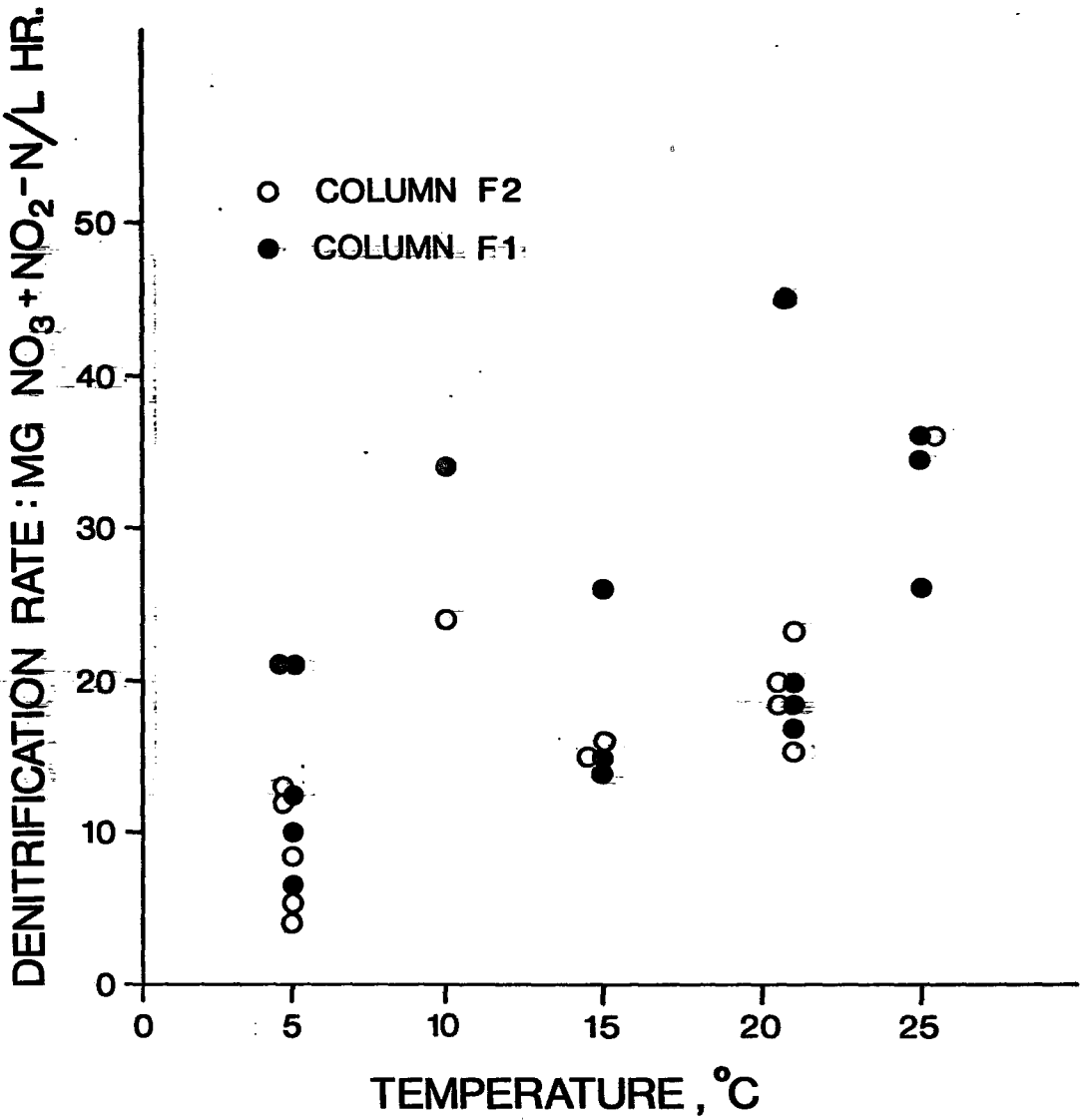


could result in very high calculated denitrification rates. Most researchers in the past have used theoretical detention times, either empty bed or packed bed, when expressing biological reaction rates in packed columns. Therefore, to serve as a comparison to Figure 34, the denitrification rates were recalculated using the theoretical packed bed residence time. The results are shown in Figure 35. Although a large degree of scatter is still present, there does seem to be a recognizable pattern of increased reaction rate with increased temperature if the 10°C runs are ignored. It is also evident by a comparison of Figures 34 and 35 that use of the estimated true residence time to partially compensate for the non steady state nature of column operation does nothing to reduce the variation of the data as would be expected. If anything, the variation seems to be increased. This indicates that factors in addition to detention time and temperature affect the columns' denitrifying efficiencies. It would be natural to suspect a concentration dependency, however, upon careful examination of the data, no such correlation was found.

Due to the inconclusiveness of the column results, no attempt was made to compare the temperature sensitivity of the stirred tank denitrification system with that of the column reactors.

FIGURE 35

DENITRIFICATION RATE VERSUS TEMPERATURE. RATES BASED ON THEORETICAL PACKED BED DETENTION TIME



General Performance:

Although nitrate removal from the columns proved to be somewhat erratic and unpredictable because of the unsteady state nature of the process, the system, nevertheless, did denitrify significant quantities of nitrate and nitrite at all temperature levels and with minimum maintenance. In order to provide a clearer perspective of the denitrifying capabilities of the two column reactors used in this study, it is possible to compare the current results with results quoted by Sutton (1973). Sutton's denitrification columns utilized a feed that was very similar to the feed used for F1 and F2. Table 13 shows the separate results for F1 and F2 as well as results from Sutton's columns which were packed with .375 inch (.95 cm) and .5 inch (1.27 cm) Intalox Saddles. Nitrate removal rates are all expressed in terms of grams of NO_3-N plus NO_2-N removed per cubic meter of packing per hour. This was done so that all of the rate data would be expressed in comparable units. This also provides a view of the "volumetric" efficiency of these column reactors. The results listed in Table 13 show quite clearly that the two columns of this study with their larger packing media were over twice as efficient "volumetrically" than were Sutton's column reactors.

Of major interest for municipal denitrifying systems is the question of whether or not low enough effluent nitrate plus nitrite concentrations can be attained. In this study, it was noticed that effluent levels of nitrate plus nitrite

TABLE 13

NITRATE PLUS NITRITE REMOVAL RATE COMPARISON

RATES EXPRESSED AS GRAMS OF NO_3-N + NO_2-N REMOVED PER CUBIC METER OF PACKING PER HOUR. AVERAGE RATES FOR EACH TEMPERATURE USED

TEMPERATURE	THIS WORK		SUTTON (1973)	
	1 in Pall Rings	2 in Pall Rings	.375 in Intalox Saddles	.5 in Intalox Saddles
°C	$gm/m^3 \cdot hr$	$gm/m^3 \cdot hr$	$gm/m^3 \cdot hr$	$gm/m^3 \cdot hr$
5	15.6	9.2	5.1	4.0
10	41.0	26.8	6.6	5.3
15	18.5	14.8	5.1	4.0
20	29.4	21.6	14.4	11.4
25	35.9	39.8	16.6	13.2
LOADING -	.64 gal/ft^2 min 31 l/m^2 min		3.1, 1.6 gal/ft^2 min 151, 76 l/m^2 min	

nitrogen were rarely if ever below 1.5 mg/ℓ even when influent concentrations were low. This could be explained by a system that exhibited significant bypass flow. In such processes, complete treatment is impossible. For instance, if 10 percent of a particular feed containing 20 mg NO_3-N/l bypasses the biologically active zones in a reactor, there will always be a minimum of 10 percent of the initial concentration or 2 mg NO_3-N/l in the effluent. This will always be the case no matter how rapidly the bacteria are able to denitrify. It has already been shown that severe short circuiting occurred in the columns and it is reasonable to hypothesize that the equivalent of partial bypass flow was affecting removal efficiencies. If this were the case, anaerobic columns of the nature used in this study could never be expected to compete with stirred tanks for municipal wastewater denitrification since there would always be significant nitrate residuals. Applications for columns may be found, however, as roughing processes for high strength nitrate wastes when effluent concentrations are not as important.

CONCLUSIONS

1. The Rotating Biological Contactor is a simple, reliable and effective system,under all temperature conditions studied for, BOD_5 removal and nitrification with municipal wastewater.

2. The fact that nitrification in the RBC was shown to be less temperature dependent than nitrification in a two stage activated sludge process provides an important advantage for the RBC when consideration is being given to the design of treatment facilities for areas in which sewage temperatures exhibit large annual fluctuations.

3. In cold climates, sewage cooling as a result of heat transfer between the RBC disc surfaces and the atmosphere could significantly reduce biological activity and may even cause unit icing problems. To minimize this problem covers should be placed over all units and in some extreme cases, the desirability of installing the RBC's in a partially heated building should be evaluated.

4. Denitrification of municipal waste water using columns with media similar to the packings used in this study is not as reliable as the stirred tank process for the

4. following reasons:

   a) Consistent nitrate removal efficiencies cannot be maintained since continuous solids accumulations and increased short circuiting prohibits the establishment of a steady state operation in the columns.

   b) Conventional backwashing is not effective and even if it were, it would be difficult to determine when backwashings were necessary.

   c) Short circuiting and the likelihood of some bypass flow makes it almost impossible to achieve effluent nitrate concentrations below 1.5-2.0 mg/ℓ as NO_3-N.

5. The use of actual hydraulic residence times for calculating reaction rates in packed columns seems no more adequate in providing meaningful characterization of the denitrification process than when theoretical packed bed residence times are used.

6. Although denitrifying efficiencies varied somewhat unpredictably in the columns, the two units did remove significant quantities of nitrate from the wastewater at all temperature. In fact, because the nitrate removals were generally high in terms of NO_3-N removed per volume of packing per time, these types of columns may be suitable for treating higher strength nitrate

6. wastes as a roughing process where effluent nitrate concentrations may not be as important as the total mass of nitrate removed.

RECOMMENDATIONS

1. An attempt should be made to determine conclusively whether or not simultaneous nitrification-denitrification occurs in the films of the RBC.

2. An RBC system modified such that the disc surfaces remain completely submerged at all times should be investigated for denitrification effectiveness.

3. Further work should be initiated to investigate heat transfer from RBC's during cold weather. This should include a survey of the operations of existing pilot and full scale systems during cold weather as well as research to directly compare heat transfer from an activated sludge plant in cold weather with heat transfer from an RBC.

4. Any future pilot plant denitrification studies for municipal wastewater with packed columns should be directed toward systems which have shown significant promise such as with the fluidized bed process of Jeris and Flood (1974).

5. A number of runs should be conducted with the RBC under conditions such that effluent soluble TKN is varied between 0 mg/ℓ and 10 mg/ℓ in order to gain more data concerning the possibility of a concentration dependency on the rate of nitrification.

ABBREVIATIONS AND SYMBOLS

RBC	: Rotating Biological Contactor
F1	: packed column containing 1" polypropylene Norton Poll Rings
F2	: packed column containing 2" polypropylene Norton Poll Rings
CSTR	: continuous stirred tank reactor
ℓ	: liter
hr	: hour
m, m^2	: meter, square meter
ft, ft^2	: foot, square foot
RPM	: revolutions per minute
min	: minute
mg	: milligram
#/day-1000 ft^2	: pounds per day per thousand square feet
IGPD	: Imperial gallons per day
IGPM	: Imperial gallons per minute
MLVSS	: mixed liquor volatile suspended solids in milligrams per liter
mg/ℓ	: milligrams per liter
cal/mole	: calories per gram mole
kcal/mole	: kilocalories per gram mole
^oC	: degrees Centigrade
^oF	: degrees Fahrenheit
Σ	: the sum of
Imp gal	: Imperial gallons
BTU	: British thermal unit
gm/m^3 hr	: grams per cubic meter per hour

mg/m-hr	: milligrams per meter of column height per hour
BTU	: British Thermal Unit

REFERENCES

Ahlberg, N.R., Kwong, T.S., "Process Evaluation of a Rotating Biological Contactor for Municipal Wastewater Treatment", Ministry of the Environment, Ontario, Research Paper W2041, (1974).

American Chemical Society, Cleaning Our Environment The Chemical Basis for Action, A report by the Subcommittee on Environmental Improvement, Committee on Chemistry and Public Affairs, Washington, D.C., 106, (1969).

Antonie, R.L., "Nitrification of Activated Sludge Effluents: Bio-surf Process", Water and Sewage Works Jour., 121, 44-47, (1974A).

Antonie, R.L., "Application of the Bio-Disc Process to Treatment of Domestic Waste Water". Paper presented at the 43rd Annual Conf. of the Water Pollution Control Fed., Boston, (1970).

Antonie, R.L., "Evaluation of a Rotating Disk Wastewater Treatment Plant", Jour. Wat. Poll. Cont. Fed., 46, 498-511 (1974B).

Barth, E., Smith, J., "Control of Nitrogen in Waste Water Effluents", presented at the EPA Technology Transfer Design Seminar, Atlanta, Georgia, May, (1973).

Bishop, Fred, Personal communication to D.S. Parker, Environmental Protection Agency, Washington, D.C., April, 1974.

Borchardt, J.A., "Biological Waste Treatment Using Rotating Discs", Biological Waste Treatment (Edited by Canale) Wiley Interscience, New York, 131-140, (1971).

Brown and Coldwell Consulting Engineers, "Case Histories of Nitrification and Denitrification Facilities", Prepared for the EPA Technology Transfer Design Seminar for Wastewater Treatment Facilities, Orlando, Florida, May 7-9, (1974).

Dawson, R.N., "Batch Studies on the Biological Denitrification of Wastewater", Ph.D. Thesis, McMaster University, (1971).

Dawson, R.N., Murphy, K.L., "Factors Affecting Biological Denitrification of Wastewater", Advances in Water Pollution Research, Jerusalem, 671, (1972).

Delwiche, C.C., "Denitrification". "A Symposium on Inorganic Nitrogen Metabolism". (Edited by McElroy and Glass), John Hopkins Press, 233, (1956).

Downing, A.L., Hopwood, A.P., "Some Observations on the Kinetics of Nitrifying Activated Sludge Plants", Schweiz Zeits. Hydrol., 26, 271-288, (1964).

Duddles, G.A., Richardson, S.E., Barth, E., "Plastic Medium Trickling Filters for Biological Nitrogen Control", Jour. Water Poll. Control Fed., 46, 937-946, (1974).

English, J.N., Carry, C.W., Masse, A.N., Pitkin, J.B., Dryden, F.D., "Denitrification in Granular Carbon and Sand Columns", Jour. Water Poll. Control Fed., 46, 28-42, (1974).

European Inland Fisheries Advisory Commission Working Party on Water Quality Criteria for European Freshwater Fish, Status Report, (1973).

Beak Consultants Ltd., "An Evaluation of European Experience with the Rotating Biological Contactor", EPS Report 4-WP-73-4, 71, Oct. (1973).

Fair, G.M., Geyer, J.C., Okun, D.A., "Water and Wastewater Engineering, Volume 2, Water Purification and Wastewater Treatment and Disposal", John Wiley and Sons Inc., New York, 28-45, (1968).

Ferguson, F.A., "A Nonmyophic Approach to the Problem of Excess Algae Growths", Environmental Science and Technology, 2, 188-195 (1968).

Fewson, C.A., Nicholas, D.J.D., "Nitrate Reductase from Pseudomonas Aeroginosa", Biochim. Biophys. Acta, 49, 335-349, (1961).

Fox, M.E., "Rapid Gas Chromatographic Method for Determination of Residual Methanol in Sewage", Environmental Science and Technology, 7, 838-840, (1973).

Gibson, C.E., "Nutrient Limitation", Jour. Water Poll. Control Fed., 43, 2436-2440, (1971).

Grieves, C., "Dynamic and Steady State Models for the Rotating Biological Disc Contactor", Ph.D. Thesis, Clemson University, (1972).

Haug, R.T., McCarty, P.L., "Nitrification with the Submerged Filter", Tech. Report 149, Dept. of Civil Engineering, Stanford University, Aug., (1971).

Himmelblau D.M., "Process Analysis by Statistical Methods", John Wiley and Sons Inc., 194, (1970).

Huang, C.S., Hopson, N.E., "Nitrification Rate in Biological Processes", Jour. Envir. Eng. Div., Proceedings of the American Soc. of Civil Engineers, 100, 409-422, April, (1974).

Jeris, J.S., Flood, F.J., "Plant Gets New Process - Biological Denitrification is Employed in Nassau County Wastewater Reclamation Plant", Water and Waste Engineering, 50, 45-48, (1974).

Johnson, W.K., Schroepfer, G.J., Nitrogen Removal by Nitrification and Denitrification", Jour. of the Water Poll.Control Fed., 36, 1016-1036, (1964).

Jones, A., "Denitrification by Anaerobic Filters and Ponds-Phase II", Bioengineering Aspect of Agricultural Drainage, San Joaquin Project, Environmental Protection Agency, 13030 UBH 6/71-14, June, (1971).

Kehrberger, G.J., Norman, J.D., Schroeder, E.D., Busch, A.W., "BOD Progression in Soluble Substrates - VII Temperature Effects", Proceedings of the 19th Ind. Waste Conf., Purdue, Series 117, 953-964, (1964).

Kerr, P.C., Brockway, D.L., Paris, D.F., "The Interrelation of Carbon and Phosphorus in Regulating Heterotrophic and Autotrophic Populations in an Aquatic Ecosystem", Proceedings of the 25th Industrial Waste Conf., Purdue, 112 -140, (1970).

Laidler, K.J., "Chemical Kinetics", McGraw-Hill, 2nd Ed. (1965).

Levenspiel, O., "Chemical Reaction Engineering", John Wiley and Sons Inc., 5th Ed., 242-302, (1967).

Lue-Hing, C., Obayashi, A.W., Zenz, D.R., Washington, B., Sawyer, B.M., "Nitrification of a High Ammonia Content Sludge Supernatant by Use of Rotating Discs", Paper presented at the 29th Annual Industrial Waste Conf., Purdue, (1974).

Massey, A., Robinson, J., "A Review of Factors Limiting the Growth of Nuisance Algae", Water and Sewage Works Jour., 118, 352-355, (1971).

McCarty, P.L., Beck, L., St. Amant, P.J., "Biological Denitrification of Wastewater by Addition of Organic Materials", Proceedings 24th Industrial Waste Conf., Purdue, 1271-1285, (1969).

McCarty, P.L., "Stoichiometry of Biological Reactions", Short Course on Biological Waste Treatment, Manhattan College, (1970).

McCarty, P.L., "Nitrification-Denitrification by Biological Treatment", Correspondence Conference on Denitrification of Municipal Wastes, University of Massachussetts, (1973).

Mulbarger, M.C., "Nitrification and Denitrification in Activated Sludge Systems", Jour. Water Poll. Cont. Fed.,43, 2059-2070, (1971).

Myers, J., Matsen, F.A., "Kinetic Characteristics of Warburg Manometry", Arch. Biochem.and Biophys., 55, 373-388, (1955).

Painter, H.A., "A Review of Literature on Inorganic Nitrogen Metabolism in Microorganisms", Water Research, Pergamon Press, 4, 391-450, (1970).

Pretorius, W.A., "Nitrification on the Rotating Disc Unit", Paper presented at the 7th Int. Conf. of Water Poll. Res., Paris, (1974).

Requa, D.A., Schroeder, E.D., "Kinetics of Packed Bed Denitrification", Jour. Water Poll. Cont. Fed., 45, 1696-1707, (1973).

Riemer, M., "Denitrification in Anaerobic Filters", Private Communication to Dr. K.L. Murphy, Denmark, (1974).

Sawyer, C.N., "Sources of Nitrogen in the Water Resource and its Role in Eutrophication", Proceedings of the Correspondence Conference on the Denitrification of Municipal Wastes", University of Massachussetts, April, (1973).

Schmidt, B., Kampf, W.D., "Uber den Einfluss des Saverstagge auf die Denitrifikabonsleistung von Pseudomonos fluorescens", Arch. Hrg. Bakt., 146, 171-182, (1962).

Shapiro, J., Ribeiro, R., "Algae Growth and Sewage Effluent in the Potomac Estuary", Jour. Water Poll. Cont. Fed., 37, 1034-1043, (1965).

Smith, J.M., Marse, A.N., "Nitrogen Removal from Municipal Wastewater by Columnar Denitrification", Report FWQA, U.S.A., (1970).

Steels, I.H., "Design Basis for Rotating Disc Processes", Effluent and Water Treatment Jour., 431-445, (1974).

Streeter, H.W., Phelps, E.B., "A Study of the Pollution and Natural Purification of the Ohio: III. Factors Concerned in the Phenomena of Oxidation and Reaeration", U.S. Public Health Bulletin, 146, FEB, (1925).

Sutton, P.M., "Continuous Biological Denitrification of Wastewater", Masters Thesis, Dept. of Chem. Eng., McMaster University, (1973).

Sutton, P.M., Murphy, K.L., Jank, B.E., Monaghan, B.A., "Biological Nitrogen Removal - The Efficacy of the Nitrification Step", Paper presented at the 47th Annual Conf. Water Poll. Cont., Fed., Denver, Oct., (1974).

Sword, B.R., "Denitrification by Anaerobic Filters and Ponds", Bio-Engineering Aspects of Agricultural Drainage, San Joaquin Project, Environmental Protection Agency, 13030, UBH, April, (1971).

Timpany, P.L., "Variations of Axial Mixing in an Aeration Tank", Master's Thesis, Dept. of Civil Eng., McMaster University, (1966).

Torpey, W., Heukelekian, H., Kaplovsky, A.J., Epstein, R., "Effects of Exposing Slimes on Rotating Discs to Atmospheres Enriched with Oxygen", Advances in Water Pollution Research, Pergamon Press, London, 405-418, (1972).

Tamblyn, T.A., Sword, B.R., "The Anaerobic Filter for the Denitrification of Agricultural Subsurface Drainage", Proceedings of the 24th Ind. Waste Conf., Purdue University, 1135-1150, (1969).

Wild, H.E., Sawyer, C.N., McMahon, T.C., "Factors Affecting Nitrification Kinetics", Jour. Water Poll. Cont. Fed., 43, 1845-1854, (1971).

APPENDIX A

REACTOR OPERATING DATA PLUS ANALYTICAL RESULTS

The abbreviations and symbols used in Appendix A can be summarized in four general sections. These are Column Operation, RBC Operation, Sample Designation and Analytical Results.

Column Operation

SOLIDS : suspended solids in milligrams per liter

FLOW : column feed rates in imperial gallons per minute

HACH NH3N : ammonia N as determined by the portable HACH method and expressed in milligrams per liter

HACH NO3N NO2N : nitrate plus nitrite N as determined by the portable HACH method and expressed in milligrams per liter

EFF TEMP : feed temperature in degrees centigrade measured in Cooler 2

pH : logarithm of the reciprocal hydrogen ion concentration

Cooler DO : the dissolved oxygen concentration in Cooler 2 expressed in milligrams per liter

Rotating Biological Contactor Operation

ALK : alkalinity expressed as milligrams of calcium carbonate per liter

30 MIN SET : volume in milliliters occupied by settled solids in a one liter IMHOFF cone after thirty minutes of settling

TEMP : temperature in degrees centigrade

DO : dissolved oxygen in milligrams per liter

ATM TEMP : average of three separate readings for the air temperature above the rotating discs inside the RBC hood. Temperature is in degrees centigrade

---C : any numerical value followed immediately by a "c" signified that the analysis was done on a 24 hour composite sample. All composite samples refer to the RBC raw feed or the effluent

Sample Designation

IE : grab influent sample to the RBC

EE1 : grab sample taken from the first compartment after the feed in the RBC

EE2 : grab sample taken from the second compartment after the feed in the RBC

EE3 : grab sample taken from the third compartment in the RBC

EE4 : grab sample taken from the fourth compartment in the RBC

EEDR : grab final effluent from the RBC

RF-C : 24 hour composite feed sample to the RBC

EEDR-C : 24 hour composite effluent sample from the RBC

GAM : grab sample taken before noon

GPM : grab sample taken in the afternoon

IC1BE : grab sample influent to reactor C1, column F1, and column F2 before the addition of methanol. Samples were taken from cooler 2

IC1AF : grab sample influent to reactor C1, column F1 and F2 after methanol addition

IF1, IF2 : grab samples of column influents taken from valves located on the feed lines just prior to the feed entering the reactors

EF1-2, EF2-2: grab samples taken from the second ports from the bottom of F1 and F2 respectively

EF1-4, EF2-4: grab samples taken from the fourth ports from the bottom of F1 and F2 respectively

EF1, EF2 : final effluents from columns F1 and F2

Analytical Results

BOD_5 : 5 day biochemical oxygen demand in mg/ℓ

COD : chemical oxygen demand in mg/ℓ

TKN : total kjeldahl nitrogen in mg/ℓ

TOC : total soluble organic carbon in mg/ℓ

METH : methanol in mg/ℓ

NH3N : ammonia as nitrogen in mg/ℓ

NO2N : nitrite as nitrogen in mg/ℓ

NO3N : nitrate as nitrogen in mg/ℓ

BIODISC OPERATION

DATE DAY	MON	SAMPLE	SOLIDS	FLOW	ALK	PH	30 MIN SET	HACH NO2N NH3N	HACH NO3N	TEMP	DO	ATM TEMP
THE BIODISC WAS FIRST STARTED UP IN MID APRIL HOWEVER, FLOW THROUGH THE SYSTEM WAS HIGH ALLOWING LITTLE OR NO NITRIFICATION												
04	06	IE		126C						5.8		
		EEDR		227C								
06	06	IE		476C						5.6		22.0
		EEDR		330C	.182							
10	06	IE						38.0	0.0	8.2	3.8	27.0
		EE1								13.3	4.7	
		EE2								14.8	4.6	
		EE3								16.2	4.9	
		EE4								17.0	4.7	
		EEDR			.180		10.0	18.5	7.8			
11	06	IE		382						8.9	2.7	22.0
		EE1								10.8	5.3	
		EE2								11.5	5.5	
		EE3								12.3	5.5	
		EE4								13.0	5.2	
		EEDR		268	.170		10.0					
12	06	IE	232	234				25.0	1.2	9.2		21.4
		EE1								11.2		
		EE2								11.9		
		EE3								12.6		
		EE4								13.1	5.7	
		EEDR	254	222	.172			13.5	9.5			
13	06	IE	598	588				28.0		9.3	3.8	24.0
		EE1		210C						11.3	5.9	
		EE2								11.9	6.0	
		EE3								12.5	5.9	
		EE4								13.1	5.7	
		EEDR	216	236	.185			21.5	11.0			
				202C								
14	06	IE	146	232						8.0	5.5	22.0
		EE1								10.5	6.3	
		EE2								11.4	6.8	
		EE3								12.2	6.4	
		EE4								12.7	6.4	
		EEDR	114	132	.185		7.5					
THE HOOD CONTAINING A 5000 BTU CONDITIONER WAS INSTALLED.												
17	06	IE	322	306				14.0	0.1	9.0	5.6	23.0
		EE1								9.8	5.2	
		EE2								10.2	5.5	
		EE3								10.5	5.8	
		EE4								10.7	5.7	
		EEDR	166	202	.185		9.0					

BIODISC OPERATION

DATE DAY	MON	SAMPLE	SOLIDS	FLOW	ALK	PH	30 MIN SET	HACH NH3N	HACH NO2N NO3N	TEMP	DO	ATM TEMP
18	06	IE	240	230						9.0	5.6	21.0
		EE1		264C						10.1	5.9	
		EE2								10.7	5.6	
		EE3								11.1	5.7	
		EE4								11.6	5.9	
		EEDR	136	150	.183		6.0					
				198C								
19	06	IE	128	128						8.7	5.6	23.5
		EE1								9.7	5.8	
		EE2								10.1	5.7	
		EE3								10.3	5.6	
		EE4								10.6	5.4	
		EEDR	156	160	.178		6.0					
20	06	IE	112	120						9.1	3.3	22.5
		EE1		186						9.3	6.2	
		EE2		162						9.7	6.2	
		EE3		108						10.1	6.3	
		EE4		112						10.3	6.4	
		EEDR	104	102	.183		5.5					
21	06	IE	492	478						15.0		24.0
		EEDR	126	128	.190		5.5			14.5		

FEED PROBLEMS WERE EXPERIENCED MOST OF 24/06 AND PART OF 25/06. THE RATE DAY MOVED TO WEDNESDAY AND FRIDAY THIS WEEK.

24	06	EEDR			.181							
25	06	IE								15.2	3.9	
		EE1								14.8	2.9	
		EE2								14.6	4.0	
		EE3								14.3	5.0	
		EE4								14.1	5.4	
		EEDR			.182		16.0					

STARTING 26/06 THE ATM TEMPERATURE REFERS TO THE HOOD TEMPERATURE.

26	06	IE	230	230						17.8	2.9	
		EE1		176C						17.0	4.5	
		EE2								16.6	4.6	
		EE3								16.1	5.0	
		EE4								15.8	5.2	
		EEDR	236	250	.184		12.0					
				276C								
27	06	IE								15.2	6.4	13.5
		EE1								15.1	5.5	
		EE2								15.0	5.7	
		EE3								15.0	5.7	
		EE4								15.0	5.6	
28	06	IE	222	204						14.8	2.5	14.0
		EE1	180C	186						15.2	4.7	
		EE2		186						15.2	4.5	
		EE3		194						15.3	4.2	
		EE4								15.4	4.0	
		EEDR	200	184	.178		7.5					
			334C									

BIODISC OPERATION

DAY	MON	SAMPLE	SOLIDS		FLOW	ALK	PH	30 MIN SET	HACH NO2N NH3N	HACH NO3N	TEMP	DO	ATM TEMP
02	07	IE	210	272			7.2				15.0	3.2	17.5
		EE1	280C								15.1	4.1	
		EE2									15.3	4.3	
		EE3									15.4	4.4	
		EE4									15.5	4.5	
		EEDR	144	118	.184		7.2	7.5			•	•	
			265C								•	•	
03	07	IE				110.					13.6	3.4	18.0
		EE1									14.8	4.5	
		EE2									15.3	4.5	
		EE3									15.6	4.8	
		EE4									15.8	4.8	
		EEDR				55.							
THE FEED WAS OFF FOR FOUR HOURS ON 04/07.													
05	07	IE	344	376							13.6	4.2	14.0
		EE1	268C								13.6	5.6	
		EE2									13.6	6.0	
		EE3									13.6	6.0	
		EE4									13.6	5.8	
		EEDR	302	308	.188			16.0			•	•	
			278C								•	•	
08	07	IE							14.8	0.0	6.1	6.7	10.5
		EE1									8.2	6.9	
		EE2									8.8	6.3	
		EE3									9.2	6.3	
		EE4									9.5	6.5	
		EEDR			.180			5.2	2.3	8.0	•	•	
09	07	IE									4.5	4.5	
		EE1									7.5	5.4	
		EE2									8.2	5.7	
		EE3									8.8	5.6	
		EE4									9.2	5.6	
10	07	IE	240	248							6.0	5.1	12.0
		EE1	192C								9.0	5.1	
		EE2									9.7	5.2	
		EE3									10.4	5.2	
		EE4									10.7	5.0	
		EEDR	236	226	.183			9.5					
			223C										
11	07	IE				119.	7.5				5.0	4.4	12.0
		EE1									6.9	5.9	
		EE2									7.6	5.7	
		EE3									8.3	5.7	
		EE4									8.7	5.7	
		EEDR			.183	94.	7.7	3.0					
12	07	IE	284	268									
		EE1	182C								5.7	3.6	12.0
		EE2									6.7	6.0	
		EE3									7.3	5.4	
		EE4									8.1	5.7	
		EEDR	108	166	.183			3.0			8.6	5.6	
			160C										

BIODISC CPERATION

DATE DAY MON	SAMPLE	SOLIDS	FLOW	ALK	PH	30 MIN SET	HACH NH3N	NO2N NO3N	TEMP	DO	ATM TEMP
ON JULY 12 THE RAW REED TURNEL AN ORNAGE COLOUR LAB ANALYSIS SHCWED HIGH IRON,LEAD AND COPPER.THE METALS PRESENT WERE NOT THOUGHT TO BE IN TOXIC QUANTITIES											
NO RATES WERE MEASURED FOR THE WEEK OF 15/07 TO 19/07											
16 07	IE					55.0					
	EEDR					28.7			16.0		
17 07	IE								13.3	2.5	
	EE1								14.9	3.1	
	EE2								15.3	3.7	
	EE3								15.7	3.6	
	EE4								16.1	4.2	
19 07	IE								13.6	2.2	15.0
	EE1								13.6	3.8	
	EE2								13.6	5.0	
	EE3								13.5	4.7	
	EE4								13.4	4.4	
STARTING 19/07 THE ATM TEMP RECCRCED FOR THE HOOD IS THE AVERAGE OF MEASUREMENTS TAKEN AT THREE LOCATIONS.											
22 07	IE	156	128		94.	7.5		27.	14.3	3.1	13.3
	EE1								14.1	4.2	
	EE2								13.8	4.3	
	EE3								13.4	4.7	
	EE4								13.2	4.4	
	EEDR	227	204	.172	62.2	7.55	8.0	16.5			
THE UNIT TEMPERATURE WAS CHANGED TO 20 DEGREES TUESDAY MORNING HENCE NO RATES WERE TAKEN UNTIL THURSDAY.											
23 07	IE	218	211		114.0	7.65			19.2	1.4	21.3
	EE1								19.1	2.3	
	EE2								19.1	2.7	
	EE3								18.9	3.0	
	EE4								18.8	2.9	
	EEDR	275	275	.187	79.9	7.65	10.0				
24 07	IE	210	204		113.2	7.65			19.3		22.3
	EE1								19.4		
	EE2								19.4		
	EE3								19.4		
	EE4								19.4		
	EEDR	392	365		82.1	7.65					
25 07	IE	233	227			7.65			19.2	2.2	22.7
	EE1	244C	332						19.8	3.0	
	EE2		296						19.8	2.5	
	EE3		280						19.8	2.8	
	EE4								19.8	3.1	
	EEDR	270	270								
		3560		.181			13.5				

BIODISC CPERATICN

DATE DAY	MON	SAMPLE	SOLIDS	FLOW	ALK	PH	30 MIN SET	HACH NO2N NH3N	HACH NO3N	TEMP	CO	ATM TEMP
26	07	IE	170	166		7.65				20.2	2.1	22.7
		EE1								20.4	3.0	
		EE2								20.6	2.7	
		EE3								20.7	3.4	
		EE4								20.7	3.2	
		EEDR	336	231		7.65						
29	07	IE	128	122		7.6				19.7	2.6	23.0
		EE1								20.3	2.9	
		EE2								20.4	3.0	
		EE3								20.4	3.3	
		EE4								20.6	3.4	
		EEDR	198	185	.171	7.7	6.5					
30	07	IE	209	215		7.6				19.9		21.8
		EE1	272C							20.1		
		EE2								20.1		
		EE3								20.1		
		EE4								20.1		
		EEDR	227	220	.184	7.5	10.5					
			234C									
31	07	IE	164			7.5				20.0	2.8	21.3
		EE1								19.6	4.9	
		EE2								19.4	5.2	
		EE3								19.2	5.3	
		EE4								19.0	5.6	
		EEDR	182	194		7.5						
MIXED LIQUOR IN RAW REED MOST OF THE NIGHT												
02	08	IE	201	188		7.65				20.0	4.6	23.3
		EE1								20.0	5.2	
		EE2								20.0	6.3	
		EE3								20.0	5.5	
		EE4								20.0	5.7	
		EEDR	267	305	.188	7.7	11.0					
06	08	IE	561C							20.7	2.4	24.7
		EE1								20.5	4.1	
		EE2								20.4	4.4	
		EE3								20.0	5.5	
		EE4								20.0	5.4	
		EEDR	617C		.186							
07	08	IE	382	442		7.2				20.2	3.9	22.5
		EE1								20.0	4.8	
		EE2								19.9	4.7	
		EE3								19.8	4.4	
		EE4								19.7	5.2	
		EEDR	362	402	.189	7.2	16.5					
08	08	IE	941	900		7.35				20.4	2.1	22.3
		EE1								20.1	3.6	
		EE2								20.0	4.2	

BIODISC OPERATION

DATE DAY	MON	SAMPLE	SOLIDS		FLOW	ALK	PH	30 MIN SET	HACH NH3N	HACH NO2N NO3N	TEMP	DO	ATM TEMP
		EE3									19.8	4.2	
		EE4									19.7	4.3	
		EEDR	213	218	.178		7.45	38.0	7.5				
HEAVY SOLIDS WERE NOTICED IN THE RAW REED ON 08/08													
09	08	IE					7.55				19.7	3.0	21.8
		EE1									20.2	4.1	
		EE2									20.5	3.7	
		EE3									20.5	4.1	
		EE4									20.5	4.5	
		EEDR			.176		7.45	65.					
THE HYDRAULIC LOADING WAS ROUGHLY DOUBLED ON 10/08													
12	08	IE	173				8.05				20.7	2.8	24.3
		EE1									21.2	3.9	
		EE2									21.6	3.8	
		EE3									22.0	4.1	
		EE4									22.3	4.9	
		EEDR	181	143	.327		7.8	5.5	.5				
A LIME GREEN FEED ENTERED THE PLANT ON 12/08 FOR A HALF HOUR													
13	08	IE	176C				7.1				20.9	3.1	24.5
		EE1									21.1	4.2	
		EE2									21.3	4.2	
		EE3									21.6	3.2	
		EE4									21.8	4.4	
		EEDR	192C		.349		7.55						
14	08	IE					6.8				20.9	3.9	21.5
		EE1									20.4	4.0	
		EE2									20.2	4.6	
		EE3									19.9	4.7	
		EE4									19.5	4.4	
		EEDR			.353		7.15	11.0					
15	08	IE	125	133			6.85				20.0	3.7	20.8
		EE1	184C								20.9	4.6	
		EE2									20.0	4.8	
		EE3									19.9	5.2	
		EE4											
		EEDR	143	142	.349		7.3	4.5					
			216C										
16	08	IE									68.3	4.5	15.2
		EE1									9.2	6.5	
		EE2									10.3	6.8	
		EE3									10.5	7.4	
		EE4									11.0	6.8	
		EEDR			.356			12.5					
20	08	IE	201	196		120.4	7.55				7.8	4.6	15.0
		EE1	192C								8.8	6.7	
		EE2									9.3	7.2	
		EE3									9.8	7.0	

BIODISC OPERATION

DATE	SAMPLE	SOLIDS		FLOW	ALK	PH	30 MIN SET	HACH NO2N NH3N	HACH NO3N	TEMP	DO	ATM TEMP
Y MON												
	EE4									10.3	7.0	
	EEDR	166	156	.362	101.	7.65	6.0					
		224C										
21 08	IE	152	182		186.6	7.45				8.4	6.1	15.8
	EE1									9.1	7.2	
	EE2									9.3	7.4	
	EE3									9.8	7.3	
	EE4									10.1	7.1	
	EEDR			.317	92.8	7.55	6.5					
22 08	IE	171	158									
	EE1	264C	344			8.1				10.6	4.4	15.3
	EE2		266							11.2	5.8	
	EE3		270							11.6	6.3	
	EE4									11.8	6.1	
	EEDR	214	230	.383		7.5	13.0			12.0	6.1	
		271C										

THE HACH TEST INDICATED A RISE CF 2 PPM IN NO3+NO2 BETWEEN INF AND EFF ON 24/08

MIXED LIQUOR ENTERED THE SYSTEM ON 26/08

27 08	IE	270	266							5.4	3.8	11.3
	EE1	444C								6.1	6.1	
	EE2									6.5	6.5	
	EE3									7.1	6.8	
	EE4									7.7	6.5	
	EEDR	340	320	.328	81.6C	7.5C	13.5					
		369C										

SOME PROBLEMS IN MAINTAINING A CONSTANT LOW FEED TEMPERATURE

28 08	IE									4.4	3.9	12.7
	EE1									5.2	7.0	
	EE2									6.0	7.0	
	EE3									6.5	7.1	
	EE4									7.1	7.4	
	EEDR			.321			31.0			•	•	
					94.4C	6.8C				•	•	
29 08	IE	720C	308		114.	7.3			2.3	4.3	3.7	9.8
	EE1		404							5.5	7.2	
	EE2		380							6.3	8.0	
	EE3		416							6.6	8.1	
	EE4									7.0	8.0	
	EEDR	392C	432	.333	111.	7.7	23.0		1.0	•	•	
					106.6C	7.5C				•	•	
30 08	IE									5.5	3.7	10.3
	EE1									6.4	7.4	
	EE2									6.7	8.3	
	EE3									7.1	8.5	
	EE4									7.4	8.5	
	EEDR			.347			16.0					
04 09	IE	190	188			7.0				27.1	1.6	24.5
	EE1									25.8	2.4	

BIODISC OPERATION

DATE DAY	MON	SAMPLE	SOLIDS	FLOW	ALK	PH	30 MIN SET	HACH NO2N NH3N	HACH NO3N	TEMP	DO	ATM TEMP
		EE2								25.6	2.6	
		EE3								25.5	2.9	
		EE4								25.5	2.9	
		EEDR		.307		7.1	8.5					
05	09	IE			140.8	8.2						
		EEDR			111.2	7.85						
06	09	IE	400C	276	146.9	7.3				24.9	0.6	24.7
		EE1			129.5C	7.4C				25.0	1.8	
		EE2								25.0	2.5	
		EE3								24.9	3.4	
		EE4								25.0	3.2	
		EEDR	388C	260	.314	123.4	7.3	8.0				
						115.8C	7.3C					
THE FLOW WAS REDUCED BECAUSE IT WAS FEARED THAT NO NITRIFICATION WAS TAKING PLACE AT 5 DEGREES												
10	09	IE	472C			134.6	7.4			26.1	2.6	24.8
		EE1				111.2C	7.4C			25.5	3.1	
		EE2								25.3	3.0	
		EE3								25.3	2.8	
		EE4								25.2	3.3	
		EEDR	314C		.204	77.4	7.3	9.0				
						75.5C	7.3C					
12	09	IE	384C			111.2C	7.2C			25.7	1.2	25.0
		EE1								25.1	2.3	
		EE2								25.0	2.8	
		EE3								25.0	3.1	
		EE4								25.1	3.3	
		EEDR	374C		.175	41.8C	7.2C					
16	09	IE				125.5C	7.8C			20.5		12.8
		EEDR	428C		.185	81.6C	7.5C			14.0		
17	09	IE					7.5C			20.0		13.6
		EE1				115.3C				17.5		
		EE2								16.5		
		EE3								15.6		
		EE4								15.0		
		EEDR	368C		.185	79.1C	7.5C					
18	09	IE				114.2C	7.4C			20.3		9.6
		EE1								16.8		
		EE2								15.7		
		EE3								14.4		
		EE4								13.8		
		EEDR	312C		.170	80.1C	7.5C					
19	09	IE				112.7C	7.4C			20.0		
		EE1								16.7		
		EE2								15.6		
		EE3								14.5		
		EE4								13.9		
		EEDR			.187	90.3C	7.4C					

BIODISC OPERATION

DATE DAY	MON	SAMPLE	SOLIDS	FLOW	ALK	PH	30 MIN SET	HACH NO2N NH3N	HACH NO3N	TEMP	DO	ATM TEMP
20	09	IE								24.0		12.0
		EE1								20.2		
		EE2								19.0		
		EE3								17.5		
		EE4								16.4		
		EEDR		.201								
23	09	IE			122.4C	7.6C				19.1		
		EEDR		.155	95.9C	7.6C						
24	09	IE			98.4C	7.4C				19.9		
		EEDR		.205	80.1C	7.5C				13.5		
25	09	IE			132.1C	7.7C						
		EEDR			97.9C	7.6C						
26	09	IE			113.2C	7.4C						
		EEDR			89.8C	7.5C						
03	10	IE		.166						6.0		
		EEDR								6.5		
08	10	IE			108.2C					7.5		
		EEDR		.155	95.0C					8.0		
10	10	IE			107.0C					8.0		
		EEDR		.155	85.8C					8.0		
18	10	IE								21.0		
		EEDR		.166						22.0		

MIXED LIQUOR ENTERED THE PLANT FOR A LONG PERIOD DURING NIGHT OF OCT 19.

25	10	IE			193.0C					25.0		
		EEDR		.187	143.0C					26.0		
06	11	IE			168.0C					25.0		
		EEDR		.180	115.0C					23.0		

DAY	MON	SAMPLE DESIGNATION	UNFILTERED COD	UNFILTERED BOD	UNFILTERED TKN	FILTERED COD	FILTERED BOD	FILTERED TOC	FILTERED NH3N	FILTERED NO2N	FILTERED NO3N	FILTERED TKN
ANALYTICAL DATA FOR THE BIODISC												
TEMPERATURE CONTROL IN THE BIODISC WAS UNSATISFACTORY PRIOR TO JUNE 15												
30	05	IE GAM	183	52	19.7	37	18		18.9	0.6	6.7	18.9
30	05	EE1 GAM							12.0	1.8	18.2	12.0
30	05	EE2 GAM							9.0	2.1	22.9	9.0
30	05	EE3 GAM							5.7	2.6	28.4	5.7
30	05	EE4 GAM							3.7	2.6	29.4	3.7
30	05	EEDR GAM	125	34	7.5	27	6					
04	06	RF-C	310	117	27.5	83	32	34	19.1	0.3	3.1	19.1
04	06	EEDR-C			15.3	39	4		6.9	2.2	22.8	6.9
06	06	IE GAM						29	25.2	0.4	2.7	25.4
06	06	EE1 GAM						20	22.0	1.9	16.1	22.2
06	06	EE2 GAM						19	20.2	2.6	26.4	21.0
06	06	EE3 GAM						15	16.3	4.2	35.8	16.3
06	06	EE4 GAM						12	14.1	5.1	46.9	14.6
06	06	EEDR GAM						15	13.6	5.2	48.8	13.6
06	06	RF-C	415	116	27.6	74	30	29	18.5	0.3	2.2	18.5
06	06	EEDR-C			16.4	42	6	12	11.4	2.6	24.4	11.4
13	06	IE GPM						23	30.8	0.3	0.6	31.0
13	06	EE1 GPM						18	27.3	1.5	3.6	27.4
13	06	EE2 GPM						13	24.9	2.1	8.7	25.4
13	06	EE3 GPM						13	20.6	2.9	9.1	20.6
13	06	EE4 GPM						12	18.2	3.3	10.2	18.2
13	06	EEDR GPM						12	18.7	3.4	11.6	19.3
13	06	RF-C	342	116	27.6	74	30	29	18.5	0.3	2.2	18.5
13	06	EEDR-C			31.6	39	5	11	16.6	2.1	7.1	16.6
THE HOOD PLUS AIR CONDITIONER WERE INSTALLED FOR THE PURPOSE OF TEMPERATURE CONTROL												
18	06	RF-C	283	79	26.8	56	21	21	19.4	0.1	0.5	19.4
18	06	EEDR-C			15.3	31	4	13	10.4	1.0	8.0	10.4
NO COMPOSITE FOR THE BIODISC ON JUNE 20 DUE TO MALFUNCTION OF SAMPLER.												
20	06	IE GAM						13	13.0	0.4	2.1	13.0
20	06	EE1 GAM						12	10.6	0.8	3.9	10.6
20	06	EE2 GAM						11	10.1	1.0	4.8	10.1
20	06	EE3 GAM						11	8.1	1.2	6.6	8.1
20	06	EE4 GAM						13	7.2	1.5	9.0	7.2
20	06	EEDR GAM						13	7.0	1.0	8.5	7.0
RATE DAY FOR B WILL NOT BE USED FOR JUNE 20 DUE TO FEED PROBLEMS.												
26	06	RF-C	312	92	30.0	54	16	20	26.6	0.1	0.5	26.6
26	06	EEDR-C			12.6	25	3	13	12.5	4.0	10.5	12.5

ANALYSIS

SAMPLE DESIGNATION		UNFILTERED			FILTERED					
DAY MON		COD	BOD	TKN	COD	BOD	TOC	NH3N	NO2N	NO3N	TKN
BIODISC GRAB SAMPLES TAKEN AT 10 TO 15 MINUTE INTERVALS STARTING AT THE FEED END JUNE 28											
28 06IE	GAM				62		30	33.0	0.8	1.5	33.0
28 06EE1	GAM				50		22	22.7	3.7	3.9	22.7
28 06EE2	GAM				45		19	20.1	6.0	6.5	20.1
28 06EE3	GAM				45		13	15.9	7.5	8.0	15.9
28 06EEDR	GAM				45		16	13.3	9.0	19.5	13.3
28 06RF-C		398	134	43.3	104	76	35	33.2	0.0	3.0	33.2
28 06EEDR-C				19.6	47	7	18	17.4	5.0	7.5	17.4
02 07RF-C		349	151	40.8	100	34	30	28.9	0.2	1.0	28.9
02 07EEDR-C				17.4	33	5	15	13.1	2.5	10.5	13.1
05 07IE	GPM						23	31.4	0.2	0.3	32.5
05 07EE1	GPM						20	30.1	0.9	4.4	30.1
05 07EE2	GPM						15	31.5	1.5	6.5	31.5
05 07EE3	GPM						16	24.0	1.5	8.0	24.0
05 07EEDR	GPM						12	19.0	1.5	9.5	19.0
05 07RF-C		432	170	43.1	71	29	32	31.4	0.1	0.3	31.4
05 07EEDR-C				32.5	46	7	30	23.5	1.0	8.0	23.5
10 07RF-C		352	176	27.4	93	38	40	20.2	0.4	1.3	20.2
10 07EEDR-C				15.6	46	8	38	8.7	0.8	5.7	9.9
TWO SAMPLES,21 AND 22 WERE MISSING FROM THE 12/07 COMPOSITE A YELLOW-ORANGE FEED WHICH WAS FAIRLY HIGH IN COPPER,IRON AND LEAD WAS NOTICED FOR ABOUT ONE HOUR DURING THE 12/07 RATE DAY.NO INHIBITION IS EXPECTED AS A RESULT OF THE METALS PRESENT.											
12 07FR-C		335	25	27.6	97	36	44	20.6	0.1	0.2	20.6
12 07EEDR-C				18.9	55	9	35	12.6	0.6	3.5	12.7
12 07IE	GPM				143		60	26.8	0.2	0.8	26.8
12 07EE1	GPM				76		33	19.1	0.3	1.7	19.2
12 07EE2	GAM				67		28	17.4	0.4	2.1	17.5
12 07EE3	GAM				55		22	12.3	0.6	3.3	12.5
12 07EEDR	GAM				50		19	11.3	0.7	4.2	11.3
NO RATES WERE TAKEN FOR THE WEEK OF 13/07 TO 19/07 AS SCHEDULED.											
NO RAW REED COMPOSITE WAS TAKEN FOR 25/07 NOTICEABKE SLOUGHING FROM THE DISC SURFACE WAS SEEN DURING THIS PERIOD THIS WAS PROBABLY DUE TO THE COMBINED EFFECT OF CHANGING TO 25 DEGREES AND OF DRAINING THE DISC FOR CALIBRATION PURPOSES TWICE IN ONE WEEK.											
25 07IE	GAM			27.9	84		27	21.9	0.4	1.0	21.9
25 07EE1	GAM				63		17	13.1	0.7	1.9	14.0
25 07EE2	GAM				54		14	9.1	9.0	2.6	11.2
25 07EE3	GAM				50		13	6.0	1.4	4.6	7.5
25 07EEDR	GAM			18.4	54		12	3.5	1.6	6.0	4.7
30 07RF-C		205	102	51.3	92	37	33	40.5	0.0	2.5	47.7
30 07EEDR-C				31.2	43	5	13	24.9	0.6	1.8	25.4

ANALYSIS

SAMPLE DESIGNATION		UNFILTERED			FILTERED					
DAY MON		COD	BOD	TKN	COD	BOD	TOC	NH3N	NO2N	NO3N	TKN
RATE DAY ON AUG 1 IS POSTED DUE TO HEAVY INFLUX OF MIXED LIQUOR ONLY THE FIRST 14 HRS OF COMPOSITE FEED AND EFFLUENT WERE USED ON 06/0											
06 08RF-C		786	136	60.9	170	34	76	34.0	0.1	0.6	39.0
06 08EEDR-C		572		35.9	26	4	28	4.8	1.5	12.3	6.0
08 08IE	GAM			64.3	36		63	37.0	1.1	2.1	37.4
08 08EE1	GAM				32		37	29.6	1.2	4.5	29.6
08 08EE2	GAM				36		32	25.5	1.5	6.8	25.5
08 08EE3	GAM				36		29	22.0	1.8	8.8	22.5
08 08EEDR	GAM			48.0	36		31	18.5	1.9	11.0	19.4
NO SAMPLE FROM B SYSTEM IS AVAILABLE FOR COMPARISON WITH THE BIODISC. COMPOSITE DUE TO SAMPLER MALFUNCTION											
08 08RF-C		751	167	65.9	36	47	41	41.1	0.2	0.7	41.1
08 08EEDR-C				49.6	36	6	42	21.4	1.3	9.5	21.4
13 08RF-C		208	49	39.2	32	15	23	34.0	0.5	1.0	34.3
13 08EEDR-C				23.7	28	4	26	17.5	3.8	7.3	18.3
15 08IE				49.9	41		48	38.5	0.9	0.9	47.2
15 08EE1					29		33	36.5	1.6	1.7	40.7
15 08EE2					25		33	30.5	2.2	3.1	38.2
15 08EE3					29		25	30.0	3.0	5.2	34.1
15 08EEDR				35.0	25		24	28.5	3.2	6.6	31.9
15 08RD-C		262	72	46.2	41	24	24	38.5	0.2	0.7	39.8
15 08EEDR-C				33.8	37	5	23	22.0	3.0	5.3	26.3
20 08RF-C		332	108	33.6	78	36	30	22.0	0.1	0.2	24.3
20 08EEDR-C				28.2	45	14	17	17.0	1.2	3.6	18.2
22 08IE	GAM			33.1	54		20	26.0	0.6	0.0	33.7
22 08EE1	GAM				45		17	22.5	0.6	0.0	29.5
22 08EE2	GAM				45		15	25.5	0.7	0.5	27.4
22 08EE3	GAM				45		15	23.5	1.1	0.8	26.0
22 08EEDR	GAM			32.3	41		13	22.0	1.4	1.4	22.1
22 08RF-C		340	185	49.3	45	32	29	36.0	0.1	1.8	37.6
22 08EEDR-C				48.1	58	15	37	28.5	0.7	0.7	34.2
27 08RF-C		295	134	31.2	67	37	31	19.5	0.1	0.9	22.7
27 08EEDR-C				32.1	42	12	59	17.5	0.3	1.0	18.9
29 08IE	GAM			35.6	45	18	51	23.0	0.5	0.6	26.1
29 08EE1	GAM				37	11	48	20.5	0.5	0.6	22.9
29 08EE2	GAM				37	11	32	20.0	0.6	0.7	21.1
29 08EE3	GAM				37	9	35	16.5	0.7	1.0	19.8
29 08EEDR	GAM			34.1	29	7	39	18.0	0.7	1.3	19.2
29 08RF-C		467	184	42.0	53	27	27	21.5	0.1	0.3	25.4
29 08EEDR-C				39.4	45	13	23	21.5	0.2	1.1	23.3
TEMPERATURE CHANGED FROM 8 DEGREES TO 25 DEGREES. THEREFORE NO COMPOSIT											

SAMPLE DESIGNATION		UNFILTERED			FILTERED					
DAY	MON	COD	BOD	TKN	COD	BOD	TOC	NH3N	NO2N	NO3N	TKN
SAMPLES WERE TAKEN TUESDAY TO ALLOW SUFFICIENT ACCLIMATIZATION.											
06	09IE GPM			70.4	41		60	59.0	0.1	0.3	59.0
06	09EE1 GPM				54		27	52.6	0.2	0.6	52.6
06	09EE2 GPM				65		22	47.0	0.6	1.4	49.2
06	09EE3 GPM				30		16	46.5	1.8	2.7	46.9
06	09EEDR GPM			51.3	33		17	40.5	2.7	4.3	42.5
06	09RF-C	549	40	62.3	100	16	33	47.5	0.1	0.8	47.5
06	09EEDR-C			52.7	58	6	19	37.5	1.3	2.4	39.2
10	09RF-C	407	237	65.5	100	85	44	48.7	0.0	0.1	48.7
10	09EEDR-C			40.8	33	3	26	25.5	2.4	7.1	25.5
12	09IE GAM			71.9	53			57.5	0.5	1.1	62.5
12	09EE1 GAM				29			32.0	0.6	5.5	35.6
12	09EE2 GAM				29			25.0	1.0	8.4	26.7
12	09EE3 GAM				41			17.5	1.3	10.9	20.0
12	09EEDR GAM			32.7	45			14.0	1.1	16.0	15.6
12	09RF-C	383	100	59.6	72	24	38	49.0	0.0	0.4	56.2
12	09EEDR-C			36.3		3	18	21.0	1.0	11.0	25.6
16	09RF-C							36.0	0.4	1.7	39.1
16	09EEDR-C							16.0	0.3	7.8	16.1
17	09RF-C							45.0	0.0	0.3	45.2
17	09EEDR-C							30.0	0.6	6.9	29.2
18	09RF-C							29.0	0.0	0.9	34.4
18	09EEDR-C							17.6	0.5	6.3	17.6
19	09RF-C							48.5	0.0	0.5	49.4
19	09EEDR-C							33.5	0.5	3.6	35.6
24	09RF-C							37.0	0.0	0.9	38.2
24	09EEDR-C							25.0	0.5	3.6	25.8
25	09RF-C							47.5	0.0	0.0	47.5
25	09EEDR-C							29.5	0.8	4.7	31.1
26	09RF-C							41.0	0.0	0.4	41.0
26	09EEDR-C							24.0	0.8	29.7	24.0
03	10IE GAM			45.1	59			30.0	0.1	1.8	31.6
03	10EE1 GAM				42			18.5	0.4	2.5	22.0
03	10EE2 GAM				46			22.0	0.7	3.2	22.0
03	10EE3 GAM				43			14.5	0.9	4.3	16.0
03	10EEDR GAM			30.6	38			11.9	1.0	4.9	14.2
08	10RF-C	274		38.3	49	15	39	25.0	0.0	0.0	27.5
08	10EEDR-C	395		42.3	38	8	22	17.5	0.3	1.9	20.8
10	10RF-C	234		37.0	50	154	38	24.0	0.0	0.1	27.5
10	10EEDR-C	420		37.0	38	7	19	16.0	0.2	1.5	18.9

SAMPLE DESIGNATION		ANALYSIS								
		UNFILTERED			FILTERED					
DAY	MON	COD	BOD	TKN	COD	BOD	TOC	NH3N	NC2N	NO3N	TKN
25	10RF-C	365	151	61.0	74	45	51	38.0	0.0	0.5	49.5
25	10EEDR-C			39.8	49	3	22	18.0	7.0	1.0	23.7
06	11RF-C	392	97	72.9	92	31	34	56.0	0.0	0.7	59.4
06	11EEDR-C	279		41.2		4	15	30.5	2.9	10.3	33.8

COLUMN OPERATION

DAY	MON	SAMPLE DESIGNATION	SOLIDS	FLOW	EACH NH3N	EACH NO2N	EACH NO3N	EFF TEMP	COOLER TEMP	PH	COOLER DO
		COLUMN F1 AND F2 WERE SEEDED WITH DENTRIFYING SLUDGE FROM C1 AND THIS WAS LEFT AS A BATCH SYSTEM FOR 24 HRS.THEN A FEED RATE OF .25 IMP GAL/MIN WAS STARTED 08/06.									
10	06	EF1						18.5	15.2		
10	06	EF2						18.5	15.2		
11	06	EF1	6	.278				17.0	13.8		
11	06	EF2	16	.32				17.0	13.8		
12	06	EF1	8	0	.50			16.0	14.5		
12	06	EF2	18	10	.53			16.0	14.5		
13	06	EF1	16	14				15.5	14.5		
13	06	EF2	18	24				15.5	14.5		
14	06	EF1	8	6	.49			15.5	14.4		
14	06	IF2				4.5					
14	06	EF2	10	8	.53	5.5		15.5	14.4		
17	06	EF1			.49			15.0	13.9		
17	06	EF2			.53			15.5	13.9		
		A SPIKE OF 20 PPM NO3-N PLUS EXTRA METHANOL WAS IN EFFECT FROM 18/06 TO 20/0									
18	06	IC1BE	12	18		35.5					
18	06	EF1	12	14	.50	8.6		15.5	16.0		
18	06	EF2	18	16	.52	15.8		16.0	16.0		
19	06	IC1BE	24	26		37.0					
20	06	EF1	30	32	.50	11.8		16.0	14.5		
20	06	EF2	4	18	.52	17.0		16.0	14.5		
21	06	IC1BE	160	166							
21	06	EF1	10	14							
21	06	EF2	12	12							
25	06	EF1						6.0	2.5		
25	06	EF2						6.0	2.5		
26	06	EF1						6.0	4.0	4.0	
26	06	EF2						6.0	4.0	4.0	
27	06	IC1BE				4.8					
27	06	EF1				1.4		6.0	2.8	5.0	
27	06	EF2			.53	2.3		6.0	2.8	5.0	
28	06	EF1	14	10	.49			10.0	5.0	3.0	
28	06	EF2	14	16	.52						
		THE COOLER WAS ACCIDENTLY SHUT DOWN FOR AN HOUR HENCE,THE RATE DAY WAS MOVED TO 29/06.									
29	06	IC1BE	84	82							

COLUMN OPERATION

DAY	MON	SAMPLE DESIGNATION	SOLIDS		FLOW	HACH NH3N	HACH NO2N	HACH NO3N	EFF TEMP	COOLER TEMP	PH	COOLER CC
29	06	EF1	80	84					6.0	3.5		
29	06	EF2	30	28					6.0	3.5		
02	07	EF1							6.0	2.5		
02	07	EF2							7.0	2.5		
THE COLUMNS WERE INSULATED WITH 3/8 INCHE STYROFOAM ON 03/07												
05	07	EF1-1							5.0			
05	07	EF1	35		.50				6.0	4.0		
05	07	EF2-1							5.0			
05	07	EF2	184		.52				6.0	4.0		
SAMPLING ON 05/07 SHOWS THERE IS MINIMAL TEMPERATURE RISE THROUGH THE COLUMNS EVEN AT LOW TEMPERATURES.												
08	07	IC1BE				3.4	6.3					3.8
08	07	EF1			.51	4.5	1.1		4.5	3.0		
08	07	EF2			.51	5.0	3.8		4.5	3.0		
10	07	EF1	38	34	.51				4.0	1.0		4.1
10	07	EF2	36	40	.51				4.0	1.0		
11	07	EF1							5.0	2.1		2.7
11	07	EF2							5.0	2.1		
12	07	IC1BE					5.1					
12	07	EF1					1.8		4.0	1.9		
12	07	EF2					2.6		4.0	1.9		
15	07	IC1BE				2.0	16.0					2.0
15	07	EF1			.51	3.7	1.5		14.0	13.0		
15	07	EF2			.51	2.5	3.7		14.0	13.0		
16	07	IC1BE									7.1	
16	07	EF1							14.4	14.2	7.2	
16	07	EF2							14.4	14.2	7.2	
17	07	IC1BE					15.5					2.3
17	07	EF1			.51		2.7		14.5	11.4		
17	07	EF2			.51		5.1		14.5	11.4		
18	07	EF1	78	78	.51					10.5		2.4
18	07	EF2	96	96	.51							
19	07	EF1							13.8	10.2		2.2
19	07	EF2							14.2	10.2		
22	07	IC1BE	27	31		4.3					6.8	2.0
22	07	EF1	34	36							7.4	
22	07	EF2	46	49							7.4	
23	07	IC1BE	36.5	37								
23	07	EF1	25	23	.472				19.8	18.4		
23	07	EF2	167	132								

COLUMN OPERATION

DATE DAY	MON	SAMPLE DESIGNATION	SOLIDS		FLOW	NH3N	NO3N	NO2N	EFF TEMP	COOLER TEMP	PH	COOLER DO	
A NO3-N SPIKE OF 15 PPM WAS ADDED TO COOLER 2 DURING 23/07 AND 24/07													
24	07	IC1BE	29.7	32							7.2	2.3	
24	07	EF1	24.2	25	.49				21.3	20.6	7.7		
24	07	EF2	27.3	20	.50				21.2	20.5	7.6		
25	07	IC1BE	39	39									
25	07	EF1		61	.49				21.5	20.8			
25	07	EF2	38	34	.50				21.5	20.8			
26	07	IC1BE	37.3								7.3	3.6	
26	07	EF1	42.5	42					22.0	21.4	7.7		
26	07	EF2	19.5	20					22.0	21.4	7.7		
29	07	IC1BE	30	30							7.4	3.8	
29	07	EF1	14.7	15	.50				21.7	21.1	7.9		
29	07	EF2	22.5	18	.51								
30	07	IC1BE	27	27							6.2		
30	07	EF1	263	306					22.0	21.0	7.8		
30	07	EF2	52	50					22.0	21.0	7.6		
31	07	IC1BE	30	31							6.3		
31	07	EF1	55	54	.471				21.9	21.2	7.9		
31	07	EF2	26	27	.51				21.9	21.2	7.7		
RAW FEED CONTAINED MIXED LIQUOR DURING THE EVENING. FOR A SUFFICIENT TIME TO CAUSE SOLIDS TO GET INTO COOLER 2 AND THE DENITRIFYING SYSTEMS													
02	08	IC1BE	37	32							7.2	5.5	
02	08	EF1	22	19	.49				21.5	21.5	7.5		
02	08	EF2	37		.51				21.5	21.5	7.5		
NITROGEN BALANCES WERE ATTEMPTED FOR BOTH COLUMNS DURING THE PERIOD 05/08 TO 16/08.													
06	08	IC1BE	40	34								3.6	
06	08	EF1	93	146	.49				21.5	21.1			
06	08	EF2	36	42	.49				21.5	21.0			
07	08	IC1BE	126	117	.							3.4	
07	08	EF1	82	84	.485				21.5	21.0			
07	08	EF2	114	114	.49				21.5	21.0			
08	08	EF1	127	123	.49				21.0	19.7		2.8	
08	08	EF2	93	85	.51				21.	19.7			
09	08	IC1BE					27.0						
09	08	EF1			.50				21.5	19.5			
09	08	EF2					5.0		21.5	19.5			
10	08	EF1			.49				21.5	19.5			
12	08	IC1BE	28				9.4				7.3	5.6	
12	08	EF1			.49				21.5	20.8	7.2		
12	08	EF2	33		.52		2.6		21.5	20.8	7.3		

COLUMN OPERATION

DATE DAY	MON	SAMPLE DESIGNATION	SOLIDS	FLOW	HACH NH3N	HACH NO2N NO3N	EFF TEMP	COOLER TEMP	PH	COOLER DO
13	08	IC1BE	26	29						4.0
13	08	EF1	54	66	.480		21.5	20.4		
13	08	EF2	47	45	.508					
14	08	IC1BE							6.8	3.6
14	08	EF1			.481		21.5	21.1	7.2	
14	08	EF2			.495		21.5	21.1	7.2	
15	08	IC1BE	33.5	28					6.7	4.2
15	08	EF1	41		.505		21.5	20.4	7.4	
15	08	EF2	65		.486		21.5	20.4	7.4	
16	08	IC1BE							6.8	3.7
16	08	EF1			.486		20.5	20.0	6.9	
16	08	EF2			.488		20.5	20.0	6.9	
19	08	EF1					15.8	13.3		4.4
19	08	EF2					15.5	13.3		
20	08	IC1BE	37	35					6.9	5.1
20	08	EF1	53	46	.486		15.7	12.7	7.8	
20	08	EF2	88	62	.501		15.6	12.7	7.2	

TRACER STUDIES WERE CONDUCTED ON BOTH COLUMNS ON 20/08. AFTER THE STUDIES WERE FINISHED BOTH COLUMNS UNDERWENT 15 MINUTE BACKWASHES. THE BACKWASH RATES WERE MOSTLY BELOW 3 GAL/MIN FT2.

DATE DAY	MON	SAMPLE DESIGNATION	SOLIDS	FLOW	HACH NH3N	HACH NO2N NO3N	EFF TEMP	COOLER TEMP	PH	COOLER DO
21	08	IC1BE	17	19	8.5				6.9	2.9
21	08	EF1	18.5	19	3.0		15.9	13.2	7.1	
21	08	EF2	20	20	.517	3.6	15.9	13.2	7.1	
22	08	IC1BE	24	24	17.8				6.7	3.7
22	08	EF1	12.5	12	4.6		16.4	14.9	6.5	
22	08	EF2	12.5	14			16.4	14.9	7.0	

ANOTHER PAIR OF TRACER STUDIES WERE CONDUCTED ON 23/08 TO SEE THE EFFECT OF BACKWASHING.

DATE DAY	MON	SAMPLE DESIGNATION	EFF TEMP
24	08	EF1	9.6
24	08	EF2	9.0

A LONGER MORE VIGOROUS BACKWASH WAS CONDUCTED WITH COLUMN F1 ON 24/08. IT LASTED ROUGHLY 75 MINUTES BUT THIS STILL HAD VER LITTLE EFFECT ON SHORT CIRCUITING AS SEEN FROM A DYE STUDY DONE RIGHT AFTER FINISHING THE BACKWASH

BACKWASH WAS LEFT ON COLUMN F1 OVERNIGHT COVERING ALMOST 17 HOURS WITH RATES OF ROUGHLY 13 GAL/MIN FT2. ANOTHER DYE STUDY WAS THEN RUN ON 25/08.

MIXED LIQUOR GOT INTO THE SYSTEM AS FAR AS COOLER 2 AND THE DENITRIFICATION UNITS LAST NIGHT. F1 AND F2 WERE SHUT DOWN FOR A WHILE AS THE COOLER WAS DRAINED AND CLEANED OUT.

COLUMN OPERATION

DATE DAY	MON	SAMPLE DESIGNATION	SOLIDS	FLOW	HACH NH3N	HACH NO2N NO3N	EFF TEMP	COOLER TEMP	PH COOLER	DO
		COLUMN F2 WAS BACKWASHED AT A MEDIUM FLOW FOR A COUPLE OF HOURS ON 27/08 TO HELP CLEAR OUT SOME OF THE MIXED LIQUOR SOLIDS THAT MIGHT HAVE BECOME TRAPPED.								
27	08	IC1BE	36	40						3.4
27	08	EF1	24	27	.482		9.0	6.5		
27	08	EF2	18.5	18	.512		9.0	6.5		
28	08	EF1					10.0	6.3		3.6
28	08	EF2					10.0	6.3		
29	08	IC1BE		29						3.5
29	08	EF1		69	.485		10.0	8.0		
29	08	EF2		62	.512		10.0	8.0		
		LOW NITRATE LEVELS ARE EXPECTED IN THE COLUMN FEED FOR 29/08 BECAUSE THE AMMONIA SPIKE BROKE DOWN DURING THE NIGHT. THIS WILL PROBABLY KEEP NITRIFICATION AT A LOW LEVEL IN A AND B.								
04	09	EF1					24.5			
04	09	EF2					24.5			
		A NITRATE SPIKE OF ROUGHLY 15 PPM WAS ADDED TO COOLER 2 FOR 04/06								
06	09	IC1BE	43.5						6.4	1.3
06	09	EF1	27		.485		25.0	24.7	7.1	
06	09	EF2	159		.495		25.0	24.7	7.1	
		ANOTHER NITRATE SPIKE WAS PREPARED FOR ADDITION OF 15 PPM NO3N FOR THE RATE DAY OF 06/09								
12	09	IC1BE							6.8	1.3
12	09	EF1			.489		26.0	25.5	7.1	
12	09	EF2			.515		26.0	25.5	7.1	
		COLUMN F1 WAS DUMPED AND CLEANED ON SATURDAY 07/09. REASSEMBLY WAS ALSO COMPLETED ON 07/09. DYE STUDIES WERE RUN BEFORE AND AFTER F1 WAS SEEDED WITH KNO3, METHANOL, WATER AND RETURN SLUDGE FROM B1 A TRACER STUDY WAS AGAIN RUN ON SATURDAY SEPT 14. THIS WAS SIX DAYS AFTER THE COLUMN HAD BEEN RE-STARTED AT THE NORMAL HYDRAULIC LOADING OF .5 GAL/MIN								
18	09	IC1BE	42.5							
		A NITRATE SPIKE OF 15 PPM NO3N WAS RUN FOR THE 19/09 RATE DAY								
19	09	IC1BE	54							
19	09	EF1	62		.485		20.5			
19	09	EF2	53		.508		20.5			
		SOLIDS COMING OUT OF F1 ARE A MUCH LIGHTER BROWN COLOUR THAN IN F2. SOLIDS RESEMBLE MIXED LIQUOR FROM C1.								
29	09	IC1BE	48.5							
27	09	EF1			.49		11.0	9.5		

COLUMN OPERATION

DATE DAY	MON	SAMPLE DESIGNATION	SOLIDS	FLOW	HACH NH3N	HACH NO2N	HACH NO3N	EFF TEMP	COOLER TEMP	PH COOLER CC
27	C9	EF2		.504				11.0	9.5	

DURING THE ENTIRE PERIOD OF COLUMN OPERATION THERE WAS NO SIGNIFICANT RISE IN PRESSURE IN EITHER UNIT DUE TO MEDIA CLOGGING

ON SEPT 29,DUE TO A REDUCTION IN FLOW THROUGH UNIT A,TAP WATER WAS ADDED DIRECTLY TO COOLER TO ALLOW BOTH COLUMNS AND THE STIRRED TANK SYSTEM TO CONTINUE OPERATION.THIS WASTED TWO WEEKS,THE DURATION OF THE 5 DEGREE NITRIFICATION RUNS.AT THE SAME TIME A NITRATE SPIKE WAS SET TO RUN ALL WEEKEND DELIVERING ROUGHLY 8 PPM NO3N TO THE 1.2 GAL/MIN OF TAP WATER

28	10	EF1		.51				25.		
28	10	EF2		.50				25.		
07	11	EF1		.49				25.		
07	11	EF2		.51				25.		

ANALYSIS

DATE DAY	MO	SAMPLE DESIGNATION	UNFILTERED COD	BOD	TKN	FILTERED COD	BOD	TOC	NH3N	NO2N	NO3N	TKN	METH
ANALYTICAL DATA FOR DENITRIFICATION COLUMNS													
COLUMN F1 CONTAINS 1 INCHE NORTON POLYPROPYLENE PALL RINGS													
COLUMN F2 CONTAINS 2 INCHE PALL RINGS													
THE COLUMNS BEGAN ACCLIMATIZATION JUNE 7 AND CONTINUOUS OPERATION JUNE 8.HYDRAULIC LOADING WAS INCREASED TO .5 IMP GAL/MIN JUNE 11.													
THE REGULAR SAMPLING BEGAN JUNE 13													
13	06	IC1BE GAM	54	16.4	38	13	15.0	2.2	14.8	15.0			
13	06	IC1AF GAM				32							14.5
13	06	EF1-2 GAM			54	30	15.1	1.0	2.5	15.5			
13	06	EF1-4 GAM			132	28	16.4	1.3	4.7	16.4			
13	06	EF1 GAM	143	17.7	87	29	16.4	1.0	2.7	16.4	18.5		
13	06	EF2-2 GAM			70	28	14.7	1.7	4.0	15.2			
13	06	EF2-4 GAM			136	35	17.2	1.5	8.8	17.7			
13	06	EF2 GAM	165	17.4	94		16.7	1.4	7.0	16.7	17.5		
RATE DAYS STARTED 20/06 FOR F1 AND 29/06 FOR F2.													
20	06	IC1BE GPM	46	1.4	25	11	0.5	0.5	38.5	0.7			
20	06	IC1AF GPM				70							44.0
20	06	EF1-2 GPM			170	51	0.0	4.5	24.5	1.1			
20	06	EF1-4 GPM			136	48	0.0	3.8	23.7	1.1			
20	06	EF1 GPM	155	2.3	123	37	0.0	4.0	5.7	0.9	16.5		
20	06	EF2-2 GPM			88	46	0.0	6.5	8.5	1.5			
20	06	EF2-4 GPM			98	42	0.0	4.6	8.3	1.3			
20	06	EF2 GPM	159	1.1	146	44	0.0	3.5	25.1	0.8	14.0		
29	06	IC1BE GAM	70	7.1	45	15	4.0	5.8	23.2	4.0	35.5		
29	06	EF1-2 GAM			161	45	2.5	5.0	18.5	3.0			
29	06	EF1-4 GAM			128	41	0.5	2.0	14.5	2.4			
29	06	EF1 GAM	202	5.5	99	34	0.2	0.7	4.9	2.4	12.0		
29	06	EF2-2 GAM			161	49	2.0	5.5	21.0	3.2			
29	06	EF2-4 GAM			145	45	2.0	4.0	18.0	3.0			
29	06	EF2 GAM	174	5.4	136	39	0.1	2.2	11.9	2.6	14.5		
05	07	IC1BE GPM	42	2.4	21	12	0.4	0.5	20.5	1.7			
05	07	IC1AF GPM				63							27.0
05	07	EF1-1 GPM			184		2.0	1.5	24.0	2.0			
05	07	EF1-2 GPM			159	54	0.5	1.5	17.0	2.5			
05	07	EF1-3 GPM			126		0.0	1.1	13.2	2.7			
05	07	EF1-4 GPM			150	49	0.0	1.4	13.7	2.0			
05	07	EF1-5 GPM			117		0.0	1.4	10.1	1.5			
05	07	EF1-6 GPM			88		0.0	1.2	7.7	1.9			
05	07	EF1 GPM	130	2.5	92	32	0.0	1.3	5.0	1.5	12.5		
05	07	EF2-1 GPM			176		0.5	1.0	21.0	1.7			
05	07	EF2-2 GPM			150		0.1	1.3	17.6	1.7			
05	07	EF2-3 GPM			142		0.0	1.4	16.0	1.2			
05	07	EF2-4 GPM			130		0.0	1.2	13.5	1.6			

ANALYSIS

DATE DAY	MO	SAMPLE DESIGNATION	UNFILTERED COD	UNFILTERED BOD	UNFILTERED TKN	FILTERED COD	FILTERED BOD	FILTERED TOC	FILTERED NH3N	FILTERED NO2N	FILTERED NO3N	FILTERED TKN	FILTERED METH
05	07	EF2-5 GPM				142			0.0	1.7	14.5	1.7	
05	07	EF2-6 GPM				121			0.0	1.5	12.6	1.8	
05	07	EF2 GPM	331		11.6	113	45		0.0	1.4	9.8	2.1	19.5
10	07	IC1BE GPM	79		7.4	37	14		6.8	0.2	14.5	6.8	
10	07	IC1AF GPM					51						22.0
10	07	EF1-2 GPM				139	57		6.5	0.5	12.1	7.2	
10	07	EF1-4 GPM				109	50		5.9	0.4	11.3	7.0	
10	07	EF1 GPM	151		7.9	109	42		5.2	0.5	4.9	6.1	16.0
10	07	EF2-2 GPM				151	53		6.5	0.4	11.9	7.5	
10	07	EF2-4 GPM				118	50		5.9	0.6	10.4	6.8	
10	07	EF2 GPM	172		8.3	109	46		5.5	0.6	7.9	6.8	18.5
18	07	IC1BE GPM	59		5.5	30	14		3.8	1.1	18.9	4.9	
18	07	IC1AF GPM					60						50.5
18	07	EF1-2 GPM				130	38		2.6	1.1	14.5	4.5	
18	07	EF1-4 GPM				130	39		2.4	1.1	12.4	3.9	
18	07	EF1 GPM	170		6.3	88	30		1.8	0.9	3.9	3.3	17.5
18	07	EF2-2 GPM				169	50		2.6	1.2	14.5	3.6	
18	07	EF2-4 GPM				89	39		2.0	1.4	11.2	3.8	
18	07	EF2 GPM	194		5.2	46	25		1.6	1.4	4.9	2.9	16.0
25	07	IC1BE GPM			3.5	196	10		0.1	0.3	27.2	2.1	
25	07	IC1AF GPM					51						24.5
25	07	EF1-2 GPM				159	46		0.0	1.0	14.3	2.4	
25	07	EF1-4 GPM				79	37		0.1	1.7	10.5	2.0	
25	07	EF1 GPM	125		3.2	58	28		0.1	1.2	1.7	2.2	11.0
25	07	EF2-2 GPM				113	34		0.0	1.5	13.7	2.0	
25	07	EF2-4 GPM				96	33		0.1	2.7	11.2	2.0	
25	07	EF2 GPM	142		2.9	84	27		0.3	2.6	3.2	1.9	18.5
06	08	IC2BE GPM	81		2.1	30	11		0.1	0.0	25.5	0.4	
06	08	IC1AF GPM					40						
06	08	EF1-2 GPM				68	59		0.2	0.8	15.2	2.1	
06	08	EF1-4 GPM				68	52		0.2	1.2	10.9	2.1	
06	08	EF1 GPM	244		5.3	51	43		0.1	0.7	2.4	2.4	3.5
06	08	EF2-2 GPM				85	59		0.1	0.6	22.9	2.8	
06	08	EF2-4 GPM				68	46		0.2	1.2	11.8	2.5	
06	08	EF2 GPM	188		3.2	60	38		0.1	1.5	5.5	2.3	21.0
08	08	IC1BE GPM	72		16.9	16	12	14.0	0.1	40.5	15.3	.	
08	08	IC1AF GPM					57						21.0
08	08	EF1-2 GPM				72	87		0.4	0.2	8.0	4.5	
08	08	EF1-4 GPM				72	78		0.3	0.1	6.5	2.9	
08	08	EF1 GPM	336		8.4	60	62		0.3	0.1	0.2	2.4	34.0
08	08	EF2-2 GPM				68	78		0.4	0.1	12.1	3.4	
08	08	EF2-4 GPM				68	86		0.6	0.1	0.4	2.1	
08	08	EF2 GPM	288		8.1	48	65		0.1	0.0	0.0	2.3	14.0

RESULTS OF FEED ANALYSIS ON 08/08 INDICATES A PROBLEM WITH THE SAMPLE HENCE THE DATA WILL NOT BE USED FOR RATE CALCULATIONS.

ANALYSIS

DATE DAY	MO	SAMPLE DESIGNATION		UNFILTERED			FILTERED						
				COD	BOD	TKN	COD	BOD	TOC	NH3N	NO2N	NO3N	TKN	METH
13	08	IC1BE	GPM	40		9.2	12	10	7.5	0.2	27.8	8.3		
13	08	IC1AF	GPM					50						27.0
13	08	EF1-2	GPM				44	64	4.1	2.0	9.9	6.7		
13	08	EF1-4	GPM				44	62	3.5	2.5	7.7	5.2		
13	08	EF1	GPM	172		7.2	41	32	2.7	0.7	1.3	4.6	6.0	
13	08	EF2-2	GPM				53		5.2	2.4	13.8	6.7		
13	08	EF2-4	GPM				45	68	4.0	3.2	8.5	5.7		
13	08	EF2	GPM	184		6.5	41	34	2.5	1.6	2.7	4.3	7.0	
THE FOLLOWING SAMPLES WERE TAKEN FOR NITROGEN BALANCE PRUPOSES.														
09	08	IF1-S				4.6			1.6	0.4	28.6	2.2		
09	08	EF1-S				2.1			0.4	0.1	8.5	1.3		
12	08	IF1-S				2.1			0.1	0.1	10.6	0.1		
12	08	EF1-S				2.6			0.0	0.0	1.1	1.5		
13	08	IF1-S				7.5			6.3	0.1	27.4	7.5		
13	08	EF1-S				5.1			2.0	0.5	1.2	3.3		
13	08	EF2-S				8.7			7.3	0.1	27.0	7.9		
13	08	EF2-S				6.4			1.9	1.2	3.7	3.4		
14	08	IF2-S				5.4			2.6	0.3	22.2	4.3		
14	08	EF2-S				4.3			0.6	1.5	4.8	2.3		
15	08	IF2-S				6.9			4.9	0.1	23.0	5.9		
15	08	EF2-S				4.0			0.7	1.8	2.0	2.2		
16	08	IF2-S				4.4			2.3	0.1	26.0	3.2		
16	08	EF2-S				3.9			0.9	4.3	2.6	2.7		
THE ABOVE SAMPLES WERE ALL GRABS TAKEN AT THE SAME TIME THAT GAS RATES WERE MEASURED														
15	08	IC1BE	GPM	49		13.1	25	10	11.0	0.1	27.4	12.3		
15	08	IC1AF	GPM					47						55.0
15	08	EF1-2	GPM				193	97	4.8	1.9	11.3	7.4		
15	08	EF1-4	GPM				102	85	4.6	2.9	7.5	6.5		
15	08	EF1	GPM	270		6.9	70	53	2.6	1.2	1.1	5.0	33.0	
15	08	EF2-2	GPM				53	55	6.5	2.1	17.9	8.4		
15	08	EF2-4	GPM				41	62	4.9	3.2	6.7	6.8		
15	08	EF2	GPM	238		8.1	45	50	3.2	1.7	1.0	5.0	34.0	
SAMPLES WERE COLLECTED ON 20/08 JUST PRIOR TO THE FIRST BACKWASH TO BE CONDUCTED ON THE COLUMNS SINCE START-UP 73 DAYS PREVIOUSLY														
20	08	IC1BE	GPM				21		1.9	0.7	18.2	3.5		
20	08	EF1-2	GPM				62		0.2	0.3	11.7	2.0		
20	08	EF1-4	GPM				54		0.1	0.3	10.0	1.8		
20	08	EF1	GPM				33		0.1	0.7	0.6	1.5		
20	08	EF2-2	GPM				83		0.2	1.0	11.6	1.6		
20	08	EF2-4	GPM				37		0.1	1.0	3.2	1.2		
20	08	EF2	GPM				41		0.1	0.8	1.9	0.3		
THURSDAY RATES ARE TAKEN 60 HRS AFTER 15 MINUTE BACKWASH														
22	08	IC1BE	GPM	50		3.9	17	22	1.7	1.2	14.8	2.4		

ANALYSIS

DATE DAY	MO	SAMPLE DESIGNATION		UNFILTERED COD	BOD	TKN	FILTERED COD	BOD	TOC	NH3N	NO2N	NO3N	TKN	METH
22	08	IC1AF	GPM						26					26.0
22	08	EF1-2	GPM				107		35	0.6	1.3	18.5	3.0	
22	08	EF1-4	GPM				112		32	0.7	1.8	12.8	2.3	
22	08	EF1	GPM	103		2.5	62		21	0.5	1.5	4.0	1.6	15.5
22	08	EF2-2	GPM				103		38	0.6	1.5	17.0	1.9	
22	08	EF2-4	GPM				107		31	1.3	1.6	8.9	3.2	
22	08	EF2	GPM				66		24	0.4	1.7	5.1	1.6	7.5
SAMPLE FOR 28/08 WAS A SPECIAL RUN ON THE COLUMNS TO SEE THE EFFECT OF LOW INFLUENT NITRATE LEVELS ON REMOVAL														
COLUMN F1 WAS BACKWASHED VIGOROUSLY FOR 16 HRS ON AUG 24 AND 25														
28	08	IC1BE	GAM							9.8	0.1	7.0	10.6	
28	08	EF1	GAM							7.8	0.3	4.6	10.2	
28	08	EF2	GAM							8.7	0.3	4.4	10.3	
29	08	IC1BE	GPM	58	18	16.5	29		13	12.0	0.1	8.5	15.1	
29	08	EC1AF	GPM						20					
29	08	EF1-2	GPM				45		47	7.5	0.2	8.1	9.6	
29	08	EF1-4	GPM				37		40	7.2	0.2	8.2	9.3	
29	08	EF1	GPM	135		12.3	33		27	6.6	0.2	6.3	9.5	
29	08	EF2-2	GPM				41		39	7.6	0.2	8.3	9.9	
29	08	EF2-4	GPM				29		18	7.3	0.2	7.4	9.7	
29	08	EF2	GPM	123		12.2	37		17	6.7	0.1	5.1	9.6	
SAMPLES FOR 04/09 WERE ALSO TAKEN TO SEE THE EFFECT OF LOW INF NO3 CONCENTRATIONS ON TOTAL REMOVAL.														
04	09	IC1BE	GAM						10	0.3	0.1	16.4	1.8	
04	09	EF1	GAM						24	0.6	0.2	1.1	1.9	
04	09	EF2	GAM						24	0.4	0.3	1.7	1.7	
06	09	IC1BE	GPM	75		15.6	29		11	14.0	0.5	48.0	14.3	
06	09	IC1AF	GPM						44					
06	09	EF1-2	GPM				83		36	12.5	4.3	24.7	12.5	
06	09	EF1-4	GPM				54		29	11.4	5.7	14.8	11.4	
06	09	EF1	GPM	83		14.2	48		17	11.3	4.2	1.5	11.6	
06	09	EF2-2	GPM				100		39	12.4	3.9	37.9	12.4	
06	09	EF2-4	GPM				75		29	11.4	5.7	18.3	11.4	
06	09	EF2	GPM			20.7	46		22	11.2	4.7	3.6	11.5	
ON FRIDAY AFTERNOON AND SATURDAY COLUMN F1 WAS DISASSEMBLED, THE PACKING WAS CLEANED AND THE UNIT WAS RE-STARTED WITH A 24 HR NO3 PLUS METHANOL BATCH SPIKE. A TRACER STUDY WAS CONDUCTED BEFORE SPIKING RETURN SLUDGE FROM CLARIFIER B1 WAS USED AS A SEEDING MATERIAL.														
12	09	IC1BE	GPM	77		14.0	40		18	11.2	0.1	35.5	13.6	
12	09	IC1AF	GPM						78					
12	09	EF1-2	GPM				57			8.3	4.7	19.3	8.7	
12	09	EF1-4	GPM				57			7.3	7.2	11.8	8.8	
12	09	EF1	GPM	100		11.8	37		23	6.2	8.5	5.5	7.7	

ANALYSIS

DATE	SAMPLE DESIGNATION	UNFILTERED			FILTERED						
DY MO		COD	BOD	TKN	COD	BOD	TOC	NH3N	NO2N	NO3N	TKN METH
12 09	EF2-2 GPM				61			7.5	8.2	13.3	8.7
12 09	EF2-4 GPM				41			5.4	9.8	2.7	7.0
12 09	EF2 GPM	79		7.5	37	23		4.7	8.0	3.6	6.3
09 09	IC1BE GPM	52		7.1	34	12		4.5	0.2	41.3	5.5
19 09	IC1AF GPM					63		.	.	.	.
19 09	EF1-2 GPM							2.4	3.7	17.3	4.4
19 09	EF1-4 GPM							0.9	3.1	7.6	2.2
19 09	EF1 GPM			3.3				0.4	1.1	1.8	1.5
19 09	EF2-2 GPM							3.7	2.8	24.8	5.0
19 09	EF2-4 GPM							2.9	3.4	21.6	4.1
19 09	EF2 GPM			4.7				1.6	4.3	10.2	3.1
27 09	IF1				132			9.1	0.1	40.4	11.7
27 09	EF1-2				77			5.8	0.8	23.2	8.3
27 09	EF1-4				56			4.3	1.4	10.5	7.6
27 09	EF1	196		13.1	45	36		2.5	1.4	1.8	5.2
27 09	IF2				65			8.9	0.1	40.4	10.0
27 09	EF2-2				80			8.2	0.1	33.4	8.8
27 09	EF2-4				81			6.8	0.2	27.3	8.7
27 09	EF2	344		15.5	93	91		4.2	5.2	7.3	4.8
28 10	IF1				47			0.5	1.9	91.1	2.7
28 10	EF1-2				40			1.9	2.0	77.0	3.3
28 10	EF1-4				36			1.1	2.4	59.6	2.5
28 10	EF1	275		17.4	40	18		2.0	2.3	53.7	4.1
28 10	IF2				40			0.4	1.9	90.1	2.7
28 10	EF2-2				40			0.6	2.3	88.7	2.4
28 10	EF2-4				38			0.9	2.6	67.4	2.4
28 10	EF2	485		39.8	40			1.0	4.5	68.5	3.7
07 11	IF1							0.2	2.0	52.0	1.1
07 11	EF1-2							0.1	3.7	41.3	1.6
07 11	EF1-4							0.7	4.0	28.0	2.4
07 11	EF1			12.5			24	1.6	3.2	23.8	3.1
07 11	IF2							0.1	1.8	60.2	1.0
07 11	EF2-2							0.4	3.2	56.8	1.8
07 11	EF2-4							1.4	5.5	34.5	3.5
07 11	EF2			5.0			31	0.5	6.2	45.8	2.3

APPENDIX B

ANALYTICAL METHODS

ANALYTICAL METHODS:

Total Kjeldahl Nitrogen

Total Kjeldahl nitrogen analyses (organic plus ammonia nitrogen) were performed according to Technicon Auto-analyzer Industrial Method 30-69A. Essentially this procedure consists of digestion of organic matter at 380 degrees C followed by measurement of the ammonia produced using the Berthelot reaction in which the formation of a blue indophenol complex occurs when ammonia reacts with sodium phenate followed by the addition of sodium hypochlorite. Glycine standards were used for calibration. For keeping unfiltered samples homogenized in the sample cups the system has two air aspirators. One aspirator provides complete mixing in the cup being sampled while the second aspirator mixes the next cup on the tray.

Ammonia Nitrogen

Analyses of ammonia nitrogen were conducted using Technicon Auto-analyzer Industrial Method 18-69W. This is essentially the same technique employed for Total Kjeldahl nitrogen with the omission of the selenium dioxide/sulphuric acid/perchloric acid digestion step which ammonifies the organic nitrogen fraction. Ammonium chloride standards provided calibration.

Nitrite

Technicon Auto-analyzer Industrial Method 35-69W was used for nitrite nitrogen determinations. This technique involves a reaction between nitrite and sulphanilamide under acid conditions to form a diazo compound which in turn is coupled with N-1-naphthylethylenediamine to form a reddish purple azo dye. Colorimetric determination is then made on the sample.

Nitrate + Nitrite

Nitrate plus nitrite nitrogen analyses were performed using Technicon Auto-analyzer Industrial Method 33-69W. In this method, the nitrate nitrogen is reduced to nitrite in a copper-cadium reduction column. The sample is then analyzed for nitrite nitrogen as described previously.

Chemical Oxygen Demand (COD)

Early COD determinations were done according to the dichromate reflux method described in "Standard Methods" (1971). During the research period, a modified version of Technicon Auto-analyzer Industrial Method No. 268-73W was adapted for COD analysis. A Technicon Solidprep II sampler was introduced in place of the normal sampler. This allowed analysis of samples containing suspended solids and provided high shear homogenization of samples with the dichromate and sulphuric acid reagents. Standard solutions were prepared using a combination of urea, beef extract and chloride salts.

The standards were first analyzed using the "Standard Methods" reflux technique and then analyzed on the Technicon equipment. The standard peaks produced on the Technicon System were then calibrated against the "Standard Methods" results. This complicated approach was necessary since the sample digestion time in the Auto-analyzer was shorter than that in the standard reflux test. This resulted in a lower degree of reaction completion with the Auto-analyzer when heterogeneous sewage samples were tested. With this procedure modification in effect, Auto-analyzer COD results for sewage samples were generally only 5 to 7 percent lower than results obtained via the "Standard Methods" technique.

Biochemical Oxygen Demand (BOD)

The 5 day, 20 degree C BOD determinations were performed according to the method described in "Standard Methods" pages 489-495 (1971).

Total Soluble Organic Carbon (TOC)

Twenty micro-liter samples previously acidified and purged were injected into a Beckman Infrared Carbon Analyzer. The resulting peaks were compared to a calibration curve prepared from standards using anhydrous potassium biphthalate.

Suspended Solids

Gelman .45 micron glass fiber filters were dried, but not washed, for at least two hours in a 103 degree C oven.

They were then cooled in a dessicator and weighed. Suspended solids determinations were made by filtering a minimum of 10 mℓ of solution through a filter. The filter was then re-dried at 103 degrees for two or more hours, dessicated for 15 minutes and re-weighed. The increase in weight was taken as a measure of the suspended solids.

Dissolved Oxygen

An Electronic Instruments Ltd. Dissolved Oxygen Meter Model 15A was used for dissolved oxygen determinations. It was found necessary to calibrate the probe roughly once a week.

Temperature

The D.O. meter also included a temperature probe and this was used for temperature measurements of the feed streams and the RBC. Normal centigrade calibrated laboratory thermometers were used to measure column effluent and air temperatures.

pH

pH was measured using an Orion Specific Ion Meter (Model 401) together with Fisher Combination electrodes (Cat. 13-639-90).

Alkalinity

By using the Orion pH meter, 50 mℓ samples were

titrated to a pH of 4.8 by addition of .02 N sulphuric acid. Results were expressed as mg/ℓ as calcium carbonate.

Methanol

Direct aqueous injection gas chromatography on a porous polymer column was employed to determine methanol. Filtered samples were acidified by addition of concentrated hydrochloric acid to a pH around 2.0. The samples were then frozen until the time of analysis. A description of the procedure is given by Fox (1973).

Gas Analysis

A Fisher Hamilton gas partitioner (Model 29) with helium carrier gas was used to separate and analyze the mixture of gases collected from the denitrification columns. A Hamilton Co. (Reno Nevada) Gas-Tight syringe, 1001-LT, was used to inject .5 mℓ gas samples into the chromatograph. A 42 inch silica gel column and a second column consisting of 13 feet of molecular sieve 13x were employed to separate the mixture. Known mixtures of oxygen, nitrogen, carbon dioxide and methane were used to provide a calibration of the instrument. Operating details are discussed fully in the manual which is supplied with the partitioner.

Dissolved nitrogen gas concentrations in liquid samples were also measured using the same gas partitioner. A small liquid retention chamber was added to the system into which .5 mℓ samples of liquid containing dissolved

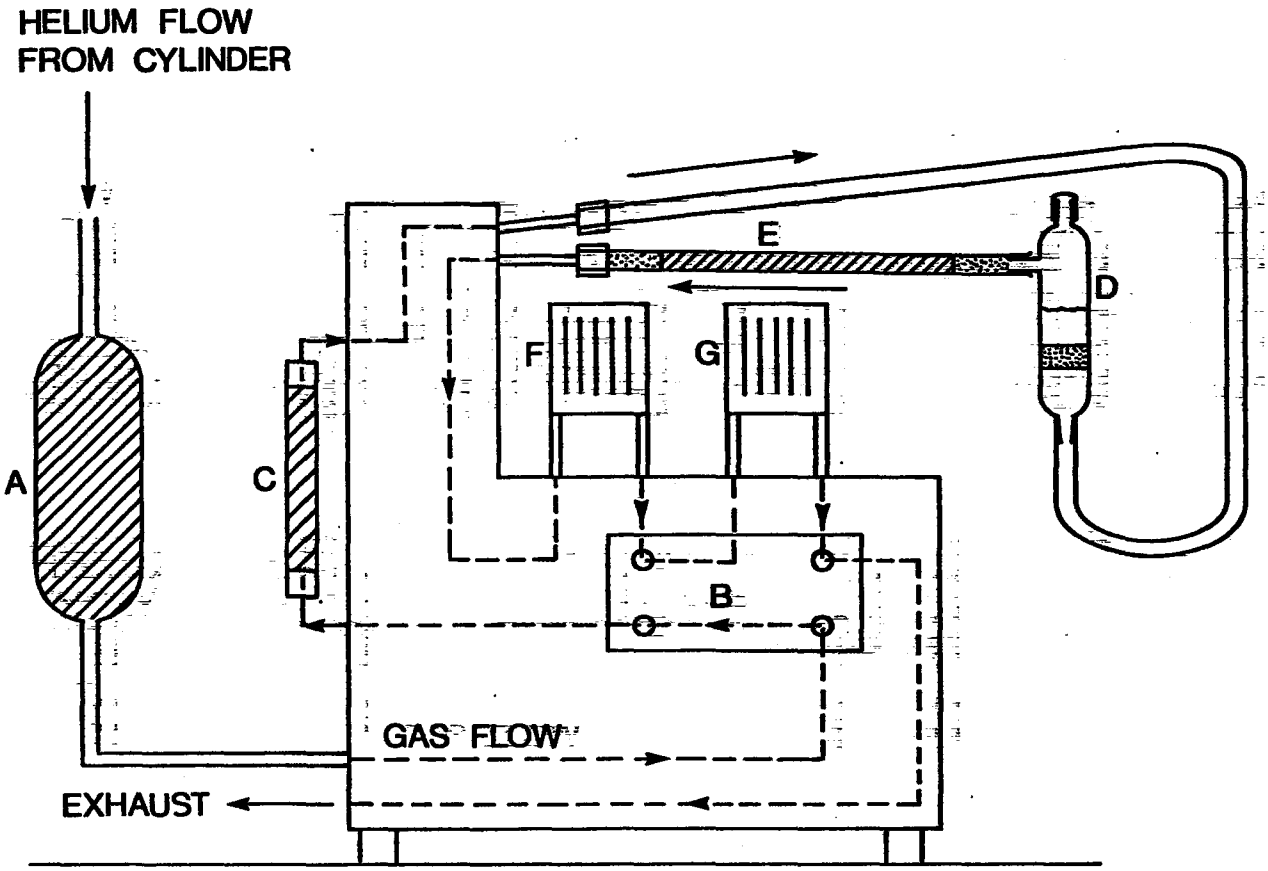
nitrogen were injected. The nitrogen in the sample was stripped from the liquid by carrier gas which passed through the chamber on its way to the partitioning columns. Calibration was provided by saturating aliquots of distilled water (with nitrogen gas) at various temperatures between 0 degrees C and 40 degrees C and then injecting these into the special chamber. Saturation concentrations of nitrogen in water at varying temperatures were plotted from data given in Fair and Geyer (1968). A flow diagram of the gas partitioner as it was set up for dissolved gas analysis is given in Figure B-1. Normally about five liquid injections could be made before it was necessary to eliminate the pressure in the system by shutting off the carrier gas so that the chamber could be emptied and dried. Even if larger capacity chambers were used, it is not recommended that more than about five samples be run at any one time as it is important to ensure rapid stripping of the dissolved gases by the helium after injection. If stripping is too slow, separation of the gases in the columns can become a problem. Also, frequent replacement of the Drierite packing in the tubing following the liquid injection chamber was necessary to prevent water vapor from reaching the silica gel and molecular sieve columns. Figure B-2 shows typical results of a dissolved gas analysis using effluent from the denitrification columns.

It should be noted that dissolved gas analyses could have been facilitated somewhat by inserting a four way valve

into the system that would allow the carrier gas flow to by-pass the liquid chamber. This would allow chamber clean-out and replacement without affecting the gas flow through the detector which is sensitive to gas flow fluctuations.

FIGURE B-1

FISHER HAMILTON GAS PARTITIONER (MODEL 29) GAS FLOW DIAGRAM FOR DISSOLVED GAS ANALYSIS



FRONT VIEW OF PARTITIONER
WITH HOOD REMOVED

A: DRYING TUBE CONTAINING DIERITE

B: THERMAL CONDUCTIVITY DETECTION CELL

C: SMALL DRYING TUBE WITH DIERITE

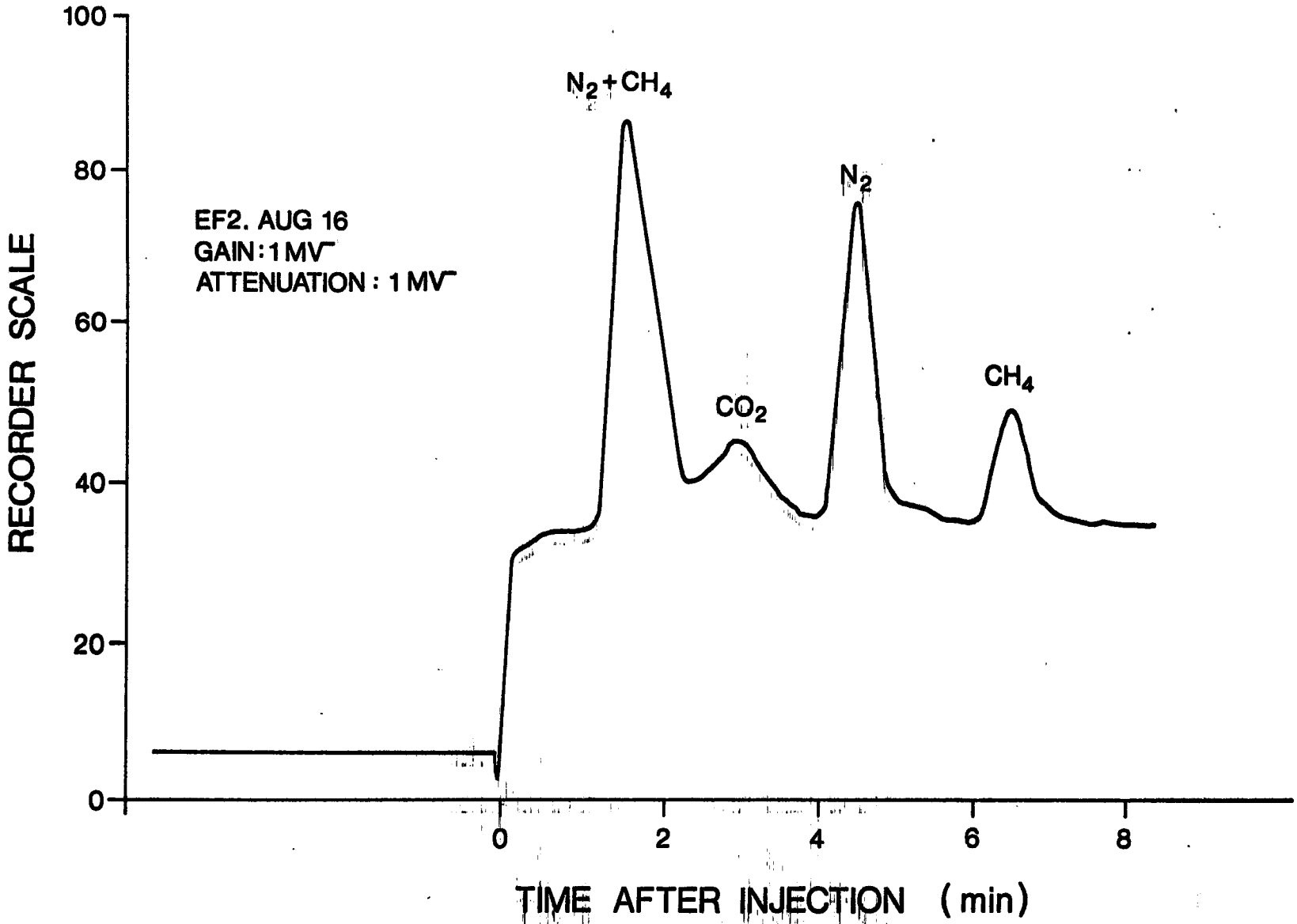
D: LIQUID INJECTION CHAMBER WITH PORUS DIFFUSER AND SERUM CAP

E: PVC TUBING CONTAINING DIERITE

F: SILICA GEL COLUMN

G: MOLECULAR SIEVE COLUMN

FIGURE B-2
SAMPLE OUTPUT FOR DISSOLVED GAS ANALYSES



APPENDIX C

COMPUTER PROGRAMMES

```
RAM TST          73/73    OPT=0    TRACE                    FTN 4.2+P383        12/09

      PROGRAM TST (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
CCC   THE TWO CHIEF REFERENCES USED FOR THIS PROGRAMME ARE
CCC        1. LEVENSPIEL , CHEMICAL REACTION ENGINEERING , CHAPTER 9
CCC        2. TIMPANY , VARIATION IN AXIAL MIXING IN AN AERATION
CCC           TANK. MASTERS THESIS, DEPT. OF CHEM ENG., MCMASTER
CCC           UNIVERSITY , 1966.
CCC   THE D/UL VALUE FOR THE DISPERSION MODEL IS SOLVED BY USING THE
CCC   CORRELATIONS OF PEAK TIME VERSUS D/UL DEVELOPED BY TIMPANY.(PP 31 - 32
CCC   THE CSTR IN SERIES MODEL IS SOLVED BY TAKING THE DERIVATIVE OF
CCC   EQUATION 9-35 IN LEVENSPIEL - EQUATING THE RESULT TO ZERO AND
CCC   SOLVING FOR THE NUMBER OF EQUAL TANKS IN SERIES, J , IN TERMS
CCC   OF THETA.THETA IS FOUND BY DIVIDING THE PEAK DYE TIME BY THE
CCC   THEORETICAL RESIDENCE TIME.
CCC   THE C/CO VALUES FOR THE DISPERSION MODEL ARE SOLVED BY ITERATION
CCC   USING EQUATION 8 IN CHAPTER 2 OF TIMPANY.
CCC   THE C/CO VALUES FOR THE CSTR IN SERIES MODEL ARE SOLVED USING
CCC   EQUATION 9-35 IN LEVENSPIEL FOR VARIOUS VALUES OF THETA.
CC
      DIMENSION C(500),CUL(500),TANKS(5),AW(5),DULP(5),THETA(2,100)
      DIMENSION CCO(2,100),U(500),AMU(5,500),COCO(5,500),CCI(100)
      DIMENSION TTB(100),TBAR(2),RATIO(500),BETA(500),ETA(500)
      DIMENSION BLUE(100)
      DIMENSION CE(200)
C
CCC   VOLT=TANK VOLUME IN LITRES          VFLR=FLOW IN LITRES/MIN
CCC   TPEAK=PEAK TIME IN MINUTES          DYIN=AMOUNT OF DYE IN LITRES
C     DYCON=CONC. OF DYE IN PPB           DT=MINUTES BETWEEN DATA PTS
CCC   N=NUMBER OF DATA PTS
CCC   C(I)=CONC OF DYE IN EFFLUENT PPB
C
      READ(5,1) VOLT,VFLR,TPEAK,DYIN,DYCON,DT
      READ(5,2) N
      READ(5,3) (C(I),I=1,N)
C
CC    PERCENT DYE RECOVERY
C
      AMT = C(1)*DT*VFLR*10.**(-6)
      CUL(1) = AMT
      DO 100 I=2,N
      AMT = .5*(C(I)+C(I-1))*DT*VFLR*10.**(-6)
      LUL = I-1
      CUL(I) = CUL(LUL)+AMT
  100 CONTINUE
      DYE = DYCON*DYIN*10.**(-6)
      PER = CUL(N)/DYE*100.
C
CC    CALCULATION OF MEAN RESIDENCE TIME OF THE TOTAL DYE RETRIEVED
C     CALCULATION OF PERCENT STAGNANT ZONE
```

2

PROGRAM TST 73/73 OPT=0 TRACE FTN 4.2+P

```
      C
            TBAR(1) = VOLT/VFLR
60          ANT = 1.
            I = 1
            ZONE = CUL(N)/2.
        201 IF(CUL(I).GT.ZONE) GO TO 200
            ANT = ANT + 1.
65          I = I +1
            GO TO 201
        200 TBAR(2) = ANT*DT
            DEAD = (TBAR(1)-TBAR(2))/TBAR(1)
      C
70    C     CALCULATION NUMBER OF TANKS IN SERIES
      C
            TP1 = TPEAK/TBAR(1)
            TP2 = TPEAK/TBAR(2)
            TANKS(1) = 1./(TP1*(1./TP1-1.))
75          TANKS(2) = 1./(TP2*(1./TP2-1.))
      C
      C     TRUNCATE TO NEAREST WHOLE NUMBER OF TANKS
      C
            AW(1) = TANKS(1)
80          AA = 1.5
        203 IF(AW(1).LT.AA) GO TO 202
            AA = AA + 1.
            GO TO 203
        202 AW(1) = AA - .5
85          AW(2) = TANKS(2)
            AA = 1.5
        205 IF(AW(2).LT.AA) GO TO 204
            AA = AA + 1.
            GO TO 205
90      204 AW(2) = AA - .5
      C
      C     CALCULATION OF TIMPANY'S PEAK TIME DULL VALUES
      C
            IF((TP1.GT.0.03).AND.(TP1.LT.0.3)) GO TO 206
95          IF((TP1.GT.0.3).AND.(TP1.LT.0.8)) GO TO 207
            GO TO 208
        206 DULP(1)= .2*(TP1**(-1.34))
            GO TO 209
        207 DULP(1) = 4.027*(10.**(-2.09*TP1))
100         GO TO 209
        208 WRITE(6,300)
            IF(TP1.LE.0.03) GO TO 206
            GO TO 207
        209 CONTINUE
105         IF((TP2.GT.0.03).AND.(TP2.LE.0.3)) GO TO 210
            IF((TP2.GT.0.3).AND.(TP2.LE.0.8)) GO TO 211
            GO TO 213
        210 DULP(2) = .2*(TP2**(-1.34))
            GO TO 214
110     211 DULP(2) = 4.027*(10.**(-2.09*TP2))
            GO TO 214
        213 WRITE(6,300)
            IF(TP2.LE.0.03) GO TO 210
            GO TO 211
```

```
  214 CONTINUE
C
C     CALCULATION OF  C/CO VS THETA VALUES FOR CSTR MODELS
C     DERIVATIVE AT PEAK DYE CONC METHOD USED
C
      DO 101 I=1,2
      X=AW(I)**AW(I)
      XX=1.
      BB=1.
  216 IF(AW(I).EQ.BB) GO TO 215
      XX=XX*(AW(I)-BB)
      BB=BB+1.
      GO TO 216
  215 FACT = XX
      THETA(I,1) =0.
      DO 102 J=2,21
      THETA(I,J) = THETA(I,J-1) + .05
  102 CCO(I,J)= X/XX*THETA(I,J)**(AW(I)-1.)*EXP(-AW(I)*THETA(I,J))
      DO 103 J= 22,37
      THETA(I,J) = THETA(I,J-1) + .2
  103 CCO(I,J)= X/XX*THETA(I,J)**(AW(I)-1.)*EXP(-AW(I)*THETA(I,J))
  101 CONTINUE
C
C     CLACULATION OF ACTUAL C/CO VALUES FROM EXPERIMENTAL DATA
C
      CNOT = DYIN*DYCON/VOLT*PER/100.
      MM = 0
      DRAG = 0.
      NN = 0
      DO 104 I = 1,30
      NN = NN + 3
      MM = MM + 1
      RATIO(MM) = C(NN)/CNOT
      DRAG = DRAG + 3*DT
      BETA(MM) = DRAG/TBAR(1)
  104 ETA(MM) = DRAG/TBAR(2)
      IM = (N- 90)/10 + 29
      DO 105 I = 31, IM
      MM = MM + 1
      DRAG = DRAG + 10.*DT
      NN = NN + 10
      RATIO(MM) = C(NN)/CNOT
      BETA(MM) = DRAG/TBAR(1)
      ETA(MM) = DRAG/CNOT
  105 CONTINUE
C
C     CALCULATION OF C/CO VALUES VS THETA FOR D/UL METHOD
C
C
      M = 1
   40 I=1
      AMU(M,I)=1.4
      U(M)=.5/DULP(M)
   45 AMU(M,I)=AMU(M,I)-.001
      FR= COS(AMU(M,I))/SIN(AMU(M,I))
      FR= FR - AMU(M,I)*DULP(M)+ .25/(AMU(M,I)*DULP(M))
      IF(FR)45,45,50
```


3

```
PROGRAM TST          73/73   OPT=0   TRACE                    FTN 4.2+P383

   50 AMU(M,I) = AMU(M,I) + .00001
      FR = COS(AMU(M,I))/SIN(AMU(M,I))
      FR= FR - AMU(M,I)*DULP(M) + .25/(AMU(M,I)*DULP(M))
      IF(FR)55,50,50
   55 AMU(M,I) = AMU(M,I) - .0000001
      FR = COS(AMU(M,I))/SIN(AMU(M,I))

      FR = FR - AMU(M,I)*DULP(M) + .25/(AMU(M,I)*DULP(M))
      IF(FR)55,55,60
   60 I= I + 1
      AMU(M,I) = AMU(M,I-1)+3.1417
      IF(I.LE.50) GO TO 45
      M = M + 1
      IF(M.LE.2) GO TO 40
      DO 80 M=1,2
  999 ZETA = 0.0
      DO 70 K=1,30
      ZETA = ZETA + .1
      COCO(M,K) = 0.0
      DO 65 I=1,50
      A=2.0*AMU(M,I)*(U(M)*SIN(AMU(M,I)) + AMU(M,I)*COS(AMU(M,I)))
      B=EXP(U(M)-((U(M)**2 + AMU(M,I)**2)/(2.0*U(M)))*ZETA)
      D=U(M)**2 + 2.0*U(M) + AMU(M,I)**2
  998 CE(I) = A*B/D
      COCO(M,K) = COCO(M,K) + CE(I)
   65 CONTINUE
   67 CONTINUE
   70 CONTINUE
   80 CONTINUE
C
CC    PRINT INSTRUCTIONS AND DATA PRESENTATION FORMAT
C
      WRITE(6,700)
  700 FORMAT(≠1≠,≠                              TRACER RESPONSE ANALYSIS≠,///
      WRITE(6,701)
  701 FORMAT(≠ ≠,≠                              DENITRIFICATION COLUMNS≠,//)
      WRITE(6,702)
  702 FORMAT(≠ ≠,≠                              HYDRAULIC CHARACTERIZATION≠,/
     6/)
      WRITE(6,703)
  703 FORMAT(≠ ≠,≠                        TEST METHOD USING A PULSE INPUT OF RODAMI
     6E DYE≠,////)
      WRITE(6,704)
  704 FORMAT(≠ ≠,≠          REACTOR OPERATION AND TEST CONDITIONS≠,///)
      WRITE(6,705) VOLT
  705 FORMAT(≠ ≠,≠                VOLUME OF REACTOR = ≠,F7.2,≠  LITRES≠)
      WRITE(6,706) VELR
  706 FORMAT(≠ ≠,≠                HYDRAULIC LOADING = ≠,F7.2,≠  LITRES/MIN
     6)
      WRITE(6,707) TBAR(1)
  707 FORMAT(≠ ≠,≠                THEORETICAL DET.  = ≠,F7.2,≠  MIN≠)
      WRITE(6,708) DYIN
  708 FORMAT(≠ ≠,≠                DYE INJECTION     = ≠,F7.4,≠  LITRES≠)
      WRITE(6,709) DYCON
  709 FORMAT(≠ ≠,≠                CONC OF DYE ADDED = ≠,E10.3,≠  ppB≠)
      WRITE(6,710) CNOT
  710 FORMAT(≠ ≠,≠                DYE / TANK VOLUME = ≠,F7.2,≠  PPB≠,////)
```


4

```
)AM TST        73/73    OPT=0    TRACE                    FTN 4.2+P383        12/0
      WRITE(6,711)
  711 FORMAT(≠ ≠,≠      TEST RESULTS AND CALCULATED VALUES≠,///)
      WRITE(6,712) TPEAK
  712 FORMAT(≠ ≠,≠                DYE PEAK TIME     = ≠,F7.2,≠  MIN≠)
      WRITE(6,713) TP1
  713 FORMAT(≠ ≠,≠                PEAK/THEOR. DET   = ≠,F7.3)
      WRITE(6,714) TP2
  714 FORMAT(≠ ≠,≠                PEAK/MEAN DYE RES = ≠,F7.3,/)
      WRITE(6,715) TBAR(2)
  715 FORMAT(≠ ≠,≠                MEAN DYE RESIDENCE= ≠,F7.2,≠  MIN≠)
      WRITE(6,716) PER
  716 FORMAT(≠ ≠,≠                PER DYE RECOVERY  = ≠,F7.3,≠  %≠)
      WRITE(6,717) DEAD
  717 FORMAT(≠ ≠,≠                FR. STAGNANT ZONE = ≠,F7.3,/)
      WRITE(6,718) TANKS(1)
  718 FORMAT(≠ ≠,≠                CSTR S IN SERIES USING THEORETICAL RES. =
     6 ≠,F7.2)
      WRITE(6,719) TANKS(2)
  719 FORMAT(≠ ≠,≠                CSTR S IN SERIES USING MEAN DYE RES.    =
     6 ≠,F7.2)
      WRITE(6,720) DULP(1)
  720 FORMAT(≠ ≠,≠                D/UL VALUE USING THEORETICAL RESIDENCE  =
     6 ≠,E11.4)
      WRITE(6,721) DULP(2)
  721 FORMAT(≠ ≠,≠                D/UL VALUE USING MEAN DYE RESIDENCE     =
     6 ≠,E11.4)
      WRITE(6,722)
  722 FORMAT(≠1≠,/////,≠                EXPERIMENTAL RESULTS C/CO VERSUS
     6 THETA≠,/////)
      WRITE(6,723)
  723 FORMAT(≠ ≠,≠                THETA                C/CO≠,///)
      WRITE(6,724) (BETA(I),RATIO(I),I=1,MM)
  724 FORMAT(15X,F5.3,15X,F5.3)
      WRITE(6,725)
  725 FORMAT(≠1≠,/////,≠                CALCULATED C/CO VERSUS THETA VAL
     6UES≠)
      WRITE(6,726)
  726 FORMAT(≠ ≠,≠                FOR CSTR IN SERIES MODEL≠,////
     6/)
      WRITE(6,727)
  727 FORMAT(≠ ≠,≠            THEORETICAL DETENTION            ACTUAL DE
     6TENTION≠,///)
      WRITE(6,728)
  728 FORMAT(≠ ≠,≠)                THETA      C/CO                THETA
     6   C/CO≠,//)
      WRITE(6,729) (THETA(1,J),CCO(1,J),THETA(2,J),CCO(2,J),J=2,37)
  729 FORMAT(15X,F5.3,6X,F5.3,15X,F5.3,6X,F5.3)
      WRITE(6,725)
      WRITE(6,730)
  730 FORMAT(≠ ≠,≠                FOR DISPERSION MODEL≠,/////)
      WRITE(6,727)
      BLUE(1)= .1
      DO 731 K=2,30
      BLUE(K)= BLUE(K-1) + .1
  731 CONTINUE
      WRITE(6,729) (BLUE(K),COCO(1,K),BLUE(K),COCO(2,K),K=1,30)
    1 FORMAT(4F10.4,E10.2,F10.4)

    2 FORMAT(I10)
    3 FORMAT(5F10.2)
  300 FORMAT(≠1≠,≠ PEAK TIME OUTSIDE LIMIT FOR D/UL CALCULATION≠)
      STOP
      END
```

PROGRAMME #2

```
$JOB,660,031LINR,3,1000,300,,,  DOUG BEECROFT
$SCHED,SCR=5,CORE=52
$FTNU(S,X,L,P)
      PROGRAM LINRG                                                      LI
C                                                                        LI
C       DOUG BEECROFT, ENVIRCNMENTAL PROTECTION SERVICE, SEPTEMBER 1972LI
C                                                                        LI
C       THIS PROGRAM USES LEAST SQUARES TO ESTIMATE THE REGRESSION       LI
C       COEFFICIENTS FOR ANY LINEAR FUNCTION INVOLVING LESS THAN TEN     LI
C       INDEPENDENT VARIABLES.  CUTPUT INCLUDES MEANS AND STANDARD       LI
C       DEVIATIONS FOR ALL VARIABLES, THE CORRELATION MATRIX,            LI
C       REGRESSION COEFFICIENTS, AN ANALYSIS OF VARIANCE TABLE, THE      LI
C       SQUARE OF THE MULTIPLE CORRELATION COEFFICIENT, AND A TABLE OF LI
```

```
C       RESIDUALS.  THE REQUIRED DATA CARDS ARE LISTED BELOW.
C
C            A.  COL.  1- 8  PROBLM, AN EIGHT CHARACTER ALPHANUMERIC
C                            CODE TO BE USED IN IDENTIFYING THE
C                            PROBLEM.
C
C                COL.  9-11  NPTS, THE NUMBER OF OBSERVATIONS.  NPTS
C                            MUST BE LESS THAN 251.
C
C                COL. 12-13  NVAR, THE TOTAL NUMBER OF VARIABLES (THE
C                            NUMBER OF INDEPENDENT VARIABLES + 1).
C                            NVAR MUST BE LESS THAN 11.
C
C                COL. 14-15  NDEPND, THE NUMBER OF THE DEPENDENT
C                            VARIABLE, THAT IS, THE COLUMN OF THE INPU
C                            DATA MATRIX CONTAINING THE VALUES OF THE
C                            DEPENDENT VARIABLE.
C
C            B.  COL.  1-72  VARIABLE FORMAT CARD WITH WHICH THE INPUT
C                            DATA IS TO BE READ.  SEE THE BMD MANUAL,
C                            PAGES 22-28, FOR A MORE COMPLETE
C                            DESCRIPTION OF THIS TYPE OF CARD.
C
C            C.  THE INPUT DATA.  EACH CARD CONTAINS ONE OBSERVATION O
C                            EACH VARIABLE.  THE GENERAL FORM OF THE
C                            INPUT DATA IS THE SAME AS FOR THE BMD
C                            PROGRAMS (BMD MANUAL, PAGES 11-12).
C
C            D.  EOF CARD (STANDARD C.C.I.W. GREY-STRIPED ECE)
C
C       NOTE -- CARDS A THROUGH C MAY BE REPEATED AS OFTEN AS DESIRED.
C
      COMMON CORMAT,NINDEP
      REAL MEANS(10),COEFF(9)
      DIMENSION DATMAT(250,10),DATUSE(250,10),RESID(250),VARFMT(9)
      DIMENSION CORMAT(10,10),SI(10),SPARE(9),IVAR(10),YFIT(250)
      EQUIVALENCE (DATUSE(1),YFIT(1)),(DATUSE(251),RESID(1))
      EQUIVALENCE (VARFMT,DATUSE)
C
C       READ CONTROL INFORMATION
C
   10 READ 99, PROBLM,NPTS,NVAR,NDEPND,VARFMT
   99 FORMAT (A8,I3,2I2/9A8)
      IF (IFEOF(60).EQ.-1) STOP
      DO 100  I=1,NPTS
  100 READ (60,VARFMT) (DATMAT(I,J),J=1,NVAR)
      NINDEP=NVAR-1
C
C       COMPUTE MEANS OF ALL VARIABLES, CENTRE DATA
C
      DO 200  I=1,NVAR
      MEANS(I)=0.0
      DO 300  J=1,NPTS
  300 MEANS(I)=MEANS(I)+DATMAT(J,I)
      MEANS(I)=MEANS(I)/NPTS
      DO 200 J=1,NPTS
  200 DATUSE(J,I)=DATMAT(J,I)-MEANS(I)
C
C       COMPUTE SUM OF SQUARES OF DEVIATIONS FROM MEAN FOR VARIABLES
C
      DO 500  I=1,NVAR
      S(I)=0.0
```

```
  600 S(I)=S(I)+DATUSE(J,I)**2
      SAVE=SQRT(S(I))
      DO 500  J=1,NPTS
  500 DATUSE(J,I)=DATUSE(J,I)/SAVE
;
;        PRINT CONTROL INFORMATION, MEANS, AND STANDARD DEVIATIONS
;
      PRINT 44, PROBLM,NPTS,NVAR,NDEPND
   44 FORMAT (27H1MULTIPLE LINEAR REGRESSION
     1       /13H0PROBLEM CODE,A23
     2       /23H NUMBER OF OBSERVATIONS,10X,I3
     3       /20H NUMBER OF VARIABLES,I16
     4       /29H DEPENDENT VARIABLE IS NUMBER,I7//
     5       /30H0MEANS AND STANDARD DEVIATIONS
     6  //11X,42HVARIABLE NO.     MEAN     STANDARD DEVIATION/)
      DO 1030  I=1,NVAR
      SAVE=SQRT(S(I)/(NPTS-1))
 1030 PRINT 22,I,MEANS(I),SAVE
   22 FORMAT (16X,I2,2F15.5)
C
C        COMPUTE AND PRINT CORRELATION MATRIX
C
      DO 700  I=1,NVAR
      DO 700  J=1,NVAR
      CORMAT(I,J)=0.0
      DO 700  K=1,NPTS
  700 CORMAT(I,J)=CORMAT(I,J)+DATUSE(K,I)*DATUSE(K,J)
      PRINT 88,(I,I=1,NVAR)
   88 FORMAT (/19H0CORRELATION MATRIX//9X,10(7X,I2))
      DO 800  I=1,NVAR
  800 PRINT 77,I,(CORMAT(I,K),K=1,NVAR)
   77 FORMAT (8X,I1,3X,10F9.5)
C
C        TRANSFER DEPENDENT VARIABLE TO LAST ROW AND LAST COLUMN
C
      DO 18  I=1,NVAR
   18 IVAR(I)=I
      IF (NDEPND.EQ.NVAR) GO TO 32
      DO 17  I=1,NVAR
      SWAP=CORMAT(I,NVAR)
      CORMAT(I,NVAR)=CORMAT(I,NDEPND)
   17 CORMAT(I,NDEPND)=SWAP
      DO 16  I=1,NVAR
      SWAP=CORMAT(NVAR,I)
      CORMAT(NVAR,I)=CORMAT(NDEPND,I)
   16 CORMAT(NDEPND,I)=SWAP
      IVAR(NDEPND)=NVAR
      IVAR(NVAR)=NDEPND
C
C        COMPUTE PRODUCT OF TRANSPOSE MATRIX OF X VALUES WITH Y VALUES
C
   32 DO 900  I=1,NINDEP
      SPARE(I)=0.0
      L=IVAR(I)
      DO 900  K=1,NPTS
  900 SPARE(I)=SPARE(I)+DATUSE(K,L)*DATUSE(K,NDEPND)
C
C        COMPUTE INVERSE OF CORRELATION MATRIX
C
      CALL MATINV
C
```

```
C         COMPUTE AND PRINT REGRESSION COEFFICIENTS
C
      PRINT 66
   66 FORMAT (//24H REGRESSION COEFFICIENTS
     1    //11X,27HVARIABLE NO.    COEFFICIENT/)
      CONST=MEANS(NDEPND)
      DO 1000  I=1,NINDEP
      COEFF(I)=0.0
      L=IVAR(I)
      DO 400  K=1,NINDEP
  400 COEFF(I)=COEFF(I)+CORMAT(I,K)*SPARE(K)
      COEFF(I)=COEFF(I)*SQRT(S(NDEPND)/S(L))
      CONST=CONST-COEFF(I)*MEANS(L)
 1000 PRINT 55, L,COEFF(I)
   55 FORMAT (14X,I2,E21.5)
      PRINT 14, CONST
   14 FORMAT (/11X,38HCONSTANT TERM IN PREDICTION EQUATION =,F12.5/)
C
C         PRINT ANALYSIS OF VARIANCE AND CORRELATION COEFFICIENT
C
      REGSS=0.0
      DO 1040  I=1,NPTS
      YFIT(I)=CONST
      DO 1050  J=1,NINDEP
      L=IVAR(J)
 1050 YFIT(I)=YFIT(I)+COEFF(J)*DATMAT(I,L)
      RESID(I)=DATMAT(I,NDEPND)-YFIT(I)
 1040 REGSS=REGSS+YFIT(I)*DATMAT(I,NDEPND)
      TOTAVG=NPTS*MEANS(NDEPND)**2
      TOTSS=TOTAVG+S(NDEPND)
      RESSS=TOTSS-REGSS
      REGSS=S(NDEPND)-RESSS
      REGMS=REGSS/NINDEP
      I=NPTS-1
      J=NPTS-NVAR
      VARYNC=RESSS/J
      F=REGMS/VARYNC
      CORRCO=REGSS/S(NDEPND)
      PRINT 1107,TOTSS,NPTS,TOTAVG,S(NDEPND),I,REGSS,NINDEP,REGMS,F,
     1    RESSS,J,VARYNC,CORRCO
 1107 FORMAT (21H0ANALYSIS OF VARIANCE/1H0,12X,71HSOURCE OF VARIATION
     1SUM OF SQUARES   DEGREES OF FREEDOM   MEAN SQUARE,10X,1HF
     2    /1H0,12X,19HTOTAL (UNCORRECTED),F16.4,I15/1H ,27X,4HMEAN,
     3    F16.4,14X,1H1/1H ,14X,17HTOTAL (CORRECTED),F16.4,I15/1H ,21)
     4    10HREGRESSION,F16.4,I15,F21.4,F15.4/1H ,23X,8HRESIDUAL,F16.
     5    I15,F21.4/33H0CORRELATION COEFFICIENT (R**2) =,F9.5)
C
C         PRINT TABLE OF RESIDUALS
C
      PRINT 12
   12 FORMAT (19H1TABLE OF RESIDUALS
     1         /1H0,4X,29HOBSERVATION NO.    OBSERVED Y,8X,8HFITTED Y,8
     2          8HRESIDUAL/)
      DO 1060  I=1,NPTS
 1060 PRINT 13, I,DATMAT(I,NDEPND),YFIT(I),RESID(I)
   13 FORMAT (10X,I3,10X,F11.5,6X,F11.5,5X,F10.5)
      GO TO 10
      END
      SUBROUTINE MATINV
C
C         MATRIX INVERSION
C
```

```
      COMMON A,N
      DIMENSION A(10,10),INDEX(10,3)
      EQUIVALENCE (IROW,JROW),(ICCLUM,JCOLUM),(AMAX,T,SWAP)
      DO 60  J=1,N
   60 INDEX(J,3)=0
C
C        SEARCH FOR PIVOT ELEMENT
C
      DO 550  I=1,N
      AMAX=0.0
      DO 105  J=1,N
      IF (INDEX(J,3).EQ.1) GO TO 105
      DO 100  K=1,N
      IF (INDEX(K,3)-1) 80,100,715
   80 IF (AMAX.GE.ABS(A(J,K))) GO TO 100
      IROW=J
      ICOLUM=K
      AMAX=ABS(A(J,K))
  100 CONTINUE
  105 CONTINUE
      INDEX(ICOLUM,3)=INDEX(ICOLUM,3)+1
      INDEX(I,1)=IROW
      INDEX(I,2)=ICOLUM
      IF (IROW.EQ.ICOLUM) GO TO 310
C
C        INTERCHANGE ROWS
C
      DO 200  L=1,N
      SWAP=A(IROW,L)
      A(IROW,L)=A(ICOLUM,L)
  200 A(ICOLUM,L)=SWAP
C
C        REDUCE NON-PIVOT ROWS
C
  310 PIVOT=A(ICOLUM,ICOLUM)
      A(ICOLUM,ICOLUM)=1.0
      DO 350  L=1,N
  350 A(ICOLUM,L)=A(ICOLUM,L)/PIVOT
      DO 550  L1=1,N
      IF (L1.EQ.ICOLUM) GO TO 550
      T=A(L1,ICOLUM)
      A(L1,ICOLUM)=0.0
      DO 450  L=1,N
  450 A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
  550 CONTINUE
C
C        INTERCHANGE COLUMNS
C
      DO 710  I=1,N
      L=N+1-I
      IF (INDEX(L,1).EQ.INDEX(L,2)) GO TO 710
      JROW=INDEX(L,1)
      JCOLUM=INDEX(L,2)
      DO 705  K=1,N
      SWAP=A(K,JROW)
      A(K,JROW)=A(K,JCOLUM)
  705 A(K,JCOLUM)=SWAP
  710 CONTINUE
      DO 730  K=1,N
      IF (INDEX(K,3).NE.1) GO TO 715
  730 CONTINUE
      RETURN
```

```
C
C         PRINT ERROR MESSAGE
C
  715 PRINT 99
   99 FORMAT (61HOINVERSE OF MATRIX CANNOT BE COMPUTED -- EXECUTION TERM
     1INATED)
      STOP
      END
          FINIS
$MAP=N
$X,LGO
   LINRG 25 3 2
(4X,F5.1,E6.1,F5.1)
35.3 20.0 10.98 35.3
29.7 20.0 11.13 29.7
30.8 23.0 12.51 30.8
58.8 20.0  8.40 58.8
61.4 21.0  9.27 61.4
71.3 22.0  8.73 71.3
74.4 11.0  6.36 74.4
76.7 23.0  8.50 76.7
70.7 21.0  7.82 70.7
57.5 20.0  9.14 57.5
46.4 20.0  8.24 46.4
28.9 21.0 12.19 28.9
28.1 21.0 11.88 28.1
39.1 19.0  9.57 39.1
46.8 23.0 10.94 46.8
48.5 20.0  9.58 48.5
59.3 22.0 10.09 59.3
70.0 22.0  8.11 70.0
70.0 11.0  6.83 70.0
74.5 23.0  8.88 74.5
72.1 20.0  7.68 72.1
58.1 21.0  8.47 58.1
44.6 20.0  8.86 44.6
33.4 20.0 10.36 33.4
28.6 22.0 11.08 28.6
```

```
0001          PROGRAM CON95
0002      C
0003      C       DOUG BEECROFT, ENVIRONMENTAL PROTECTION SERVICE, OCTOBER 1972
0004      C
0005      C       THIS PROGRAM COMPUTES THE 95 PERCENT CONFIDENCE LIMITS FOR ANY
0006      C       LINEAR REGRESSION EQUATION.  THE NECESSARY DATA CARDS ARE
0007      C       LISTED BELOW.
0008      C
0009      C            A.  COL.  1- 8  PROBLM, AN EIGHT CHARACTER ALPHANUMERIC
0010      C                            CODE USED TO IDENTIFY THE PROBLEM.
0011      C
0012      C                COL.  9-11  NPTS, THE NUMBER OF OBSERVATIONS USED IN
0013      C                            COMPUTING THE REGRESSION COEFFICIENTS.
0014      C                            NPTS MUST BE LESS THAN 501.
0015      C
0016      C                COL. 12-13  NVAR, THE TOTAL NUMBER OF VARIABLES
0017      C                            INVOLVED IN THE REGRESSION (THE NUMBER OF
0018      C                            INDEPENCENT VARIABLES + 1).  NVAR MUST BE
0019      C                            LESS THAN 11.
0020      C
0021      C                COL. 14-16  NLIM, THE NUMBER OF CONFIDENCE LIMITS TO
0022      C                            BE COMPUTED.
0023      C
0024      C                COL. 17-30  VARYNC, THE RESIDUAL MEAN SQUARE OR
0025      C                            VARIANCE ABOUT THE REGRESSION.  THIS
0026      C                            STATISTIC IS GIVEN IN THE ANALYSIS OF
0027      C                            VARIANCE TABLE COMPUTED BY LINRG OR STPRG
0028      C                            THE NUMBER MUST CONTAIN A DECIMAL POINT.
0029      C
0030      C            B.  THE COMPUTED REGRESSION COEFFICIENTS.  EACH
0031      C                            COEFFICIENT, BEGINNING WITH THE CONSTANT
0032      C                            TERM AND FOLLOWED BY THE VARIABLE
0033      C                            COEFFICIENTS, IN ORDER, MUST OCCUPY 15
0034      C                            COLUMNS OF THE CARD.  IF NVAR IS GREATER
0035      C                            THAN 5, TWO CARDS WILL BE REQUIRED.
0036      C
0037      C            C.  COL.  1-72  VARIABLE FORMAT CARD TO BE USED IN READIN
0038      C                            THE INPUT DATA.  SEE THE BMD MANUAL, PAGE
0039      C                            22-28 FOR A DESCRIPTION OF THIS TYPE OF
0040      C                            CARD.  ONLY THE INDEPENDENT VARIABLE
0041      C                            VALUES NEED BE READ IN.
0042      C
0043      C            D.  THE INPUT DATA.  THE RAW DATA FROM WHICH THE
0044      C                            REGRESSION COEFFICIENTS WERE CALCULATED.
0045      C                            THE OBSERVED VALUES OF THE DEPENDENT
0046      C                            VARIABLE MUST NOT BE INCLUDED.  VALUES
0047      C                            OF THE OTHER VARIABLES MUST APPEAR IN THE
0048      C                            SAME ORDER AS THEIR RESPECTIVE
0049      C                            COEFFICIENTS IN CARD B.
0050      C
0051      C            E.  COL.  1-72  VARIABLE FORMAT CARD TO BE USED IN READI
0052      C                            THE POINTS AT WHICH CONFIDENCE LIMITS AR
0053      C                            TO BE COMPUTED.
0054      C
```

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$I FCRTRAN(2,3)/MASTER     INTEGER WORD SIZE = 1 , * OPTION IS  OFF , 0 OPTION IS

LN 0055     C              F.  THE POINTS AT WHICH LIMITS ARE TO BE COMPUTED.  THE
LN 0056     C                              GENERAL FORM IS SIMILAR TO THE INPUT DAT
LN 0057     C
LN 0058     C              G.  EOF CARD (STANDARD C.C.I.W. GREY-STRIPED EOF)
LN 0059     C
LN 0060     C         NOTE -- CARDS A THROUGH F MAY BE REPEATED AS OFTEN AS DESIRED
LN 0061     C
LN 0062           COMMON COVINV,NVAR
LN 0063           DIMENSION COVINV(10,10),TVALUES(33),POINT(10),XMATRX(500,10)
LN 0064           DIMENSION VARFMT(9),COEFF(10)
LN 0065           DATA TVALUES /12.706,4.303,3.182,2.776,2.571,2.447,2.365,2.306,
LN 0066          1    2.262,2.228,2.201,2.179,2.160,2.145,2.131,2.120,2.110,2.101,
LN 0067          2    2.093,2.086,2.080,2.074,2.069,2.064,2.060,2.056,2.052,2.048,
LN 0068          3    2.045,2.042,2.021,2.000,1.980/
LN 0069     C
LN 0070     C         READ AND PRINT CONTROL INFORMATION
LN 0071     C
LN 0072          60 READ 99, PROBLM,NPTS,NVAR,NLIM,VARYNC,(COEFF(I),I=1,NVAR)
LN 0073          99 FORMAT (A8,I3,I2,I3,F14.4/5F15.5,5X)
LN 0074           IF (IFEOF(60).EQ.-1) STOP
LN 0075           READ 88, VARFMT
LN 0076          88 FORMAT (9A8)
LN 0077           DO 100  I=1,NPTS
LN 0078           XMATRX(I,1)=1.0
LN 0079         100 READ (60,VARFMT) (XMATRX(I,J),J=2,NVAR)
LN 0080           PRINT 77, PROBLM,NPTS,NVAR,NLIM,VARYNC
LN 0081           77 FORMAT (29H195 PERCENT CONFIDENCE LIMITS/
LN 0082          1         13HOPROBLEM CODE,A23/
LN 0083          2         23H NUMBER OF OBSERVATIONS,I13/
LN 0084          3         20H NUMBER OF VARIABLES,I16/
LN 0085          4         32H NUMBER OF LIMITS TO BE COMPUTED,I4/
LN 0086          5         21H RESIDUAL MEAN SQUARE,F19.4///
LN 0087          6         24HOREGRESSION COEFFICIENTS//11X,
LN 0088          7         22HVARIABLE   COEFFICIENT//)
LN 0089           DO 300  I=2,NVAR
LN 0090           J=I-1
LN 0091         300 PRINT 55, J,COEFF(I)
LN 0092          55 FORMAT (I16,F17.5)
LN 0093           PRINT 44, COEFF(1)
LN 0094          44 FORMAT (/10X,38HCONSTANT TERM IN PREDICTION EQUATION =,F12.5///
LN 0095          1              18HOCONFIDENCE LIMITS//10X,
LN 0096          2              48HLIMIT NO.   LOWER LIMIT   FITTED Y   UPPER LIMI
LN 0097     C
LN 0098     C         COMPUTE INVERSE OF COVARIANCE MATRIX
LN 0099     C
LN 0100           DO 700  I=1,NVAR
LN 0101           DO 700  J=1,NVAR
LN 0102           COVINV(I,J)=0.0
LN 0103           DO 700  K=1,NPTS
LN 0104         700 COVINV(I,J)=COVINV(I,J)+XMATRX(K,I)*XMATRX(K,J)
LN 0105     C
LN 0106     C         COMPUTE COVARIANCE MATRIX
LN 0107     C
LN 0108           CALL MATINV
```

```
I FORTRAN(2.3)/MASTER     INTEGER WORD SIZE = 1 , * OPTION IS OFF , 0 OPTION IS

N 0109     C
N 0110     C         READ IN THE CO-ORDINATES OF THE POINT AND COMPUTE THE FITTED Y
N 0111     C
N 0112           READ 88, VARFMT
N 0113           DO 70  J=1,NLIM
N 0114           POINT(1)=1.0
N 0115           READ (60,VARFMT) (POINT(I),I=2,NVAR)
N 0116           YFIT=COEFF(1)
N 0117           DO 200  I=2,NVAR
N 0118       200 YFIT=YFIT+COEFF(I)*POINT(I)
N 0119     C
N 0120     C         COMPUTE PRODUCT OF THE POINT AND THE COVARIANCE MATRIX
N 0121     C
N 0122           CONFID=0.0
N 0123           DO 800  I=1,NVAR
N 0124           SPARE=0.0
N 0125           DO 900  K=1,NVAR
N 0126       900 SPARE=SPARE+POINT(K)*COVINV(K,I)
N 0127       800 CONFID=CONFID+SPARE*POINT(I)
N 0128     C
N 0129     C         CHOOSE APPROPRIATE T VALUE AND COMPUTE CONFIDENCE LIMIT
N 0130     C
N 0131           IJK=NPTS-NVAR
N 0132           IF (IJK.GT.30) GO TO 10
N 0133           T=TVALUES(IJK)
N 0134           GO TO 20
N 0135        10 IF ( IJK.GT.35) GO TO 30
N 0136           T=TVALUES(30)
N 0137           GO TO 20
N 0138        30 IF (IJK.GT.50) GO TO 40
N 0139           T=TVALUES(31)
N 0140           GO TO 20
N 0141        40 IF (IJK.GT.90) GO TO 50
N 0142           T=TVALUES(32)
N 0143           GO TO 20
N 0144        50 T=TVALUES(33)
N 0145        20 CONFID=SQRT(CONFID*VARYNC)*T
N 0146           UP=YFIT+CONFID
N 0147           DOWN=YFIT-CONFID
N 0148        70 PRINT 66, J,DOWN,YFIT,UP
N 0149        66 FORMAT (I15,F18.5,F11.5,F14.5)
N 0150           GO TO 60
N 0151           END

    USASI FORTRAN DIAGNOSTIC RESULTS FOR CON95

         NO ERRORS
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```
NSI FORTRAN(2,3)/MASTER     INTEGER WORD SIZE = 1 , * OPTION IS  OFF , 0 OPTION IS

AN 0001           SUBROUTINE MATINV
N 0002      C
N 0003      C        MATRIX INVERSION
N 0004      C
N 0005            COMMON A,N
N 0006            DIMENSION A(10,10),INDEX(10,3)
N 0007            EQUIVALENCE (IROW,JROW),(ICOLUM,JCOLUM),(AMAX,T,SWAP)
N 0008            DO 60  J=1,N
N 0009         60 INDEX(J,3)=0
N 0010      C
N 0011      C        SEARCH FOR PIVOT ELEMENT
N 0012      C
N 0013            DO 550  I=1,N
N 0014            AMAX=0.0
N 0015            DO 105  J=1,N
N 0016            IF (INDEX(J,3).EQ.1) GO TO 105
N 0017            DO 100  K=1,N
N 0018            IF (INDEX(K,3)-1) 80,100,715
N 0019         80 IF (AMAX.GE.ABS(A(J,K))) GO TO 100
N 0020            IROW=J
N 0021            ICOLUM=K
N 0022            AMAX=ABS(A(J,K))
N 0023        100 CONTINUE
N 0024        105 CONTINUE
N 0025            INDEX(ICOLUM,3)=INDEX(ICOLUM,3)+1
N 0026            INDEX(I,1)=IROW
N 0027            INDEX(I,2)=ICOLUM
N 0028            IF (IROW.EQ.ICOLUM) GO TO 310
N 0029      C
N 0030      C        INTERCHANGE ROWS
N 0031      C
N 0032            DO 200  L=1,N
N 0033            SWAP=A(IROW,L)
N 0034            A(IROW,L)=A(ICOLUM,L)
N 0035        200 A(ICOLUM,L)=SWAP
N 0036      C
N 0037      C        REDUCE NON-PIVOT ROWS
N 0038      C
N 0039        310 PIVOT=A(ICOLUM,ICOLUM)
N 0040            A(ICOLUM,ICOLUM)=1.0
N 0041            DO 350  L=1,N
N 0042        350 A(ICOLUM,L)=A(ICOLUM,L)/PIVOT
N 0043            DO 550  L1=1,N
N 0044            IF (L1.EQ.ICOLUM) GO TO 550
N 0045            T=A(L1,ICOLUM)
N 0046            A(L1,ICOLUM)=0.0
N 0047            DO 450  L=1,N
N 0048        450 A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
N 0049        550 CONTINUE
N 0050      C
N 0051      C        INTERCHANGE COLUMNS
N 0052      C
N 0053            DO 710  I=1,N
N 0054            L=N+1-I
```

```
I FCRTRAN(2.3)/MASTER     INTEGER WORD SIZE = 1 , * OPTION IS OFF , 0 OPTION IS

N 0055           IF (INDEX(L,1).EQ.INDEX(L,2)) GO TO 710
N 0056           JROW=INDEX(L,1)
N 0057           JCOLUM=INDEX(L,2)
N 0058           DO 705  K=1,N
N 0059           SWAP=A(K,JROW)
N 0060           A(K,JROW)=A(K,JCOLUM)
N 0061       705 A(K,JCOLUM)=SWAP
N 0062       710 CONTINUE
N 0063           DO 730  K=1,N
N 0064           IF (INDEX(K,3).NE.1) GO TO 715
N 0065       730 CONTINUE
N 0066           RETURN
N 0067     C
N 0068     C        PRINT ERROR MESSAGE
N 0069     C
N 0070       715 PRINT 99
N 0071        99 FORMAT (61HOINVERSE OF MATRIX CANNOT BE COMPUTED -- EXECUTION TE
N 0072          1INATED)
N 0073           STOP
N 0074           END

    USASI FORTRAN DIAGNOSTIC RESULTS FOR MATINV

          NO ERRORS
```

95 PERCENT CONFIDENCE LIMITS

PROBLEM CODE	95 CONF
NUMBER OF OBSERVATIONS	21
NUMBER OF VARIABLES	2
NUMBER OF LIMITS TO BE COMPUTED	5
RESIDUAL MEAN SQUARE	0.0566

REGRESSION COEFFICIENTS

VARIABLE	COEFFICIENT
1	-7128.00000

CONSTANT TERM IN PREDICTION EQUATION = 3.35000

CONFIDENCE LIMITS

LIMIT NO.	LOWER LIMIT	FITTED Y	UPPER LIMIT
1	2.47157	2.64433	2.81709
2	2.77093	2.90806	3.04519
3	3.24133	3.35000	3.45867
4	3.63441	3.77055	3.90669
5	3.98338	4.17685	4.37031

APPENDIX D

NITROGEN BALANCES

NITROGEN BALANCES

The results of the nitrogen balances performed on the packed columns are summarized in Tables D-1 and D-2. For each balance, influent and effluent liquid samples were analyzed for soluble nitrate and nitrite nitrogen as well as for total unfiltered Kjeldahl nitrogen. It was assumed that this accounted for all of the significant nitrogen compounds, both organic and inorganic, in the system. A second set of influent and effluent samples were measured for dissolved nitrogen gas using the method outlined in Appendix B. The influent sample was obtained from the cooling unit which was located just upstream of the columns. Care was taken to avoid agitation of each sample and to keep it out of contact with the atmosphere once it was obtained. The effluent samples were collected from the port indicated in Figure D-1. The BOD bottle used for this was flushed with sufficient effluent to assure that the final sample had not come in contact with the outside atmosphere. In both cases, dissolved gas analyses were done within fifteen minutes of collection. Gas evolution rates were measured by a simple water displacement technique. The time required to collect one litre of gas was recorded as close as possible to the time of liquid sampling. Normally this took one half to three quarters of an hour. Figure D-1 also shows the method used to collect gas samples. Once again, precautions were taken to exclude air from the system well before gas samples were obtained. It is assumed that

the procedure used was adequate since the Gas Partitioner results showed no oxygen peaks.

TABLE - D1

DENITRIFICATION COLUMN F1

NITROGEN BALANCES

Aug. 9 (20°C)

Gas Flow = 57.6 l/day at 72 % N_2
Liquid Flow = 3298 l/day
Gas Temp = 22 degrees C

COMPONENT	INFLUENT		EFFLUENT		DIFF.
	mg/l	gm/day	mg/l	gm/day	(IN-OUT) gm/day
Unfiltered TKN	4.6	15.2	2.1	6.9	
NO_3-N	28.6	94.3	8.5	28.0	
NO_2-N	0.4	1.3	0.1	0.3	
Dissolved N_2	11.8	38.9	13.6	44.9	
Gaseous N_2	0.0	0.0	72%	48.0	
		149.7		128.1	21.6

Aug. 12 (20°C)

Gas Flow = 10.5 l/day at 66% N_2
Liquid Flow = 3224 l/day
Gas Temp = 22 degrees C

COMPONENT	INFLUENT		EFFLUENT		DIFF.
	mg/l	gm/day	mg/l	gm/day	(IN-OUT) gm/day
Unfiltered TKN	2.1	6.8	2.6	8.3	
NO_3-N	10.6	34.2	1.1	3.6	
NO_2-N	0.1	.3	0.0	0.0	
Dissolved N_2	15.3	49.3	16.6	53.5	
Gaseous N_2	0.0	0.0	66%	8.0	
		90.6		73.4	17.2

TABLE - D1 (CONTINUED)

Aug. 13 ($20^{o}C$)

Gas Flow = 83.9 1/day at 69% N_2
Liquid Flow = 3142 1/day
Gas Temp. = $22^{o}C$

COMPONENT	INFLUENT mg/l	INFLUENT gm/day	EFFLUENT mg/l	EFFLUENT gm/day	DIFF. (IN-OUT) gm/day
Unfiltered TKN	7.5	23.6	5.1	16.1	
NO_3-N	27.4	86.1	1.2	3.8	
NO_2-N	0.1	0.3	0.5	1.6	
Dissolved N_2	15.5	48.7	16.1	50.6	
Gaseous N_2	0.0	0.0	69%	67.0	
		158.7		139.1	19.6

TOTAL OF THREE DAYS 399.0 340.6 58.4

AVERAGE PERCENT NITROGEN LOSS = 15%

TABLE D2

DENITRIFICATION COLUMN F2

NITROGEN BALANCES

Aug. 13 (20°C)

Gas Flow = 63.4 l/day at 66.5% N_2
Liquid Flow = 3248 l/day
Gas Temp = 22°C

COMPONENT	INFLUENT mg/l	INFLUENT gm/day	EFFLUENT mg/l	EFFLUENT gm/day	DIFF. (IN-OUT)
Unfiltered TKN	8.7	28.9	6.4	21.3	
NO_3-N	27.0	89.7	3.7	12.3	
NO_2-N	0.1	0.3	1.2	4.0	
Dissolved N_2	17.2	57.2	17.2	57.2	
Gaseous N_2	-	-	66.5%	48.8	
		176.1		143.6	32.5

Aug. 14 (20°C)

Gas Flow = 27.4 l/day at 73.5% N_2
Liquid Flow = 3248 l/day
Gas Temp - 22°C

COMPONENT	INFLUENT mg/l	INFLUENT gm/day	EFFLUENT mg/l	EFFLUENT gm/day	DIFF. (IN-OUT)
Unfiltered TKN	5.4	17.5	4.3	14.0	
NO_3-N	22.2	72.1	4.8	15.6	
NO_2-N	0.3	1.0	1.5	4.9	
Dissolved N_2	16.5	53.6	16.0	52.0	
Gaseous N_2	-	-	73.5%	23.3	
		144.2		109.8	34.4

TABLE - D2 (CONTINUED)

Aug. 15 (20°C)

Gas Flow = 56.4 1/day at 76%
Liquid Flow = 3298 1/day
Gas Temp. = 22°C

COMPONENT	INFLUENT mg/1	INFLUENT gm/day	EFFLUENT mg/1	EFFLUENT gm/day	DIFF. (IN-OUT)
Unfiltered TKN	6.9	22.8	4.0	13.2	
NO_3-N	23.0	75.9	2.0	6.6	
NO_2-N	0.1	0.3	1.8	5.9	
Dissolved N_2	13.2	43.5	15.0	49.5	
Gaseous N_2	--	--	76%	49.6	
		142.5		124.8	17.7

Aug. 16 (20°C)

Gas Flow - 28.6 1/day at 76% N_2
Liquid Flow = 3176 1/day
Gas Temp. = 22°C

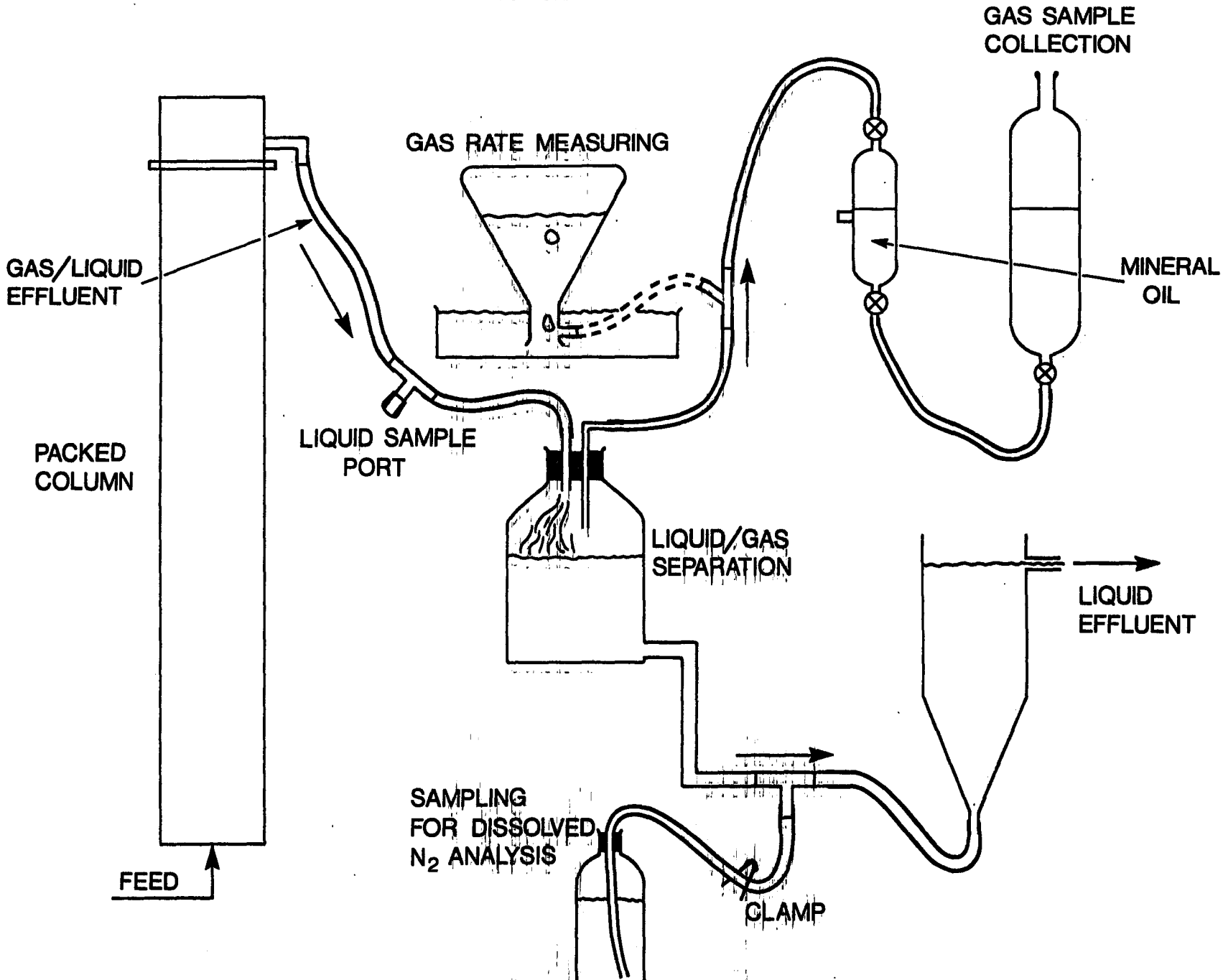
COMPONENT	INFLUENT mg/1	INFLUENT gm/day	EFFLUENT mg/1	EFFLUENT gm/day	DIFF. (IN-OUT)
Unfiltered TKN	4.4	14.0	3.9	12.4	
NO_3-N	26.0	82.6	2.6	8.3	
NO_2-N	0.1	0.3	4.3	13.7	
Dissolved N_2	15.2	48.3	17.2	54.6	
Gaseous N_2	-	-	76%	25.1	
		145.2		114.1	31.1

TOTAL OF FOUR DAYS	608.0	492.3	115.7

AVERAGE PERCENT NITROGEN LOSS = 19%

FIGURE D-1

SAMPLE COLLECTION FOR NITROGEN BALANCES



APPENDIX E

NITRIFICATION

TABLE E-1

CALCULATION OF RBC TKN REMOVAL RATES BASED ON ZERO ORDER KINETICS

Surface Area A = 250 ft^2 (23.2m^2)

RUN	TEMPERATURE	FLOW	SOL. TKN IN S_1	SOL. TKN OUT S_0	TKN REMOVAL RATES $\frac{(S_1-S_0)\ Flow}{A}$
	°C	1/hr	mg/1	mg/1	$mg/m^2 \cdot hr$
R16	7	89.3	22.7	18.9	14.7
R16	7	92.1	25.4	23.3	8.3
R8	7	49.8	20.6	12.7	17.0
R20	7	42.2	27.5	20.8	12.1
R21	7	42.2	27.5	18.9	15.7
R1	10	49.8	19.4	10.4	19.3
R7	10	49.8	20.2	9.9	22.1
R14	10	98.6	24.3	18.2	26.0
R15	12	104	37.6	34.2	15.2
R6	13.5	51.2	31.4	23.5	17.5
R3	15	50.1	26.6	12.5	30.6
R4	15	48.5	33.2	17.4	33.2
R5	15	50.1	38.9	13.1	34.2
R10	20	50.1	47.7	25.4	48.3
R11	20	48.5	41.1	21.4	41.3
R13	20	95.1	39.8	26.3	55.5
R12	21.5	95.1	34.3	18.3	65.8
R18	25	55.6	48.7	25.5	55.7
R19	25	47.7	56.2	25.0	64.3
R22	25	50.9	49.5	23.7	56.7
R23	25	49.0	59.4	33.8	54.2

TABLE E-2

CALCULATION OF TKN REMOVAL RATES FOR THE RBC BASED ON FIRST ORDER KINETICS

$$\text{Rate} = \frac{K \cdot C_2 \cdot V_{1/2}}{A_{1/2}}$$

$$K = \frac{1}{\bar{t}_{1/2}} \left[\left(\frac{C_0}{C_2} \right)^{1/2} - 1 \right]$$

$A_{1/2}$ = surface area of each CSTR. = 11.6 m^2

$V_{1/2}$ = hydraulic volume of each CSTR. = 64 ℓ

$\bar{t}_{1/2}$ = hydraulic detention time for each CSTR.

C_0 = influent soluble TKN concentration to the first CSTR.

C_2 = effluent soluble TKN concentration from the second CSTR.

RUN	TEMPERATURE	C_0	C_2	$\bar{t}_{1/2}$	K	RATE
	°C	mg/1	mg/1	hr	hr^{-1}	$mg/m^2 \cdot hr$
R16	7	22.7	18.9	.717	.132	13.8
R17	7	25.4	23.3	.717	.060	7.7
R8	7	20.6	12.7	1.285	.212	14.8
R20	7	27.5	20.8	1.52	.098	11.3
R21	7	27.5	18.9	1.52	.135	14.1
R1	10	19.4	10.4	1.29	.282	16.2
R7	10	20.2	9.9	1.29	.333	18.2
R14	10	24.3	18.2	.649	.237	23.8
R3	15	26.6	12.5	1.28	.358	24.6
R4	15	33.2	17.4	1.32	.288	27.7
R5	15	38.9	13.1	1.28	.38	27.5
R10	20	47.7	25.4	1.28	.288	40.3
R11	20	21.1	21.4	1.32	.291	34.4
R13	20	39.8	26.3	.673	.342	49.5
R18	25	48.7	25.5	1.15	.331	46.6
R19	25	56.2	25.0	1.34	.373	51.5
R22	25	49.5	23.7	1.26	.353	46.2
R23	25	59.4	33.8	1.31	.23	43.0

NITRIFICATION:

Analysis of Variance

The analysis of variance results for the linearized Arrhenius models were obtained from the output of Computer Programme No. 2 (Appendix C). The mean square pure error estimates were obtained from repeats (Himmelblau, 1970). If an F-test showed the mean square lack of fit to be not significantly greater than the error mean square at the 95% confidence level, it was inferred that in light of the pilot plant results, there was no lack of fit in the model.

ANOVA No. 1 RBC Results

Reparameterized and linearized Arrhenius Model

$$\ln K = -\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right) + \ln\left(Ae^{-E/RT_o}\right)$$

Regression Results

$$\ln K = -7128\left(\frac{1}{T} - \frac{1}{T_o}\right) + 3.35$$

where $T_o = 288$

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Total	242.819	21		
Mean	235.023	1		
Total (corrected for the mean)	7.796	20		
Regression	6.720	1	6.720	118.7
Residual	1.075	19	0.057	
*Pure Error (S^2_{PE})	.466	13	0.036	
Lack of Fit	.610	6	0.101	2.81

$F_{6,13,.95} = 2.92$

Pure Error Estimate

S_t^2 = estimated variance of data at T °C

ν_T = degrees of freedom at T °C (observations -1)

$$S_{PE}^2 = \frac{\nu_7 S_7^2 + \nu_{10} S_{10}^2 + \nu_{15} S_{15}^2 + \nu_{20} S_{20}^2 + \nu_{25} S_{25}^2}{\nu_7 + \nu_{10} + \nu_{15} + \nu_{20} + \nu_{25}}$$

$$S_{PE}^2 = \frac{4(.0834) + 2(.0224) + 2(.0035) + 2(.0204) + 3(.0131)}{4 + 2 + 2 + 2 + 3}$$

$= .036$; degrees of freedom = 13

ANOVA No. 2 Pilot Plant B Results

Reparameterized and linearized Arrhenius Model

$$\ln K = -\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right) + \ln\left(Ae^{-E/RT_o}\right)$$

Regression Results

$$\ln K = -10{,}200\left(\frac{1}{T} - \frac{1}{T_o}\right) - 3.055$$

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Total	274.953	23		
Mean	259.540	1		
Total (corrected for the mean)	15.413	22		
Regression	13.166	1	13.166	123.02
Residual	2.247	21	.107	
*Pure Error	.838	13	.0645	
Lack of Fit	1.409	8	.176	2.75

$F_{8,\ 13,\ .95} = 2.77$

* calculated in the same manner as above

Heat Transfer Coefficient for RBC

Programme No. 2 (Appendix C) was also used to fit a linear model to the heat flux and temperature driving force data which was calculated in Table E-3. The following model was used

$$y = ax + B$$

x = driving force between atmosphere and liquid in ^{o}C

a = heat transfer coefficient in Kcal/hr m^2 ^{o}C

B = constant term

Regression Result

$$y = 2.1 (T_{LIQ} - T_{ATM}) - 2.1$$

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Total	1594.9	20		
Mean	1.2	1		
Total (corrected for the mean)	1593.7	19		
Regression	1409.3	1	1409.3	137.5
Residual	184.4	18	10.2	

$$F_{1, 18, .95} = 4.41$$

Therefore, the regression model significantly reduces the residual sum of squares.

HEAT FLUX IN THE RBC

All heat flux data was taken from days in which the air conditioner was cooling the air circulating above the discs. This assures:

1. Conditions of air flow around the discs is similar for every set of data.
2. The air in the hood was at or close to 100% relative humidity for each set of data. This minimizes any evaporative cooling effects.

Total area of discs = 250 ft^2 (23.2 sq m)

DATE	FLOW	LIQ. TEMPERATURE		FLUX	AVE. TEMPERATURES		DRIVING FORCE
		IN	OUT		LIQ.	AIR.	
	kg/hr	°C	°C	$\frac{kcal}{m^2 hr}$	°C	°C	°C
26/06	49.9	17.75	16.4	-2.98	16.4	15	-1.5
02/07	50.4	15.0	15.3	.65	15.3	17.5	2.2
05/07	51.3	13.6	13.6	0.00	13.6	14	.4
08/07	49.0	6.1	8.9	5.90	8.9	10.5	1.6
10/07	49.9	6.0	10.0	8.62	10.0	12.	2.0
12/07	49.9	5.7	7.7	4.31	7.7	12	4.3
22/07	46.8	14.3	13.6	-1.42	13.6	13.3	- .3
16/08	97.2	8.3	10.2	7.97	10.2	15.0	4.8
20/08	98.5	7.8	9.6	7.63	9.6	15.0	5.4
21/08	86.3	8.4	9.6	4.48	9.6	15.0	5.4
22/08	104.4	10.6	11.6	4.48	11.6	15.3	3.7
27/08	89.4	5.4	6.9	5.78	6.9	11.3	4.4
28/08	87.6	4.4	7.0	10.2	6.2	12.7	6.5
29/08	92.2	4.3	7.0	10.7	6.3	9.8	3.5
30/08	94.4	5.5	7.4	7.72	6.9	10.3	3.4
16/09	50.4	20.5	14.0	-14.1	15.8	12	-3.8
17/09	50.4	20.0	15.0	-10.9	16.2	13.6	-2.6
18/09	46.3	20.3	13.8	-13.0	15.2	9.6	-5.6
19/09	50.8	20.0	13.9	-13.4	15.2	9.7	-5.5
20/09	54.5	24.0	16.4	-17.8	18.3	12	-6.3

APPENDIX F

DYE STUDIES

DYE STUDIES

All dye studies were conducted with a Turner Model 111 continuous flow fluorometer. The dye used in each run was prepared from 20% by weight stock Rodamine WT. For the RBC studies, a slug of dye was dumped into the feed end of the first compartment of the unit. In the case of the packed columns, a system was arranged such that dye could be injected into the feed lines with a syringe. In this way, the normal flows of the columns and the RBC were not disturbed during dye additon. Effluent samples were then taken at close intervals. Approximately 200 mℓ of each was filtered through .45 micron Gelman glass fiber filters. This provided a sufficient volume to permit fluorometer analysis by continuous flow. Before each experimental run, a filtered sample of reactor effluent was prepared to provide base line calibration of the fluorometer. The machine was re-zeroed every time the reading scale was changed. Calibration curves for the four fluorometer scales were provided by running dye solutions of known concentration through the unit. This produced straight line correlations between the fluorometer scale readings and dye concentration in parts per billion.

The dye study analysis programme listed in Appendix C was used to fit dispersion models and equal tanks in series models. The mean dye residence time for each study was also calculated and printed in the output.

Tank in Series Model

The particular flow patterns which produce the effluent dye concentration curves in tracer studies can often be approximated by effluent concentrations predicted for a number of equal sized continuous stirred tanks in series (CSTR's).

The final effluent of a system of j equal sized CSTR's can be found from the following equation:

$$\frac{C}{C_o} = \frac{j^j \theta^{j-1}}{(j-1)!} e^{-j\theta}$$

where: C = effluent tracer concentrations

θ = dimensionless time

j = number of tanks

C_o = the quantity of tracer added divided by the volume of the entire system.

This applies only to a pulse input of tracer. In this type of system, as j approaches large values (say 15), the flow regime approximates plug flow whereas, when j is equal to 1, the flow is completely mixed. If the time at which the peak dye concentration occurs is shown, the above equation can be solved for j by taking the derivative and equating the result to zero. Theta peak is determined by dividing the peak time by the residence time. The final form of the equation is:

$$j = \frac{1}{1 - \theta}$$

Dispersion Models

The dispersion model is developed in such a way that it assumes plug flow for a given reactor system with the inclusion of a term which describes the degree of molecular dispersion or deviation from the ideal. The general equation for this model is:

$$\frac{D\partial^2 C}{\partial x^2} - \frac{u\partial C}{\partial x} - \frac{C}{+} = 0$$

Where u = mean displacement velocity

C = concentration

$\frac{C}{x}$ = concentration gradient

$\frac{C}{+}$ = reaction term

D = turbulence expression

The solution of this equation for a tracer pulse input to a closed vessel given by Mujachi (1953) is quoted by Timpany (1967).

$$\frac{C}{C_o} = 2\sum_{n=1}^{\infty} \frac{U_n(U \sin U_n + U_n \cos n)}{(U^2 + 2U + U_n^2)} \text{ EXP } U - \left(\frac{U^2 + U_n^2}{2U}\right)\theta$$

where $U_n = \text{COT}^{-1} U_n \left(\frac{U_n}{U} - \frac{U}{U_n}\right)/2$

$U = \frac{uL}{2D}$

L = tank length

The value U_n is best calculated by trial and error using an iterative approach. Also, the summation in equation 4 is taken to some reasonably large but finite value

for practical purposes.

Instead of determining a value for D by the normal variance technique suggested by Levenspiel (1967), a correlation between peak time and D/uL developed by Timpany (1967) has been used. Proper use of the variance method for D/uL calculation generally requires concentration data to be entered to at least seven detention times. This is rarely practical.

The discussions given above form the basis for the analytical procedures designed into the computer programme.

The remainder of this Appendix lists summaries of the results for all of the dye studies that were run.

TRACER RESPONSE ANALYSIS

ROTATING BIOLOGICAL CONTACTOR.

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	127.00	LITRES
HYDRAULIC LOADING =	.82	LITRES/MIN
THEORETICAL DET. =	155.45	MIN
DYE INJECTION =	.0130	LITRES
CONC OF DYE ADDED =	.238E+07	PPB
DYE / TANK VOLUME =	212.60	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	70.50	MIN
PEAK/THEOR. DET =	.454	
PEAK/MEAN DYE RES =	.443	
MEAN DYE RESIDENCE =	159.00	MIN
PER DYE RECOVERY =	87.264	%
FR. STAGNANT ZONE =	-.023	

CSTR'S IN SERIES USING THEORETICAL RES. =	1.83
CSTR'S IN SERIES USING MEAN DYE RES. =	1.80
D/UL VALUE USING THEORETICAL RESIDENCE =	.4540E+00
D/UL VALUE USING MEAN DYE RESIDENCE =	.4767E+00

RBC TRACER STUDY CONDUCTED MAY 31 1974 AFTER GROWTH ON DISCS WAS ESTABLISHED.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.058	.028
.116	.188
.174	.400
.232	.517
.289	.583
.347	.635
.405	.663
.463	.673
.521	.659
.579	.635
.637	.611
.695	.579
.753	.555
.811	.527
.868	.508
.926	.494
.984	.470
1.042	.452
1.100	.433
1.158	.414
1.216	.390
1.274	.362
1.332	.329
1.390	.306
1.447	.287
1.505	.268
1.563	.249
1.621	.235
1.679	.221
1.737	.202
1.930	.174
2.123	.151
2.316	.132
2.509	.113
2.702	.094
2.895	.085
3.088	.075
3.281	.066
3.474	.061
3.667	.052
3.860	.052
4.053	.047
4.246	.040
4.439	.035
4.632	.031
4.825	.026

CALCULATED C/CO VERSUS THETA VALUES FOR CSTR IN SERIES MODEL

THEORETICAL DETENTION		ACTUAL DETENTION	
THETA	C/CO	THETA	C/CO
.050	.181	.050	.181
.100	.327	.100	.327
.150	.444	.150	.444
.200	.536	.200	.536
.250	.607	.250	.607
.300	.659	.300	.659
.350	.695	.350	.695
.400	.719	.400	.719
.450	.732	.450	.732
.500	.736	.500	.736
.550	.732	.550	.732
.600	.723	.600	.723
.650	.709	.650	.709
.700	.690	.700	.690
.750	.669	.750	.669
.800	.646	.800	.646
.850	.621	.850	.621
.900	.595	.900	.595
.950	.568	.950	.568
1.000	.541	1.000	.541
1.200	.435	1.200	.435
1.400	.341	1.400	.341
1.600	.261	1.600	.261
1.800	.197	1.800	.197
2.000	.147	2.000	.147
2.200	.108	2.200	.108
2.400	.079	2.400	.079
2.600	.057	2.600	.057
2.800	.041	2.800	.041
3.000	.030	3.000	.030
3.200	.021	3.200	.021
3.400	.015	3.400	.015
3.600	.011	3.600	.011
3.800	.008	3.800	.008
4.000	.005	4.000	.005
4.200	.004	4.200	.004

CALCULATED C/CO VERSUS THETA VALUES
FOR DISPERSION MODEL

THEORETICAL DETENTION		ACTUAL DETENTION	
.100	.051	.100	.062
.200	.463	.200	.492
.300	.783	.300	.799
.400	.899	.400	.902
.500	.896	.500	.890
.600	.838	.600	.827
.700	.758	.700	.747
.800	.674	.800	.664
.900	.594	.900	.585
1.000	.521	1.000	.513
1.100	.455	1.100	.449
1.200	.397	1.200	.392
1.300	.346	1.300	.342
1.400	.301	1.400	.299
1.500	.262	1.500	.260
1.600	.228	1.600	.227
1.700	.199	1.700	.198
1.800	.173	1.800	.173
1.900	.150	1.900	.151
2.000	.131	2.000	.131
2.100	.114	2.100	.114
2.200	.099	2.200	.100
2.300	.086	2.300	.087
2.400	.075	2.400	.076
2.500	.065	2.500	.066
2.600	.057	2.600	.058
2.700	.049	2.700	.050
2.800	.043	2.800	.044
2.900	.037	2.900	.038
3.000	.033	3.000	.033

TRACER RESPONSE ANALYSIS

ROTATING BIOLOGICAL CONTACTOR.

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	129.25	LITRES
HYDRAULIC LOADING =	1.68	LITRES/MIN
THEORETICAL DET. =	77.12	MIN
DYE INJECTION =	.1350	LITRES
CONC OF DYE ADDED =	.238E+06	PPB
DYE / TANK VOLUME =	220.31	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	44.00	MIN
PEAK/THEOR. DET =	.571	
PEAK/MEAN DYE RES =	.524	
MEAN DYE RESIDENCE =	84.00	MIN
PER DYE RECOVERY =	88.625	%
FR. STAGNANT ZONE =	-.089	

CSTR S IN SERIES USING THEORETICAL RES. =	2.33	
CSTR S IN SERIES USING MEAN DYE RES. =	2.10	
D/UL VALUE USING THEORETICAL RESIDENCE =	.2585E+00	
D/UL VALUE USING MEAN DYE RESIDENCE =	.3238E+00	

TRACER STUDY CONDUCTED ON AUGUST 19 1974 DURING A PERIOD OF HIGH HYDRAULIC LOADING.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.117	.499
.233	0.000
.350	.186
.467	.631
.584	.649
.700	.608
.817	.540
.934	.483
1.050	.424
1.167	.372
1.284	.334
1.400	.300
1.517	.266
1.634	.245
1.751	.220
1.867	.195
1.984	.182
2.101	.172
2.217	.159
2.334	.148
2.451	.135
2.567	.123
2.684	.113
2.801	.104
2.918	.098
3.034	.091
3.151	.085
3.268	.083
3.384	.078
3.501	.073
3.890	.061
4.279	.041
4.668	.027
5.057	.016

CALCULATED C/CO VERSUS THETA VALUES FOR CSTR IN SERIES MODEL

THEORETICAL DETENTION		ACTUAL DETENTION	
THETA	C/CO	THETA	C/CO
.050	.181	.050	.181
.100	.327	.100	.327
.150	.444	.150	.444
.200	.536	.200	.536
.250	.607	.250	.607
.300	.659	.300	.659
.350	.695	.350	.695
.400	.719	.400	.719
.450	.732	.450	.732
.500	.736	.500	.736
.550	.732	.550	.732
.600	.723	.600	.723
.650	.709	.650	.709
.700	.690	.700	.690
.750	.669	.750	.669
.800	.646	.800	.646
.850	.621	.850	.621
.900	.595	.900	.595
.950	.568	.950	.568
1.000	.541	1.000	.541
1.200	.435	1.200	.435
1.400	.341	1.400	.341
1.600	.261	1.600	.261
1.800	.197	1.800	.197
2.000	.147	2.000	.147
2.200	.108	2.200	.108
2.400	.079	2.400	.079
2.600	.057	2.600	.057
2.800	.041	2.800	.041
3.000	.030	3.000	.030
3.200	.021	3.200	.021
3.400	.015	3.400	.015
3.600	.011	3.600	.011
3.800	.008	3.800	.008
4.000	.005	4.000	.005
4.200	.004	4.200	.004

CALCULATED C/CO VERSUS THETA VALUES
FOR DISPERSION MODEL

THEORETICAL DETENTION		ACTUAL DETENTION	
.100	.002	.100	.010
.200	.160	.200	.267
.300	.514	.300	.636
.400	.793	.400	.855
.500	.925	.500	.925
.600	.944	.600	.905
.700	.897	.700	.839
.800	.817	.800	.755
.900	.725	.900	.667
1.000	.633	1.000	.583
1.100	.546	1.100	.505
1.200	.468	1.200	.436
1.300	.399	1.300	.375
1.400	.339	1.400	.322
1.500	.287	1.500	.276
1.600	.243	1.600	.237
1.700	.205	1.700	.203
1.800	.173	1.800	.174
1.900	.146	1.900	.149
2.000	.123	2.000	.127
2.100	.104	2.100	.109
2.200	.088	2.200	.093
2.300	.074	2.300	.080
2.400	.062	2.400	.068
2.500	.052	2.500	.058
2.600	.044	2.600	.050
2.700	.037	2.700	.043
2.800	.031	2.800	.037
2.900	.026	2.900	.031
3.000	.022	3.000	.027

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR	=	158.00	LITRES
HYDRAULIC LOADING	=	2.08	LITRES/MIN
THEORETICAL DET.	=	75.96	MIN
DYE INJECTION	=	.0070	LITRES
CONC OF DYE ADDED	=	.238E+07	PPB
DYE / TANK VOLUME	=	105.44	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME	=	64.70	MIN
PEAK/THEOR. DET	=	.852	
PEAK/MEAN DYE RES	=	.973	
MEAN DYE RESIDENCE	=	66.50	MIN
PER DYE RECOVERY	=	92.657	%
FR. STAGNANT ZONE	=	.125	

CSTR'S IN SERIES USING THEORETICAL RES.	=	6.75
CSTR'S IN SERIES USING MEAN DYE RES.	=	36.94
D/UL VALUE USING THEORETICAL RESIDENCE	=	.6681E-01
D/UL VALUE USING MEAN DYE RESIDENCE	=	.3729E-01

TRACER STUDY CONDUCTED ON COLUMN F1 JUNE 6 BEFORE ANY GROWTH HAD OCCURRED.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.020	0.000
.039	0.000
.059	0.000
.079	0.000
.099	0.000
.118	0.000
.138	0.000
.158	0.000
.178	0.000
.197	0.000
.217	0.000
.237	0.000
.257	0.000
.276	0.000
.296	0.000
.316	0.000
.336	0.000
.355	0.000
.375	0.000
.395	0.000
.415	0.000
.434	0.000
.454	0.000
.474	0.000
.494	0.000
.513	0.000
.533	.616
.553	.749
.573	.863
.592	.986
.658	1.214
.724	1.432
.790	1.660
.856	1.745
.922	1.318
.987	.967
1.053	.825
1.119	.759
1.185	.749
1.251	.266
1.316	.427
1.382	.275
1.448	.199
1.514	.175
1.580	.138
1.646	.126
1.711	.119
1.777	.104
1.843	.095

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	158.00	LITRES
HYDRAULIC LOADING =	2.21	LITRES/MIN
THEORETICAL DET. =	71.49	MIN
DYE INJECTION =	.0150	LITRES
CONC OF DYE ADDED =	.793E+06	PPB
DYE / TANK VOLUME =	63.59	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	7.00	MIN
PEAK/THEOR. DET =	.098	
PEAK/MEAN DYE RES =	.292	
MEAN DYE RESIDENCE =	24.00	MIN
PER DYE RECOVERY =	84.465	%
FP. STAGNANT ZONE =	.664	

CSTR S IN SERIES USING THEORETICAL RES. =	1.11	
CSTR S IN SERIES USING MEAN DYE RES. =	1.41	
D/UL VALUE USING THEORETICAL RESIDENCE =	.4501E+01	
D/UL VALUE USING MEAN DYE RESIDENCE =	.1043E+01	

TRACER STUDY #2 FOR COLUMN F1 WAS COMPLETED ON AUGUST 23 1974 BEFORE A GENTLE BACKWASH WAS CONDUCTED. THIS REPRESENTS APPROXIMATELY 74 DAYS OF CONTINUOUS OPERATION SINCE STARTUP.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.042	.629
.084	2.673
.126	2.611
.168	2.044
.210	1.557
.252	1.219
.294	.967
.336	.833
.378	.731
.420	.637
.462	.566
.504	.511
.546	.480
.587	.456
.629	.440
.671	.417
.713	.393
.755	.370
.797	.346
.839	.330
.881	.307
.923	.291
.965	.275
1.007	.252
1.049	.236
1.091	.220
1.133	.204
1.175	.189
1.217	.181
1.259	.173
1.399	.142
1.539	.126
1.678	.110
1.818	.102
1.958	.094
2.098	.079
2.238	.071
2.378	.063
2.518	.055
2.658	.055

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR	=	158.00	LITRES
HYDRAULIC LOADING	=	2.22	LITRES/MIN
THEORETICAL DET.	=	71.17	MIN
DYE INJECTION	=	.0150	LITRES
CONC OF DYE ADDED	=	.793E+06	PPB
DYE / TANK VOLUME	=	75.28	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME	=	6.50	MIN
PEAK/THEOR. DET	=	.091	
PEAK/MEAN DYE RES	=	.361	
MEAN DYE RESIDENCE	=	18.00	MIN
PER DYE RECOVERY	=	86.579	%
FR. STAGNANT ZONE	=	.747	
CSTR'S IN SERIES USING THEORETICAL RES.	=	1.10	
CSTR'S IN SERIES USING MEAN DYE RES.	=	1.57	
D/UL VALUE USING THEORETICAL RESIDENCE	=	.4941E+01	
D/UL VALUE USING MEAN DYE RESIDENCE	=	.7084E+00	

TRACER STUDY #3 WAS CONDUCTED ON AUGUST 23 1974 AFTER THE BACKWASH WAS FINISHED.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.042	.558
.084	3.294
.126	2.750
.169	2.032
.211	1.408
.253	.996
.295	.797
.337	.644
.379	.598
.422	.558
.464	.485
.506	.425
.548	.385
.590	.352
.632	.332
.674	.319
.717	.299
.759	.272
.801	.252
.843	.239
.885	.239
.927	.232
.969	.225
1.012	.220
1.054	.213
1.096	.205
1.138	.199
1.180	.186
1.222	.173
1.265	.159
1.405	.120
1.546	.100
1.686	.066
1.827	.053
1.967	.046

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	158.00	LITRES
HYDRAULIC LOADING =	2.33	LITRES/MIN
THEORETICAL DET. =	67.81	MIN
DYE INJECTION =	.0150	LITRES
CONC OF DYE ADDED =	.793E+06	PPB
DYE / TANK VOLUME =	75.28	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	16.00	MIN
PEAK/THEOR. DET =	.236	
PEAK/MEAN DYE RES =	.727	
MEAN DYE RESIDENCE =	22.00	MIN
PER DYE RECOVERY =	102.004	%
FR. STAGNANT ZONE =	.676	
CSTR'S IN SERIES USING THEORETICAL RES. =		1.31
CSTR'S IN SERIES USING MEAN DYE RES. =		3.67
D/UL VALUE USING THEORETICAL RESIDENCE =		.1385E+01
D/UL VALUE USING MEAN DYE RESIDENCE =		.1216E+00

TRACER STUDY #4 FOR COLUMN F1 WAS RUN ON AUGUST 25 1974 AFTER COMPLETION OF A 16 HOUR BACKWASH AT A HIGH HYDRAULIC FLOW.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.088	.013
.177	2.285
.265	3.161
.354	1.687
.442	.903
.531	.558
.619	.412
.708	.319
.796	.266
.885	.226
.973	.193
1.062	.167
1.150	.151
1.239	.135
1.327	.120
1.416	.112
1.504	.104
1.593	.096
1.681	.082
1.770	.066
1.858	.054
1.947	.046
2.035	.040
2.124	.040
2.212	.033
2.301	.033
2.389	.027
2.477	.027
2.566	.020
2.654	.020
2.949	.013

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR	=	158.00	LITRES
HYDRAULIC LOADING	=	2.24	LITRES/MIN
THEORETICAL DET.	=	70.54	MIN
DYE INJECTION	=	.0150	LITRES
CONC OF DYE ADDED	=	.793E+06	PPB
DYE / TANK VOLUME	=	75.28	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME	=	57.80	MIN
PEAK/THEOR. DET	=	.819	
PEAK/MEAN DYE RES	=	.814	
MEAN DYE RESIDENCE	=	71.00	MIN
PER DYE RECOVERY	=	100.764	%
FR. STAGNANT ZONE	=	-.007	

CSTR S IN SERIES USING THEORETICAL RES.	=	5.54
CSTR S IN SERIES USING MEAN DYE RES.	=	5.38
D/UL VALUE USING THEORETICAL RESIDENCE	=	.7805E-01
D/UL VALUE USING MEAN DYE RESIDENCE	=	.8008E-01

TRACER STUDY #5 FOR COLUMN F1 WAS DONE ON SEPTEMBER 8 1974 AFTER COLUMN CLEANOUT AND BEFORE GROWTH HAD RESTARTED.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.043	0.000
.085	0.000
.128	0.000
.170	0.000
.213	0.000
.255	0.000
.298	0.000
.340	0.000
.383	0.000
.425	0.000
.468	0.000
.510	0.000
.553	.033
.595	.246
.638	.638
.681	1.009
.723	1.395
.766	1.501
.808	1.521
.851	1.514
.893	1.461
.936	1.381
.978	1.262
1.021	1.129
1.063	1.009
1.106	.897
1.148	.784
1.191	.684
1.233	.598
1.276	.525
1.418	.425
1.559	.359
1.701	.306
1.843	.239
1.985	.166
2.127	.120
2.268	.053

CALCULATED C/CO VERSUS THETA VALUES FOR CSTR IN SERIES MODEL

THEORETICAL DETENTION		ACTUAL DETENTION	
THETA	C/CO	THETA	C/CO
.050	.000	.050	.001
.100	.002	.100	.008
.150	.012	.150	.031
.200	.037	.200	.077
.250	.085	.250	.146
.300	.156	.300	.235
.350	.250	.350	.340
.400	.361	.400	.451
.450	.482	.450	.563
.500	.605	.500	.668
.550	.722	.550	.762
.600	.826	.600	.840
.650	.913	.650	.901
.700	.980	.700	.944
.750	1.025	.750	.969
.800	1.048	.800	.977
.850	1.052	.850	.970
.900	1.037	.900	.949
.950	1.007	.950	.918
1.000	.964	1.000	.877
1.200	.722	1.200	.669
1.400	.470	1.400	.456
1.600	.276	1.600	.286
1.800	.150	1.800	.169
2.000	.076	2.000	.095
2.200	.037	2.200	.051
2.400	.017	2.400	.027
2.600	.008	2.600	.013
2.800	.003	2.800	.007
3.000	.001	3.000	.003
3.200	.001	3.200	.002
3.400	.000	3.400	.001
3.600	.000	3.600	.000
3.800	.000	3.800	.000
4.000	.000	4.000	.000
4.200	.000	4.200	.000

CALCULATED C/CO VERSUS THETA VALUES FOR DISPERSION MODEL

THEORETICAL DETENTION		ACTUAL DETENTION	
.100	.000	.100	-.000
.200	.000	.200	.000
.300	.024	.300	.027
.400	.186	.400	.198
.500	.525	.500	.540
.600	.893	.600	.902
.700	1.144	.700	1.143
.800	1.232	.800	1.222
.900	1.184	.900	1.171
1.000	1.052	1.000	1.040
1.100	.884	1.100	.875
1.200	.714	1.200	.708
1.300	.559	1.300	.556
1.400	.428	1.400	.427
1.500	.322	1.500	.322
1.600	.238	1.600	.240
1.700	.174	1.700	.177
1.800	.127	1.800	.129
1.900	.091	1.900	.093
2.000	.065	2.000	.067
2.100	.047	2.100	.048
2.200	.033	2.200	.034
2.300	.023	2.300	.024
2.400	.016	2.400	.017
2.500	.012	2.500	.012
2.600	.008	2.600	.009
2.700	.006	2.700	.006
2.800	.004	2.800	.004
2.900	.003	2.900	.003
3.000	.002	3.000	.002

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	158.00	LITRES
HYDRAULIC LOADING =	2.31	LITRES/MIN
THEORETICAL DET. =	68.40	MIN
DYE INJECTION =	.0150	LITRES
CONC OF DYE ADDED =	.793E+06	PPB
DYE / TANK VOLUME =	75.28	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	52.20	MIN
PEAK/THEOR. DET. =	.763	
PEAK/MEAN DYE RES =	.768	
MEAN DYE RESIDENCE =	68.00	MIN
PER DYE RECOVERY =	108.662	%
FR. STAGNANT ZONE =	.006	

CSTR S IN SERIES USING THEORETICAL RES. =	4.22
CSTR S IN SERIES USING MEAN DYE RES. =	4.30
D/UL VALUE USING THEORETICAL RESIDENCE =	.1023E+00
D/UL VALUE USING MEAN DYE RESIDENCE =	.1001E+00

TRACER STUDY #6 FOR COLUMN F1 WAS RUN ON SEPTEMBER 10 1974, THIS WAS 2 DAYS AFTER STARTUP.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.088	0.000
.175	0.000
.263	0.000
.351	0.000
.439	.199
.526	.584
.614	1.049
.702	1.295
.789	1.328
.877	1.169
.965	1.016
1.053	.863
1.140	.704
1.228	.578
1.316	.472
1.404	.392
1.491	.332
1.579	.292
1.667	.272
1.754	.252
1.842	.232
1.930	.213
2.018	.193
2.105	.173
2.193	.139
2.281	.120
2.368	.102
2.456	.090
2.544	.076
2.632	.060
2.924	.027

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	158.00	LITRES
HYDRAULIC LOADING =	2.24	LITRES/MIN
THEORETICAL DET. =	70.54	MIN
DYE INJECTION =	.0150	LITRES
CONC OF DYE ADDED =	.793E+06	PPB
DYE / TANK VOLUME =	75.28	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	33.00	MIN
PEAK/THEOR. DET =	.468	
PEAK/MEAN DYE RES =	.500	
MEAN DYE RESIDENCE =	66.00	MIN
PER DYE RECOVERY =	103.262	%
FR. STAGNANT ZONE =	.064	

CSTR S IN SERIES USING THEORETICAL RES. =	1.88	
CSTR S IN SERIES USING MEAN DYE RES. =	2.00	
D/UL VALUE USING THEORETICAL RESIDENCE =	.4238E+00	
D/UL VALUE USING MEAN DYE RESIDENCE =	.3631E+00	

TRACER STUDY #7 FOR COLUMN F1 WAS DONE 6 DAYS AFTER STARTUP ON SEPTEMBER 14 1974.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CC
.085	0.000
.170	.213
.255	.458
.340	.717
.425	.810
.510	.810
.595	.784
.681	.744
.766	.697
.851	.638
.936	.578
1.021	.531
1.106	.485
1.191	.438
1.276	.398
1.361	.365
1.446	.339
1.531	.325
1.616	.306
1.701	.292
1.786	.279
1.871	.259
1.956	.239
2.042	.226
2.127	.213
2.212	.186
2.297	.153
2.382	.133
2.467	.106
2.552	.080
2.835	.066

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	158.00	LITRES
HYDRAULIC LOADING =	2.22	LITRES/MIN
THEORETICAL DET. =	71.17	MIN
DYE INJECTION =	.0150	LITRES
CONC OF DYE ADDED =	.753E+06	PPB
DYE / TANK VOLUME =	75.28	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	27.00	MIN
PEAK/THEOR. DET =	.379	
PEAK/MEAN DYE RES =	.482	
MEAN DYE RESIDENCE =	56.00	MIN
PER DYE RECOVERY =	105.642	%
FR. STAGNANT ZONE =	.213	

CSTR S IN SERIES USING THEORETICAL RES. =	1.61
CSTR S IN SERIES USING MEAN DYE RES. =	1.93
D/UL VALUE USING THEORETICAL RESIDENCE =	.6488E+00
D/UL VALUE USING MEAN DYE RESIDENCE =	.3956E+00

TRACER STUDY #8 FOR COLUMN F1 WAS DONE 14 DAYS AFTER STARTUP ON SEPTEMBER 22 1974.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CC
.084	.013
.169	.325
.253	.731
.337	.990
.422	1.003
.506	.956
.590	.877
.674	.790
.759	.704
.843	.624
.927	.545
1.012	.491
1.096	.438
1.180	.405
1.265	.379
1.349	.352
1.433	.319
1.517	.287
1.602	.255
1.686	.232
1.770	.213
1.855	.195
1.939	.183
2.023	.173
2.108	.166
2.192	.153
2.276	.139
2.361	.120
2.445	.100
2.529	.086
2.810	.046

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR	=	158.00	LITRES
HYDRAULIC LOADING	=	2.17	LITRES/MIN
THEORETICAL DET.	=	72.81	MIN
DYE INJECTION	=	.0150	LITRES
CONC OF DYE ADDED	=	.793E+06	PPB
DYE / TANK VOLUME	=	75.28	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME	=	14.00	MIN
PEAK/THEOR. DET	=	.192	
PEAK/MEAN DYE RES	=	.538	
MEAN DYE RESIDENCE	=	26.00	MIN
PER DYE RECOVERY	=	111.320	%
FR. STAGNANT ZONE	=	.643	

CSTR S IN SERIES USING THEORETICAL RES.	=	1.24
CSTR S IN SERIES USING MEAN DYE RES.	=	2.17
D/UL VALUE USING THEORETICAL RESIDENCE	=	.1822E+01
D/UL VALUE USING MEAN DYE RESIDENCE	=	.3017E+00

TRACER STUDY #9 FOR COLUMN F1 WAS DONE ON OCTOBER 2. THIS WAS 24 DAYS AFTER STARTUP.

CALCULATED C/CO VERSUS THETA VALUES FOR DISPERSION MODEL

THEORETICAL DETENTION		ACTUAL DETENTION	
.100	.744	.100	.007
.200	.921	.200	.231
.300	.860	.300	.600
.400	.775	.400	.838
.500	.696	.500	.927
.600	.624	.600	.918
.700	.559	.700	.857
.800	.501	.800	.774
.900	.449	.900	.684
1.000	.403	1.000	.597
1.100	.361	1.100	.517
1.200	.324	1.200	.445
1.300	.290	1.300	.382
1.400	.260	1.400	.327
1.500	.233	1.500	.280
1.600	.209	1.600	.239
1.700	.187	1.700	.204
1.800	.168	1.800	.174
1.900	.151	1.900	.148
2.000	.135	2.000	.126
2.100	.121	2.100	.107
2.200	.108	2.200	.092
2.300	.097	2.300	.078
2.400	.087	2.400	.066
2.500	.078	2.500	.057
2.600	.070	2.600	.048
2.700	.063	2.700	.041
2.800	.056	2.800	.035
2.900	.050	2.900	.030
3.000	.045	3.000	.025

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	158.00	LITRES
HYDRAULIC LOADING =	2.50	LITRES/MIN
THEORETICAL DET. =	63.20	MIN
DYE INJECTION =	.0150	LITRES
CONC OF DYE ADDED =	.357E+06	PPB
DYE / TANK VOLUME =	33.89	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	3.00	MIN
PEAK/THEOR. DET =	.047	
PEAK/MEAN DYE RES =	.693	
MEAN DYE RESIDENCE =	4.33	MIN
PER DYE RECOVERY =	121.324	%
FR. STAGNANT ZONE =	.932	

CSTR S IN SERIES USING THEORETICAL RES. =	1.05
CSTR S IN SERIES USING MEAN DYE RES. =	3.26
D/UL VALUE USING THEORETICAL RESIDENCE =	.1188E+02
D/UL VALUE USING MEAN DYE RESIDENCE =	.1434E+00

TRACER STUDY #10 WAS THE LAST STUDY FOR COLUMN F1 AND WAS FINISHED ON DECEMBER 6 1974.

PEAK TIME OUTSIDE LIMIT FOR D/UL CALCULATION

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR	=	163.00	LITRES
HYDRAULIC LOADING	=	2.52	LITRES/MIN
THEORETICAL DET.	=	64.68	MIN
DYE INJECTION	=	.0125	LITRES
CONC OF DYE ADDED	=	.238E+07	PPB
DYE / TANK VOLUME	=	182.52	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME	=	37.00	MIN
PEAK/THEOR. DET	=	.572	
PEAK/MEAN DYE RES	=	.831	
MEAN DYE RESIDENCE	=	44.50	MIN
PER DYE RECOVERY	=	98.996	%
FR. STAGNANT ZONE	=	.312	
CSTR S IN SERIES USING THEORETICAL RES.	=	2.34	
CSTR S IN SERIES USING MEAN DYE RES.	=	5.93	
D/UL VALUE USING THEORETICAL RESIDENCE	=	.2567E+00	
D/UL VALUE USING MEAN DYE RESIDENCE	=	.7366E-01	

TRACER STUDY #1 FOR COLUMN F2 WAS DONE ON JUNE 5 1974 PRIOR TO STARTUP OF DENITRIFICATION.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.023	0.000
.046	0.000
.070	0.000
.093	0.000
.116	0.000
.139	0.000
.162	0.000
.186	0.000
.209	0.000
.232	0.000
.255	.077
.278	.170
.301	.334
.325	.477
.348	.657
.371	.833
.394	1.057
.417	1.129
.441	1.381
.464	1.381
.487	1.562
.510	1.523
.533	1.507
.557	1.605
.580	1.479
.603	1.479
.626	1.523
.649	1.507
.673	1.452
.696	1.414
.773	1.189
.850	.920
.928	.674
1.005	.521
1.082	.466
1.160	.384
1.237	.345
1.314	.279
1.391	.192
1.469	.151
1.546	.137
1.623	.118

CALCULATED C/CO VERSUS THETA VALUES FOR CSTR IN SERIES MODEL

THEORETICAL DETENTION		ACTUAL DETENTION	
THETA	C/CO	THETA	C/CO
.050	.181	.050	.000
.100	.327	.100	.002
.150	.444	.150	.012
.200	.536	.200	.037
.250	.607	.250	.085
.300	.659	.300	.156
.350	.695	.350	.250
.400	.719	.400	.361
.450	.732	.450	.482
.500	.736	.500	.605
.550	.732	.550	.722
.600	.723	.600	.826
.650	.709	.650	.913
.700	.690	.700	.980
.750	.669	.750	1.025
.800	.646	.800	1.048
.850	.621	.850	1.052
.900	.595	.900	1.037
.950	.568	.950	1.007
1.000	.541	1.000	.964
1.200	.435	1.200	.722
1.400	.341	1.400	.470
1.600	.261	1.600	.276
1.800	.197	1.800	.150
2.000	.147	2.000	.076
2.200	.108	2.200	.037
2.400	.079	2.400	.017
2.600	.057	2.600	.008
2.800	.041	2.800	.003
3.000	.030	3.000	.001
3.200	.021	3.200	.001
3.400	.015	3.400	.000
3.600	.011	3.600	.000
3.800	.008	3.800	.000
4.000	.005	4.000	.000
4.200	.004	4.200	.000

CALCULATED C/CO VERSUS THETA VALUES FOR DISPERSION MODEL

THEORETICAL DETENTION		ACTUAL DETENTION	
.100	.002	.100	.000
.200	.157	.200	.000
.300	.510	.300	.018
.400	.791	.400	.161
.500	.925	.500	.490
.600	.945	.600	.872
.700	.899	.700	1.147
.800	.819	.800	1.254
.900	.727	.900	1.213
1.000	.634	1.000	1.080
1.100	.548	1.100	.907
1.200	.469	1.200	.728
1.300	.400	1.300	.567
1.400	.339	1.400	.430
1.500	.288	1.500	.320
1.600	.243	1.600	.234
1.700	.205	1.700	.170
1.800	.173	1.800	.122
1.900	.146	1.900	.086
2.000	.123	2.000	.061
2.100	.104	2.100	.043
2.200	.087	2.200	.030
2.300	.074	2.300	.021
2.400	.062	2.400	.014
2.500	.052	2.500	.010
2.600	.044	2.600	.007
2.700	.037	2.700	.005
2.800	.031	2.800	.003
2.900	.026	2.900	.002
3.000	.022	3.000	.002

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	163.00	LITRES
HYDRAULIC LOADING =	2.29	LITRES/MIN
THEORETICAL DET. =	71.18	MIN
DYE INJECTION =	.0250	LITRES
CONC OF DYE ADDED =	.7693E+06	PPB
DYE / TANK VOLUME =	121.63	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	9.00	MIN
PEAK/THEOR. DET =	.126	
PEAK/MEAN DYE RES =	.346	
MEAN DYE RESIDENCE =	26.00	MIN
PER DYE RECOVERY =	89.244	%
FR. STAGNANT ZONE =	.635	
CSTR S IN SERIES USING THEORETICAL RES. =	1.14	
CSTR S IN SERIES USING MEAN DYE RES. =	1.53	
D/UL VALUE USING THEORETICAL RESIDENCE =	.3195E+01	
D/UL VALUE USING MEAN DYE RESIDENCE =	.7612E+00	

TRACER STUDY #2 FOR COLUMN F2 WAS DONE ON AUGUST 23 AFTER 73 DAYS OF CONTINUOUS OPERATION SINCE STARTUP.

EXPERIMENTAL RESULTS C/CC VERSUS THETA

THETA	C/CC
.084	1.110
.169	2.351
.253	1.217
.337	.691
.421	.510
.506	.411
.590	.325
.674	.288
.759	.267
.843	.247
.927	.230
1.012	.209
1.096	.194
1.180	.183
1.264	.173
1.349	.158
1.433	.146
1.517	.141
1.602	.136
1.686	.132
1.770	.119
1.854	.115
1.939	.107
2.023	.103
2.107	.099
2.192	.095
2.276	.090
2.360	.082
2.445	.074
2.529	.062
2.810	.049

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR	=	163.00	LITRES
HYDRAULIC LOADING	=	2.33	LITRES/MIN
THEORETICAL DET.	=	69.96	MIN
DYE INJECTION	=	.0150	LITRES
CONC OF DYE ADDED	=	.793E+06	PPB
DYE / TANK VOLUME	=	72.98	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME	=	10.00	MIN
PEAK/THEOR. DET	=	.143	
PEAK/MEAN DYE RES	=	.500	
MEAN DYE RESIDENCE	=	20.00	MIN
PER DYE RECOVERY	=	94.565	%
FR. STAGNANT ZONE	=	.714	

CSTR'S IN SERIES USING THEORETICAL RES.	=	1.17
CSTR'S IN SERIES USING MEAN DYE RES.	=	2.00
D/UL VALUE USING THEORETICAL RESIDENCE	=	.2711E+01
D/UL VALUE USING MEAN DYE RESIDENCE	=	.3631E+00

TRACER STUDY #3 FOR COLUMN F2 WAS DONE AFTER COMPLETION OF THE BACKWASH ON AUGUST 23 1974.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.086	.754
.172	3.220
.257	1.535
.343	.795
.429	.507
.515	.397
.600	.329
.686	.288
.772	.260
.858	.233
.943	.219
1.029	.212
1.115	.192
1.201	.185
1.287	.164
1.372	.123
1.458	.110
1.544	.096
1.630	.096
1.715	.089
1.801	.082
1.887	.082
1.973	.075
2.058	.075
2.144	.069
2.230	.062
2.316	.062
2.401	.055
2.487	.055
2.573	.048
2.859	.041

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR	=	163.00	LITRES
HYDRAULIC LOADING	=	2.33	LITRES/MIN
THEORETICAL DET.	=	69.96	MIN
DYE INJECTION	=	.0150	LITRES
CONC OF DYE ADDED	=	.793E+06	PPB
DYE / TANK VOLUME	=	72.98	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME	=	6.00	MIN
PEAK/THEOR. DET	=	.086	
PEAK/MEAN DYE RES.	=	.600	
MEAN DYE RESIDENCE	=	10.00	MIN
PER DYE RECOVERY	=	107.415	%
FR. STAGNANT ZONE	=	.857	
CSTR S IN SERIES USING THEORETICAL RES.	=	1.09	
CSTR S IN SERIES USING MEAN DYE RES.	=	2.50	
D/UL VALUE USING THEORETICAL RESIDENCE	=	.5375E+01	
D/UL VALUE USING MEAN DYE RESIDENCE	=	.2244E+00	

TRACER STUDY #4 FOR COLUMN F2 WAS DONE ON OCTERBER 2. THIS WAS ROUGHLY 118 DAYS AFTER THE INITIAL STARTUP.

EXPERIMENTAL RESULTS C/CO VERSUS THETA

THETA	C/CO
.043	1.932
.086	7.619
.129	5.522
.172	3.152
.214	1.781
.257	1.083
.300	.713
.343	.562
.386	.425
.429	.315
.472	.274
.515	.254
.557	.226
.600	.214
.643	.206
.686	.189
.729	.175
.772	.167
.815	.137
.858	.096
.901	.069
.943	.055
.986	.055
1.029	.052
1.072	.049
1.115	.047
1.158	.044
1.201	.041
1.244	.040
1.287	.038
1.429	.034

TRACER RESPONSE ANALYSIS

DENITRIFICATION COLUMNS

HYDRAULIC CHARACTERIZATION

TEST METHOD USING A PULSE INPUT OF RODAMINE DYE

REACTOR OPERATION AND TEST CONDITIONS

VOLUME OF REACTOR =	163.00	LITRES
HYDRAULIC LOADING =	2.40	LITRES/MIN
THEORETICAL DET. =	67.92	MIN
DYE INJECTION =	.0150	LITRES
CONC OF DYE ADDED =	.357E+06	PPB
DYE / TANK VOLUME =	32.85	PPB

TEST RESULTS AND CALCULATED VALUES

DYE PEAK TIME =	5.00	MIN
PEAK/THEOR. DET =	.074	
PEAK/MEAN DYE RES =	.667	
MEAN DYE RESIDENCE=	7.50	MIN
PER DYE RECOVERY =	92.109	%
FR. STAGNANT ZONE =	.890	

CSTR S IN SERIES USING THEORETICAL RES. =	1.08
CSTR S IN SERIES USING MEAN DYE RES. =	3.00
D/UL VALUE USING THEORETICAL RESIDENCE =	.6596E+01
D/UL VALUE USING MEAN DYE RESIDENCE =	.1628E+00

TRACER STUDY #5 FOR COLUMN F2 WAS THE LAST AND THIS WAS RUN ON DECEMBER 5.