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A PILOT PLANT EVALUATION OF NITRIFICATION IN FIXED-GROWTH REACTORS

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ABSTRACT

Many small municipalities may be faced with severe budgetary problems when forced to comply with effluent limitations on nutrient discharges. This study was undertaken to evaluate the performance of fixed-growth biological reactors for combined BOD_5 removal and nitrification. The conclusions are intended to provide an economical solution for upgrading existing treatment facilities.

Data was collected from two fixed-growth reactors over a period of one year. One unit was a conventional, circular, rock media reactor, while the other was a deep bed reactor incorporating a synthetic media. Data analysis consisted of a comparison of nitrification rates as a function of organic loading, ammonia loading, contact time, and temperature, in both systems. These results were also compared to those obtained in other investigations.

It was found that by using the hydraulic application rate, recycle ratio, and media depth as controlling variables, as high as 90% nitrification could be obtained while still achieving satisfactory secondary treatment. Applied BOD_5 loading, applied ammonia loading, and especially temperature were shown to influence the rate of nitrification in both reactors.

TABLE OF CONTENTS

TABLE OF CONTENTS CONTINUED

LIST OF FIGURES

LIST OF FIGURES CONTINUED | Page

LIST OF TABLES

INTRODUCTION

Recent concern over the quality of natural waters has led to increasing requirements for nutrient removal from domestic wastewater. Of the major vegetative nutrients available in a typical waste stream, nitrogen in the form of ammonia has the potential for being the most harmful. Several workers have documented the effects of ammonia on receiving waters (1-6). Ammonia nitrogen is in equilibrium in aqueous solution as given by Equation 1.

$$NH_4^+ = NH_3 + H^+, \ pK_a = 9.3 \qquad (1)$$

All nitrogen that exists in either of these two forms is considered to be ammonia nitrogen. Under pH conditions encountered in a domestic wastewater, most of the ammonia is in the ionized form.

In the process of nitrification, ammonia is oxidized by certain species of bacteria present in waste stream as well as in natural waters. As biological treatment becomes more prevalent, there is increasing concern over the non-carbonaceous oxygen demand (nitrogenous oxygen demand) exerted during nitrification. Methods of ammonia removal include controlled nitrification in fixed or suspended growth systems; air stripping; breakpoint chlorination; catalysis by activated carbon; and ion-exchange. These operations can be very efficient in affecting ammonia removal, but require significant capital and operating expenditures.

In the many small streams that serve as receiving waters for wastewater discharges in rural areas, nitrogenous oxygen demand is only of concern during the warmer months. This corresponds to periods of low flow and reduced dissolved oxygen (DO) levels, during which discharges containing ammonia may reduce the stream DO below the required minimum. Thus ammonia removal may be required, but only on a seasonal basis. As such, the incorporation of expensive treatment facilities is unwarranted for the typically low capacity plants located on these small streams. Many of these small plants already have conventional high-rate fixed-growth systems which could by proper operation satisfy the seasonal ammonia removal requirements.

To date, the operation of these fixed-growth reactors for optimization of nitrification has not been seriously considered. It is the possibility of such an optimization that is proposed as a method of upgrading treatment plants to meet at least seasonal ammonia discharge limitations.

STUDY OBJECTIVES

The objective of this study was to determine the operating conditions necessary to achieve a significant degree of nitrification in a fixed-growth system used to provide secondary treatment of domestic wastewater. A typical rock media reactor was compared to a deep, plastic media reactor for all parameters considered. The conclusions are intended to be used as design aids in upgrading existing trickling filter facilities and in planning new treatment schemes.

Several factors were of primary concern. By use of the hydraulic application rate and recycle ratio, the amount of organic substrate to each system was controlled. This enabled study of the effect of organic concentration (BOD_5) on the nitrification rate in each reactor. The effect of contact time was determined by using various media depths in conjunction with differences in construction and hydraulic residence time. Because fixed-growth reactors rely on mass transport across a liquid film, the ammonia concentration in the wastewater may affect the nitrification rate. To clearly show the rate of nitrification, overall nitrogen balances were performed across each reactor. As importantly, the dependency of system operation on wastewater temperature was closely investigated because of the direct application of results to the New England region.

BACKGROUND

Basic Operation of Fixed-Growth Reactors

Fixed-growth biological reactors, commonly referred to by the misnomer "trickling filters," have been used for domestic wastewater treatment since 1889 (15). They combine simplicity in operation and maintenance with stability in performance. By providing a surface to which the organisms may become attached, it is possible for solids to be retained for up to 100 days (6). Long solids retention times are necessary in biological systems to insure a stable nitrifying population. This is due to the difference in growth rates between the heterotrophic and the autotrophic populations. The shortest generation time for *Nitrosomonas sp*. in activated sludge is 2 days at 20°C, whereas the generation time for heterotrophic bacteria can be as short as 15 minutes (11). By employing a reactor with sufficient media surface area for the substrate loadings expected, it is possible to have simultaneous carbon and ammonia oxidation occur within the same reactor. The object of this study is to examine the operation of such a system.

Promoting Nitrification

The theory and operation of fixed-growth biological reactors is well known and will not be described here. There are several primary design parameters necessary for satisfactory operation of this type of system. Of interest are hydraulic surface application rate, recycle ratio, contact time, and substrate loadings.

Hydraulic application rate and recycle ratio are used to control flow and substrate loadings to the system. The application rate should insure adequate wetting of the media and proper distribution of substrates over the media surface. However, the hydraulic application should not create such high fluid velocities through the media pores that excessive amounts of organisms are detached from the surface and washed from the system. This phenomenon is known as washout and would first affect the nitrifying population because of their lower specific growth rate. When the mass loadings of substrate become too large for the amount of organisms available, effluent recycle is used to maintain adequate hydraulic loading while reducing the mass loading of the applied substrate.

Contact time between the wastewater and the biofilm is a function of media type, depth, and configuration. Contact time is not to be confused with flow through time. Craft and Ingols (16) state that there is no correlation between contact time and flow through time for different fixed-growth systems. Crushed rock has been the traditional type of media employed, but recent advances in plastics technology have made available artificial media with a much larger surface area per unit volume than rock. Being lighter, plastic media filters can be constructed with larger depths than rock filters.

Nitrification Reactions

The nitrification process is a series of biochemical reactions brought about by the respiration of several types of obligate, autotrophic, soil bacteria. The oxidation of ammonia nitrogen to nitrate nitrogen occurs in two distinct steps performed by different species of bacteria. The principal bacteria involved in the first step is Nitrosomonas sp. Other involved species are reported by Ripley (4). Equation 2 presents the biochemical reaction for the first step.

$$NH_4^+ + \frac{3}{2}O_2 \xrightarrow{\text{Nitrosomonas}} NO_2^- + H_2 \qquad (2)$$

In the second step, nitrite formed in the first step is oxidized to nitrate. The reaction is primarily performed by Nitrobactor sp. Equation 3 shows the biochemical reaction for the second step.

$$NO_2^- + \frac{1}{2}O_2 \xrightarrow{\text{Nitrobactor}} NO_3^- \qquad (3)$$

The rate limiting step of the overall process is the conversion of ammonia to nitrite. The second step is relatively instantaneous and explains why only negligible quantities of nitrite are found in active nitrifying environments. Since the species of bacteria responsible for both steps of the nitrification process are morphologically heterogenous, one step cannot be inhibited without affecting the other (7).

Factors Influencing Nitrification

The primary environmental conditions that influence the activity of nitrifying populations are pH, temperature, and DO. Although a pH of 8.4 is optimum for all species involved, organisms can acclimate to a practical range from 6.6 to 9.0, with resulting nitrification rates near the maximum (8,9). Abrupt changes in pH were shown to be more upsetting to the nitrification system than long term operation at a sub-optimum pH (10).

Temperature effects are very pronounced and under most treatment conditions, uncontrollable. Temperatures below 4°C result in a stoppage of nitrifying activity. An increase in the nitrification rate has been demonstrated to occur throughout the temperature range from 4 to 35°C (8). Hall (11) showed a doubling of the maximum specific growth rate for *Nitrosomonas sp*. for each 10°C temperature increase between 5 and 25°C.

In aqueous culture, DO levels below 0.5 mg/l have been shown to inhibit nitrification (8,12). This results from lower than stoichiometric requirements for oxygen as prescribed by Equations 2 and 3. Higher than necessary levels of DO may promote the growth of predatory crustaceans which can have a serious negative effect on the slow growing nitrifiers by depleting the biomass (10). These predators are normally present in fixed-growth systems.

Operating Conditions

When nitrifying bacteria are cultured in either suspended or fixed-growth systems for wastewater treatment, the composition of the wastewater also affects the growth and reaction rates. Nitrifying bacteria are more susceptable to damage from toxic materials than the heterotrophic bacteria found in conventional secondary treatment. Nitrification inhibitors have been described elsewhere (8).

Biochemical oxygen demand (BOD_5), alkalinity, ammonia nitrogen (NH_3-N), and suspended solids (SS), are all wastewater characteristics that must be considered in treatment facilities designed to accomplish nitrification. Because of the low specific growth rate of the autotrophs compared to the heterotrophic, carbonaceous bacteria, BOD_5 levels must be such that overcompetition from the heterotrophic population for the available growth sites does not eliminate the nitrifiers from the system. Excess BOD_5 and SS have both been shown to decrease the nitrification rate in treatment systems (6,9).

Sufficient wastewater alkalinity is necessary because the autotrophic bacteria destroy 7.2 pounds of alkalinity (as $CaCO_3$) for every pound of ammonia oxidized as a source of inorganic carbon. The overall nitrification reaction is given by Equation 4 (4,9,13).

$$22NH_4^+ + 37O_2 + 4CO_2 + HCO_3^- \longrightarrow C_5H_7O_2N + 21NO_3^- + 20H_2O + 42H^+ \quad (4)$$

Therefore, alkalinity must be present for cell synthesis and to act as a buffer against pH depression.

Low concentrations of substrate ammonia results in low nitrification rates, presumably due to the limiting rate of mass transfer through the bacterial cell wall. Several workers have shown that the nitrification rate does not increase in the range of ammonia concentrations from 6.0 to 600 mg/l (8,14). This implies that in suspended growth, the nitrification rate is zero-order and independent of substrate concentration. No substrate inhibition at high concentrations has been demonstrated.

METHODOLOGY

Pilot Plant Facilities

Data was obtained from parallel operation of two pilot-scale, fixed-growth reactors at the University of Massachusetts Wastewater Treatment Pilot Plant. Both units were exposed to the weather. Wastewater was supplied from a wet well which received primary effluent from the adjacent Amherst Sewage Treatment Plant. Most of the data used for the nitrification study was obtained from the more typical, fixed-growth reactor having a rock media. The other reactor has a media consisting of a tubular arrangement of plastic media. The two different media types were used to enable a comparison of relative performance. A flow diagram of the pilot plant is shown in Figure 1.

The rock media reactor is a conventional, circular unit with a diameter of 13 ft. (4 m.), giving an effective surface area for wastewater application of 133 ft^2 (12.6 m^2). An open impeller, submersible pump placed in the wet well supplied primary effluent to the filter up to a maximum capacity of 30 gpm (113.6 lpm). Recycle was provided by two closed impeller, high head pumps resulting in a combined maximum flow of 30 gpm (113.6 lpm). Hydraulic limitations were encountered because high recycle flows (>20 gpm) prevented the relatively low head wastewater supply pump from providing accurate, steady flow. For this reason, the upper limit on the range of available recycle ratios was 2.5.

The combined primary wastewater and recycle streams were applied

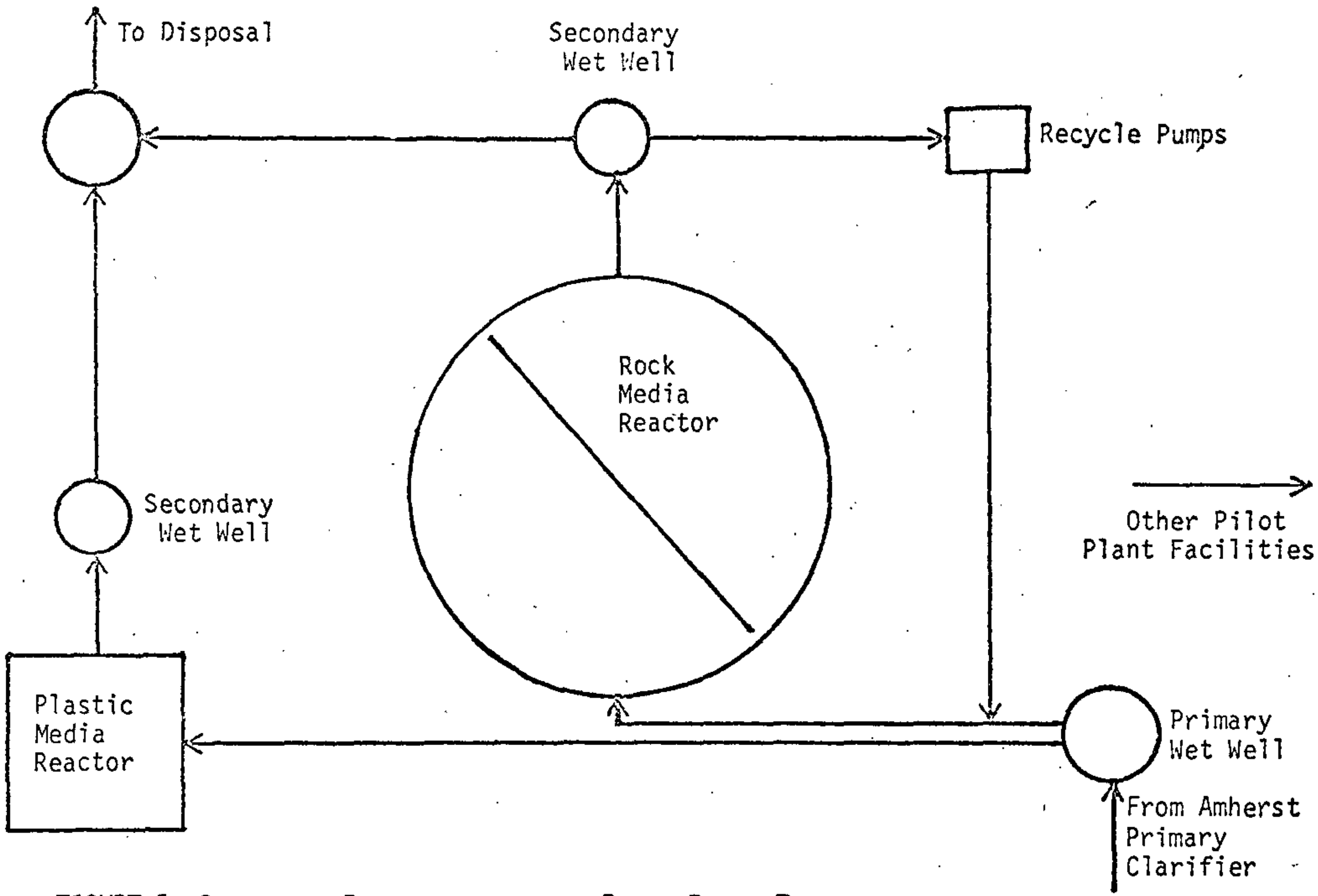

FIGURE 1 SCHEMATIC REPRESENTATION OF PILOT PLANT FACILITIES

to the surface of the rock media by a hydraulically activated distribution arm which rotated about the center of the filter. Three nozzles on each of the two rotor arms were equipped with hinged baffles to provide a fan shaped spray and an even application of the wastewater over the media surface. The construction of the distribution assembly created additional limitation to the scope of the study because surface applications of less than 0.20 gpm/ft^2 (8.13 lpm/m^2) did not produce sufficient reaction forces necessary to rotate the distribution arm.

The rock media originally consisted of a 5 ft (1.5 m) depth of 2 to 4 inch (5-10 cm) granite obtained from a nearby quarry. The media was supported over a standard high-rate, tile drainage system from which the secondary effluent is channeled into a wet well for recycle and/or final discharge. At about the midpoint of the study, another two feet of granite was added to increase the total media depth to 7 ft (2.1 m).

The plastic media reactor was of deep bed configuration, having a 24 ft. (7.3 m) depth of B.F. Goodrich Vinyl Core media. The media was constructed of vertical tubes having an approximate internal surface area of 66 ft^2/ft^3 (220 m^2/m^3). This was considerably greater than that of the rock media which was estimated at 19 ft^2/ft^3 (63 m^2/m^3)(17,18). The external surface application area for the plastic media reactor was 16 ft^2 (1.5 m^2).

The self-contained unit has two heavy duty, closed impeller pumps, each capable of delivering up to 20 gpm (76 lpm). One pump supplied the influent wastewater and the other the recycle. The influent to the plastic media reactor was obtained from the same wet well as that used for the rock media reactor (see Figure 1). Thus, the units were operated in parallel at all times. Effluent was collected in a small solids separation box located below the outlet of the plastic media tubes. The size of the box was such that only gross solids were separated; suspended and colloidal particles passed over the effluent weir. The recycle flow was pumped from the bottom of this box.

Both influent and recycle streams were pumped to the top of the tower into separate V-notch weir boxes for flow measurement and control. The flow from each weir box then went to a mixing box and finally to a perforated distribution header located directly above the media surface. Excess flow from the weir boxes and effluent from the tower were discharged to the secondary wet well. Overflow from the wet wells of each filter then flowed by gravity to a pump station for ultimate disposal to the sewer.

Several problems associated with the distribution system of the plastic media reactor resulted in hydraulic limitations similar to those encountered with the rock media reactor. To provide adequate wetting of the entire surface of the media, a minimum application of 1.0 gpm/ft^2 (40.7 lpm/m^2) was required. An upper limit of 2.5 gpm/ft^2 (101.8 lpm/m^2) at a recycle ratio of 1.0 was imposed by pump capacity. In addition, it was necessary to enclose the top of the filter with plastic to prevent wind gusts from blowing the wastewater away from the tower before it had reached the media surface. This presented both a control problem and a safety hazard.

Analytical Techniques

The operation of a fixed-growth biological reactor can be best described as pseudo steady-state; that is, while the hydraulic application was constant, there were daily variations in the strength of the wastewater associated with typical diurnal fluctuations in water use. Long term variations caused by student population changes in the Town of Amherst also significantly affect the amount and strength of the wastewater arriving at the treatment facility. Originally, 24 hour composite samplers were utilized on an equal flow basis since the actual wastewater application to the units was constant. When these samplers were no longer available, equal volume grab samples were taken on the hour from 9:00 A.M. to 3:00 P.M. and composited in sequence prior to analysis.

Since both units were operated in parallel, only one sample of the influent wastewater (primary effluent) was analyzed each day. This sample was obtained from the wet well receiving primary effluent. Effluent samples from each reactor were taken at the discharge pipe.

All analyses were performed daily, immediately following collection of the final sample. BOD_5, SS, $NH_3^{-}N$, organic nitrogen, and pH were measured in accordance with procedures outlined in Standard Methods (19). Nitrate concentrations were determined by the use of an Orion Specific Ion Electrode, which was standardized prior to each use. Before analyses were performed, each sample was allowed to settle for 30 minutes in a 1 liter beaker to simulate the action of a final clarifier, as suggested by Bruce et al. (17). Organic nitrogen determinations were performed on unsettled samples in order to obtain an overall nitrogen inventory. Analyses of dye concentrations in the contact time studies were performed using a Turner flourometer operated at maximum sensitivity.

Study Period

The rock media reactor was put back into operation at the beginning of March 1975, after extensive modification to the plumbing so that proper control of wastewater flow could be maintained. Except for relatively brief periods of mechanical failure, it was operated until the beginning of January 1976, when the study was concluded. The plastic media reactor was operated from June through December 1975, with considerably more downtime due mainly to electrical problems associated with the pumping systems. The conclusion of both studies was brought about by severe icing conditions due to the onset of prolonged cold in late December 1975.

RESULTS AND DISCUSSION

Contact Time

To make the comparison of nitrification rates in the two reactors more relevant, some indication of the length of contact time between the wastewater and the biological film is needed. The contact time is comprised of both the physical contact of the fluid with the biomass and free-fall. Due to the physical differences between the two types of media used here, the rock media reactor should have a larger proportion of free-fall time than the plastic media reactor because of the more tortuous path that a fluid droplet encounters during its passage through the rock media. While an important consideration, it is difficult to evaluate quantitatively the amount of time a fluid droplet spends in direct physical contact as compared with free-fall. Therefore in this study, contact time will refer to the mean length of the hydraulic residence time for a fluid droplet passing through the reactor.

Dye studies were performed on both reactors to establish the contact time for each. For the rock media reactor, a slug of Rhodamine WT dye was injected into the recycle line. Time zero was considered as the first appearance of the dye at the rotor nozzles. Once the dye was injected, the recycle was turned off to prevent dye recirculation. The correct application rate was maintained by an increase in the influent flow. The same procedure was followed in the plastic media reactor, except that the dye was introduced directly into the mixing box at the top of the tower and timing was initiated immediately.

Effluent dye concentrations for both reactors as a function of residence time are shown in Figures 2 and 3. No attempt was made to measure dye quantities to obtain a mass balance but only to acquire a relative comparison of concentrations. The mean contact time for the rock media reactor at a depth of 7 ft can be approximated from Figure 2 as about 140 seconds. As shown in Figure 3, the mean contact time for the plastic media reactor is only about 65 seconds or 50% that of the rock media reactor. As implied earlier, it may be misleading to conclude that the actual contact time through the rock media is greater than that through the plastic media. The dye studies can only be used to determine the overall hydraulic residence time for each reactor.

General Performance

In actual treatment plant practice, the most important concern is effluent quality. Figures 4 through 8 show the temporal variation in influent and effluent concentrations of BOD_5, $NH_3^{\cdot}N$, and $NO_3^{\cdot}N$ for both reactors. Generally, the performance of the plastic media reactor with respect to BOD_5 removal and nitrification was poorer than that of the rock media reactor. It is important to remember however that performance here is only described by effluent quality and not by mass removal rates.

Figures 4 and 5 show the extent of BOD_5 removals in the rock media reactor. For operation at higher recycle ratios, the effluent BOD_5 was consistently around 30 mg/l for both media depths investigated. BOD_5 removals were only slightly improved by operation at the greater media depth of 7 ft. Figure 8 shows that the plastic media reactor provided a

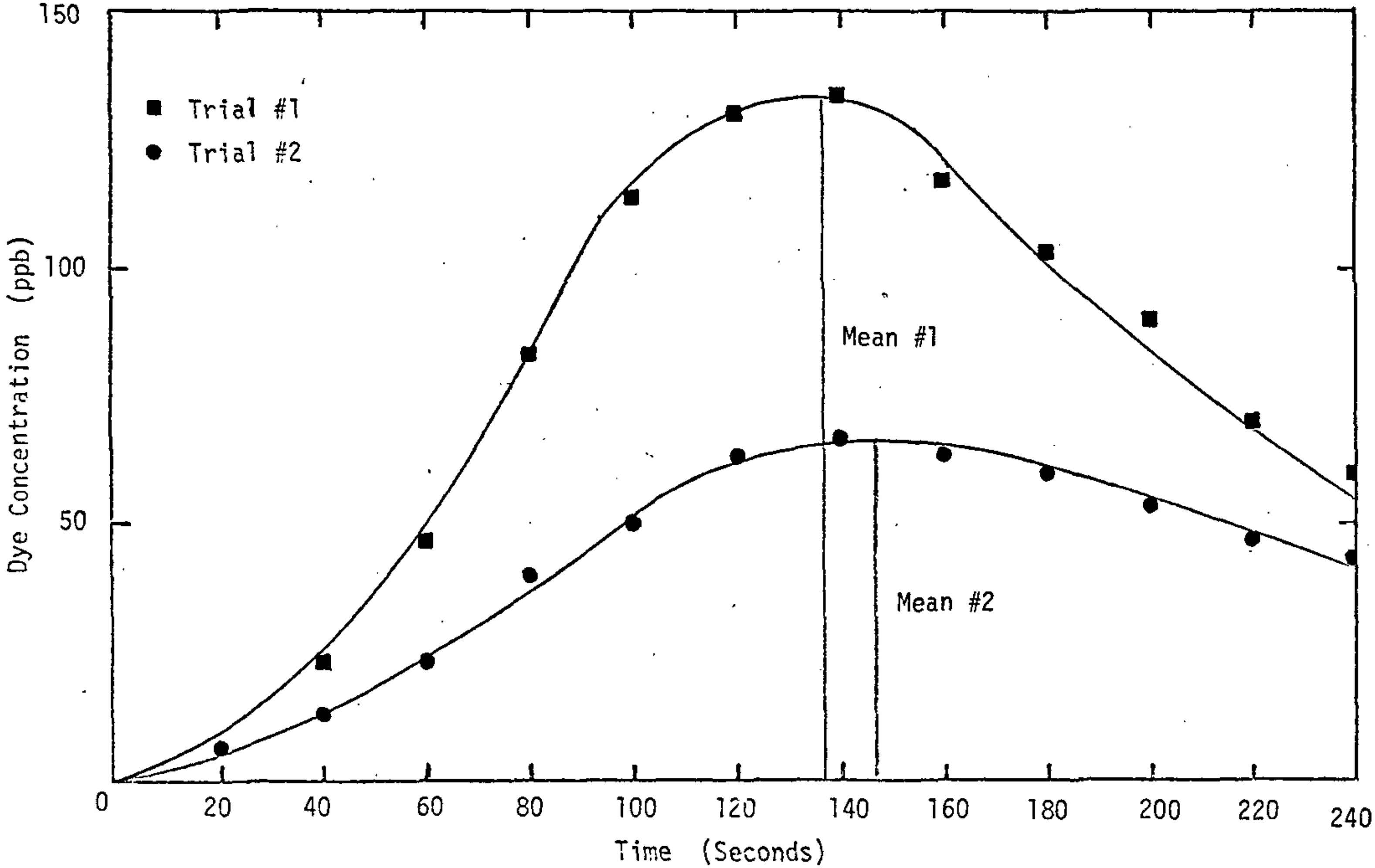

FIGURE 2. MEAN DETENTION TIME IN THE ROCK MEDIA REACTOR

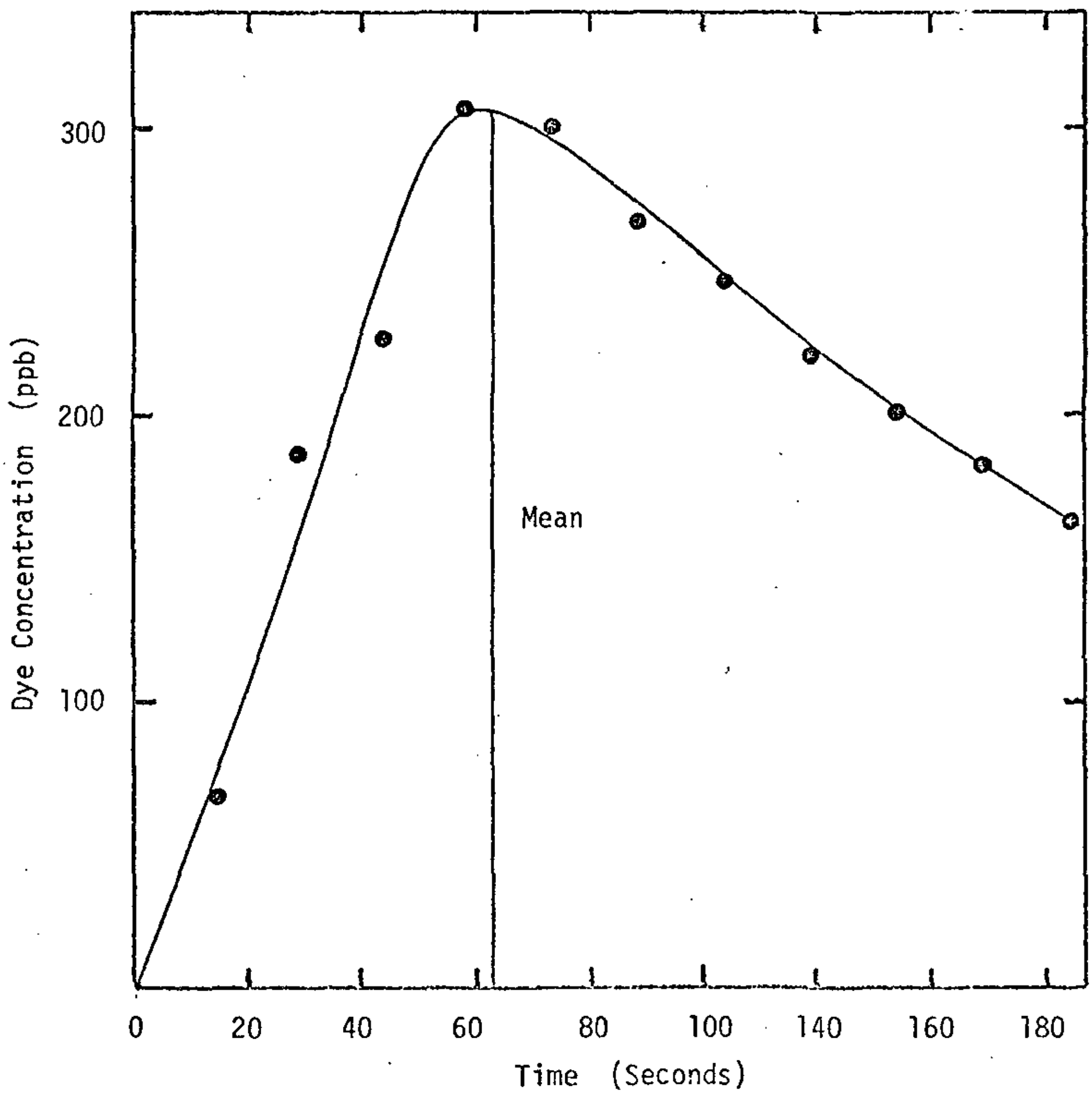

FIGURE 3. MEAN DETENTION TIME IN THE PLASTIC MEDIA REACTOR

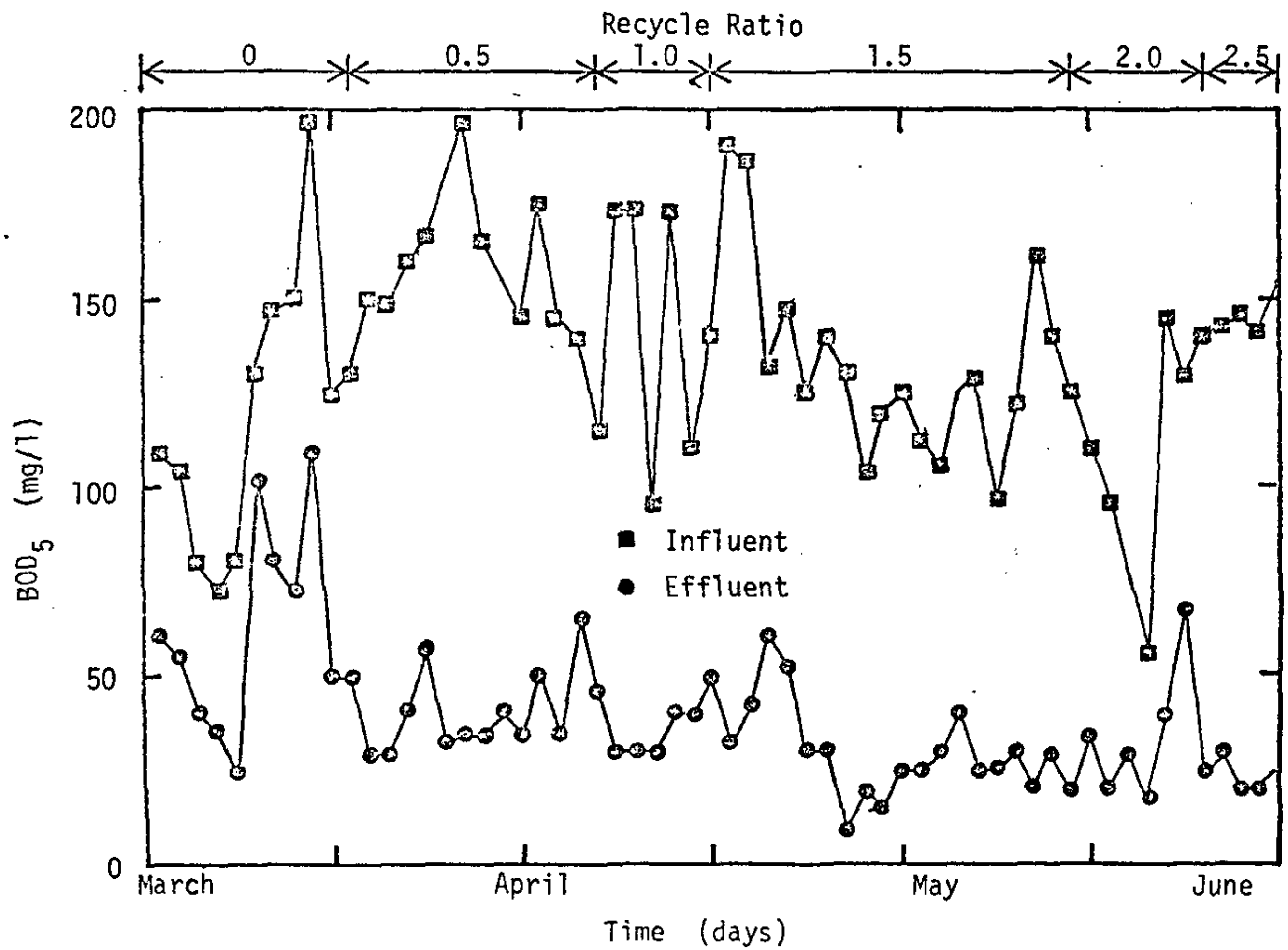

FIGURE 4. BOD_5 REMOVAL IN THE ROCK MEDIA REACTOR WITH MEDIA DEPTH OF 5 FT AND APPLICATION RATE OF 0.20 GPM/FT^2

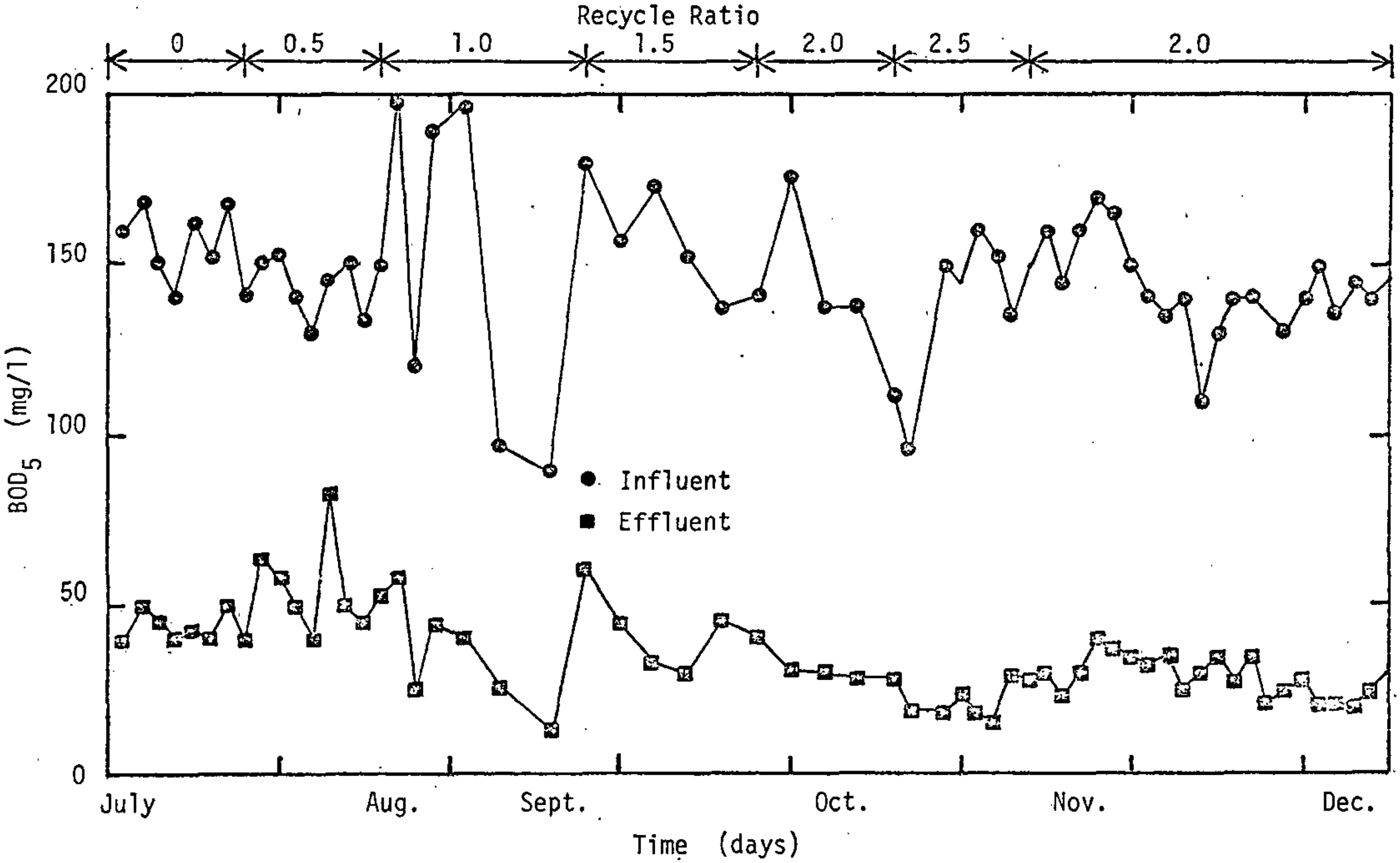

FIGURE 5. BOD_5 REMOVAL IN THE ROCK MEDIA REACTOR WITH MEDIA DEPTH OF 7 FT AND APPLICATION RATE OF 0.20 GPM/FT^2

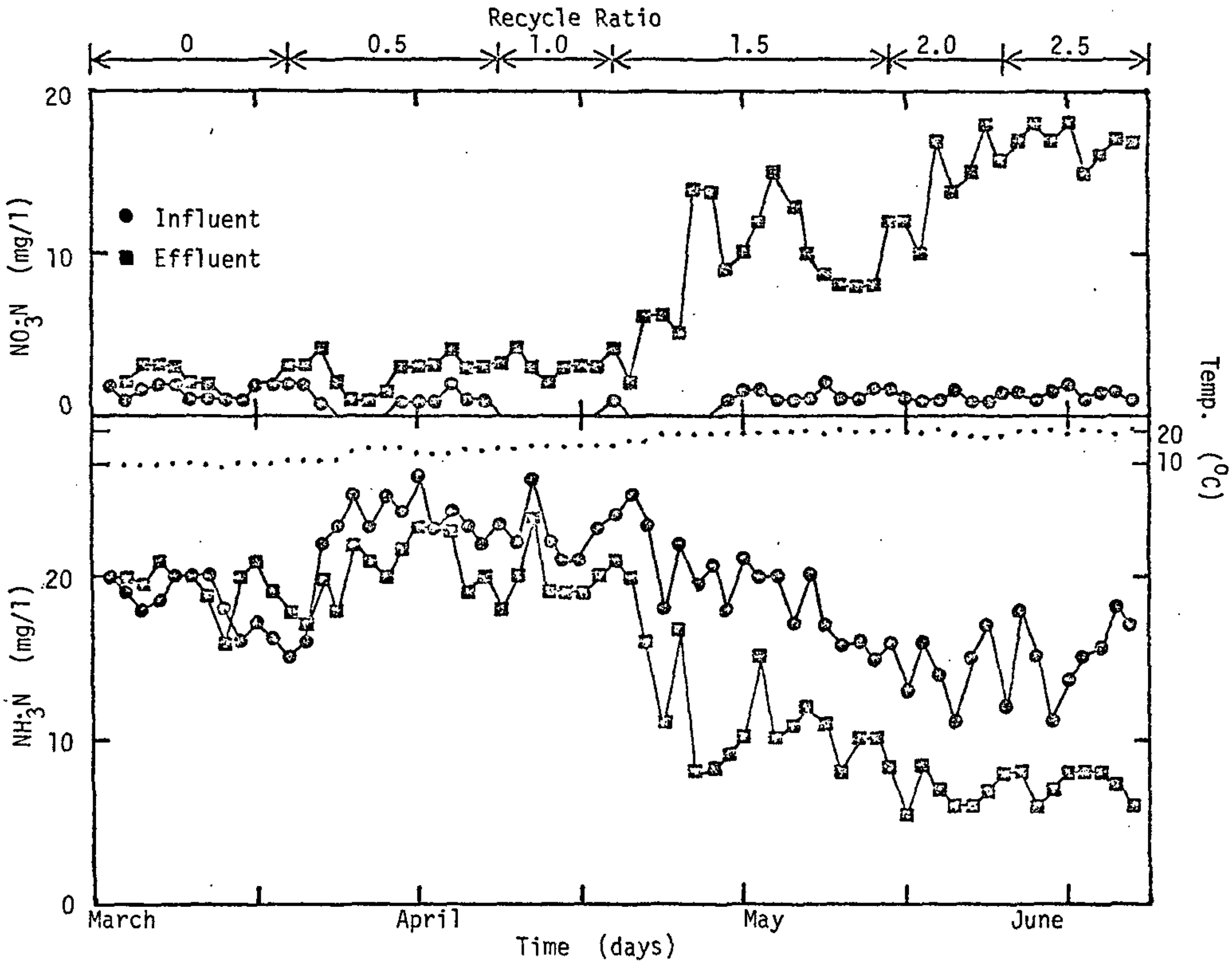

FIGURE 6. NITRIFICATION IN THE ROCK MEDIA REACTOR WITH MEDIA DEPTH OF 5 FT AND APPLICATION RATE OF 0.20 GPM/FT^2

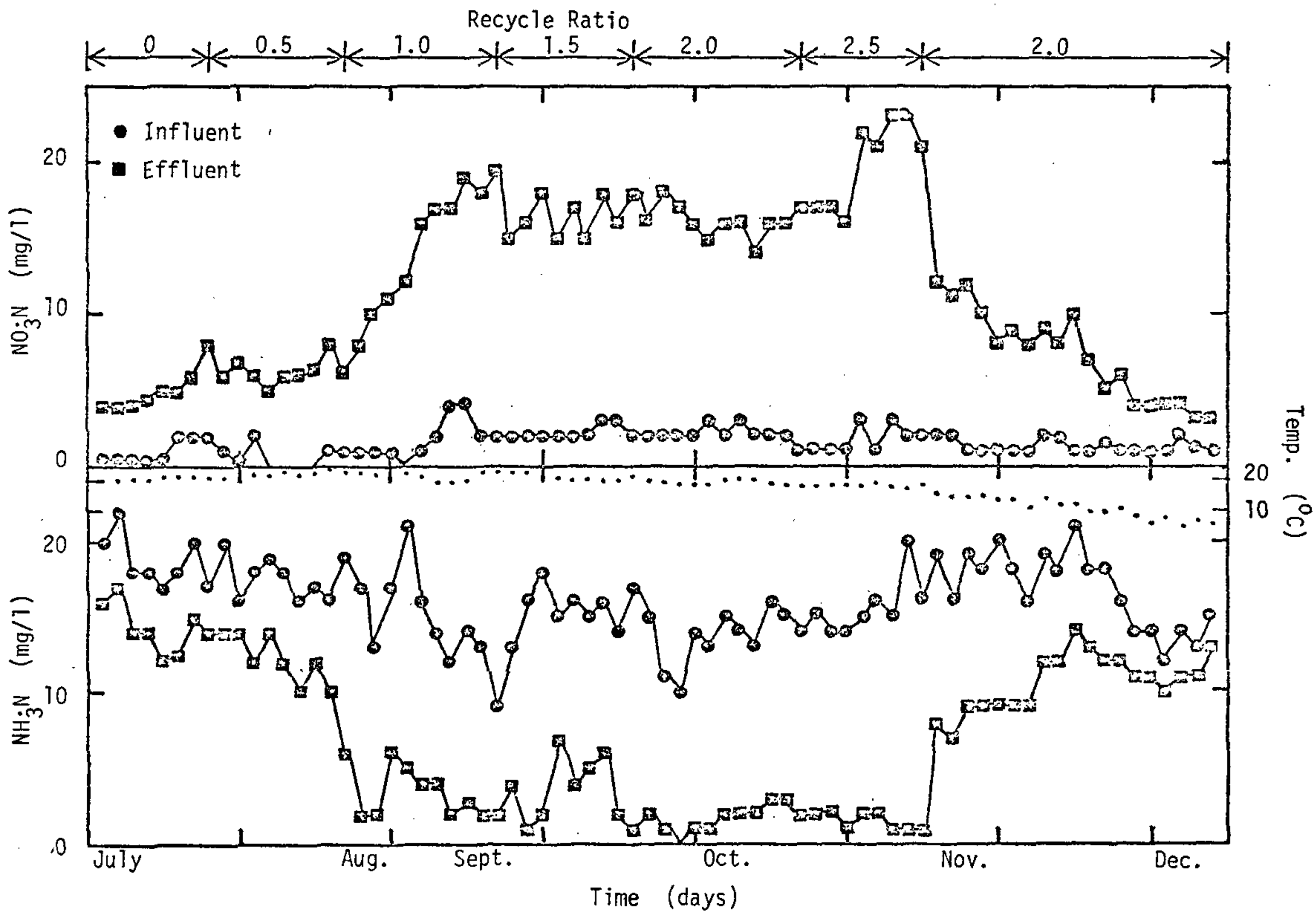

FIGURE 7. NITRIFICATION IN THE ROCK MEDIA REACTOR WITH MEDIA DEPTH OF 7 FT AND APPLICATION RATE OF 0.20 GPM/FT^2

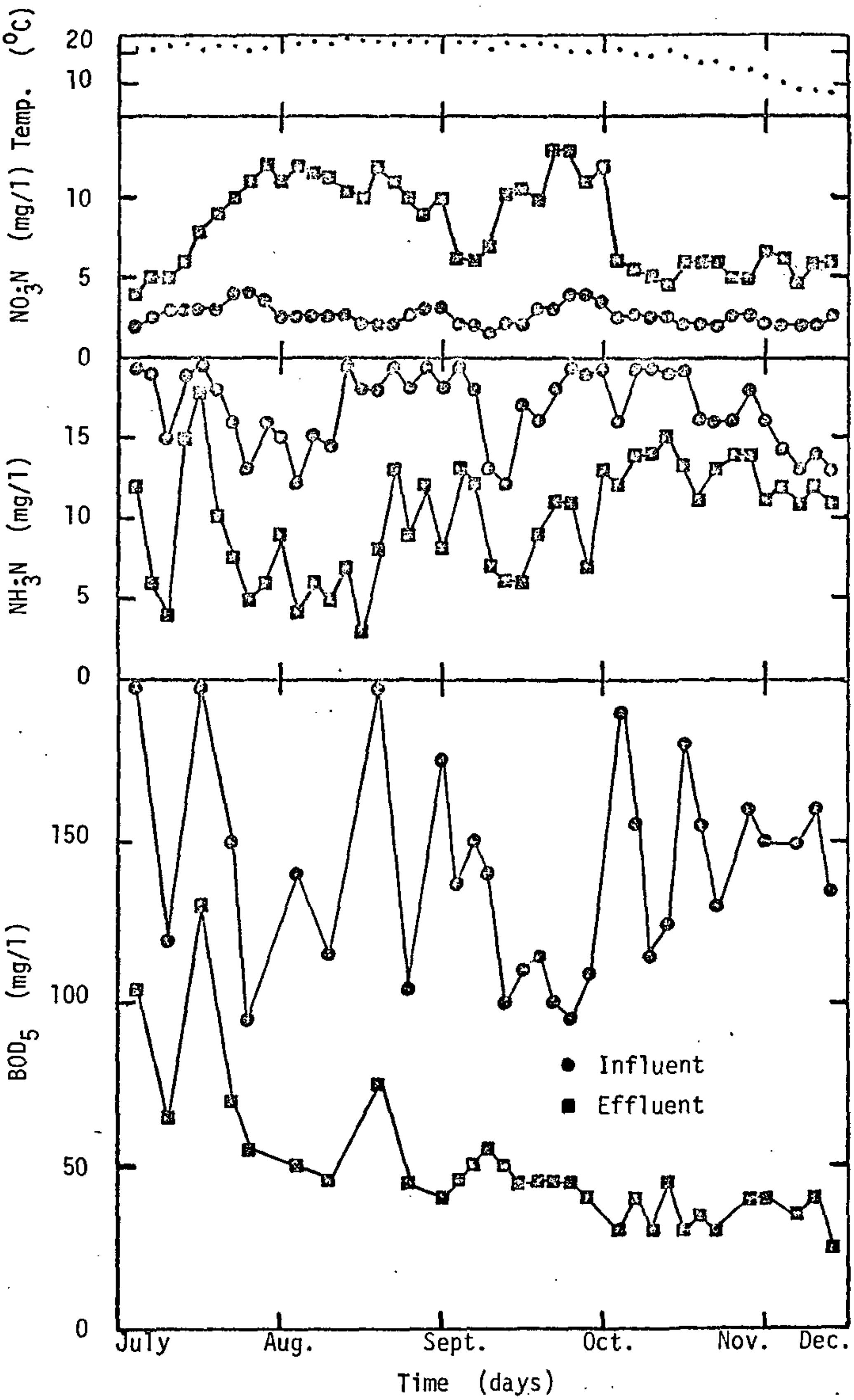

FIGURE 8. PLASTIC MEDIA REACTOR PERFORMANCE

lesser degree of organic removal with effluent BOD_5 of about 45 mg/l.

Significant nitrification was achieved at both depths in the rock media reactor; however, a marked increase was demonstrated at the greater depth. This is evidenced by the ammonia removals given in Figures 6 and 7. At higher recycle ratios, consistent effluent NH_3-N concentrations of less than 5 mg/l were maintained. Less satisfactory nitrification, with effluent NH_3-N concentrations of 5-10 mg/l, was observed in the plastic media reactor. As expected, both systems demonstrated a decreased capacity for nitrification during the colder months.

In an open system, climatic effects must be considered to insure efficient unit operation. Temperature and precipitation may play an important role in wastewater treatment. While the effect of temperature on reaction rate is more obvious, rainfall can influence operation by diluting the wastewater in several ways: (1) by infiltration into the sewer system; (2) by collection in a combined sewer system; and (3) by direct addition at the reactor surface. Hydraulic variations caused by precipitation are very important in actual treatment plant operation. However, in this study, the flowrates were kept constant, leaving only the dilution effect to be considered.

During this study, the incidence of heavy rainfall caused upset of the already overloaded primary clarifiers and resulted in an extremely turbid, almost black influent to the filter systems. During these periods, high influent BOD_5 and NH_3-N concentrations were recorded. Most of the BOD_5 was colloidal and could be removed by settling or filtration. However, the total mass of BOD_5 removed in each reactor was not significantly different than removals during dry weather. Consequently, effluent quality during periods of heavy rainfall was degraded. Because ammonia is present in the dissolved form, it is diluted by rainfall. This resulted in lower loadings to the system and subsequent lower removal efficiencies. The dilution effect and the presence of high turbidity as cited by McHarness et al. (6) may both be partly responsible for the decrease in nitrification during periods of heavy precipitation.

The mean and standard deviation of influent and effluent values of BOD_5, NH_3^-N, NO_3^-N, and organic-N are given in Tables 1 and 2 for operation of the rock media reactor at recycle ratios ranging from 0 to 2.5, and for media depths of 5 and 7 feet, respectively. A similar summary is given in Table 3 for operation of the plastic media reactor. The nitrite concentration in each sample was considered to be negligible based on other research which shows the second step of the nitrification process to be relatively instantaneous (9). As noted in each table, it was possible to achieve a good nitrogen mass balance across each reactor. This assured accuracy of analytical techniques, and the adequacy of assumptions regarding nitrogen transformation pathways.

Organic Nitrogen Hydrolysis

Organic nitrogen in each system must be measured to provide an accurate and complete nitrogen balance. The organically bound nitrogen is converted to ammonia through the decomposing action of heterotrophic bacteria and is released back into the wastewater stream. Table 4 indicates that as much as 60% of the organic nitrogen present in the influent to the rock media reactor was converted to ammonia, compared to

TABLE 1. SUMMARY OF ROCK MEDIA REACTOR PERFORMANCE

Media Depth = 5 ft.		Recycle Ratio					
		0	0.5	1.0	1.5	2.0	2.5
		$\bar{x}/\sigma$	$\bar{x}/\sigma$	$\bar{x}/\sigma$	$\bar{x}/\sigma$	$\bar{x}/\sigma$	$\bar{x}/\sigma$
BOD_5	Influent	125/39.0	155/20.8	146/34.2	134/24.7	106/30.9	144/5.3
mg/l	Effluent	62.3/28.6	41.5/10.7	37.5/7.7	31.1/11.9	33.3/16.2	24.4/4.6
NH_3-N	Influent	18.2/1.7	22.9/6.5	22.8/1.7	19.3/2.7	15.0/1.8	16.1/2.0
mg/l	Effluent	19.5/1.3	20.7/2.3	20.2/1.8	12.0/3.2	5.2/1.2	5.7/0.7
NO_3-N	Influent	1.8/0.5	0.8/0.6	0.0/0.0	0.9/0.9	0.8/0.3	0.3/0.3
mg/l	Effluent	2.4/0.6	2.8/0.7	3.2/0.8	9.8/3.3	14.8/2.5	17.5/0.7
Org. N	Influent	10.1/1.4	11.5/0.5	9.8/1.3	9.9/1.9	8.6/2.3	8.9/1.6
mg/l	Effluent	7.3/1.4	8.5/0.5	8.6/1.3	7.4/1.2	3.8/1.1	3.0/0.9
Total N	Influent	30.1	35.2	32.6	30.1	24.4	25.3
mg/l	Effluent	29.2	32.0	32.0	29.2	23.8	26.2
Avg. Temp. ^{o}C		10	13	16	19	19	19

TABLE 2. SUMMARY OF ROCK MEDIA REACTOR PERFORMANCE

Media Depth = 7 ft.		Recycle Ratio					
		0	0.5	1.0	1.5	2.0	2.5
		$\bar{x}/\sigma$	$\bar{x}/\sigma$	$\bar{x}/\sigma$	$\bar{x}/\sigma$	$\bar{x}/\sigma$	$\bar{x}/\sigma$
BOD_5	Influent	155/11.2	146/8.4	152/46.6	149/14.2	141/21.2	140/21.7
mg/l	Effluent	43.9/4.0	52.5/7.8	38.1/16.8	38.4/5.7	30.5/0.5	17.7/1.9
NH_3-N	Influent	18.9/1.4	17.1/1.7	13.9/3.1	15.2/1.4	13.5/1.7	15.6/1.6
mg/l	Effluent	14.5/1.5	11.8/2.5	3.4/1.5	3.5/2.0	1.9/0.7	1.0/0.3
NO_3-N	Influent	1.1/0.8	0.3/0.4	2.3/1.5	2.3/0.5	2.2/0.6	1.8/0.9
mg/l	Effluent	5.3/1.4	6.1/1.6	15.3/3.3	16.0/1.4	16.2/1.5	21.5/1.4
Org. N	Influent	9.8/1.2	10.8/1.9	8.3/2.0	8.0/1.1	7.3/1.3	8.7/1.1
mg/l	Effluent	7.8/1.4	7.9/2.1	4.0/1.3	5.5/1.0	4.3/1.2	3.4/0.5
Total N	Influent	29.8	28.2	24.5	25.5	23.0	26.1
mg/l	Effluent	27.6	25.8	22.7	25.0	22.4	25.9
Avg. Temp. ^{o}C		22	22	22	23	21	20

TABLE 3. SUMMARY OF PLASTIC MEDIA REACTOR PERFORMANCE

Hydraulic Application	gpm/ft^2	1.0	2.0	2.0
Recycle Ratio		1.0	1.0	2.0
		$\bar{x}/\sigma$	$\bar{x}/\sigma$	$\bar{x}/\sigma$
BOD_5	Influent	158/49.8	125/28.2	139/25.9
mg/l	Effluent	69.0/28.2	49.1/4.5	35.9/5.8
NH_3-N	Influent	14.6/3.3	14.7/2.7	7.7/2.5
mg/l	Effluent	6.8/4.0	7.4/3.3	15.1/2.8
NO_3-N	Influent	2.7/0.8	2.5/0.6	2.4/0.3
mg/l	Effluent	9.7/2.6	9.7/2.5	5.7/0.6
Org. N	Influent	8.0/1.9	7.7/1.5	11.6/2.2
mg/l	Effluent	5.8/1.0	5.2/1.6	7.2/2.0
Total N	Influent	25.3	24.9	31.7
mg/l	Effluent	22.3	22.3	28.0
Ave. Temp.	^oC	23	21	10

TABLE 4. ORGANIC NITROGEN HYDROLYSIS IN FIXED-GROWTH REACTORS

Unit	Depth ft.	Hydraulic Application gpm/ft^2	Recycle Ratio	Org. N mg/l Influent	Org. N mg/l Effluent	% Hydrolysis
Rock Media Reactor	5	0.20	0	10.1	7.3	28
	5	0.20	0.5	11.5	8.5	26
	5	0.20	1.0	9.8	8.6	12
	5	0.20	1.5	9.9	7.4	25
	5	0.20	2.0	8.6	3.8	56
	5	0.20	2.5	8.9	3.0	66
	7	0.20	0	9.8	7.8	20
	7	0.20	0.5	10.8	7.9	27
	7	0.20	1.0	8.3	4.0	52
	7	0.20	1.5	8.0	5.5	31
	7	0.20	2.0	7.3	4.3	41
	7	0.20	2.5	8.7	3.4	61
Plastic Media Reactor	24	1.0	1.0	7.8	6.0	23
	24	2.0	1.0	7.7	5.2	32
	24	2.0	2.0	11.2	7.4	34

only about 30% in the plastic media reactor. In both reactors there seemed to be a trend of increasing percent hydrolysis as the recycle ratio was increased. Whether this was an effect of longer contact time through repeated passes or as a result of increased activities at lower loadings was not established.

The quantity of ammonia nitrogen contributed by the hydrolysis process could be as high as 10 mg/l. However, for the duration of this study, the average increase through the rock media reactor was about 5 mg/l and in the plastic media reactor about 2.5 mg/l. The occasions of low effluent ammonia indicated that most of this "new" ammonia was being nitrified. Therefore, the heterotrophic activity associated with hydrolysis occurred rapidly enough to allow nitrification within the contact time provided by the reactor.

The unhydrolyzed organic nitrogen not removed by settling would eventually exert an oxygen demand on the receiving water and have much the same effect as discharged ammonia nitrogen and BOD_5. There did not seem to be any negative effect on the extent of organic nitrogen hydrolysis as the wastewater temperature decreased. This is in agreement with the temperature stability of organic removal and the postulate that organic nitrogen hydrolysis is a consequence of organic oxidation.

The SS in the effluent from the rock media reactor normally ranged from 10 to 20 mg/l, compared with 20 to 30 mg/l in the plastic media reactor. This was probably due to the decrease in removal efficiency of colloidal material in the plastic media reactor because less time was available for bioflocculation.

Despite poorer overall SS removal efficiency, the settleability of biological solids in the effluent stream from the plastic media was greater than that observed in the effluent from the rock media. This resulted in higher percent removals of organic nitrogen during final settling of the effluent from the plastic media as compared to the rock media (40% versus 30%) and suggested that most of the remaining colloidal material from the plastic media reactor was inorganic. Visual observation of the two units showed that sloughing of the biomass in the rock media reactor produced small and light, difficult to settle flocs which undoubtedly contained organic nitrogen. In contrast, sloughing of the biomass in the plastic media reactor produced a heavy, filamentous material which settled rapidly. This difference is most likely a result of media construction and subsequent flow conditions.

Factors Influencing Nitrification

The literature presents several factors as having a significant effect on the nitrification rate (2,4,6,7,8,9,20). The major factors are considered to be: (1) the organic loading applied to the system; (2) the ammonia nitrogen loading; (3) the depth of the media, or more specifically, the time of contact between the wastewater and the biomass; and (4) the temperature of the wastewater. The literature also indicates the apparent failures in using a theoretical approach to describe the complicated and co-existing set of processes taking place in a fixed-growth system. Thus, it was decided to embark on a more empirical form of analysis.

In addition to these selected parameters, toxic wastewater constituents have been documented as affecting the nitrification rate. However, based on past studies at the University of Massachusetts Wastewater Treatment Pilot Plant, the presence of toxic agents in sufficient quantity in the wastewater to significantly impair the nitrification process can be eliminated.

Although influent and effluent pH was recorded for all samples, it was not considered to be a major factor affecting nitrification in this study. Throughout the study period, the pH of the influent wastewater ranged from 7.0 to 7.5, which is below the optimum for the nitrification process. However, the autotrophic population appeared to be satisfactory and easily acclimated to the less than optimum pH conditions. Hanumanulu (21) suggested that heterogeneous trickling filter populations are more easily acclimatized to sub-optimum pH levels than those in suspended growth systems and are more stable when subject to transient fluctuations.

The effluent pH generally declined as the extent of nitrification increased, but at no point did it fall below 6.0. This is due to the liberation of hydrogen ions and the destruction of alkalinity during the reaction. Thus it was determined that pH depression was more of an effect than a cause of the nitrification process.

Effect of Hydraulic Loading Rate

Two different application rates were used in the study of the plastic media reactor: 1.0 and 2.0 gpm/ft^2 (40.7 and 81.3 lpm/m^2). From Table 3, these two rates can be directly compared since the temperatures during the periods in question were close enough to ignore as a factor (21 and 23°C). The BOD_5 removal efficiency actually improved at the higher application rate while the nitrification rate appeared to decrease. At an application rate of 1.0 gpm/ft^2 (40.7 lpm/m^2) the distribution system was not able to provide complete wetting of the media. Therefore, it was doubled for further study. At an application rate of 2.0 gpm/ft^2 (81.3 lpm/m^2) the removal efficiencies were about the same as at the lower application, indicating that the media had probably been underloaded at the lower rate. The application rate was not increased further due to pump limitations.

In the rock media reactor, all analyzed data were taken at an application rate of 0.20 gpm/ft^2 (8.13 lpm/m^2). This rate is at the lower extreme of that generally accepted as high-rate wastewater filtration. As was stated previously, lower application rates could not be used due to the hydraulic limitations of the rotor assembly. A higher application rate of 0.30 gpm/ft^2 (12.2 lpm/m^2) was tried during the late summer. The rock media reactor was operated at this higher application rate for a period of 4 weeks following 4 weeks of acclimation to the increase in flow. As shown in Figure 9, the BOD_5 removals were not significantly diminished in comparison with data from the lower application rate. However, as indicated in Figure 10, the degree of nitrification decreased considerably. In fact, nitrification continued to decrease throughout the period until it completely ceased and the study was concluded. Since the unit never attained a condition of pseudo equilibrium, subsequent data analysis would be meaningless. Following another period of 3 to 4 weeks, at the original application rate of 0.20 gpm/ft^2 (8.13 lpm/m^2), nitrification was restored to levels comparable with those achieved prior to this part of the study.

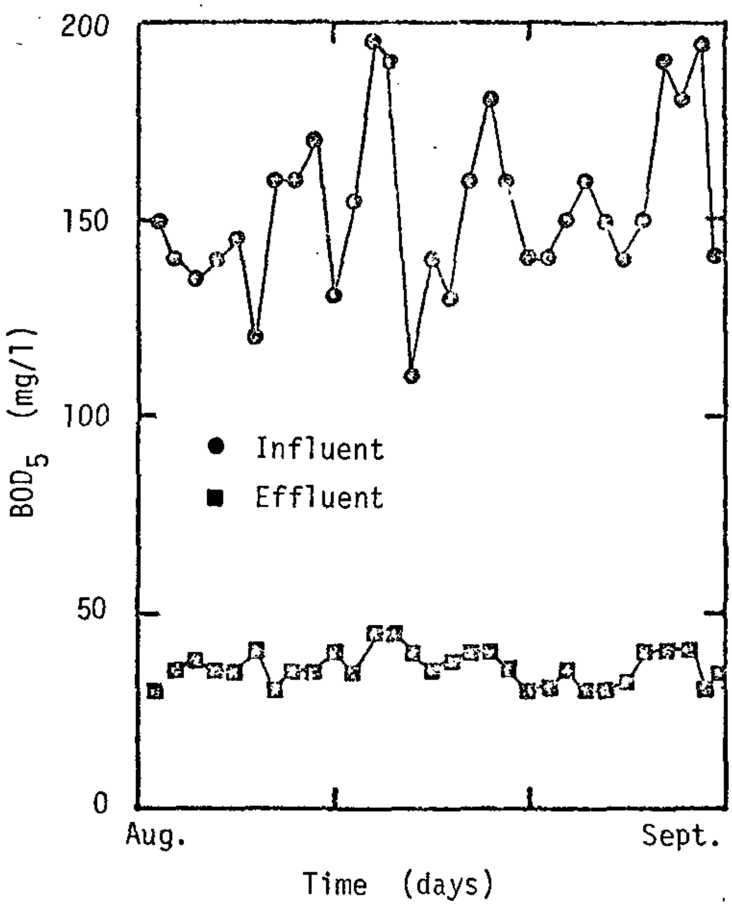

FIGURE 9. BOD_5 REMOVAL IN THE ROCK MEDIA REACTOR WITH MEDIA DEPTH OF 7 FT AND APPLICATION RATE OF 0.30 GPM/FT^2

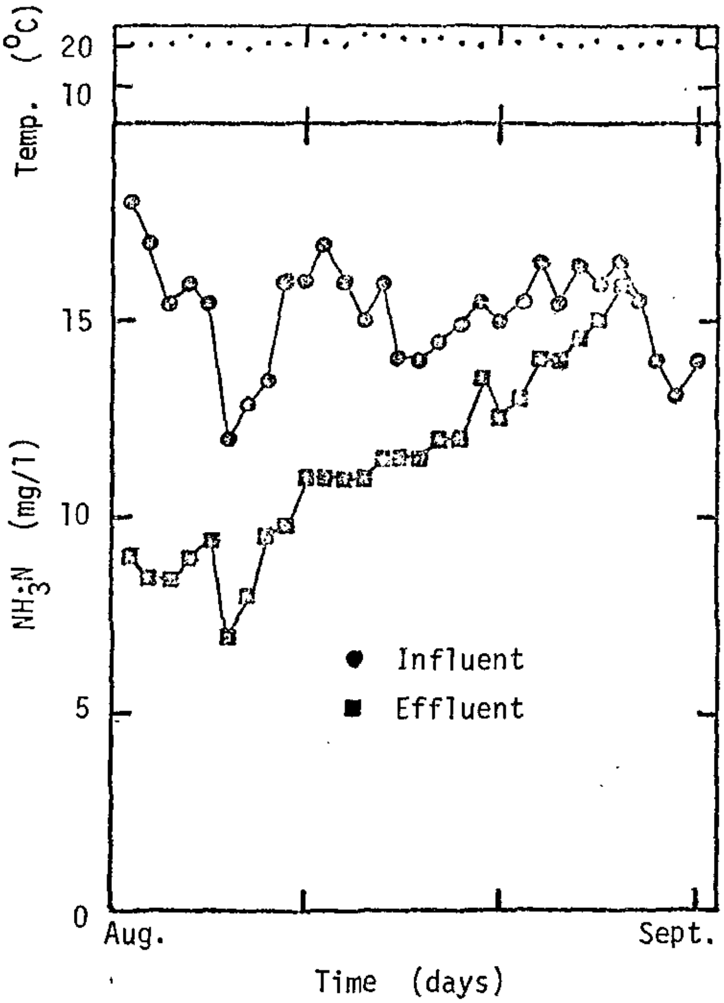

FIGURE 10. NITRIFICATION IN THE ROCK MEDIA REACTOR WITH MEDIA DEPTH OF 7 FT. AND APPLICATION RATE OF 0.30 GPM/FT^2

Attrition of organisims may expain the loss of nitrification at the higher application rate. At the lower application rate, the shear force imparted by the moving wastewater probably stabilized the thickness of the biological film. While there was some attrition of both heterotrophic and autotrophic bacteria, the losses were compensated for by new growth until relatively static conditions were reached and the film depth remained constant. When the hydraulic application rate was increased, the attrition of organisims from the media increased. This was evidenced by a slight increase in the effluent SS and turbidity. At the higher application rate the slower growth of the nitrifiers was not sufficient to overcome the organisms lost and they were gradually washed from the system. The point at which washout of the nitrifying organisms would occur is dependent on the physical characterisitics of the system such as media size, roughness, shape, composition, and arrangement. For each situation, the effect of hydraulic loading on nitrification should be established by prior study before design of a full scale treatment facility.

Recycle Ratio

In this study, recycle was not treated as a parameter affecting nitrification performance but as a means of maintaining the same hydraulic application while varying the substrate loadings to both systems. The range of recycle ratios was 0.0 to 2.5 for the rock media reactor. Recycle ratios of 1.0 and 2.0 were used during work with the plastic media reactor.

Approach to Data Analysis

During the course of the study, the influent wastewater composition varied considerably. The strength of the wastewater with respect to BOD_5 and $NH_3^{\cdot}N$ concentrations varied with weather and population changes, as mentioned earlier. Thus to analyze the effect of either BOD_5 loading or $NH_3^{\cdot}N$ loading on nitrification rate, it was necessary to isolate data while holding other parameters (temperature and contact time also) constant.

By eliminating contact time as a relatively constant factor for a particular reactor, the three major independent variables possibly affecting the nitrification rate in a fixed-growth reactor are BOD_5 loading, $NH_3^{\cdot}N$ loading, and temperature. Data collected from continuous pilot plant operation will necessarily include a wide range of values for these parameters.

In addition, the method of composite sampling used determines the smallest interval of operation which can be evaluated. Given the fixed hydraulic application rate to each reactor, it was assumed that fluctuations in sewage strength during the day were minor and that substrate loadings to each reactor remained relatively constant.

Although relatively constant temperature conditions were easy to identify by season of the year, both BOD_5 and $NH_3^{\cdot}N$ loadings showed no such seasonal trends (see Figures 4-8). In fact, there were significant variations in these loadings from day to day. Thus to carry data analysis further, it was necessary to assume that the biomass in the fixed-growth reactors may respond to these daily variations if indeed

BOD_5 or NH_3-N loadings were important factors influencing the nitrification rate.

After tabulating about 200 days of data, those days influenced by mechanical difficulties or heavy precipitation were eliminated. Influent BOD_5 values were rounded off to the nearest 20 mg/l interval to provide a means for comparing data on numerous days when influent composition was similar. While rounding off facilitated data analysis, it was also justified by the lack of precision of the BOD_5 test. The influent NH_3-N concentrations were treated in a similar manner by rounding to the nearest 3.0 mg/l.

The extent of nitrification was obtained by difference between the influent and effluent ammonia and organic nitrogen concentrations. If the hydrolysis of organic nitrogen was ignored, then a lower than actual amount of nitrification would be calculated. Concentrations, flowrates, and reactor volumes were used to express mass loadings in lbs/day/1000ft^3. Once in this form, ammonia removal rates become the dependent variable against which the various independent variables were tested. To avoid resorting to multiple regression statistical analysis, the independent variables were considered separately.

To clarify the approach to data analysis taken in this study, a matrix of representative data from the rock media reactor is given in Figure 11. Here, the coordinates of points at constant temperature are the BOD_5 and NH_3-N loadings obtained on each day of sampling. To investigate the effect of an independent variable on the nitrification rate requires that a particular row or column in the matrix be isolated. However, it can be seen that limited entries in a row or column make

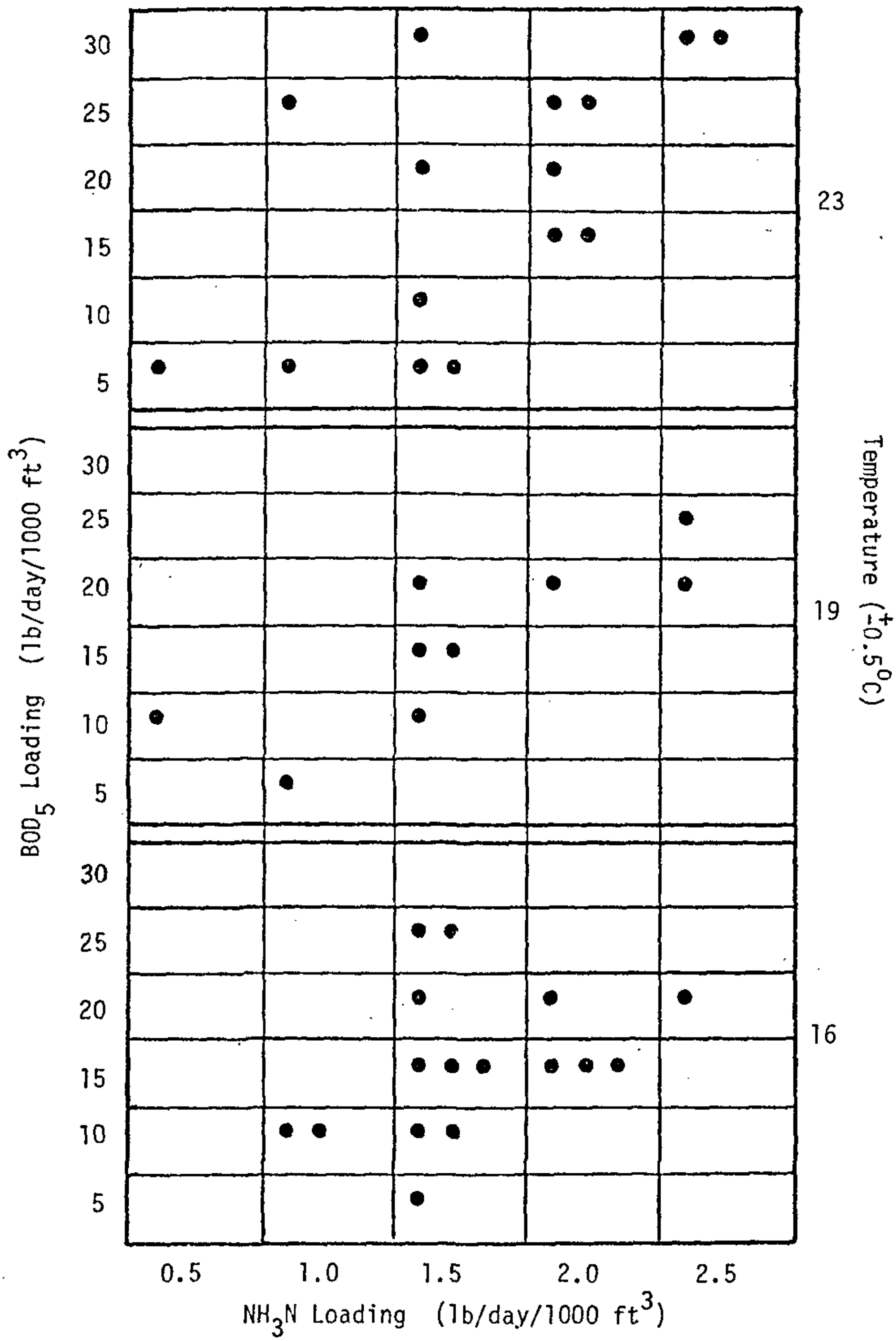

FIGURE 11. MATRIX REPRESENTATION OF DATA FOR THE ROCK MEDIA REACTOR

analysis impossible for that value of the independent variable. The plastic media reactor analysis was carried out in the same way.

Effect of Applied BOD_5

Figure 12 indicates that the nitrification rate is independent of the BOD_5 loading to the rock media reactor. However, it must also be noted that much of the variation in BOD_5 loading was on a day to day basis (see Figures 4 and 5) and there were no periods during which the BOD_5 loadings were consistently high or low for an extended number of days. Additionally, the shear stresses remained relatively constant within the bed because the hydraulic application rate was held constant. These two factors combined probably stabilized the biological population such that short term variations in BOD_5 loading did not alter the nitrification rate. This conclusion is based on the assumption that excess BOD_5 does not cause inhibition of the nitrifying population.

Although in this study, the temporal fluctuations in BOD_5 loading were caused only by changes in influent BOD_5 concentration (at constant hydraulic application), in typical operation BOD_5 loading could increase if the hydraulic loading was increased. As discussed in a previous section, increases in the hydraulic loading rate could cause a decrease in nitrification. Thus, it is important to recognize the limitations in interpreting the results given in Figure 12 for the more practical case in which BOD_5 loading increases due to increased hydraulic loading.

In contrast to the results obtained for the rock media reactor, Figure 13 shows that the nitrification rate decreased with increasing BOD_5 loadings to the plastic media reactor. Before attempting to explain

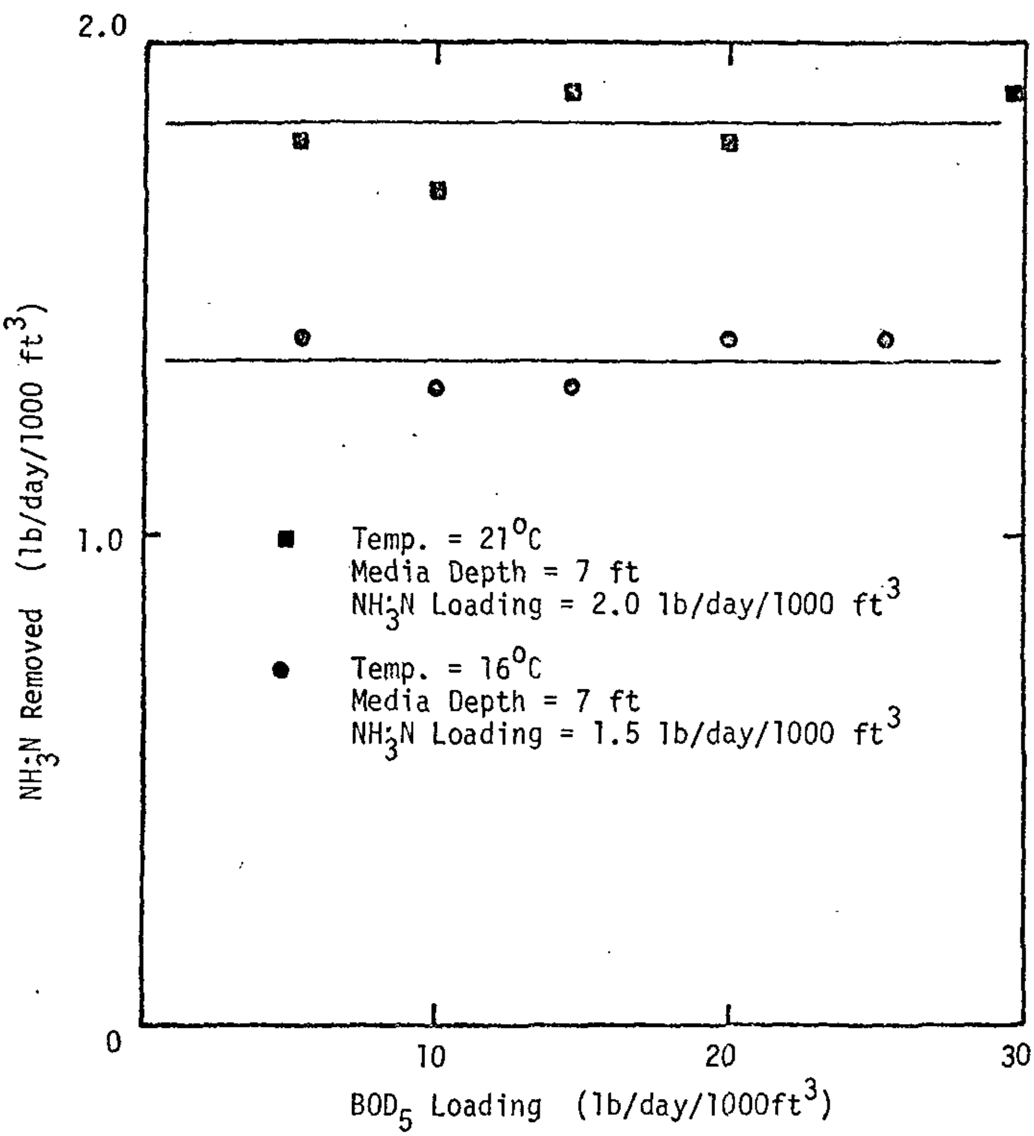

FIGURE 12. NITRIFICATION AS A FUNCTION OF BOD_5 LOADING IN THE ROCK MEDIA REACTOR

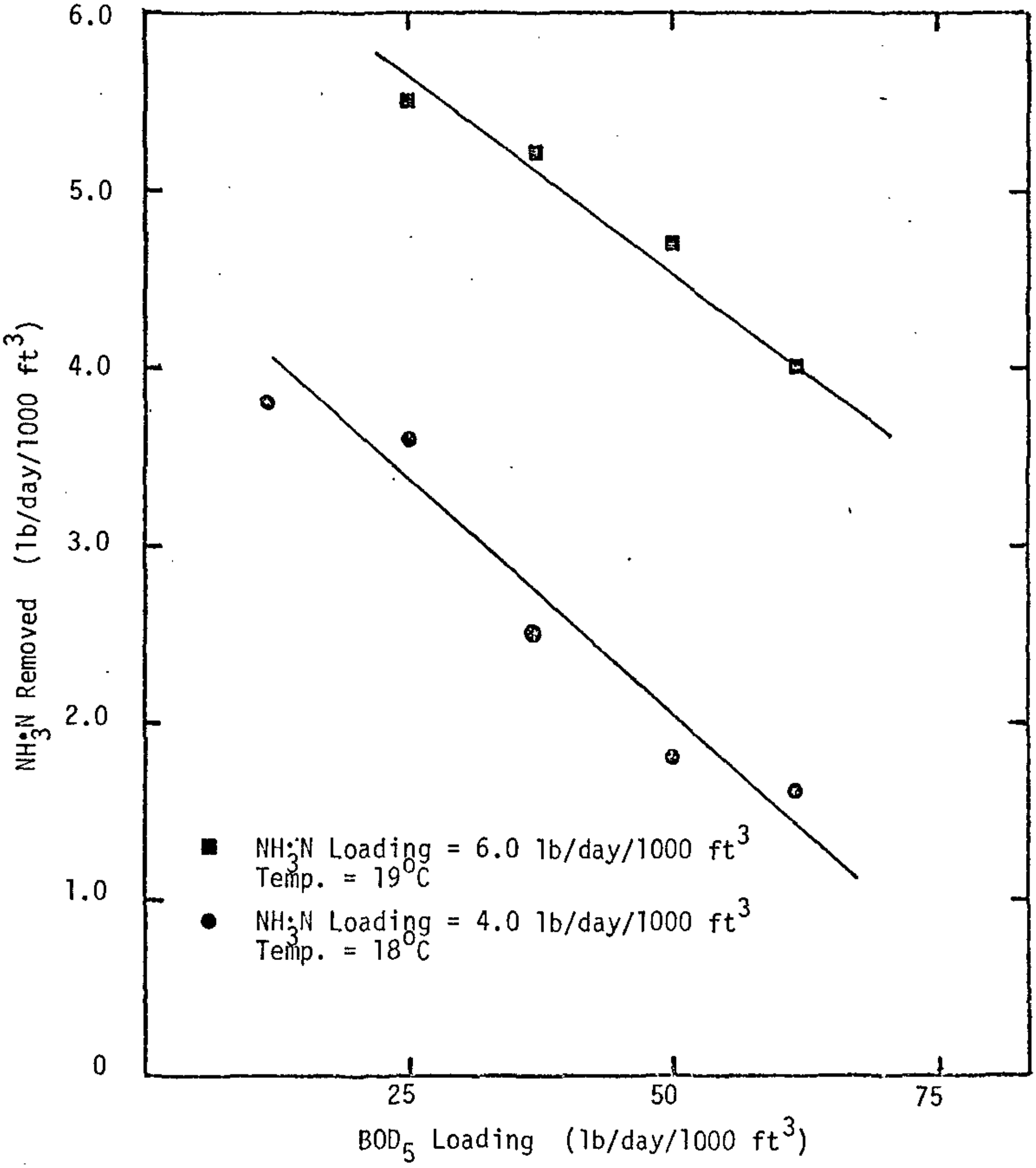

FIGURE 13. NITRIFICATION AS A FUNCTION OF BOD_5 LOADING IN THE PLASTIC MEDIA REACTOR

the difference in dependence on BOD_5 loading, it is important to recognize that while these reactors were operated in parallel, differences in internal reactor volumes and hydraulic loading resulted in higher BOD_5 loadings to the plastic media reactor. Thus, during the same operating periods two different ranges of BOD_5 loading rates were being examined.

To more clearly compare the actual difference in nitrification rates between the two reactors, it is important to consider differences in contact time and surface area. That is, the nitrification rates given in Figures 12 and 13 are based only on the internal volume (16/day/1000 ft^3). Because of structural differences comparison on this basis cannot account for actual reactor contact time and surface area, both of which affect the nitrification rate. Figure 14 shows data obtained at 23°C from both reactors normalized for internal surface area and hydraulic contact time. The figure indicates that BOD_5 loadings above 25 lb/day/1000 ft^3 decrease the nitrification rate. Accordingly, it may be reasoned that higher BOD_5 loadings than observed to the rock media reactor would also have resulted in a decrease in the nitrification rate. Thus, for any fixed-growth reactor, the long term effect of sustained high BOD_5 loading would be a diminished capacity for nitrification due to the higher growth rate of the heterotrophic bacteria.

Effect of Ammonia Loading

As shown in Figure 15, the nitrification rate generally increased with the applied ammonia loading to the rock media reactor after accounting for the effects of media depth and temperature. Because the hydraulic application rate was constant, an increased $NH_3 \cdot N$ loading incidates an

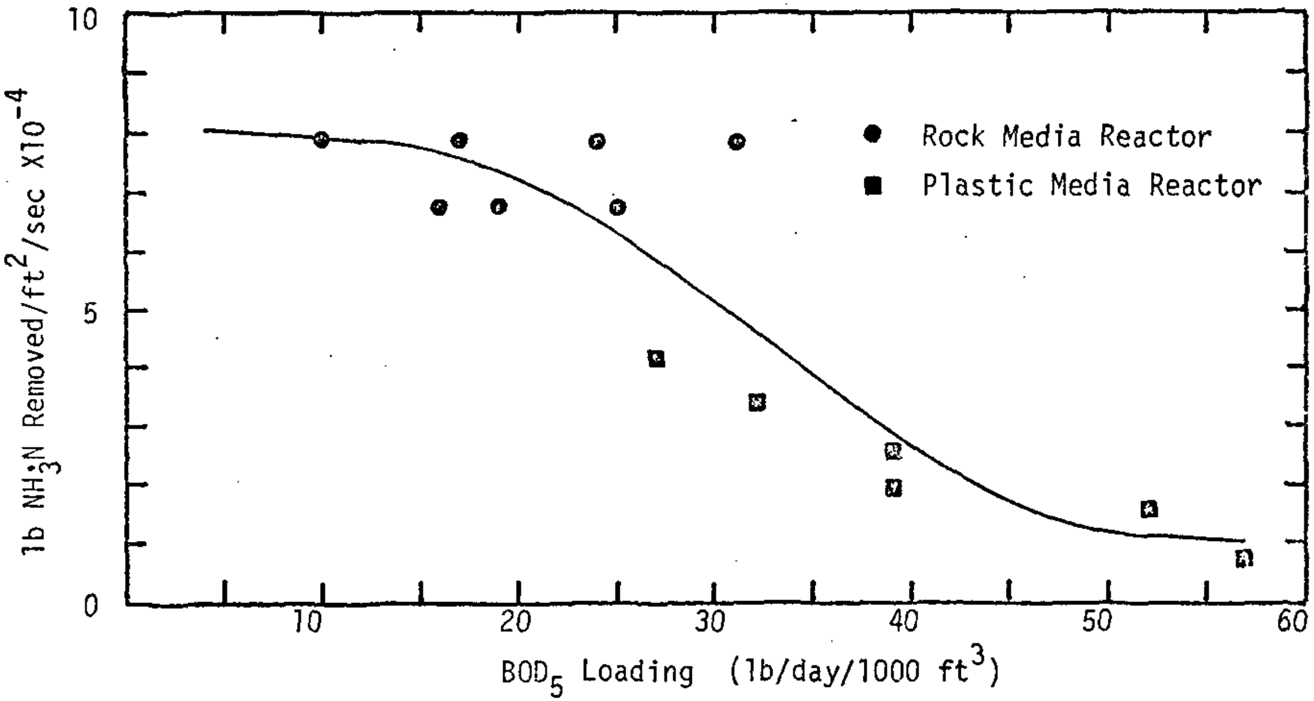

FIGURE 14. NITRIFICATION AS A FUNCTION OF BOD_5 LOADING NORMALIZED FOR MEDIA SURFACE AREA AND HYDRAULIC DETENTION TIME

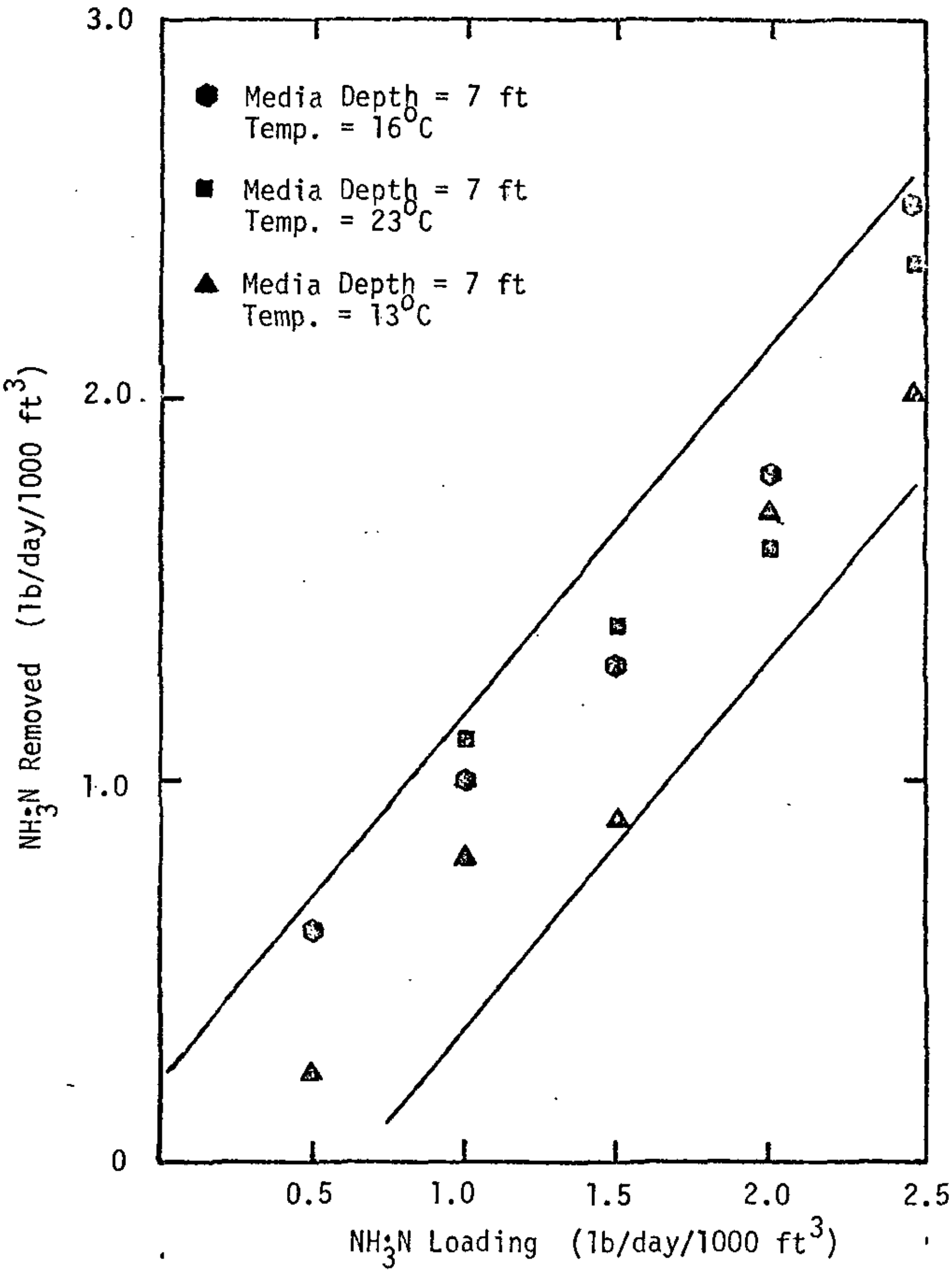

FIGURE 15. NITRIFICATION AS A FUNCTION OF AMMONIA LOADING IN THE ROCK MEDIA REACTOR

increased influent $NH_3 \cdot N$ concentration. It would seem that the upper limit was not reached where a leveling off effect on the nitrification rate would be apparent from lack of sufficient biomass to accomplish further nitrification. The obvious dependency of the nitrification rate on applied substrate concentration indicates that nitrification in the rock media reactor does not follow zero-order kinetics. Although a zero-order nitrification rate is widely accepted for suspended growth reactors, the turbulent flow associated with fixed-growth reactors causes a dependency on a substrate concentration gradient (10,11,14). This implies that a higher order overall reaction rate may govern the reactions of nitrification in a fixed-growth system (23,24). The hydraulic regime affects the rate of transfer of ammonia from the liquid phase to the film phase primarily because the fluid and the substrate are moving while the organisms are held stationary on the media. This is in contrast to a suspended growth reactor where both the organism and substrate are free to move together in order to initiate a reaction.

The influence of concentration gradients could be applied to fixed-growth systems to explain the apparent dependency on substrate concentration. As the concentration of ammonia increases, the driving force for phase transfer also increases. Additionally, there is a greater chance for contact with the organism to initiate the reaction. In a system as physically and chemically complicated as a fixed-growth reactor, there is most likely a combination of processes taking place. Laminar and turbulent flow over the biofilm could be occurring at the same time, thus changing the nitrification rate from dependency on contact time to dependency on substrate concentration and diffusion.

Figure 16 shows a similar trend of increasing nitrification rate for increased ammonia loadings to the plastic media reactor. Because data was only available for one set of operating conditions, it is difficult to generalize the findings. However, the linearity of the relationship extrapolated to negligible nitrification rates at very low ammonia loadings seems reasonable and indicates data reliability.

Normalizing the nitrification rate with respect to internal surface area and hydraulic contact time may provide insight into explaining the differences in dependency of the nitrification rate on ammonia loadings in the rock and plastic media reactors. Figure 17 shows that the normalized nitrification rate failed to produce a continuous functional relationship with ammonia loading. That is, for the same range of ammonia loadings, the nitrification rate in the plastic media reactor was lower by about a factor of five. More importantly, the nitrification rate in the plastic media reactor was far less dependent upon ammonia loading than in the rock media reactor as shown by a comparison of the slopes of the two functions. Inaccuracies in calculation of internal surface area and contact time may partially explain the difference in absolute value of the nitrification rate obtained in the two reactors for a given ammonia loading. However, these inaccuracies should not have affected the nature of the functional relationship, i.e., the slope of the nitrification rate vs. ammonia loading plots. Thus, it is apparent that some other characteristics of these two reactors account for the dissimilar dependency of nitrification rate on ammonia loadings. Differences in hydraulic flow regime may be the most reasonable explanation. Since a higher degree of turbulence results in a larger coeffi-

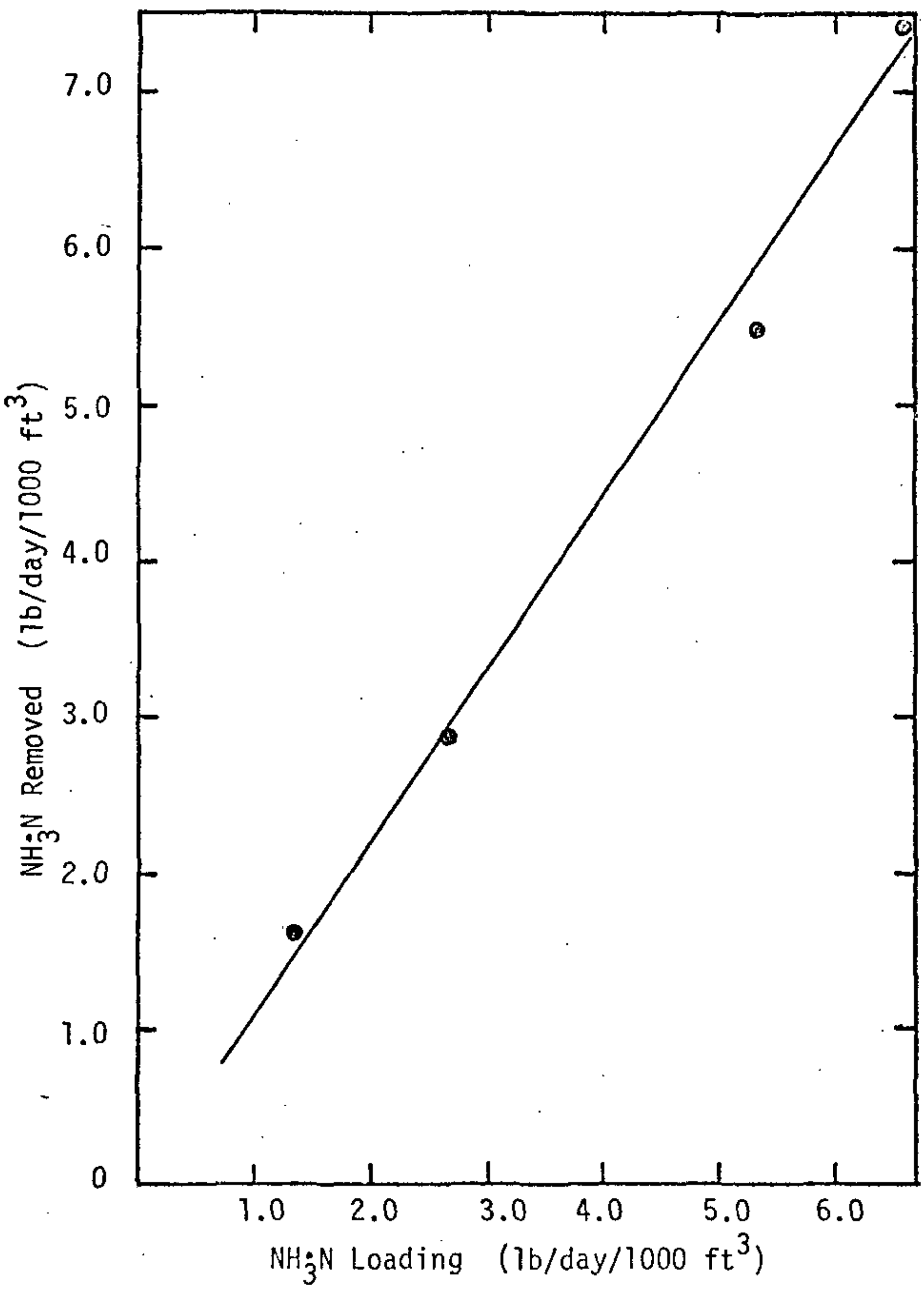

FIGURE 16. NITRIFICATION AS A FUNCTION OF AMMONIA LOADING IN THE PLASTIC MEDIA REACTOR

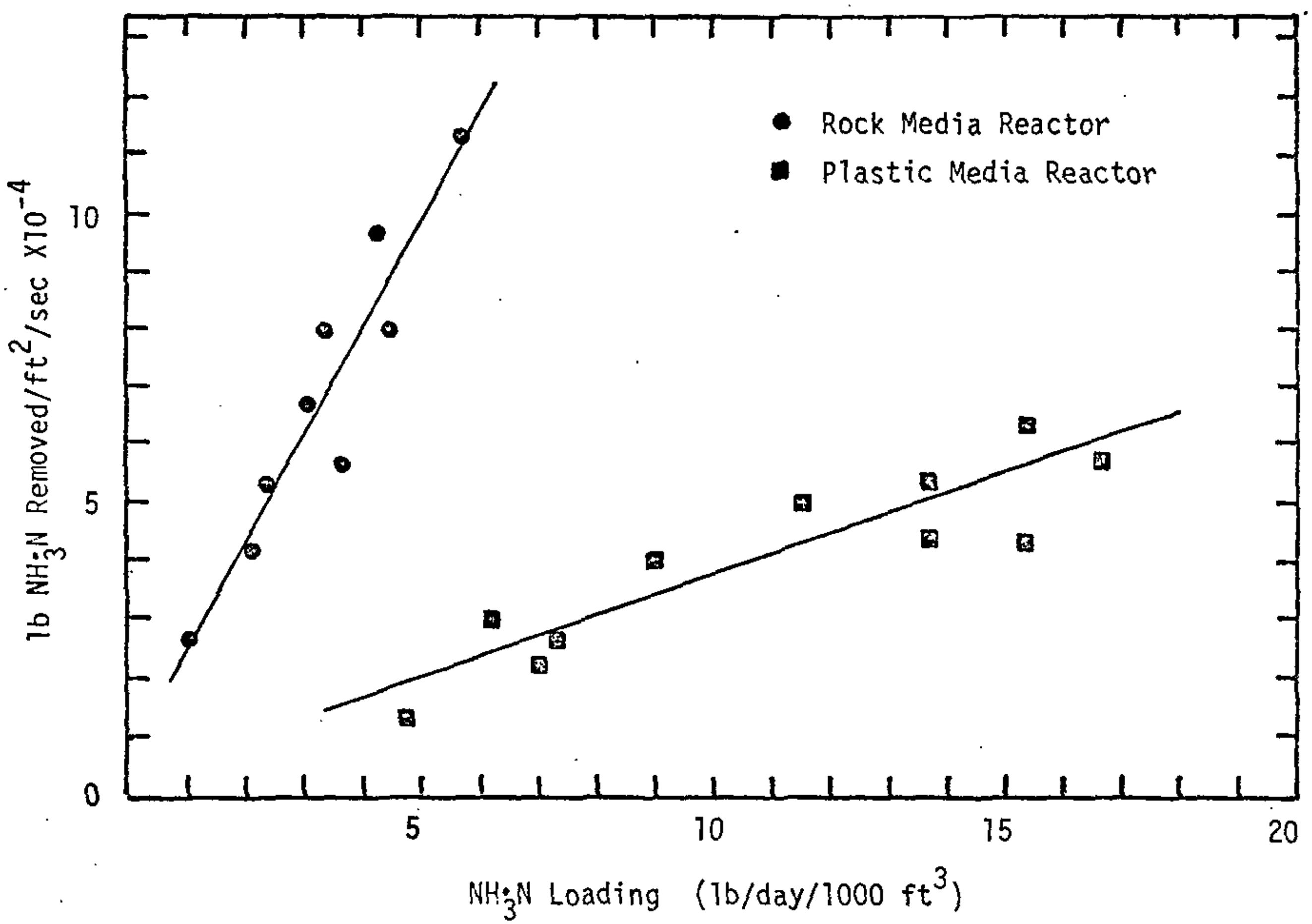

FIGURE 17. NITRIFICATION AS A FUNCTION OF AMMONIA LOADING NORMALIZED FOR MEDIA SURFACE AREA AND HYDRAULIC DETENTION TIME

cient of diffusion, the rate of nitrification would exhibit a greater response to substrate loading in a reactor with a higher degree of hydraulic turbulence. Future research should be directed at evaluating the flow conditions over different types of media.

Effect of Media Depth

Contact time between the applied wastewater and the biomass depends upon media depth. Although an increase in depth and thus in contact time would appear to improve the nitrification efficiency, Duddles (25), Hammer (26), and others concur that added media depth (i.e., contact time) yields diminished returns in terms of added treatment.

In a flow field such as described by the void spaces in a rock media reactor, changes in hydraulic application rate will only affect contact time if the void spaces are saturated. However, a mathematical description of the relationship between contact time and depth is difficult to obtain because the dependency of local velocity within the bed upon application rate may be highly variable. This effect is influenced by the size and shape of the media and the resultant void spaces.

It is important to note that similar depths of rock and plastic media do not necessarily imply similar contact times for given flow conditions. When comparing changes in depth for two different types of media, two factors must be considered: (1) that contact time is also dependent on the specific surface area over which the wastewater must move, and (2) that structure of the media determines the type of flow conditions that will exist. For these reasons, the two reactors could not be directly compared.

The simplest approach to studying the effect of contact time would be to compare the nitrification rates achieved at different depths. Grouping the data from the rock media reactor to isolate the effect of media depth, Table 5 indicates that the additional 2 feet (0.6 m) of rock almost doubled the amount of ammonia nitrified. However, the BOD_5 removal efficiency, as evidenced by effluent quality (see Figures 4 and 5) was not significantly improved. This would indicate that the contact time provided by a media depth of 5 ft (1.5 m) was sufficient to promote degradation of organics. The fact that a deeper bed had improved nitrification but not BOD_5 removal suggests stratification of organism types within the reactor. That is, the added surface area was utilized to a greater extent by the autotrophic population. This would seem reasonable because the growth rate of nitrifying bacteria is much less than that of heterotrophic bacteria. Since the shallower bed was sufficient for BOD_5 oxidation, the added depth was able to be utilized by the autotrophic population without competition for growth sites by the heterotrophs.

Regardless of the population distribution, sufficient contact time must be available for both carbon and ammonia oxidation reactions to occur. Therefore, the depth of media becomes a primary design factor when attempting to promote nitrification in a fixed-growth reactor.

To examine the effect of depth in the plastic media reactor, sampling ports were installed at 6 ft (1.8 m) intervals up the side of the tower. Samples were withdrawn through a trough-like section of 1/2 in (1.3 cm) copper pipe, inserted to collect samples representative of that cross-section of media. Periodic analyses were made for nitrogen

TABLE 5. EFFECT OF MEDIA DEPTH ON NITRIFICATION IN THE ROCK MEDIA REACTOR

Depth ft	Temperature ^{o}C	BOD_5 Loading lb/day/1000 ft^3	NH_3N Loading lb/day/1000 ft^3	$\frac{\text{lb } NH_3N \text{ Removed}}{\text{day/1000 } ft^3}$
5	19	20	3.0	1.6
7	19	15	2.0	2.5
5	19	30	3.0	1.3
7	19	20	2.0	2.2
5	17	30	4.5	1.0
7	17	20	3.0	2.3
5	17	35	4.5	1.0
7	17	25	3.0	1.9
5	16	30	4.5	1.0
7	16	20	3.0	2.2
5	16	30	3.0	0.8
7	16	20	2.0	1.9

forms and a typical result is shown in Figure 18. This figure indicates that a significant portion of the ammonia is nitrified in the upper regions of the bed, and occurs simultaneously with carbon oxidation. However, this does not prove that the autotrophs are the predominant organisms in this region. Hanumanulu (21) found that most of the organic material was degraded in the upper 6 ft (1.8 m) of an 18 ft (5.4 m) plastic media reactor. Thus it seems that most of the depth in a deep plastic reactor is relatively inefficient, serving only to polish the effluent to a higher quality rather than removing a large portion of the contaminants.

To summarize, dissimilar conclusions were reached regarding the effect of depth on nitrification for the two types of systems investigated. In the rock media reactor nitrification only occurred at the lower depths, while in contrast the upper portion of the plastic media reactor was the most effective. It should be noted that because the two reactors are constructed of media utilizing different structure and materials, direct comparison of nitrification performance is impossible. However, distinct differences in surface area and contact time produced obvious differences in the observed nitrification rates.

Effect of Temperature

Temperature is the least controllable of the major parameters affecting nitrification in a fixed-growth reactor and possibly the most critical in terms of sewage treatment in New England. This study was begun in early February 1975 and continued through December 1975 when the units became ice-coated due to prolonged sub-freezing tempera-

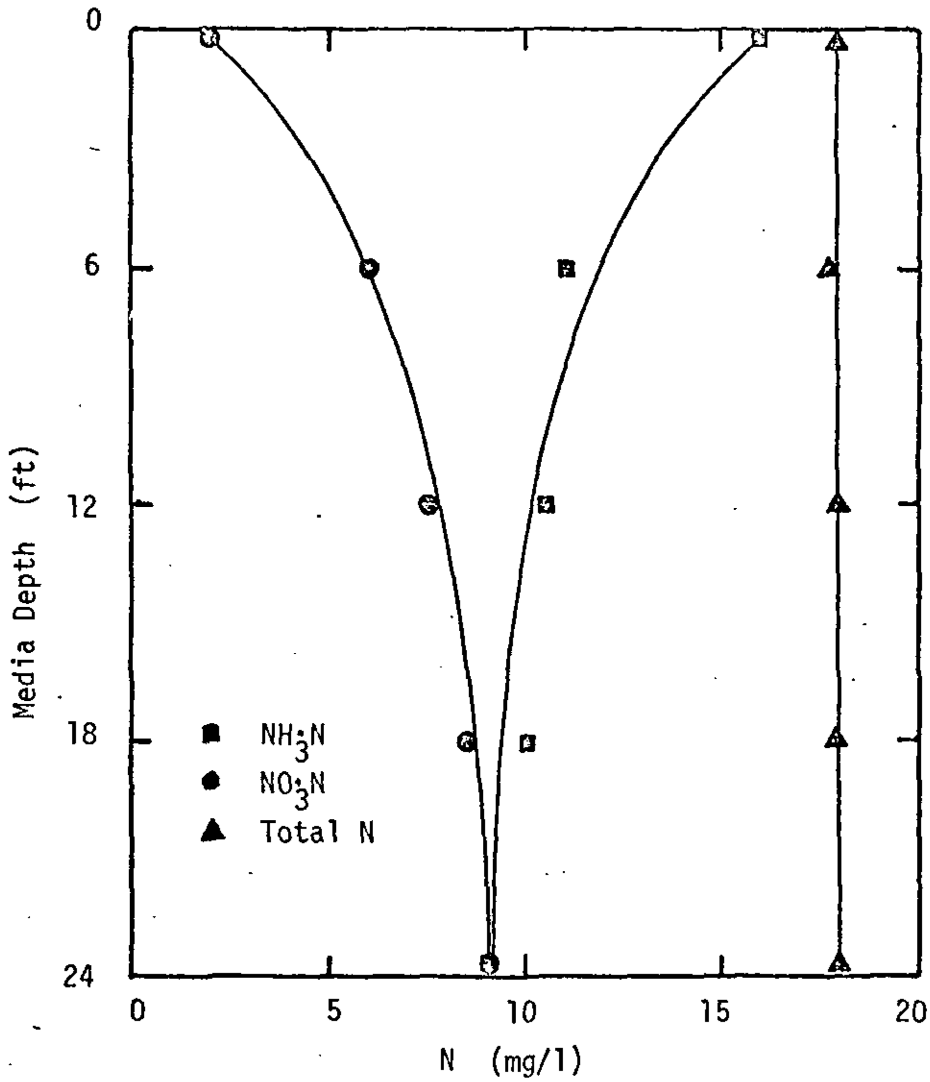

FIGURE 18. NITROGEN FORMS AT DIFFERENT DEPTHS IN THE PLASTIC MEDIA REACTOR

tures. The problem of freezing will only normally be experienced in small pilot-scale systems, where the low wastewater volume is insufficient to counter the effects of sustained low air temperatures.

A temperature drop occurred in the rock and plastic media reactors as a result of heat transfer caused by spreading the wastewater over a relatively large surface area. For example: when the ambient air temperature was 8°C, the wastewater temperature decreased from 19°C to 11°C at the top of the media. However, within the rock media reactor, the temperature normally increased by about 1°C, in contrast to the plastic media reactor, where the temperature usually decreased by about 1°C. This difference in the direction of temperature change within the reactors was probably due to structural differences and the associated draft conditions.

The effect of wastewater temperature on nitrification rate in the rock and plastic media reactors can be seen in Figures 19 and 20 respectively. As the temperature decreased below about 18°C, the nitrification rate also began to decrease. Moreover, in both reactors, nitrification ceased as the wastewater temperature fell below about 5°C. This result agrees with the EPA studies (8), which demonstrated that nitrification could not be sustained below a temperature of 4°C in a suspended growth reactor. Clearly, year round nitrification in a fixed-growth reactor will be impractical; however, seasonal ammonia removal is still possible.

As should be expected, the effect of temperature on nitrification rate was similar for both reactors. That is, biological activity rather than fixed-growth reactor characteristics are influenced by

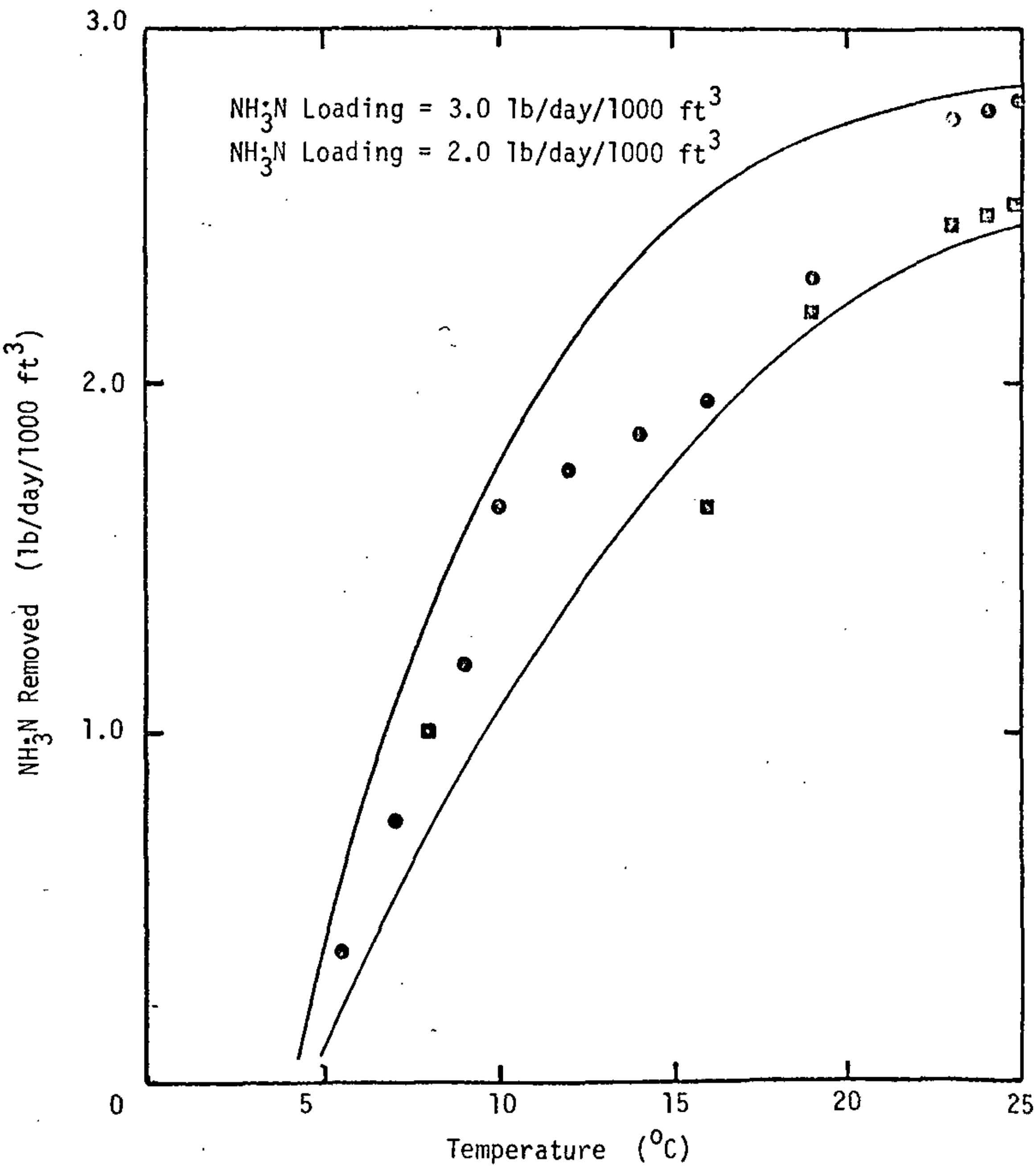

FIGURE 19. NITRIFICATION AS A FUNCTION OF TEMPERATURE IN THE ROCK MEDIA REACTOR

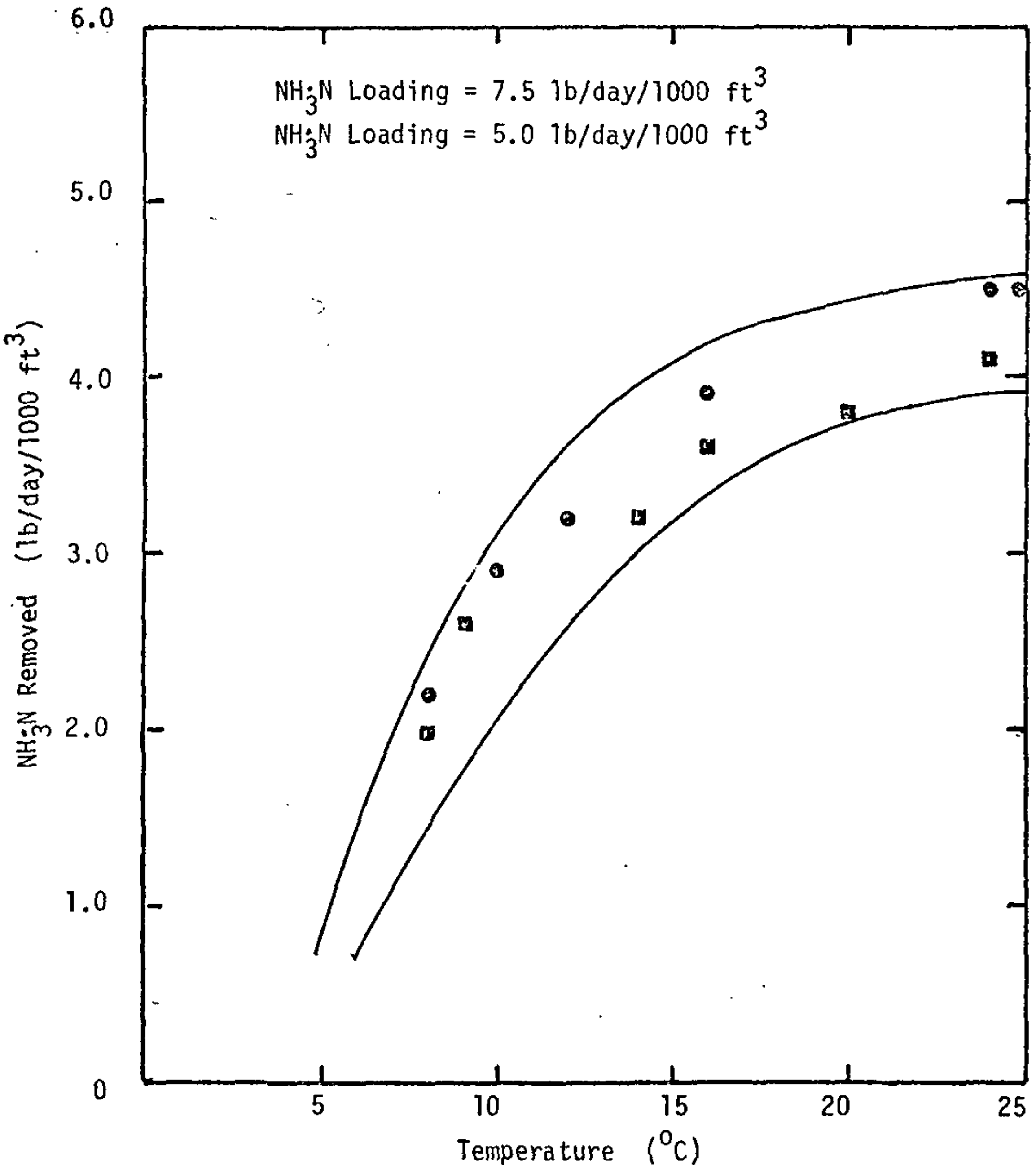

FIGURE 20. NITRIFICATION AS A FUNCTION OF TEMPERATURE IN THE PLASTIC MEDIA REACTOR

temperature and thus temperature related design criteria should be applicable to all fixed-growth systems with reasonable confidence.

Theoretically, the effect of temperature on biochemical reaction rates for both carbon and ammonia oxidation can be described by the van't Hoff-Arrhenius relationship (27):

$$\frac{K_1}{K_2} = \Theta^{(T_1 - T_2)} \tag{5}$$

where K_1 = the reaction rate at T_1 (°C)

K_2 = the reaction rate at T_2 (°C)

Θ = thermal coefficient

It is important to understand that the thermal coefficient Θ is not a true constant but is related to the activation energy of the reaction and the temperature range. However, for a limited temperature differential, Θ is considered constant for purposes of data evaluation. Equation 5 can be rewritten as

$$\log \frac{K_1}{K_2} = B(T_1 - T_2) \tag{6}$$

such that: $\Theta = 10^B$. The data given in Figures 19 and 20 was tested using Equation 6 to evaluate the thermal coefficient Θ for both types of reactors. The result of this analysis is given by Figure 21, using 15°C as a reference temperature. As expected, the effect of temperature on nitrification rate was shown to be similar for both systems. However, while the van't Hoff-Arrhenius relationship seemed to describe temperature dependency above 10°C, there was a marked departure from theory below this temperature. Therefore, the thermal coefficient Θ

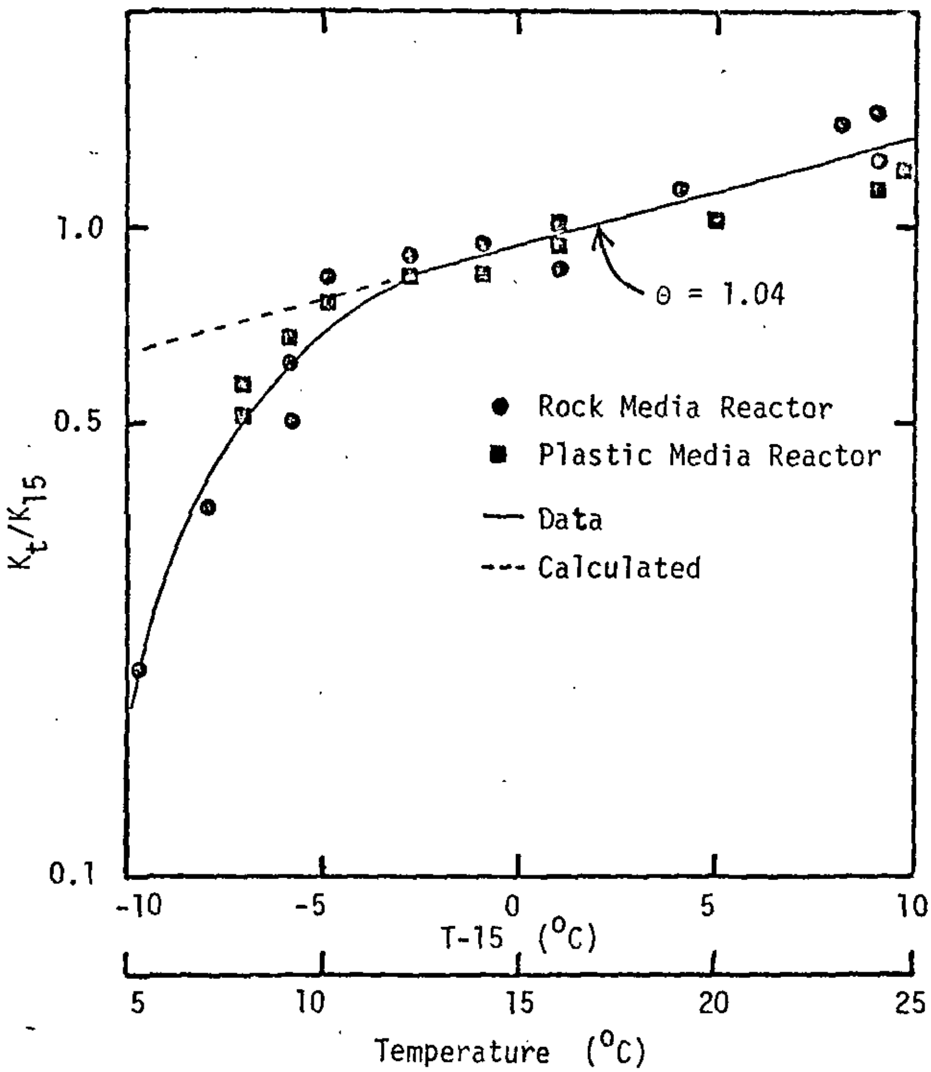

FIGURE 21. VAN'T HOFF-ARRHENIUS RELATIONSHIP

was evaluated for data taken above 10°C. The calaculated value for Θ of 1.04 is within the range of literature values (1.02-1.04) for fixed-growth reactors (27). At temperatures below 10°C, there is significant deviation from a straight line (semi-log plot), with the value of Θ increasing with decreasing temperature.

The effect of temperature on the rate of substrate utilization can be explained by two factors. The primary factor is thermochemical and related to enzyme activity within the bacterial cell. The activity of the bacteria is at a maximum near the upper limit of its temperature range (28). Increasing the temperature above this limit causes denaturing of enzymes resulting in decreased activity or cell death. Lower than optimum temperatures reduce enzyme activity with a subsequent reduction in other biochemical activity. The second factor responsible for a changing rate of substrate utilization with temperature is diffusion. As the temperature of the wastewater decreases, its density increases to a maximum at 4°C. This results in a lower rate of substrate diffusion through the cell wall. However, lower wastewater temperatures also correspond to higher DO concentrations which should enhance diffusion of this necessary electron donor into the cell. In systems where the oxygen supply is not limited, the additional diffusional flux of oxygen should be unimportant at lower temperatures.

Therefore, the inability of the van't Hoff-Arrhenius relationship to describe the change in biological reaction rate at lower temperatures may be explained by a decrease in enzyme activity. That is, as Figure 21 indicates, the value of Θ seems to be continually increasing with decreasing temperature. Higher values of Θ indicate an increase in activation energy required to initiate the reaction. In turn, in biological systems, a higher activation energy is associated with lower enzyme activity. At some low wastewater temperature, enzyme activity will cease and the biochemical reaction will stop.

Coincidentally, while nitrification steadily decreased with decreasing temperature, BOD_5 removals were largely unaffected. Effluent BOD_5 concentrations were consistently in the 20-35 mg/l range for the rock media reactor. This could be due to a wider temperature range for heterotrophic bacteria or adaptation to lower temperatures which the autotrophic bacteria failed to achieve.

Comparison With Other Investigations

Although there have been many studies of fixed-growth reactor performance, only a few have been concerned with the occurrence of simultaneous carbon and nitrogen oxidation (2,18,20,25,29,30). More importantly, the research reported in the literature on fixed growth nitrification lacks complete documentation needed to make a valid comparison between studies. However, it is important to compare results to whatever extent is possible, recognizing the difficulties of drawing conclusions with limited information.

Table 6 provides the available information for media type, depth, temperature, hydraulic application rate, recycle ratio, BOD_5 and NH_3N loadings, and ammonia removal rate collected from seven pilot plant studies conducted elsewhere in the U.S. For comparison, data taken during operation of the rock and plastic media reactors used in this study (under summer conditions) are included. It is important to

TABLE 6. COMPARISON OF AMMONIA REMOVALS OBTAINED IN PILOT PLANT STUDIES

Study Location	Media Type	Depth ft.	Temp. ^{o}C	Hydraulic Application gpm/ft^2	Recycle Ratio	BOD_5 Loading lb/day	NH_3-N Loading lb/day	NH_3-N Removed lb/day/1000 ft^3
Livermore Ca.	rock	4.3	NA	0.054	2.0	110	90	17.8
Glenwood City Wis.	rock	7.0	NA	0.23	2.0	66	4.2	1.5
Lakefield Minn.	rock	7.5	NA	0.11	0.3	54	3.5	0.5
Allentown Pa.	rock	10.0	NA	0.070	0.1	18	2.6	1.6
Ft. Ben. Har. Ind.	rock	8.0	NA	0.027	0.0	4.6	0.9	0.6
Fitchburg Ma.	rock	10.0	NA	0.064	0.0	3.7	0.4	0.4
Midland Mich.	plastic	21.5	NA	0.50	1.0	4.9	3.6	3.1
Amherst Ma.	rock	7.0	20	0.20	2.0	14	1.5	1.4
Amherst Ma.	rock	5.0	19	0.20	2.0	17	2.4	1.1
Amherst Ma.	plastic	24.0	21	2.00	1.0	62	8.9	4.4

note the absence of temperature data from the other seven studies. However, published information from each study indicated that temperatures were moderate and not detrimental to nitrification. The most obvious conclusion reached from examination of Table 6 is that a wide variation in operating conditions produced a wide range of ammonia removal rates. When formulating a comparison between different studies it is important to recognize differences in physical properties of the system such as media surface area, type of material, and roughness, etc. Also important, but less easily determined, is the possibility that the applied wastewater contained toxic substances which could have depressed the nitrification rate.

The results most directly comparable to those of this study were those obtained from Glenwood City, Wisconsin and Lakefield, Minnesota. Rock media reactors having depths of 7.0 ft (2.1 m) and 7.5 ft (2.3 m) were used in these two studies, respectively. More importantly, of the seven studies to be compared, hydraulic application rates typical of high-rate reactors were used only in these two studies. The percent ammonia removals based on influent and effluent concentrations were only 37 and 13% respectively; however, the actual nitrification rates per unit volume of media were similar to those obtained in this study. For both studies, the average sustained organic loadings were about a factor of three larger, and the ammonia loadings a factor of two larger than encountered in this study. It may be reasoned that the nitrification rate would tend to decrease with higher sustained organic loadings and increase with higher ammonia loadings. Thus, these two factors produce opposite effects on nitrification. This may offer a plausible explanation for the similarity of nitrification rates observed in these studies with those found in this study.

As also shown in Table 6, a rock media depth of only 4.3 ft (1.3 m) was used in the Livermore, California study; additionally, the BOD_5 loading was quite high. Despite these apparent detrimental factors, a relatively high nitrification rate was achieved. However, it must also be noted that the ammonia loading rate was about an order of magnitude larger than measures in this study. Thus, the higher nitrification rate may have resulted from a higher rate of mass transfer of ammonia through the biofilm which promoted the establishment of a stable autotrophic population. Nevertheless, it is impossible to generalize a relationship between ammonia loading and removal rates based on only two extremes of reported loadings; an intermediate range of ammonia loadings would need to be examined. In contrast, the Fort Benjamen Harrison, Indiana and the Fitchburg, Massachusetts studies help to indicate the effect of low ammonia loadings on nitrification rate. With the lowest reported ammonia loadings, only a marginal amount of nitrification was attained.

In the Allentown, Pennsylvania study, BOD_5 and ammonia loadings to a rock media reactor were similar to those in this study. Although 3 ft (0.3 m) deeper than the rock media reactor used in this study, the nitrification rate was only slightly higher (1.4 compared to 1.1 lbs. NH_3N removed/day/1000 ft^3). Differences in the hydraulic application rates used in the studies may account for the discrepancy in the rates measured. That is, because the hydraulic application rate in the Allentown study was only about one-third that used in this study, the higher nitrification rate found in Allentown could be attributed to the longer contact time provided by the combination of lower hydraulic loadings and greater media depth.

Only the Midland, Michigan study was aimed at investigating combined carbon and nitrogen oxidation in a plastic media reactor. A tertiary biological process was simulated by maintaining low organic loadings. However, the lower ammonia loadings and the shorter tower height used in Midland make direct comparison of results difficult. Although the nitrification rate was lower at Midland, the efficiency based on influent and effluent ammonia concentrations was much higher. That is, 88% of the influent ammonia was converted at the Midland plant as compared to only 44% in this study. The fact that a higher percent conversion was achieved at a lower nitrification rate is simply a consequence of the much lower ammonia loadings applied at Midland than in this study (3.6 versus 8.9 lbs./day/1000 ft^3).

It is important to re-emphasize the limitations of such comparisons as given by Table 6. Differences in physical characteristics such as media type, distribution system, and recycle ratio, etc., as well as differences in wastewater composition, can all combine to affect nitrification performance. However, these differences may only affect the magnitude of ammonia removal rates and not the direction of major trends noted in the comparisons attempted. The results given in Table 6 indicate that under proper operating conditions, it is possible to achieve at least seasonal nitrification in fixed-growth reactors.

SUMMARY AND APPLICATION

The results of this study indicate that, under proper operating conditions, fixed-growth reactors may be capable of achieving better than 90% nitrification while still maintaining acceptable BOD_5 removal. Of the major factors that influence nitrification, wastewater temperature was shown to exert the most dramatic effect on the rate of nitrification. The nitrification rate ranged from 0 lb./day/1000 ft^3 NH_3-N oxidized at 5°C to almost 3.0 lb./day/1000 ft^3 NH_3-N oxidized at temperatures greater than 18°C for the rock media reactor. Similar results were obtained for the plastic media reactor. Thus, for northern climates, reactors exposed to the weather can only be expected to maintain adequate nitrification on a seasonal basis. The temperature behavior of both units was shown to follow the van't Hoff-Arrhenius relationship down to temperatures of 10°C. Below this temperature, decreased enzyme activity resulted in higher activation energy requirements for the nitrification reaction and a decrease in the observed nitrification rate. The effect of organic loading on nitrification was demonstrated to be different for the two units investigated. Both the rock and plastic media reactors could be expected to exhibit decreased levels of nitrification at sustained high BOD_5 loadings. However, the nitrification rate in the rock media reactor did not respond to daily fluctuations in BOD_5 loadings, in contrast to the plastic media reactor, which showed a decreasing nitrification rate as the BOD_5 loading increased. The exact cause of this effect was not known, but was thought to be a consequence of the flow conditions resulting from the differences in media construction. The nitrification rate for both units was shown to be dependent on the applied ammonia loadings. For both reactors, the nitrification rate increased with increasing ammonia loadings. This dependency on substrate concentration implies that the nitrification reaction in a fixed-growth reactor does not follow zero-order kinetics generally accepted for nitrification reactions in suspended growth systems. The higher than zero-order reaction rate was presumably due to the added step of substrate diffusion through the fixed biofilm.

In addition to the effects of the major variables described above, several other important points were brought out by this study. In a special experiment performed with the rock media reactor, an increase in the hydraulic application rate from 0.20 gpm/ft^2 (8.13 lpm/m^3) to 0.30 gpm/ft^2 (12.2 lpm/m^2) resulted in a washout of the nitrifying bacteria from the system. This was attributed to excessive attrition of the autotrophic population as a result of increased shear forces, and the inability to produce sufficient new growth due to the low specific growth rate of the nitrifiers. Longer contact time between the wastewater and the biomass increases the nitrification rate; however, the improvement becomes marginal as the contact time is increased excessively. The effect of increased contact time will be less pronounced for medias having large specific surface areas. Organic nitrogen hydrolysis was shown to contribute significant amounts of ammonia as a result of heterotrophic activity within the fixed-growth systems. Most of this "new" ammonia was then oxidized within the contact time provided by each reactor.

The results of this study are intended to demonstrate the conditions necessary for achieving nitrification in an existing fixed-growth reactor. Modifications of operating parameters such as hydraulic application rate, recycle ratio, media type, and media depth, may be utilized to optimize the conditions necessary to promote nitrification. Based on these results, a media that would combine the high specific surface area of the plastic media and the flow characteristics of the rock media used on this study would most likely provide a highly efficient unit operation. The application of these results to existing and proposed facilities would provide a practical and economic waste treatment alternative. Capital-poor rural areas, where sophisticated treatment facilities are impractical, would benefit from the simplicity and effectiveness of such a system.

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