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Process Parameters for Separate-Stage Nitrification Activated Sludge Systems in Cold Environments

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PROCESS PARAMETERS FOR SEPARATE-STAGE NITRIFICATION ACTIVATED SLUDGE SYSTEMS IN COLD ENVIRONMENTS

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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In memory of Steve Kracke a fellow environmentalist, operator and friend.

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INTRODUCTION

Nature of the Problem

Nitrogen concentrations in raw domestic wastewater typically range from 15 to 50 mg/l, of which approximately 60 percent is in the ammonia-nitrogen form and 40 percent is the organic nitrogen form. A negligible amount (less than 2 percent) is in the nitrite-nitrogen and nitrate-nitrogen forms.(1) Nitrogen sources consist of both natural and man-made inputs. Natural nitrogen sources include the fixation of nitrogen gas from the atmosphere, the decomposition of dead animals and plants, and the decomposition of animal waste products. Primary man-made sources of nitrogen in domestic wastewater are feces, urine and food-processing discharges resulting in a per capita contribution of approximately 8 to 12 pounds of nitrogen per year.(2) The United States Environmental Protection Agency (EPA) estimates that about 0.84 million metric tons of nitrogen per year are discharged into domestic sewerage systems in the United States.(1)

Nitrogen discharge into receiving waters causes several detrimental effects. Biostimulation and dissolved oxygen depletion in the receiving waters are the main concerns, along with, toxicity to fish and adverse public health effects.(1)

Oxygen depletion of the receiving stream caused by the oxidation of ammonia-nitrogen to nitrate-nitrogen, can be eliminated if nitrogen in the ammonia-nitrogen form is oxidized to the nitrate-nitrogen form prior to discharge to the receiving stream. Biological nitrification is the treatment process commonly used to accomplish this transformation.

Objectives

The Brookings Wastewater Treatment Facility is authorized by a National Pollutant Discharge Elimination System (NPDES) Permit No. SD-002338 to discharge treated wastewater to the Big Sioux River. A summary of this permit can be found in Table 1. To provide proof of compliance with the NPDES Permit, periodic sampling and analyses of the treated effluent is required.

Primary sample points at the Brookings Wastewater Treatment Plant (BWWTP) are located at the influent to establish raw wastewater concentrations and at the effluent to determine compliance with NPDES Permit discharge parameters. This sampling regime also provides information on the overall plant performance and removal efficiency of typical domestic wastewater concentrations. Although this sampling procedure does provide the necessary information for proof of compliance with the NPDES Permit, it does not provide sufficient data to evaluate the individual performances of the various treatment processes throughout the plant.

Table 1. Summary of NPDES Discharge Permit

Wastewater Treatment Plant Brookings, South Dakota

Effective Until June 30, 1983

Parameter	Effluent Requirements	Sample Type	Frequency
Biochemical Oxygen Demand - mg/l*	20 mg/l for weekly average for entire year	Composite	3/week
Total Suspended Solids - mg/l	30 mg/l for monthly ave., 45 mg/l for weekly average*, 100 mg/l daily.	Composite	3/week
Fecal Coliform number/100 ml**	3000 April-June, only 1500 July-Sept. only	Grab	3/week
Ammonia - Nitrogen mg/l as N*	6.0 - (Nov.-Mar.), 2.0 (Apr.-June), 1.0 (Jul-Sept.) 8.0 Oct.	Composite	3/week
Total Residual Chlorine***	Shall not exceed 0.05 mg/l	Grab	Daily***
Oil and Grease	Shall not exceed 10 mg/l	Visual	5/week
Dissolved Oxygen	Greater than 7 mg/l July thru Sept. and greater than 9 mg/l rest of year	Grab	Continuous
pH-units	Shall remain between 6.0 and 9.0		2/week

* Arithmetic mean of a minimum of 3 consecutive samples collected on separate days in a 7-day period.

** Fecal coliforms averages are from grab samples and the geometric mean is determined.

***Residual chlorine monitoring required only if effluent is chlorinated.

The objectives of this study were to: (1) determine if the nitrification process at the BWWTP is operating as a separate stage or combined ammonia-nitrogen removal process, based on the magnitude of the kinetic coefficients; (2) evaluate the nitrification kinetic coefficients at the BWWTP and compare them with values reported in the literature; (3) provide a basis of information and suggestions for future research to insure optimum performance of the air activated sludge nitrification system.

Description of the Treatment Plant

The Brookings Wastewater Treatment Facility (BWWTP), the subject of investigation in this thesis, provides preliminary, primary, secondary and tertiary treatment of the incoming flows and anaerobic sludge digestion. Secondary nitrification treatment is accomplished by an air-activated sludge system. The design average flow for the BWWTP is 3 million gallons per day (mgd) with a design peak flow of 6 mgd. The majority of the commercial and industrial waste flows are contributed by South Dakota State University, 3M company and Artz Locker. Household domestic wastewater flows are the principal contributors to the hydraulic loading, aside from typical infiltration quantities.

Upon reaching the wastewater plant, the raw wastewater is lifted approximately 23 feet to the preliminary treatment units by the means of 3 influent screw pumps, each capable of pumping 3,150 gallons per minute.(3)

The first step in the treatment process is the removal of large debris to prevent plugging and or breaking of other downstream treatment processes. This is accomplished by passing the wastewater through a 3-foot wide mechanically-cleaned barscreen.(3)(4)

After passing through the bar screen, the wastewater then flows into 2 aerated grit chambers for grit settling. Grit removal is necessary to protect mechanical equipment from abrasion and prevention of deposition of the "heavy" grit particles in downstream pipes and channels. Excess grit also accumulates in the anaerobic digesters and aeration tanks. Each chamber is equipped with a positive-displacement air compressor that forces air through a diffuser causing turbulent conditions resulting in the separation of organic matter from inorganic grit particles. The grit accumulates at the sloped bottom of the 14 feet by 14 feet by approximately 13 feet deep chambers and is removed by centrifugal grit pumps into a grit truck.(3)(5)

Solid particles that still remain in the waste stream are then ground into smaller pieces to eliminate clogging problems in the remaining treatment units. The BWWTP has 2 comminutors with each unit capable of handling 2.7 mgd.(3)(4)

Flow rate measurement is accomplished by passing the wastewater through an 18-inch molded fiberglass parshall flume.(3)

Settling of solid particles by gravity is the first step in the primary treatment process. Quiescent conditions are provided in two primary clarifiers that are 61 feet in diameter with a side water depth of approximately 8.5 feet. The settled solid particles are scraped to the center of the sloped bottom floor where they are pumped periodically to the anaerobic digesters. The clarified wastewater flows over perimeter weirs into a collection trough and flows on to the next treatment process, rotating biological contactors (R.B.C.'s).(3)(2)

The primary clarifier effluent next flows into 2 trains of rotating biological discs (R.B.C.'s), 4 units to a train providing a total surface area of 800,000 square feet. A R.B.C. is made from molded polyethylene discs supported on a shaft 28 feet in length passing perpendicularly through the center of the discs. The discs are mounted such that approximately half of the disc surface area is submerged below the water surface. The units are then rotated so that a biological film will develop on the discs as the surfaces are alternately exposed to the wastewater and the atmosphere. The biological growth absorbs and assimilates biological oxygen demand (BOD) organic material which results in more biological growth. Excess biomass is sloughed off by the shearing forces exerted as the discs rotate through the wastewater, resulting in a constant fixed-film microbial population. The unoxidized BOD and the sloughed-off biomass flows on to the air activated sludge unit.(3)(4)

Next, 3 screw pumps lift the wastewater approximately 15 feet up to the influent of the aeration basins. Each screw is capable of pumping 5000 gallons per minute. The increased pumping capacity, compared to the influent pumps, is justified by the increase of flow caused by the return activated sludge from the final clarifiers which is reintroduced to the activated sludge system at the intermediate screw pumps.(3)

The secondary treatment process is a combined air-activated sludge (AAS) system that consists of aeration tanks, aeration equipment, final clarifier and solids recycle equipment. The objective of the AAS process is to oxidize ammonia-nitrogen (NH_3-N) and organic substrate (BOD) that was not removed in the RBC unit. Oxidation is accomplished by activated sludge which contains a large population of biologically active microorganisms which convert the organic wastes into more biomass and gases.(3)(4)

Aerobic conditions provided by the aeration equipment, combined with readily oxidizable organic matter and proper nutrient concentrations result in an optimum microorganism reproduction environment. The activated sludge mixture, commonly called mixed liquor, is then transferred to the final clarifier where the mixed liquor is allowed to settle out forming a sludge blanket at the bottom of the final clarifier. Consequently, clarified wastewater flows over effluent weirs and flows onto

the gravity filters for further solids removal. A fraction of the settled solids is returned to the intermediate screw pumps and mixed with the RBC effluent to initiate the biological reduction process of organic material.(3)(6)

Solids must be wasted from the AAS system to control the population of microorganisms and to prevent wash-out of solids over the final clarifier weirs. Therefore, mixed liquor is wasted to the digestion facilities to facilitate new microorganism growth and allocate room for incoming raw wastewater solids.

The aeration basins at the B.W.W.T.P. are arranged in 2 trains with 4 basins per train. The first basin is 30 feet by 35 feet with a 15.5 feet side-water depth (16,275 cf volume), the second basin is 30 feet by 40 feet with a 15.4 feet side-water depth (18480 cf volume), the third basin is 30 feet by 50 feet with a sidewater depth of 15.3 feet (22,950 cf volume) and the final basin is 30 feet by 60 feet with a 15.2 feet side-water depth (27,360 cf volume).(3)

A final clarifier facilitates each train of basins with dimensions of 29 feet in width by 160 feet in length with a side water depth of 12 feet (55,680 cf volume). Sludge recycling is executed by a traveling bridge siphon.(3)

The tertiary treatment process consists of 2 gravity filters and ozone generators for disinfection. Two chlorinators are also available as a back-up system for disinfection.

Two automatic backwash filters each 16 feet wide by 44 feet long provide suspended solid removal from the clarifier effluent.(3)

Two ozone generators are the primary disinfection means at the BWWTP. For monetary reasons, 2 chlorinators capable of delivering 250 pounds and 2000 pounds of chlorine per day respectively, were being utilized for disinfection at the time of sample collection for this paper.(3)

Table 2 provides a design summary of each of the unit processes.

Table 2. Process Design (3)

Unit Process	Dimensions and/or Capacity	Hydraulic Det. Time			Loading Rate		
		3 MGD	6 MGD	9 MGD	3 MGD	6 MGD	9 MGD
Influent Screwpumps (3)	54"Ø, 38° 3150 GPM	---	---	---	---	---	---
Mech. Cleaned Screen	½" Bars,1" Sp. x 3' wide	---	---	---	---	---	---
Aerated Grit Chambers (2)	14'x14'x13' SWD	18 min.	9 min.	6 min.	---	---	---
Comminutors (2)	Infilco #16 2.7 MGD	---	---	---	---	---	---
Parshall Flume	18 inch 15 MGD	---	---	---	---	---	---
Primary Clarifiers (2)	55 ft. weir diam.,61 ft.tank	2.8 hr.	1.4 hr.	0.93 hr.	630 $\frac{GPD}{ft.^2}$	1260 $\frac{GPD}{ft.^2}$	1890 $\frac{GPD}{ft.^2}$
Rotating Biological Discs (8)	25' shaft 100,000 $ft.^2$	0.90 hr.	0.60 hr.	0.30 hr.	2.60 $\frac{GPM}{1000\ ft.^2}$	5.20 $\frac{GPM}{1000\ ft.^2}$	7.80 $\frac{GPM}{1000\ ft.^2}$
Intermediate Screw Pumps (3)	60"Ø, 38° 5000 GPM	---	---	---	---	---	---
Aeration Basins:							
L1 & R1	30'x35'x15.5'	1 hr.ea.	.5 hr.ea.	.3 hr.ea.	---	---	---
L2 & R2	30'x40'x15.4'	1.1 hr.ea.	.55 hr.ea.	.37 hr.ea.	---	---	---
L3 & R3	30'x50'x15.3'	1.37 hr.ea.	.69 hr.ea.	.46 hr.ea.	---	---	---
L4 & R4	30'x60'x15.2'	1.64 hr.ea.	.82 hr.ea.	.55 hr.ea.	---	---	---
		5.11 $\frac{hr.}{side}$	2.56 $\frac{hr.}{side}$	1.68 $\frac{hr.}{side}$			
Final Clarifiers (2)	29'x160'x12'	6.66 hr.	3.33 hr.	2.22 hr.	323 $\frac{GPD}{ft.^2}$	646 $\frac{GPD}{ft.^2}$	969 $\frac{GPD}{ft.^2}$

LITERATURE REVIEW

Nitrogen Cycle

Nitrogen exists in many forms in the environment, the principal forms of nitrogen are nitrogen gas (N_2), ammonia (NH_3/NH_4^+), organic-nitrogen (N), nitrite-nitrogen (NO_2^-) and nitrate-nitrogen (NO_3^-). Nitrogen also exists in many compounds due to the stability of nitrogen at numerous oxidation states; the oxidation states are shown below:(1)

Oxidation State:	-3	0	+3	+5
Nitrogen Species:	NH_3/NH_4^+	N_2	NO_2^-	NO_3^-

The principal forms of nitrogen in domestic waste water are the organic and ammonia forms. Table 3 shows typical constituents and concentrations of both raw and treated domestic wastewater. The relationship of the various transformations of the nitrogen cycle are shown schematically in Figure 1.(1),(2),(4)

TABLE 3. APPROXIMATE COMPOSTION OF AN AVERAGE DOMESTIC WASTEWATER (mg/l). (2)

	Before Sedimention	After Sedimention	After Biological Treatment
Total Solids	800	680	530
Total volatile solids	440	340	220
Suspended solids	240	120	30
Volatile suspended solids	180	100	20
BOD	200	130	30
Ammonia nitrogen as N	15	15	24
Total nitrogen as N	35	30	26
Soluble phosphorus as P	7	7	7
Total phosphorus as P	10	9	8

Biological Nitrification

Biological nitrification does not actually remove ammonia from the waste water, instead, it involves the conversion of ammonia to the nitrates, which are less toxic and constitute a decrease in oxygen-depletion potential to the receiving stream. Biological nitrification is defined as the biological oxidation of the ammonium ion to the intermediate form of nitrite and finally to the stable nitrate form.(1)(6) Figure 2 is a flow diagram showing typical substrate removal as the waste stream progresses through both a combined-and separate-stage biological treatment scheme:(2)

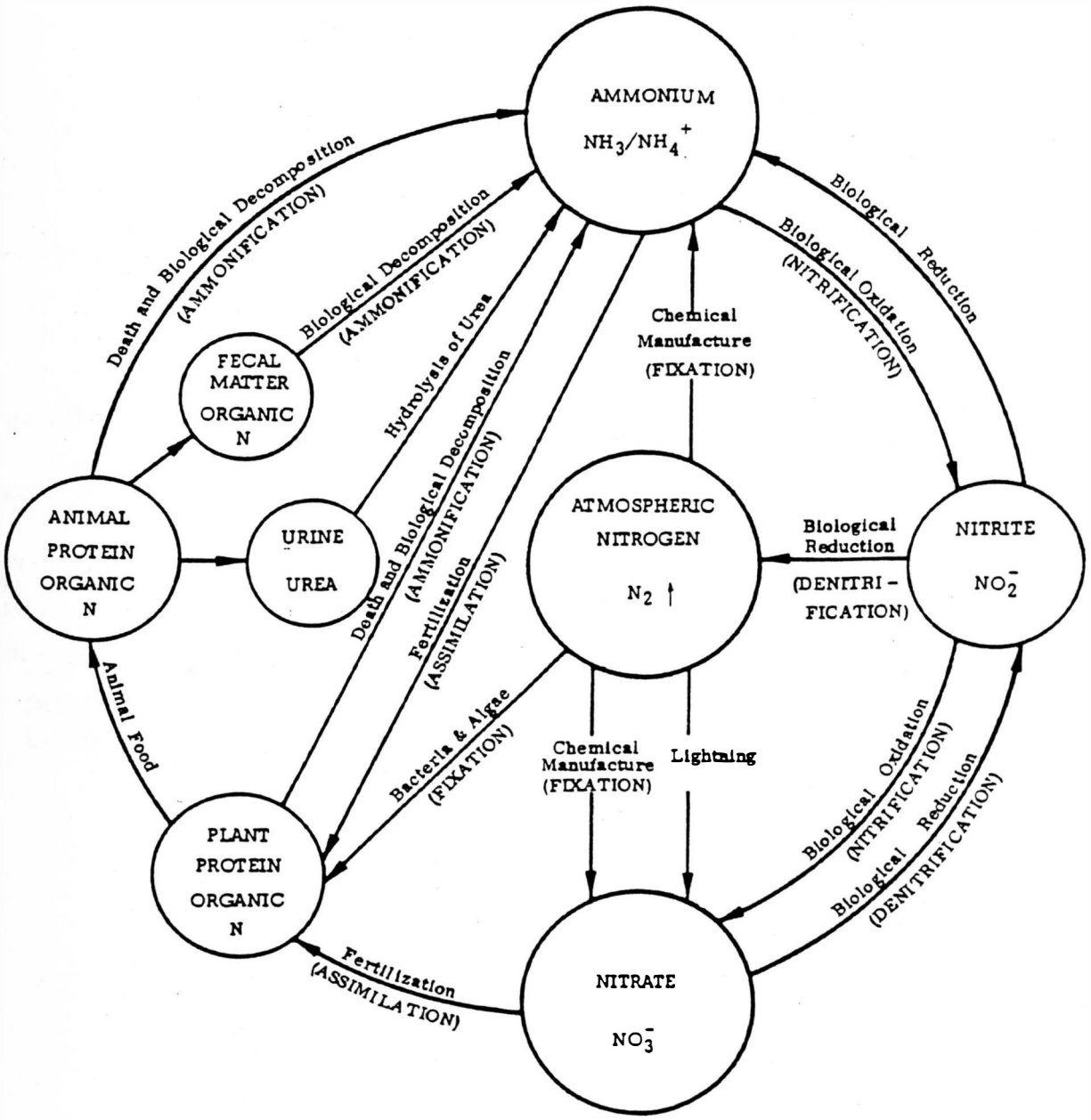


Figure 1. The Nitrogen Cycle (1)

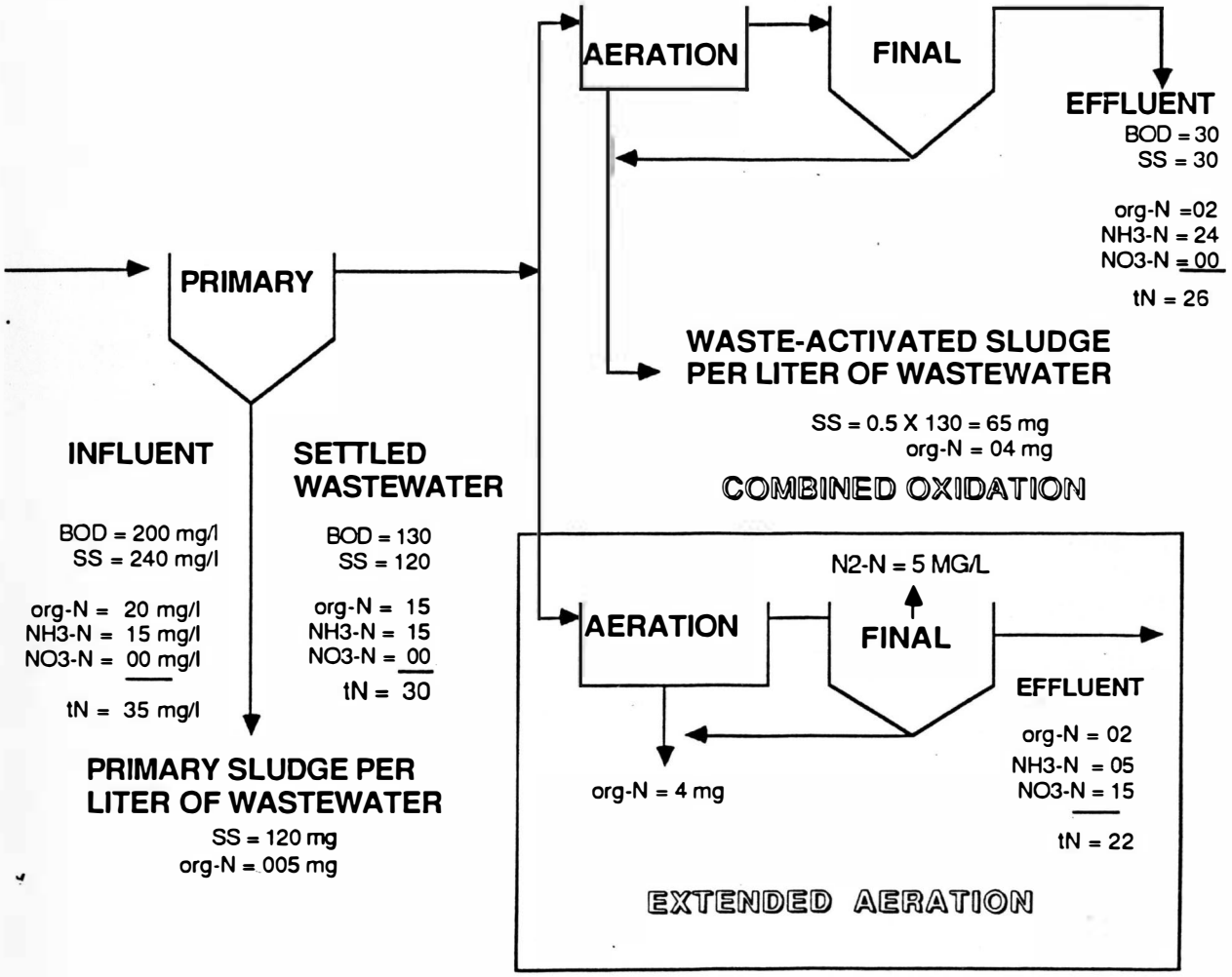


FIGURE 2. FLOW DIAGRAM OF NITRIFICATION TREATMENT SCHEME SHOWING TYPICAL REMOVAL RATES (4)

Viessman and Hammer report that primary sedimentation typically reduces the BOD demand by approximately 35 percent, suspended solids (SS) 50 percent and total nitrogen by approximately 14 percent.(2) Combined activated sludge systems typically result in an effluent BOD concentration that is approximately 15 percent of the original concentration. Suspended solids reduction is accomplished from the conversion of SS to biological biomass and by the wasting of waste activated sludge. During biological metabolism in the activated sludge process organic nitrogen (N) is converted into the ammonia form (NH_3-N). Extended aeration of the activated sludge process (separate-stage nitrification) induces further transformation (nitrification) of the NH_3-N to nitrate-nitrogen (NO_3-N). The rate of nitrification is dependent upon several factors including temperature, dissolved oxygen, pH, sludge age and the actual nitrogen concentration. Anerobic conditions in the final clarifier can result in denitrification, the conversion of NO_3-N to gaseous N_2.(2)(7)(8)

Nitrifying bacteria are common in activated sludge mixed liquors; however, they require an extended mean-cell residence time and low BOD/TKN (total Kjedahl nitrogen) ratio in order for nitrifying bacteria to establish a sufficient population. Metcalf and Eddy reported that BOD/TKN ratios between 1 and 3 typically indicate separate-stage nitrification systems.(4) They also state that the fraction of nitrifying bacteria to the total population of bacteria (at these ratios) range from 0.21 for a BOD/TKN ratio of 1 to 0.083 for a BOD/TKN ratio of 3.(4) Table 4 shows the relationship between the BOD/TKN ratio and the

nitrifier fraction.(4)

TABLE 4. RELATIONSHIP BETWEEN THE FRACTION OF NITRIFYING ORGANISMS AND THE BOD_5/TKN RATIO. (4)

BOD5/TKN ratio	Nitrifier fraction	BOD5/TKN ratio	Nitrifier fraction
0.5	0.35	5.0	0.054
1.0	0.21	6.0	0.043
2.0	0.12	7.0	0.037
3.0	0.083	8.0	0.029

Biological nitrification is accomplished by 2 principal genera, Nitrosomonas and Nitrobacter. Both of the these genera are classified as aerobic autotrophic microorganisms.(1)(8) These organisms derive energy for growth from the oxidation of inorganic nitrogen compounds and inorganic carbon (carbon dioxide) for synthesis.(1)(9)

Nitrification Stoichiometry

Nitrification is the oxidation of the ammonium ion to nitrite nitrogen by the Nitrosomonas bacteria, and further transformation to nitrate nitrogen by the Nitrobacter bacteria represented by the following two (2) equations:(1),(9),(10)

Nitrosomonas

$$NH_4^+ + 1.5O_2 \longrightarrow NO_2^- + 2H^+ + H_2O \quad (1)$$

Nitrobacter

$$NO2^- + 0.5O_2 \longrightarrow NO_3^- \quad (2)$$

With the overall oxidation reaction being:(1)

$$NH_4+ + 2O_2 \longrightarrow NO_3^- + 2H++ H_2O \quad (3)$$

Sundstrom reports that the conversion of ammonia to nitrite is the limiting constituent and controls the overall reaction; therefore, nitrite concentrations do not normally build up to significant concentrations in typical activated sludge systems.(6)

A portion of the ammonium ion is also assimilated into cell tissue. Equation (4) shows the Nitrosomonas and Nitrobacter autotrophic assimilation reactions:(1)(10)

$$15CO_2 + 13NH_4^+ \longrightarrow 10NO_2^- + 3C_5H_7NO_2 + 23H^+ + 4H_2O \quad (4)$$

$$5CO_2 + NH_4^+ + 10NO_2^- + 2H_2O \longrightarrow 10NO_3^- + C_5H_7NO_2 + H^+ \quad (5)$$

The overall oxidation and cell synthesis reaction of the ammonium ion to nitrate is:(1)(10)

$$NH_4^+ + 1.83O_2 + 1.98\ HCO_3^- \dashrightarrow 0.021\ C_5H_7NO_2 + 0.98\ NO_3^- + 1.04\ H_2O + 1.88\ H_2CO_3 \quad (6)$$

Oxygen Requirements

Oxygen is utilized in the oxidation reactions carried out by nitrifying bacteria. Oxygen consumption for complete nitrification requires approximately 4.6 mg/l of dissolved oxygen (D.O.) per mg of ammonia converted to nitrate.(1)(4)(8)

Alkalinity Requirements

Alkalinity is destroyed by the oxidation of the ammonium ion. The EPA estimates that 7.14 mg/l of alkalinity as $CaCO_3$ is utilized per mg of ammonia nitrogen oxidized.(1)

Temperature Effects on Nitrifier Growth Rates

The growth rate of Nitrosomonas microorganisms is limited by the concentration of ammonia-nitrogen, while, Nitrobacter microorganisms growth is controlled by the nitrite concentration.(1) The growth rate for nitrobacter is significantly higher than that for Nitrosomonas, therefore, the Nitrosomonas nitrifier growth rate is the limiting factor for nitrifying bacteria.(1)(6) Equation 7 shows the effect of temperature on the maximum growth rate of rate-limiting Nitrosomonas bacte-

ria as follows:(1)

$$\hat{u}_n = 0.47e^{**}0.098(T-15) \text{ 1/day} \quad (7)$$

where: $\hat{u}_n$ = peak Nitrosomonas growth rate, 1/day,

T = temperature, ^{o} Celsius.

A graphical representation of temperature effects on the half saturation constant for nitrifier growth rates is shown in Figure 3.(1)

Sharma and Ahlert stated that the overall optimum temperature for nitrifier bacteria growth is in the range of 28^{o}C to 36^{o}C.(10) Sutton et al. investigated the growth rate for nitrifiers between 7^{o} and 26^{o}C, and reported a 53 percent decrease at 5^{o}C and a 21% decreases at 7^{o}C in comparison to the growth rate at 26^{o}C.(12) Knowles et al. reported that maximum nitrifier growth rates of Nitrosomonas increased by approximately 9.5 percent for each 1^{o}C increase in temperature of the mixed liquor.(13)

Monod Biological Growth Equation

A general kinetic equation proposed by Monad,(14), is used to describe the kinetics of any biological growth where a substrate concentration is growth-limiting. Dabes et al. and Kessick have also supported the Monad expression as a model for ammonia-nitrogen removal.(15)(16) Equation (8) shows this relationship.

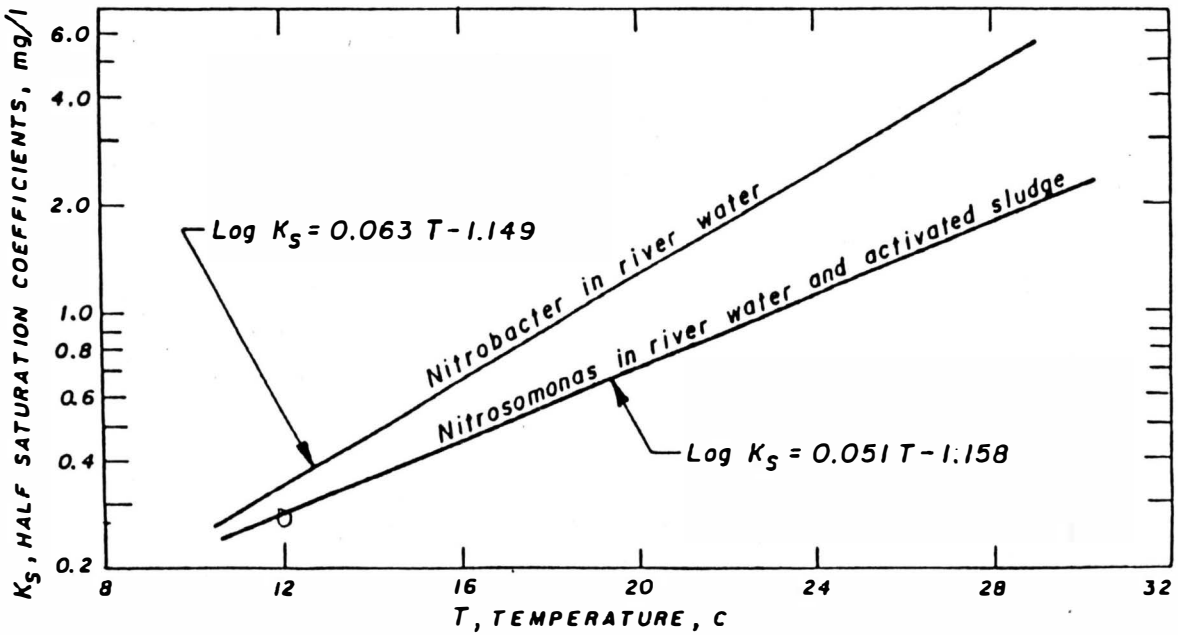


Figure 3. Temperature Dependance Of The Half-Saturation Constants Of Nitrifiers (1)

$$u_n = \hat{u} * \{S/(K_s + S)\} \quad (8)$$

where: u_n = growth rate of microorganism, 1/day,

$\hat{u}$ = maximum growth rate of microorganisms, 1/day

K_s = half velocity constant = substrate concentration, mg/l at half the maximum growth rate, mass/unit volume

S = growth-limiting substrate concentration, mg/l.

Dissolved Oxygen Effects on Nitrifier Growth Rates

The amount of dissolved oxygen (DO) available for growth significantly effects the rate of nitrifier growth, and hence, the rate of biological nitrification. Equation (9) uses the Monad relationship to estimate the effect that DO inhibits the nitrifier growth rate, assuming oxygen to be a growth-limiting substrate, as follows:(1)

$$u_n = \hat{u}_n * \{DO / (K_{o2} + DO)\} \quad (9)$$

where: DO = dissolved oxygen, mg/l, and

K_{o2}= half-saturation constant for oxygen, mg/l.

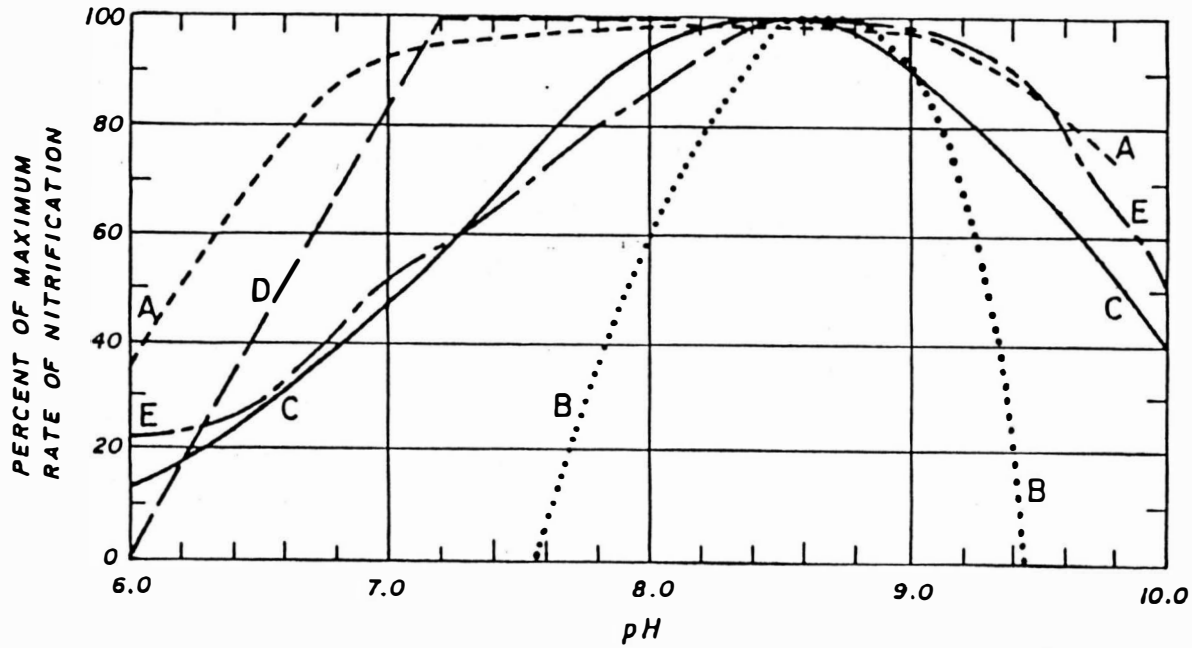
Metcalf and Eddy, Water Pollution Control Federation (W.P.C.F.) and the EPA all agree that 1.3 mg/l is a conservative estimate for a half-saturation constant for oxygen.(1)(4)(11)(5)

Knowles, Downing and Barret reported that nitrification is dissolved-oxygen-concentration-dependent below 2.0 mg/l.(13) Numerous studies have supported the theory of higher DO concentrations resulting in increased nitrification rates. Although, the effect of DO on nitrifi-

cation rates has been somewhat controversial, there are also studies that show complete nitrification with DO levels of 0.5 mg/l. However, these studies do not provide data to show that the nitrification rates were unaffected by low DO concentrations indicating that complete nitrification is possible at low DO levels as long as, increased detention times also accompany the low DO concentrations.(1) It is suggested that air-activated sludge systems operate at DO concentrations of approximately 2.0 mg/l in the contact basins to prevent a significant decrease in nitrification rates.(1)(11)

pH Effect on the Nitrifier Growth Rates

The hydrogen ion concentration (pH) has been reported by several authors to have a significant effect on the nitrification rate.(4)(6)(8) There is a wide range of reported optimum pH operating values, with the general conception being that as the pH values lower into the acidic range the rate of nitrification drops dramatically.(1)(2)(4) Figure 4 shows a graphical representation of pH effects on the rate of nitrification.



KEY

SYMBOL	ENVIRONMENT
A	Nitrosomonas - pure culture
B	Nitrosomonas - pure culture
C	Activated sludge at 20 C
D	Activated sludge
E	Attached growth reactor at 22 C

Figure 4. Effect Of pH On Nitrification Rate (1)

For pH values less than 7.2 the following equation represents the effect of pH on the nitrifier growth rate.(1)(4)

$$u_n = u_n\hat{} * [1-0.833(7.2 - pH)] \quad (10)$$

For pH values between 7.2 and 8.0 the correction factor for pH can be considered unity.(1) Wild et al. suggested that the optimum pH for nitrification is 8.4, and that 90 percent of the maximum rate occurs between 7.8 and 8.9; Outside the range of 7.0 to 9.8, less than 50 percent of the optimum rate occurs.(17) The preceding equation was developed for combined carbon oxidation-nitrification systems, but can be used for separate stage nitrification systems resulting in conservative values.

Combined Kinetic Expressions

The individual effects of temperature, DO and pH on the nitrifier growth rate has been previously presented. These parameters all act upon the nitrifier (nitrosomonas) growth rate simultaneously. The combined effects of the limiting factors on biological growth, assuming that ammonia-nitrogen concentration is not limiting, is as follows:(1)(4)

$$u^*_n = 0.47*[e**0.098(T-15)]*[DO/DO+1.3]*[1-0.833(7.2-pH)] \quad (11)$$

where: u^*_n = nitrifier (Nitrosomonas) growth rate, 1/day with no NH_4-N limitations.

Table 5 shows some typical values for maximum nitrifier growth rates in various environments.(1)

Table 5. Maximum Growth Rates For Nitrifiers In Various Environments (1)

Organism	$\hat{\mu}_N$, day-1 at stated temperature, C								Ref.	Environment
	8	12	15	16	20	21	23	25		
Nitrosomonas		0.40				0.85			4	Activated sludge, wash out
		0.34				0.65			4	Activated sludge, math model
				0.57					19	Activated sludge
								0.17	20	Activated sludge
							0.37		21	Activated sludge
					0.71				22	Activated sludge
			0.21		0.48			0.55	11	Synthetic river water
									23	
							1.08		15	Activated sludge
	0.25				0.5				24	Activated sludge
Nitrobacter			0.28			0.34		0.53	11,23	Synthetic river water
							1.44		15	Activated sludge

If ammonia-nitrogen concentrations are limiting, the constituent-limiting Monad relationship is incorporated, resulting in an overall nitrifier growth rate equation as follows:(1)

$$u_n = 0.47*[e**0.098(T-15)]*[DO/DO+1.3]*[1-0.833(7.2-pH)*[N/K_n+N] \quad (12)$$

where: N = effluent NH_4^+-N concentration, mg/l and

K_n = half-saturation constant, mg/l NH_4^+-N, mg/l,

= 10**0.051T-1.158 (1)

un = overall nitrifier growth rate, with consideration for nitrogen concentrations, (1/day).

Table 6 shows typical half-saturation constants for nitrifiers in various environments:(1)

Shammanas reported half-saturation constant values for nitrifiers at 10^oC in MLVSS concentrations of 3200 mg/l ranging from 2.5 to 3.8 mg/l.(18) Poduska and Andrews reported a half-saturation constant equal to 1.51 mg/l at 12^oC.(9) The ammonia oxidation (removal) rate is related to nitrifier growth rate, as follows:(1)(4)

Table 6. Half-Saturation Constants For Nitrifiers In Various Environments (1)

Organism	K_s, mg/l-N at stated temperature, C						Ref.	Environment
	15	20	25	28	30	32		
Nitrosomonas			0.37				20	Activated sludge
	2.8	3.6	3.4				11,23	Synthetic river water
					10		1,25	Lab culture
	0.5 to 1.0	0.5 to 1.0					2	Warburg analyses
			3.5				1,26	Lab culture
		1.0					1,27	Lab culture and activated sludge
		0.5					28	Lab culture
Nitrobacter			0.25				20	Activated sludge
	0.7	1.1	0.7				11,23	Synthetic river water
					6		1,29	Lab culture
				5			1,30	Lab culture
						8.4	1,31	Lab culture
			5				1,26	Lab culture
		0.07					28	Lab culture

$$q_n = u_n / Y_n \qquad (13)$$

where: q_n = ammonia oxidation rate, lb of HN_4^+-N oxidized per lb of VSS under aeration per day,

Y_n = organism yield coefficient, lb Nitrosomonas grown (VSS) /lb of NH_4^+-N removed.

The EPA Nitrogen Control Manual estimates Y_n = 0.15.(1) Metcalf and Eddy stated that the range for the organism yield coefficient is from 0.1 to 0.3 with a typical value of 0.2.(4) Jenkins and Garrison estimate the yield coefficient to be equal to 0.33.(19) Milbury et al. estimated a yield coefficient for activated sludge, based on COD removal, at 0.43 mg/l VSS grown per mg/l COD removed.(20) For this thesis, the value recommended by the EPA will be used in all equations that require a theoretical organism yield coefficient since it is the more conservative of the 3 reported values.

The ammonia oxidation rate can be more accurately approximated for separate-stage nitrification systems by taking into account the actual fraction of nitrification bacteria available as opposed to other heterotrophic bacteria that are present in the total mass of biological solids. The fraction of nitrifiers can be estimated, as previously discussed, by comparing the BOD concentration to the Total Kjeldahl Nitrogen (TKN) concentration. Table 2, previously introduced, shows the relationship between the nitrifier fraction and the BOD/TKN ratio. Baily et al. estimated at a BOD/TKN ratio of 0.5 g/g that 100 percent of maximum ni-

trification rate can be expected.(21) Since TKN's were not determined during the sample analysis, and the BOD values were relatively low, it is conservative to estimate the BOD/TKN ratio to be at a maximum of 0.5 resulting in a nitrifier fraction of 0.35.(1)

The nitrification rate is calculated from the ammonia oxidation rate, q_n, as follows:(1)

$$r_N = q_n * f \qquad (14)$$

where: f = nitrifier fraction of the mixed liquor solids,

r_N = nitrification rate, lb NH_4-N oxidized /lb/MLVSS/day.

Figure 5 show various nitrification rates at different temperatures.(1)

Minimum Solids Retention Time

The EPA Process Design Manual for Nitrogen Control estimates the minimum solids retention time, assuming the ammonia concentration is not limiting, by the following inverse relationship between the solids retention time and the growth rate of nitrifiers:(1)

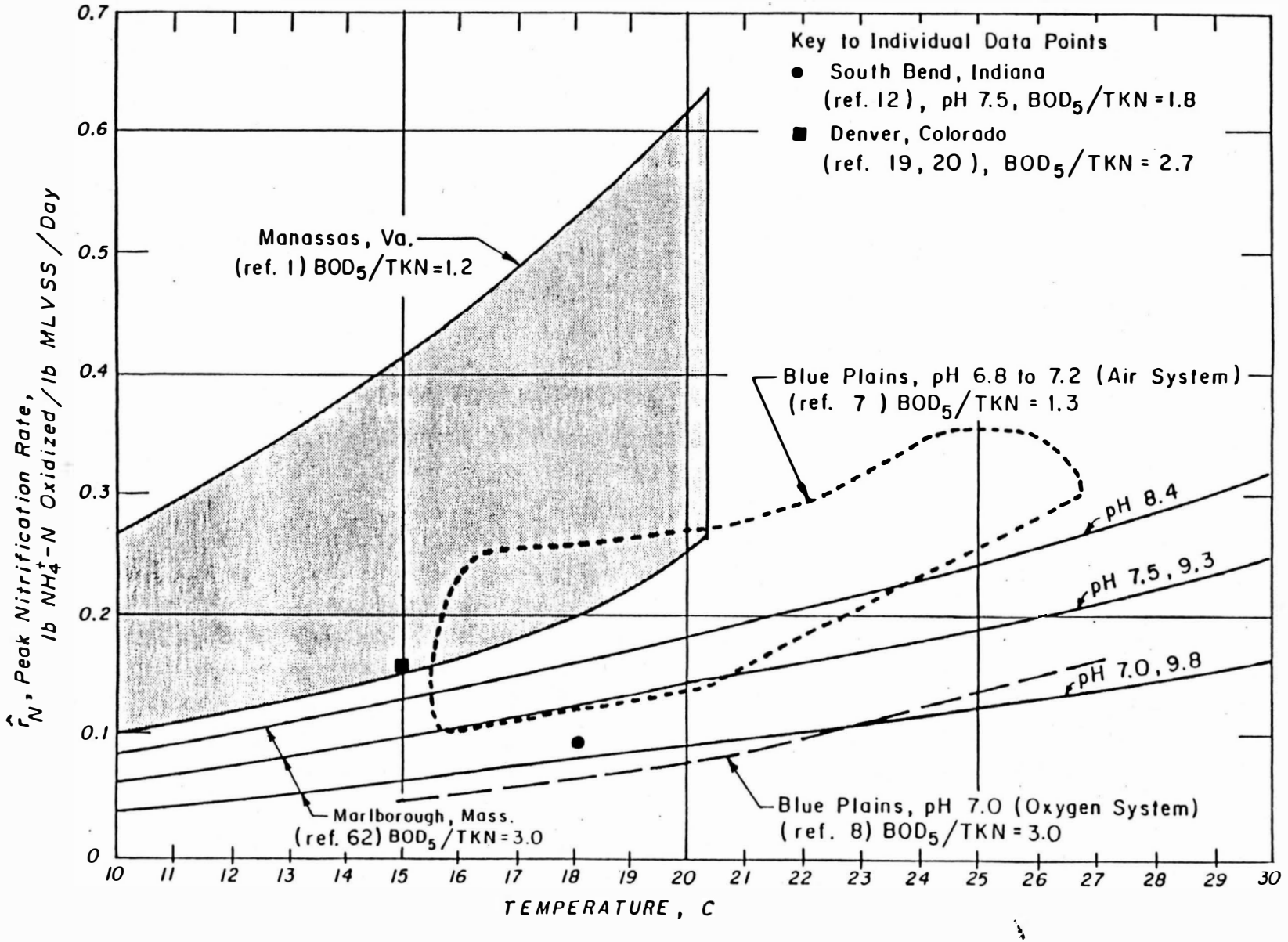


Figure 5. Observed Nitrification Rates At Various Locations (1)

$$Q_c^m = 1 / u_n \quad (15)$$

where: Q_c^m = minimum solids retention time, days, for nitrification with corrections for pH, temperature and DO.

Calculation of the minimum solids retention time is accomplished with the following equation:(1)

$$Q_c^m = 1 / [(Y_n * q_n) - k_d] \quad (16)$$

where: k_d = endogenous decay coefficient, time -1

The EPA, Metcalf and Eddy and Viessman and Hammer all agree that a reasonable estimate for the endogenous decay coefficient is 0.05 1/day, for a suspended growth nitrification process.(1)(4)(2)

Design Solids Retention Time

To prevent inadequate waste treatment, treatment systems are designed and operated with a safety factor. Therefore, the design solids retention time is calculated by the following expression:(1)

$$Q_c^d = S.F. * Q_c^m \quad (17)$$

where: Q_c^d = solids retention time of design, days,]

S.F. = safety factor.

Odens design for the B.W.W.T.P. utilized a safety factor of 1.8, which is the ratio of the peak flow to the average flow.(11)

Experimental Nitrification and Oxidation Rates

The actual experimental mean cell residence time is calculated by the following expression:(1)(4)

$$Q_c = V * X / [(Q_w * X_w) + (Q_e * X_e)] \quad (18)$$

where: Q_c = MCRT based on the aeration tank volume, day,

V = total aeration tank volume, mg

X = volatile suspended solids in the aeration tank, mg/l,

Q_w = waste sludge flowrate, mgd,

X_w = volatile suspended solids in the waste stream mg/l,

Q_e = treated effluent flowrate, mgd,

X_e = volatile suspended solids in the treated effluent mg/l.

The experimental substrate utilization rate can also be estimated on a hydraulic detention time basis, as follows:(4)

$$U = S_o - S / Q_h * X \quad (19)$$

where: $Q_h = V/Q_f$ = hydraulic detention time, time.

Q_f = flow rate, mgd.

U = experimental substrate utilization rate, time-1.

S_o = influent soluble ammonia-nitrogen concentration, mg/l.

S = effluent soluble ammonia-nitrogen concentration, mg/l.

Experimental oxygen demand (BOD) and ammonia nitrogen removal efficiencies are calculated by the following formula:(2)

$$E = [(S_o - S_e) / S_o] * 100 \quad (20)$$

where: E = efficiency of BOD and ammonia-nitrogen removal, percent

S_o = influent BOD and ammonia-nitrogen concentration, mg/l

S_e = effluent BOD and ammonia-nitrogen concentration, mg/l

Food-to-microorganism ratio (F/M), is another common loading criteria used in monitoring activated sludge processes. F/M ratios are calculated from the following expression:(2)

$$F/M = S_o / Q_h X \quad (21)$$

where: F/M = food / microorganism ratio, mg/l of BOD per MLVSS in the aeration tank.

By rearranging Equation 19 to solve for the hydraulic detention time and substituting the ammonia oxidation rate, q_n, from Equation 13,

q_n, for the experimental substrate utilization rate; results in the theoretical required hydraulic detention time. Equation 22 shows this restructuring of Equation 19:

$$Q = S_o - S \,/\, MLVSS * q_n \qquad (22)$$

A rearrangement of Equation 18 to solve for the waste activated sludge wasting rate (Q_w) and the substitution of the theoretical minimum mean cell residence time based on theoretical nitrification rates, Equation 15 (Q_c^m), for the actual mean cell residence time results in the calculation of the theoretical waste activated sludge wasting rate. Equation 23 shows this restructuring of Equation 18:

$$Q_w = [((V*X)/Q_c^m)-(Q_e*X_e)]/X_w \qquad (23)$$

Activated Sludge Systems

Activated sludge is a suspended-growth process consisting of both active and dead microorganisms held in suspension by a mechanical mixing system, forced air for this study. The organisms are suspended in wastewater consisting of both dissolved organic and inorganic materials along with both inert and non-biodegradable suspended matter.

The suspended particles in the activated sludge aeration basin are commonly referred to as mixed liquor suspended solids (MLSS). The activated sludge treatment process is an aerobic biological process in which the microorganisms metabolize and biologically floc-

culate the organic material and is typically considered as a secondary treatment process. Activated sludge effluent is then subjected to quiescent conditions in the final clarifier allowing the microorganisms to settle, thus forming a layer of clear supernatant, (final clarifier effluent). The microorganisms are then returned to the aeration tank for further metabolization. Excess activated sludge is wasted from the system in order to maintain a proper food-to-microorganism ratio (F/M) and corresponding sludge age to optimize removal efficiencies.

The organic matter in the aeration basin functions as a carbon and energy source for the active microbial population which converts the organic material into new microbial cell tissue and oxidized end products, mainly carbon dioxide. In the WPCF Manual of Practice No. 8 it is estimated that microorganisms are composed of 70 to 90 percent organic and 10 to 30 percent inorganic matter depending on the chemical composition of the wastewater.(5)

Activated sludge systems are classified as one of two processes. The first process combines both carbon oxidation (organic oxidation) and nitrification (ammonia oxidation) concurrently. The second process isolates the ammonia oxidation process, resulting in separate-stage nitrification.

Separate-stage nitrification has a low BOD_5 to ammonia-nitrogen ratio. Therefore, it is necessary to reduce the organic load to the activated sludge system by the means of various pretreatment processes. With sufficient pretreatment the population of nitrifiers is increased, resulting in higher rates of nitrification. The majority of the oxygen demand for separate stage nitrification systems is a result of the oxidation of ammonia.(8)

METHODS AND MATERIALS

The activated sludge system investigated in this study is a conventional system. This activated sludge layout consists of 4 rectangular aeration tanks operating in series. Each tank was completely mixed, with the series flow (4 tanks in series) simulating an overall plug-flow scheme. The influent wastewater and return activated sludge pass through the aeration tank train prior to introduction into the final clarifier.(1)

Five complete sample collections and analyses were performed in this study. Samples were collected during the period from December 27, 1983 to January 18, 1984. Wastewater temperatures at the time of sampling varied from 10 to 11 degrees Celsius. These conditions represent cold-weather operation for the plant.

Methods of Analysis

Tests conducted on the samples collected were as follows: suspended solids (SS), volatile suspended solids (VSS), initial dissolved oxygen concentrations (DO), total biological oxygen demand (BOD), 5-day biological oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia-nitrogen concentration (NH_3-N), temperature and pH.

Figure 6 is a graphical representation of the layout of the aeration system and final clarifier. Also shown in Figure 6 are the locations of the sample collection points.

The first sample collected for each run was of the influent to the aeration train. Sampling then progressed to each of the aeration basin effluents. Samples were collected as rapidly as possible, with the total duration of the sampling period requiring approximately 1 hour.

Suspended Solids

The suspended solids concentrations were determined using the membrane filter technique described in Standard Methods, page 94.(22) Concentrations of the mixed liquor were substantial, therefore, all samples were diluted at a ratio of 10:1 with exception of the final clarifier effluent sample which was filtered without dilution.

Volatile Suspended Solids

The volatile suspended solids determination was performed using the total volatile and fixed residue at 550^{o} C method described in Standard Methods, page 95.(22)

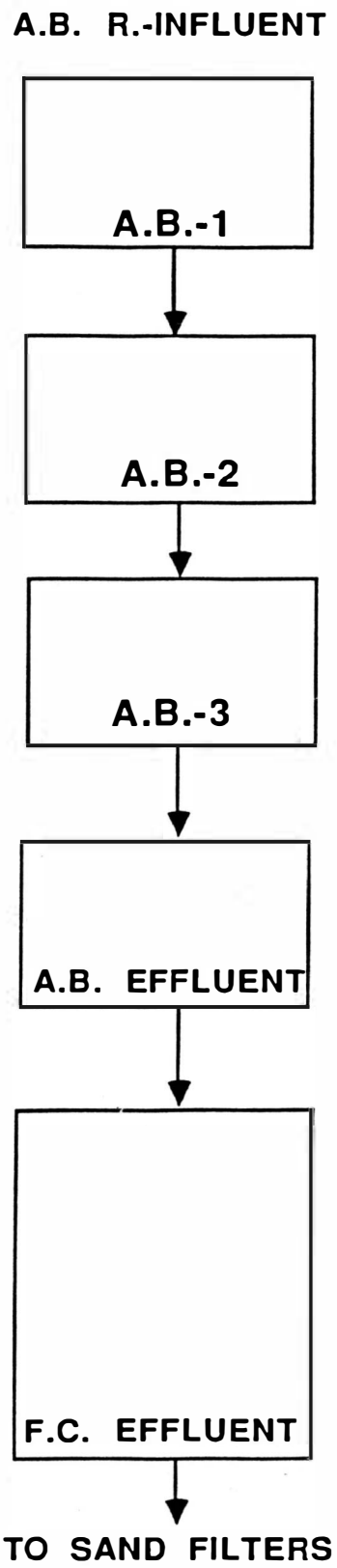


Figure 6. Aeration Schematic

Initial Dissolved Oxygen

Initial dissolved oxygen values were determined using the azide modification procedure described on page 390 in Standard Methods.(22) Dissolved oxygen samples for the mixed liquor sample points were collected with a 3-gallon sample bucket. The sample was left undisturbed for approximately 1 to 3 minutes to establish quiescent conditions to allow a majority of the solids to settle out and produce a clear lens of supernatant. A 300-ml sample was siphoned from the supernatant and immediately acid fixed at the sample site and later titrated at the lab for determination of dissolved oxygen at the time of sampling.

Soluble Five-Day Biological Oxygen Demand (BOD_5)

Soluble 5-day biological oxygen demand was determined following the procedures outlined on page 483 in Standard Methods.(22) All samples were filtered through a standard glass fiber filter with the filtrate used for determining soluble BOD_5 concentrations. The filtrate for each sample was then filtered again to insure a representative soluble sample. Nitrogen inhibition was accomplished with addition of 2-chloro-6 pyridine to each of the samples. The addition of a nitrogen inhibitor prevents ammonia oxidation, therefore, measured oxygen demand is entirely carbonaceous demand and not combined carbonaceous and nitrogenous demands. The filtering of the samples to provide soluble BOD_5 samples resulted in an insufficient population of microorganisms capable of oxidizing biodegradable organic matter. Therefore, primary clarifier effluent was added to each of the samples at a concentration of 6-ml per 1000-ml sample to provide a sufficient population of microorganisms that were

adapted to the waste.

Soluble Chemical Oxygen Demand

The analysis for soluble chemical oxygen demand (COD) was performed in accordance with Standard Methods on page 489.(22) A portion of the filtered sample used in the determination of soluble BOD_5 was also used in soluble COD analysis.

Ammonia-Nitrogen Concentration

A Fisher Expanded-Scale, Model 76, Ion meter with a ammonia-selective electrode was used to measure ammonia-nitrogen concentrations. The ammonia-nitrogen concentration determination was conducted in accordance with Standard Methods, page 362.(22) A portion of the filtered sample used in the determination of soluble BOD_5 was also used in ammonia-nitrogen analysis. The Ion Meter was standardized immediately prior to use with standard solutions covering the concentrations of 25, 10, 5, 1 and 0.5 mg/l of NH_3-N. The ammonia-nitrogen concentrations were recorded to the nearest tenth of a mg/l.

Temperature and pH

Temperature and pH measurements of the samples were taken at the time of sampling from the plant temperature and pH probes which are standardized on a weekly basis. (22))

RESULTS AND DISCUSSION

Individual test results for each of the 5 runs are tabulated in Appendix A. Also included are the BOD to COD ratios and the various loading rates encountered by the individual basins.

Nitrifier Growth Rates

Figure 7 includes the calculated nitrifier growth rates, u_n, for each basin and sample run, assuming ammonia-nitrogen concentrations were sufficient and other necessary growth constituents exist in the mixed liquor thereby resulting in significant concentrations of nitrifier populations. Maximum nitrifier growth values, assuming non-limiting ammonia-nitrogen conditions, were calculated using Equation (11):

$$u^*_n = 0.47*[e**0.098(T-15)]*[DO/DO+1.3]*[1-0.833(7.2-pH)] \qquad (11)$$

where: u^*_n = nitrifier (Nitrosomonas) growth rate, 1/day with no NH_4-N limitations.

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. A D.O. half-saturation constant of 1.3 mg/l was assumed as discussed previously in the Monod dissolved oxygen growth relationship (Equation 8). These growth-rate values represent the combined effects of dissolved oxygen concentrations and temperature on the nitrifier growth rate. Since all the pH values for this study were greater than 7.2, the effect

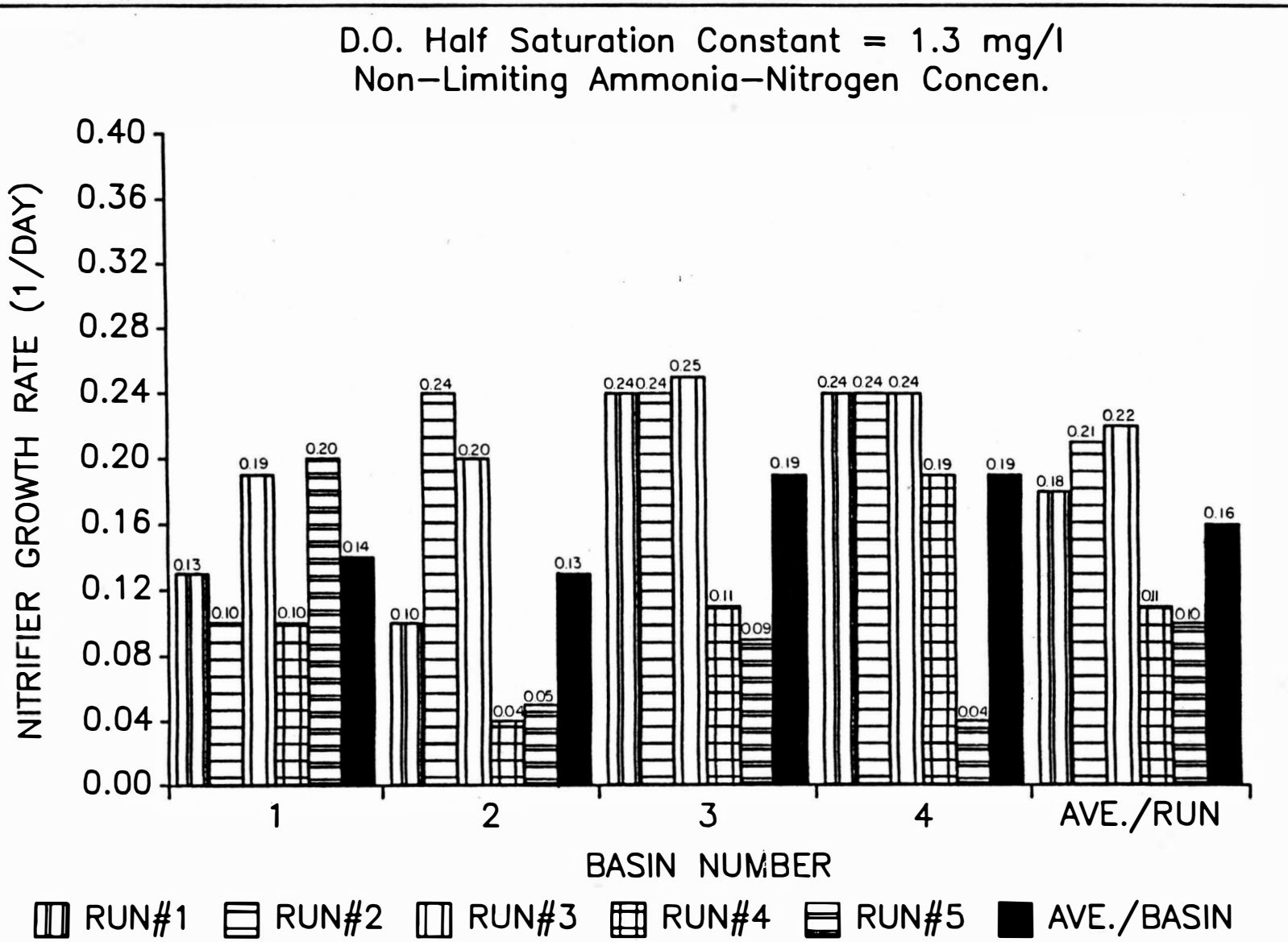


Figure 7. Calculated Nitrifier Growth Rates, Assuming Non-Limiting Ammonia-Nitrogen Conditions

of pH on the nitrifier growth rate was assumed to be unity, in occordance with the observations reported in the Literature Review.(1)(2)(4)(6)(8)

The calculated maximum nitrifier growth rates assuming limiting ammonia-nitrogen conditions for each of the basins are shown in Figure 8. The values presented in Figure 8 were calculated utilizing Equation (12):

$$u_n = 0.47*[e**0.098(T-15)]*[DO/DO+1.3]*[1-0.833(7.2-pH)*[N/K_n+N] \quad (12)$$

where: N = effluent NH_4^+-N concentration, mg/l and

K_n = half-saturation constant, mg/l NH_4^+-N, mg/l,

= 10**0.051T-1.158 (1)

un = overall nitrifier growth rate, with consideration for nitrogen concentrations, (1/day).

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. These values differ from the values reported in Figure 7 because they reflect the effect of actual effluent ammonia-nitrogen concentrations in lieu of assuming non-limiting ammonia-nitrogen concentrations. The effect of pH on nitrifier growth was again assumed to unity.

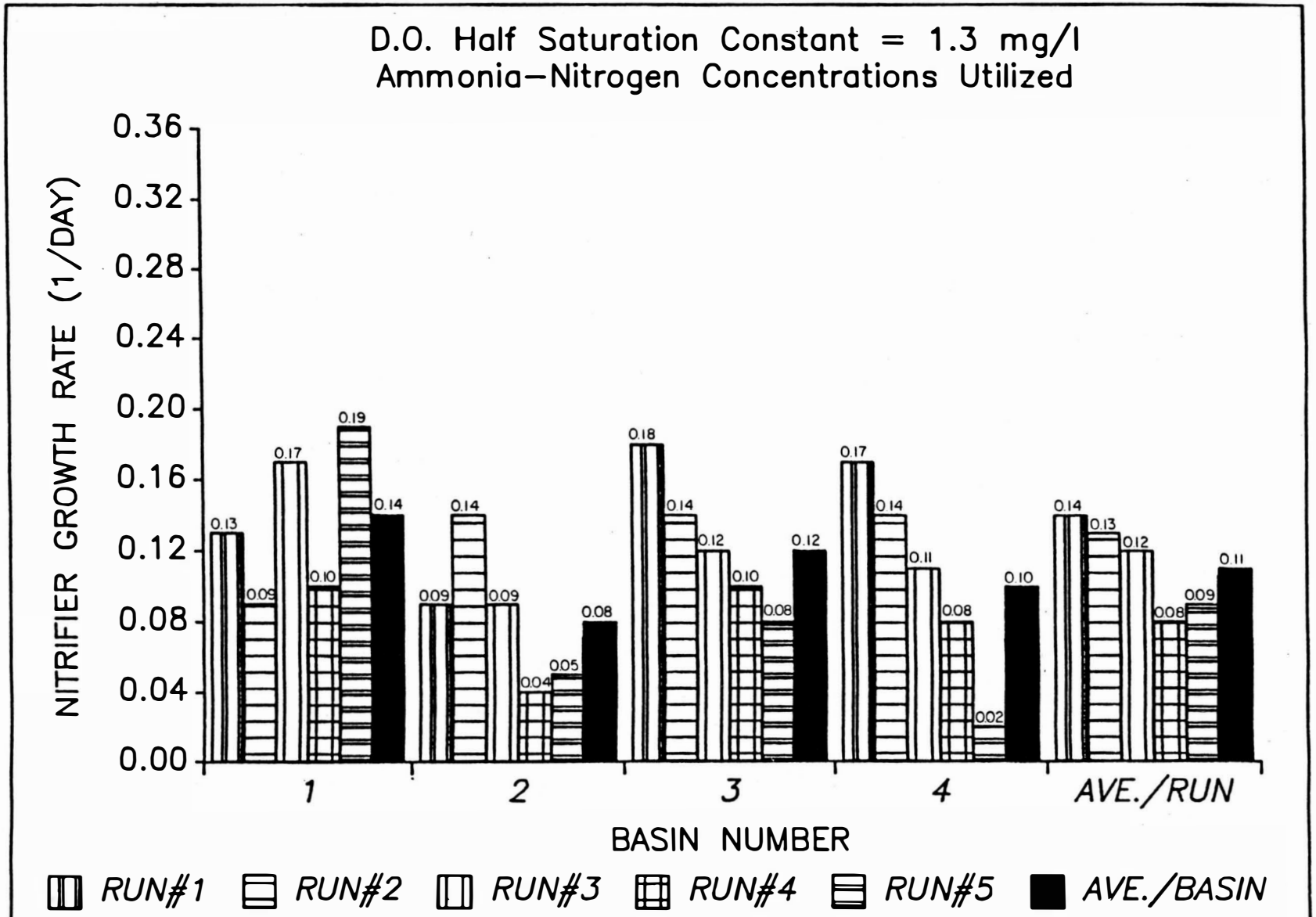


Figure 8. Maximum Nitrifier Growth Rates, Assuming Limited Ammonia-Nitrogen Conditions

Reported maximum growth rates for nitrifiers in various environments was previously summarized in Table 5. Values in this table, for activated sludge processes at 12°C, ranged from 0.40 and 0.34 (1/day). Actual experimental (11°C) nitrifier growth rates (Figure 7), assuming non-limiting nitrogen concentrations, yielded individual basin values ranging from 0.04 to 0.25 (1/day). Average values for each of the basins ranged from 0.13 to 0.19 with an overall average of 0.16 (1/day). Average values for each of the 5 runs varied from 0.10 to 0.22 with an overall average of 0.16 (1/day). Shammas reported a maximum growth rate for nitrifiers of 0.018 (1/day) for MLVSS of 3200 mg/l at 10°C.(18) Produska and Andrews reported a nitrifier growth rate at 12°C equal to 0.36 (1/day).(9)

Maximum nitrifier growth rate values for limiting ammonia-nitrogen conditions (Figure 8) accounting for actual effluent ammonia-nitrogen concentrations resulted in individual basin values ranging from 0.02 to 0.19 (1/day). Average values for each of the basins ranged from 0.08 to 0.14 with an overall average of 0.11 (1/day). Average values for each of the 5 runs varied from 0.08 to 0.14 with an overall average of 0.11 (1/day).

Ammonia Oxidation Rates

In Figure 9, ammonia oxidation rates, q_n, in pounds of ammonia-nitrogen oxidized per day per pound of mixed liquor volatile suspended solids under aeration, are shown for each of the individual basins and each corresponding sample run. These values were calculated using

Equation (13):

$$q_n = u_n / Y_n \qquad (13)$$

where: q_n = ammonia oxidation rate, lb of HN_4^+-N oxidized per lb of VSS under aeration per day,

Y_n = organism yield coefficient, lb Nitrosomonas grown (VSS) /lb of NH_4^+-N removed.

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. A value of 0.15 pounds of organisms (VSS) grown (wasted) per pound of ammonia-nitrogen removed, was assumed for the organism yield coefficient as discussed previously in the Literature Review. Figure 9 shows individual basin oxidation rates ranging from 0.26 to 1.64 with basin averages ranging from 0.85 to 1.27 (lbs NH_4^+-N / lb MLVSS under aeration / day).

Nitrification Rate

The values presented in Figure 9 (ammonia-nitrogen oxidation rates) assuming that the entire population of microorganisms are nitrifiers, where in actuality, the nitrifier population only accounts for a portion of the entire microbial population. The nitrification rates, r_N, (lbs of NH_4^+-N oxidized / lb MLVSS under aeration / day) are calculated from Equation (14):

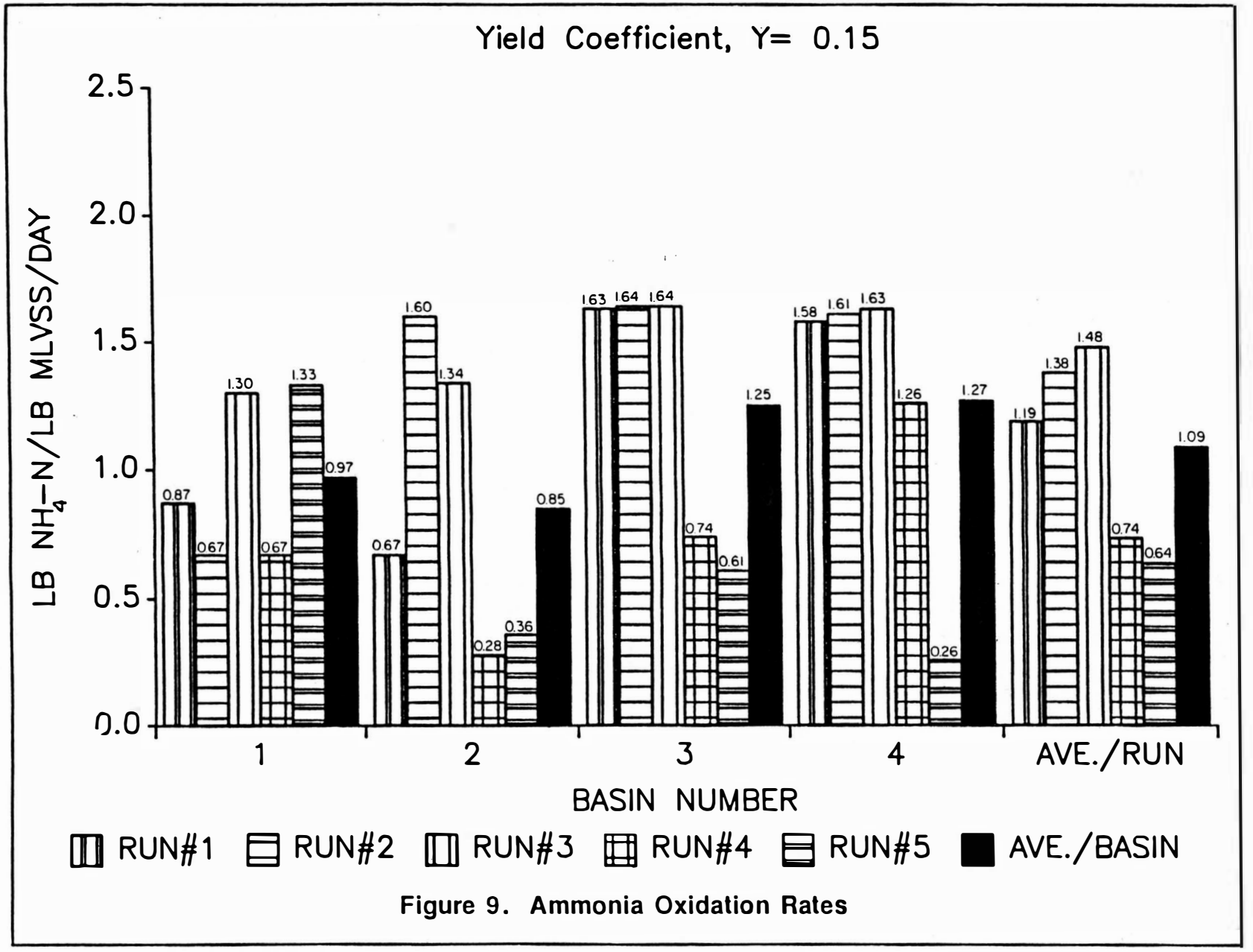


Figure 9. Ammonia Oxidation Rates

$$r_N = q_n * f \quad (14)$$

where: f = nitrifier fraction of the mixed liquor solids,

r_N = nitrification rate, lb NH_4-N oxidized /lb/MLVSS/day.

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. Figure 10 shows the nitrification rates for each of the individual basins and each corresponding sample run. A nitrifier fraction, f, of 0.35 was used for calculating the nitrification rate as selected from previously-introduced Table 4.

Figure 10 shows the individual nitrification rates ranging from 0.09 to 0.58 lbs of NH_4^+-N oxidized / lb MLVSS under aeration / day. These values were calculated accounting for limiting DO and ammonia-nitrogen concentrations by utilizing the Monod equations.(14) Average nitrification rates for each of the basins ranged from 0.3 to 0.44. The average nitrification rates for each of the runs varied from 0.22 to 0.52 with an overall average of 0.38. These values fall within the range of values for a similar nitrification system (BOD/TKN ratio = 1.2); 0.28 to 0.63, presented by the EPA in in Figure 5.(1)

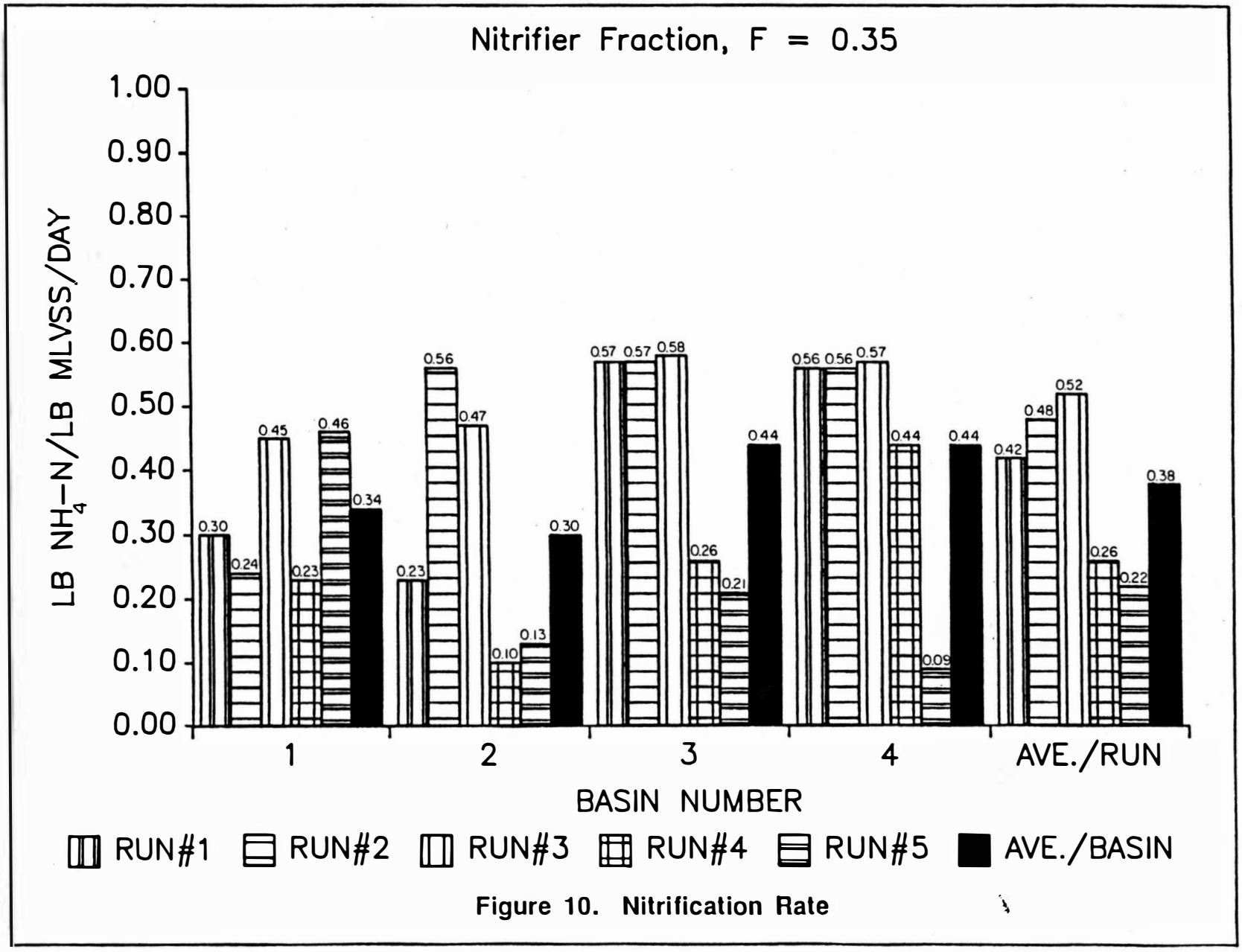


Figure 10. Nitrification Rate

Figure 5 is a plot of experimentally-determined values for peak nitrification rates, (limiting DO and ammonia concentrations were not taken into account). The BOD_5/TKN ratio's for this graph are relatively high, With lower ratios, higher nitrification rates would be expected theoretically. The nitrification rates reported in this paper are generally in agreement with the values presented in Figure 5. However, with the low BOD_5/TKN ratios that are associated with the experimental results of this paper, higher nitrification rates would be expected.

Low nitrification rates typically can be attributed to limiting DO, limiting ammonia-nitrogen concentrations and low concentrations of influent organic matter.(23) All three of these parameters are likely contributors to the lower nitrification rates obtained in this study. Batchelor reported that as influent organic matter concentrations decreased in separate-stage nitrification systems that significant concentrations of nitrates developed in the MLVSS.(24) With the high solids retention times, aerobic conditions and low influent organic matter concentrations experienced in this study, high concentrations of nitrates would seem likely in the MLVSS.

Non-limiting and limiting nitrifier growth rates are both functions of temperature as reflected in the combined-effects growth-rate equation (Equation 12). Data reported by Shammas estimates that with the temperatures encountered at the BWWTP, ranging from $10^{o}C$ to $11^{o}C$ for all 5 of the sample runs, that the ammonia oxidation rate is approximately 20

percent of the maximum nitrifier growth rates.(18)

Solids Retention Time

Solids retention time (SRT), Q_c is the relationship between the quantity of solids under aeration after taking into account the amount of solids that are lost in the effluent and the amount of solids that are wasted in the waste-activated sludge flow, as shown by Equation (18).

$$Q_c = V * X / [(Q_w * X_w) + (Q_e * X_e)] \quad (18)$$

where: Q_c = MCRT based on the aeration tank volume, day,

V = total aeration tank volume, mg

X = volatile suspended solids in the aeration tank, mg/l,

Q_w = waste sludge flowrate, mgd,

X_w = volatile suspended solids in the waste stream mg/l,

Q_e = treated effluent flowrate, mgd,

X_e = volatile suspended solids in the treated effluent mg/l.

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B.

The theoretical optimum minimum solids retention time, Q_c^m, required to provide nitrification can be calculated by various different methods as discussed previously in the literature review section of this report.

Equation 15 shows the inverse relationship between Q_c^m and the nitrifier growth rate (u_n, for non-limiting NH_4^+-N concentrations).

$$Q_c^m = 1 / u_n \qquad (15)$$

where: Q_c^m = minimum solids retention time, days, for nitrification with corrections for pH, temperature and DO.

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. Figure 11 shows the average minimum solids retention time for each of the runs calculated from experimental non-limiting nitrifier growth rates.

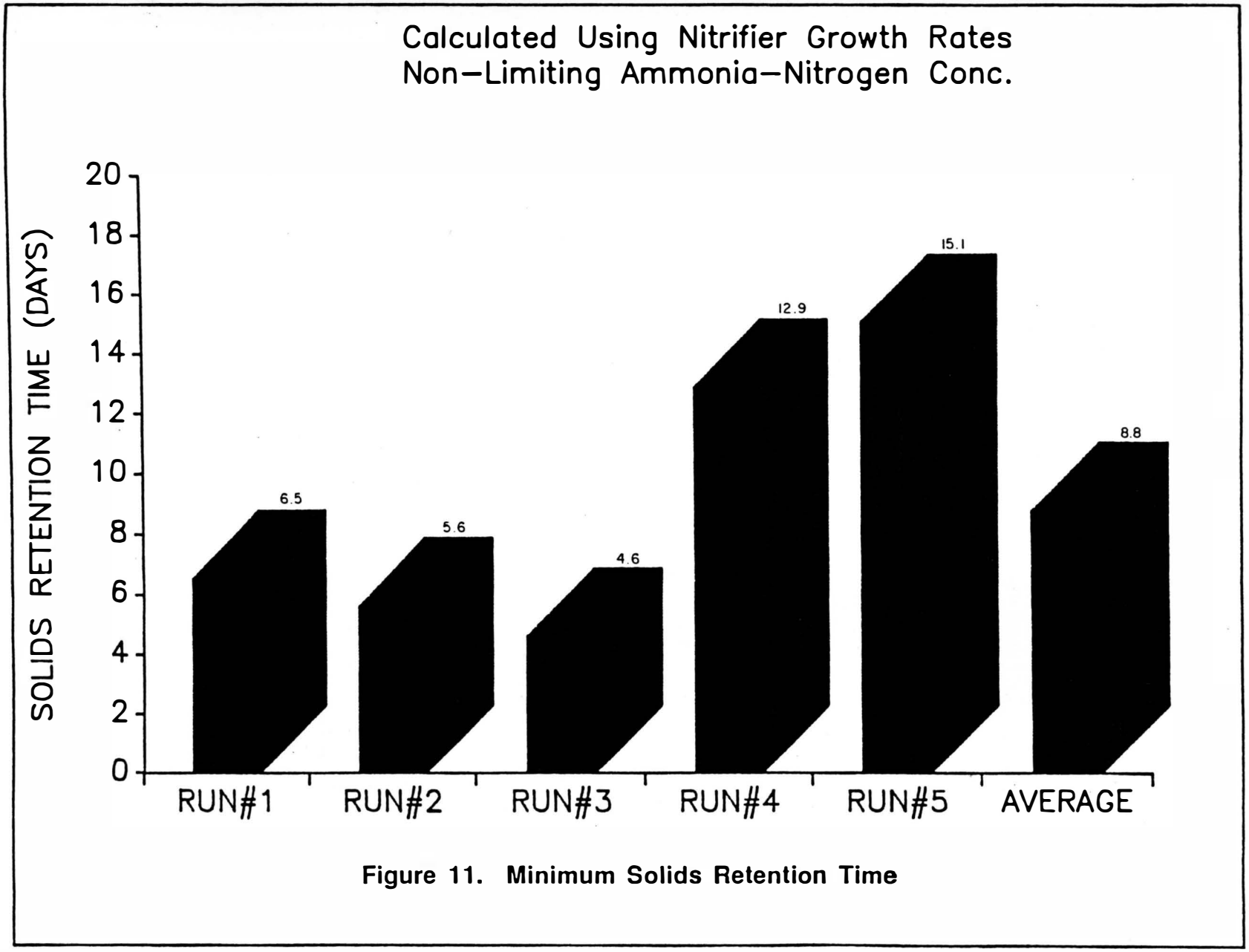


Figure 11. Minimum Solids Retention Time

If it is assumed that when low concentrations of NH_4^+-N are encountered in a nitrification treatment process, substitution of the maximum nitrifier growth rate, u_n, (limiting NH_4^+-N) would represent actual conditions and the actual required solids retention time. These values are presented in Figure 12. Figure 12 shows the average minium solids retention time required to achieve nitrification for the study-system for the concentrations of D.O., temperature and ammonia-nitrogen present during each of the sample runs.

Calculation of the theoretical minimum solids retention time can also be accomplished utilizing Equation # 16, which shows the relationship between the organism yield coefficient, Yn, ammonia oxidation rate (q_n) and an estimate of the endogenous decay coefficient (k_d).

$$Q_c^m = 1 / [(Y_n * q_n) - k_d \qquad (16)$$

where: k_d = endogenous decay coefficient, time -1

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. Figure 13 presents these theoretical optimum Q_c^m values.

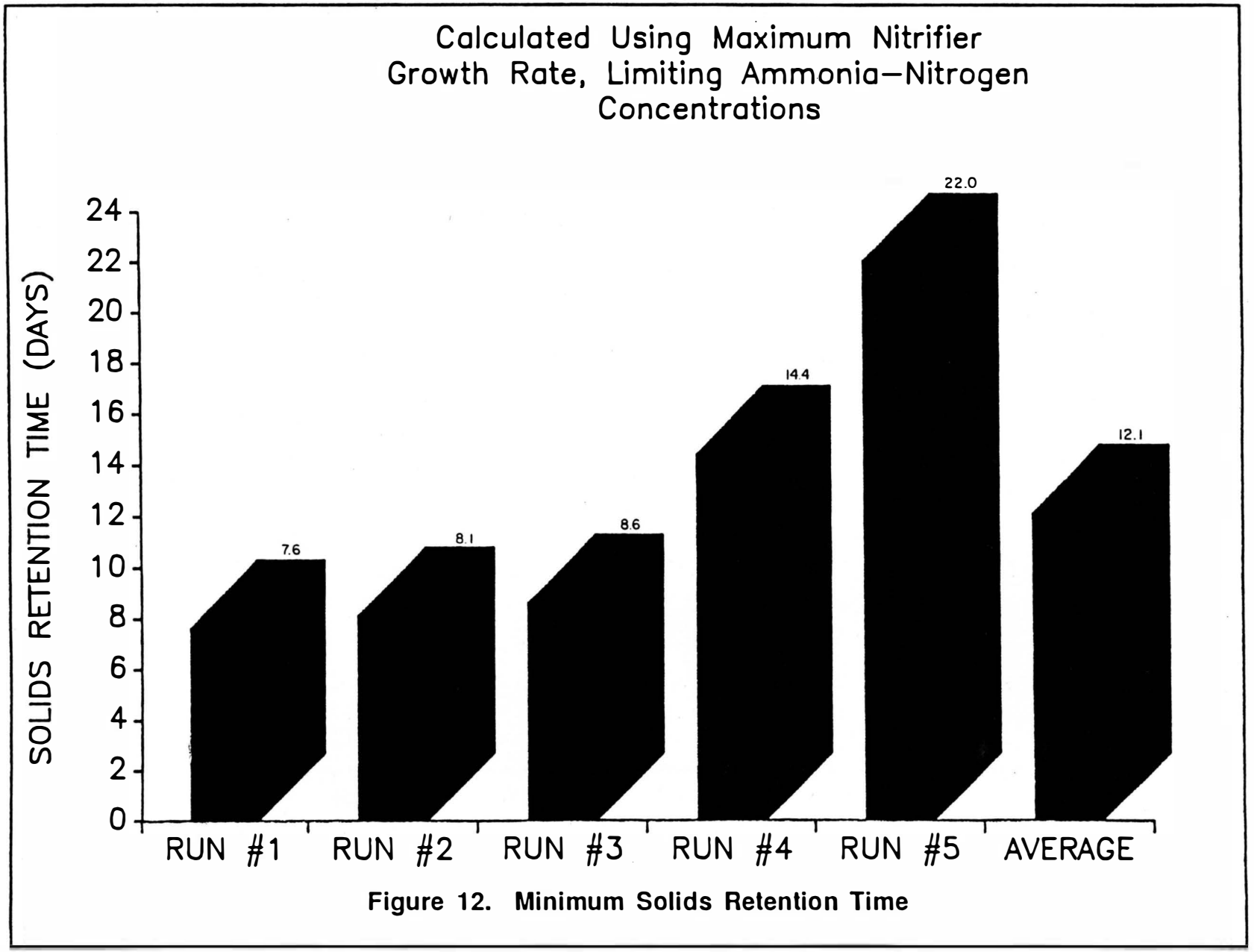


Figure 12. Minimum Solids Retention Time

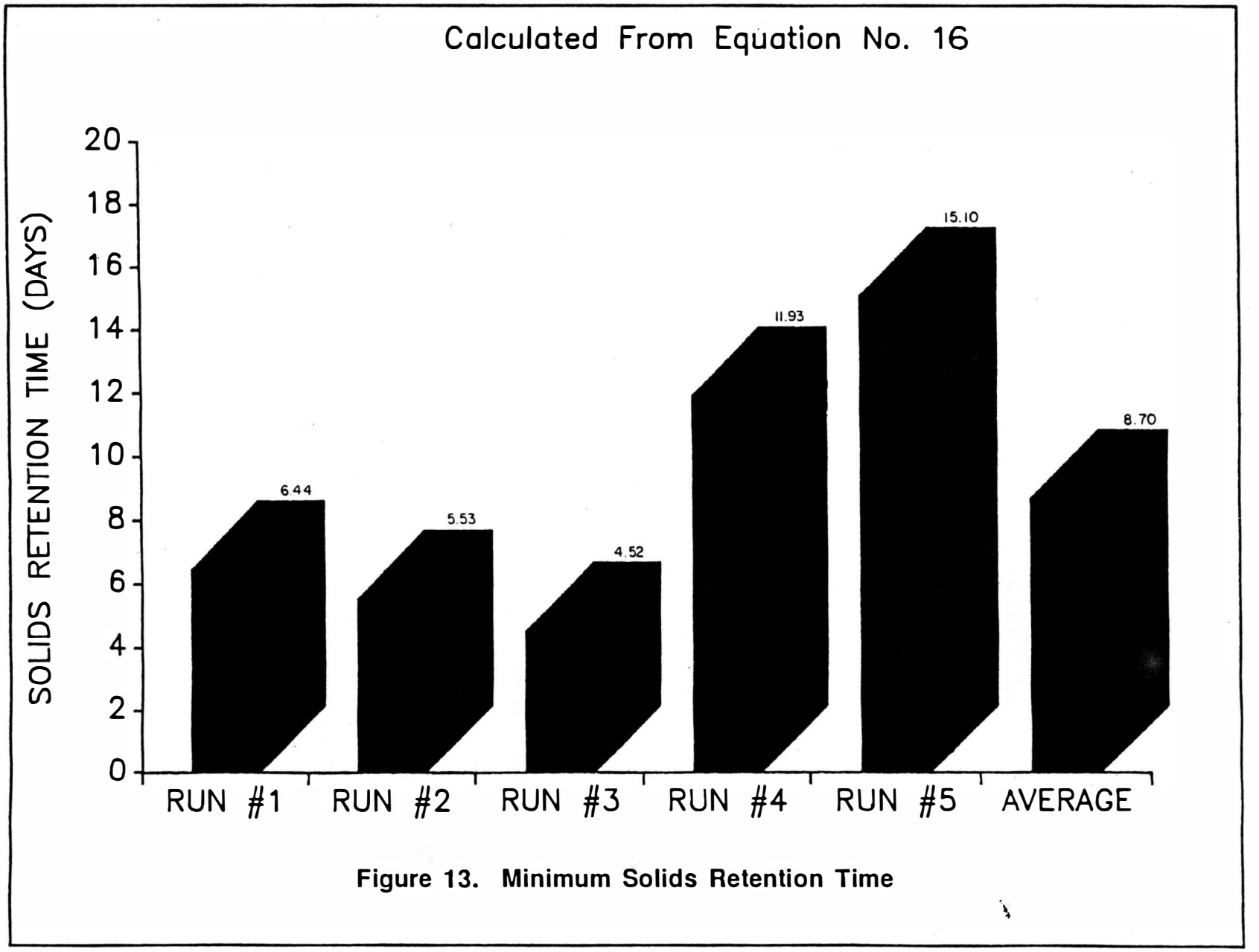


Figure 13. Minimum Solids Retention Time

To assure adequate treatment, in spite of varying influent conditions, a safety factor is applied to the minimum solids retention time, as shown in Equation 17, to obtain Q_c^d, the design solids retention time.

$$Q_c^d = S.F. * Q_c^m \quad (17)$$

where: Q_c^d = solids retention time of design, days,]

S.F. = safety factor.

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. These values are presented in Figure 14.

In prior usage, the term "sludge age" has been defined as the total sludge mass in the aeration tank divided by the incoming load (defined in terms of BOD or SS). These expressions do not yield the real age of the sludge but rather an inverse of the BOD or SS loading rates. Therefore, the actual experimental solids retention (similar to sludge age) is calculated from Equation 18. These values are shown in Figure 15.

Figure 16 represents a comprehensive summary of all 4 theoretical solids retention times and the actual experimental solids retention times.

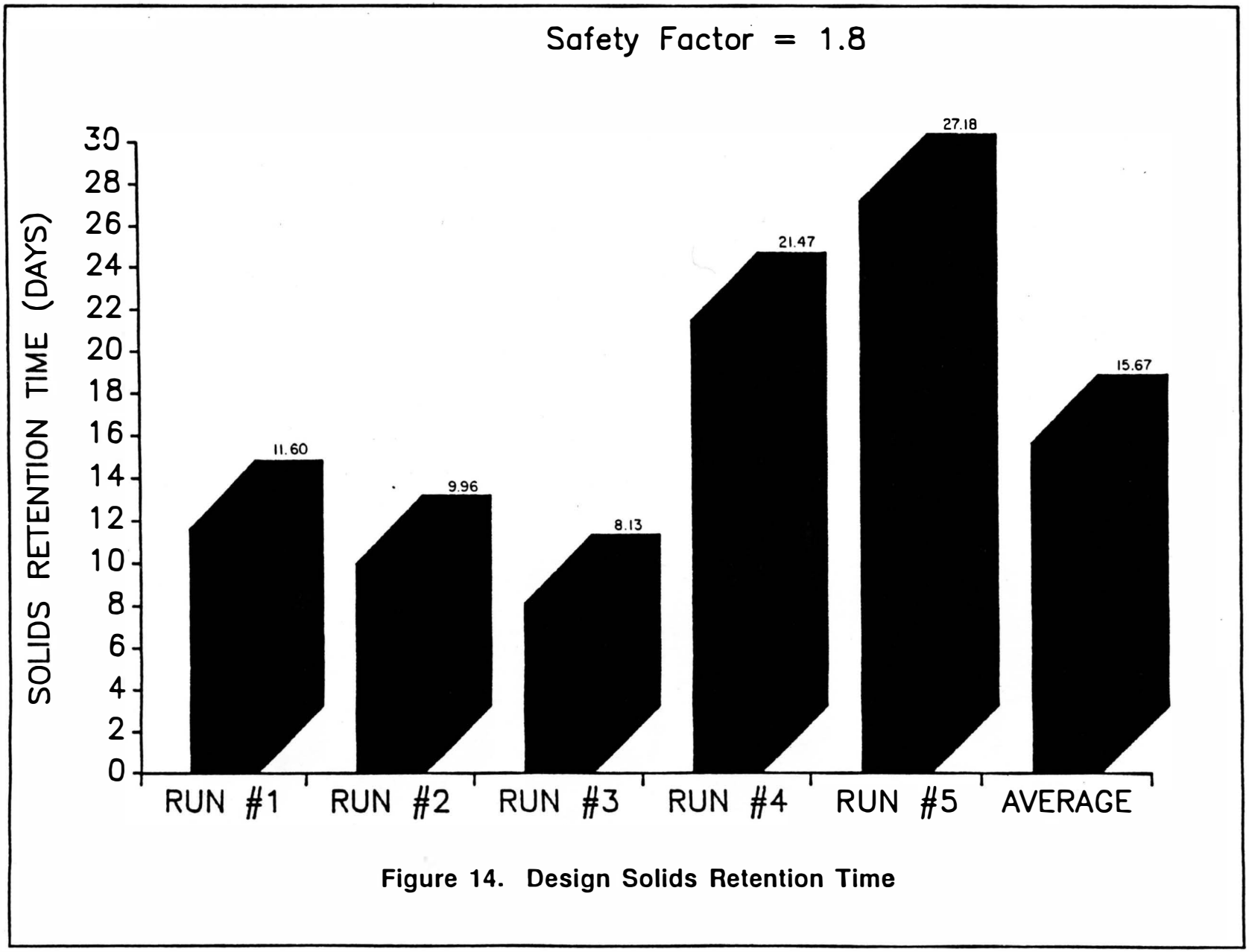


Figure 14. Design Solids Retention Time

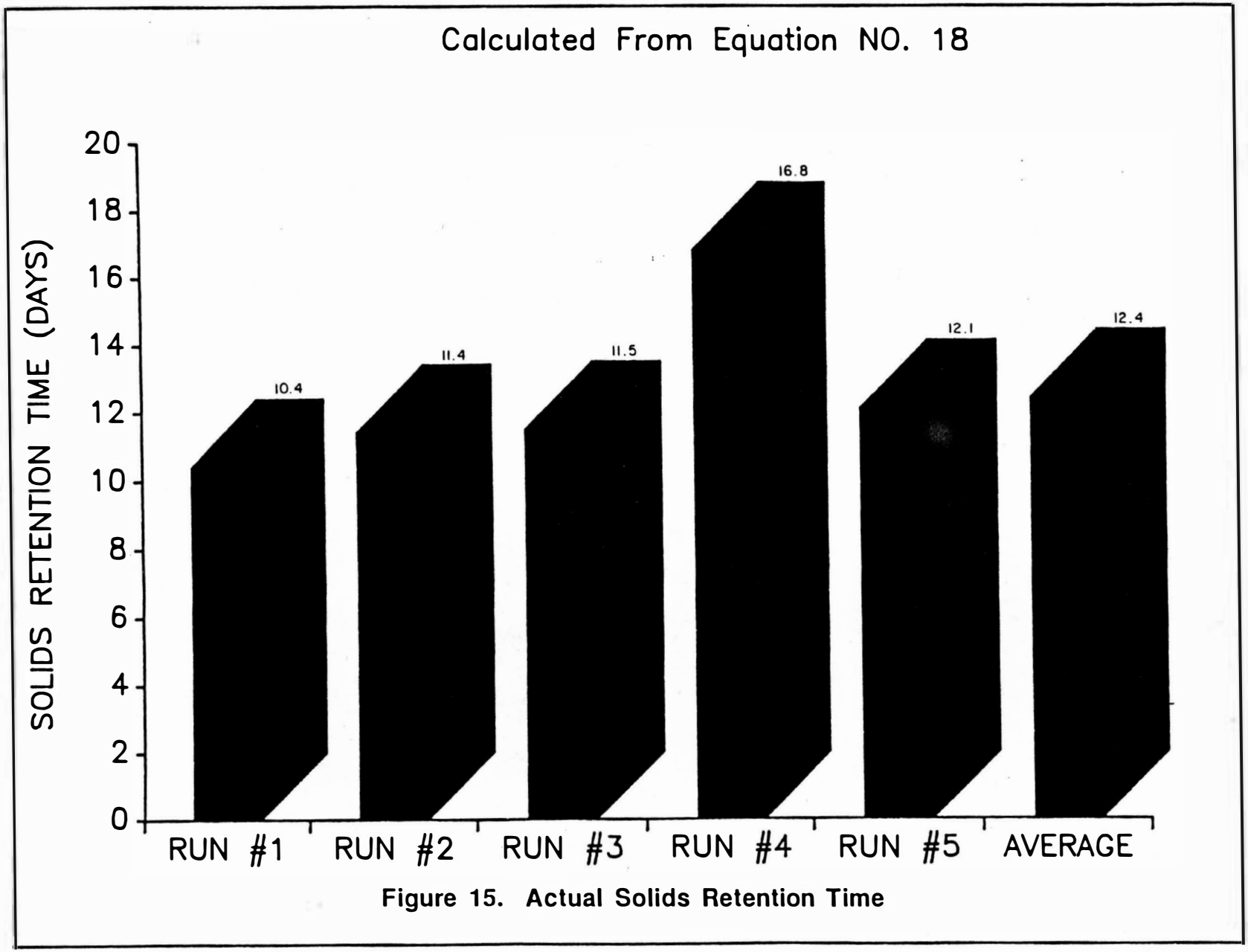


Figure 15. Actual Solids Retention Time

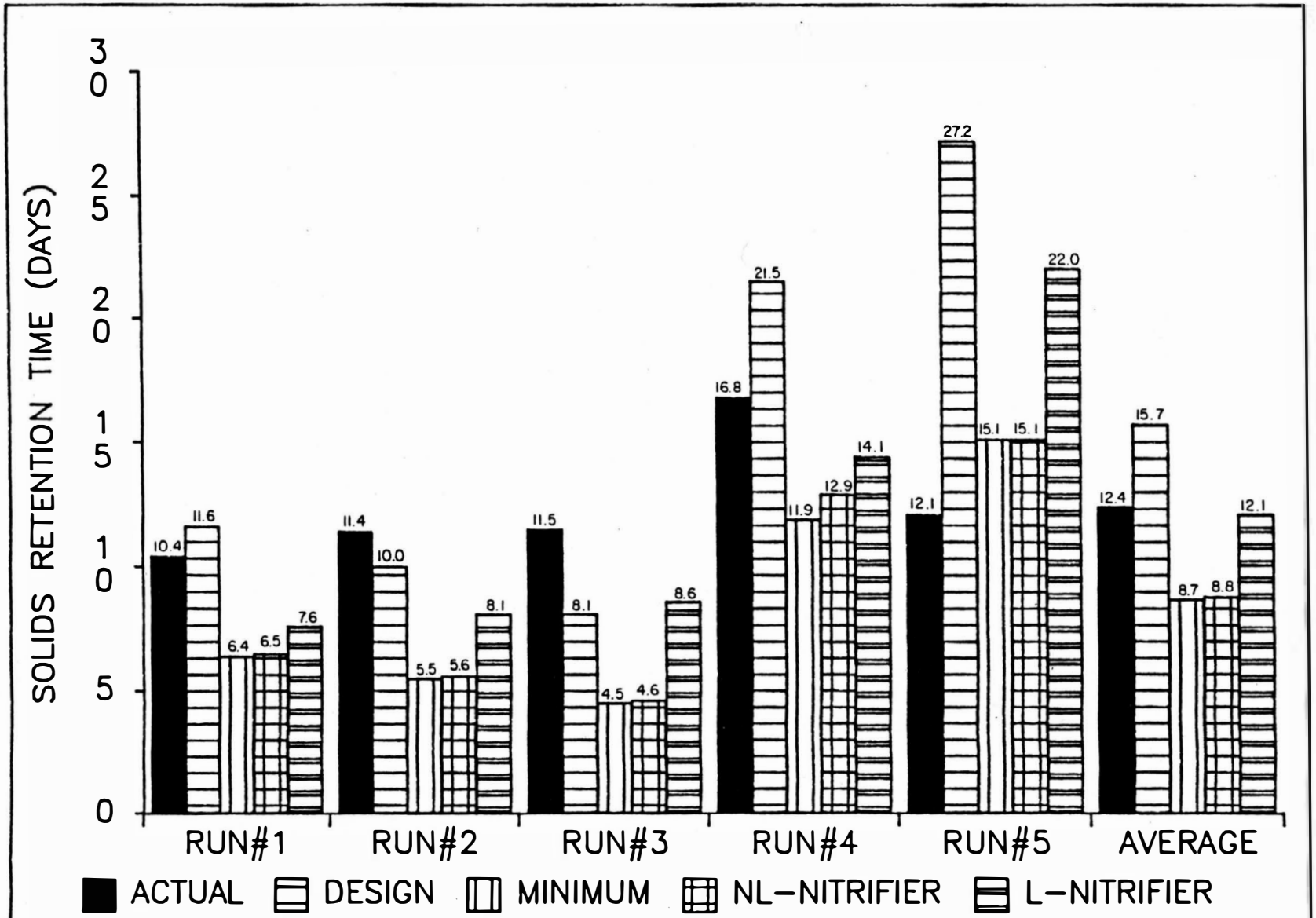


Figure 16. Comparison Of Solids Retention Times

A review of the different solids retention times shown in Figure 16 reveals, in general, that the actual solids retention times are greater than the theoretically-required retention times. A comparison of the minimum solids retention times calculated from the non-limiting nitrifier growth rate (Equation 15) reveals that in all the sample runs, with the exception of Run 5, the actual retention times were more than adequate in providing sufficient retention for nitrification based on the experimental D.O., temperature and pH values. The non-limiting nitrifier growth rate solids retention times (Equation 15) varied from 4.6 to 15.1 days with an average of 8.8 days. The actual solids retention times (Equation 18) varied from 10.4 to 16.8 days with an average of 12.4 days. A comparison of the average values shows that the actual retention times are approximately 40 percent greater than those theoretically required to provide sufficient nitrification.

Comparing the experimental values to the theoretical solids retention times based on limiting nitrifier growth rates reveals that the values are approximately equal. The limiting nitrifier retention times vary from 7.6 to 22 days with an average of 12.1 days. Although these values are substantially larger than the non-limiting values, the actual retention times are again larger than the theoretically necessary retention times for all the runs, excluding Run 5. The substantial increase in theoretical retention times obtained using the available ammonia-nitrogen concentrations seem to indicate that the ammonia-nitrogen concentrations are limiting in this activated sludge system, more so than D.O. and/or

pH.

Comparing the theoretical minimum solids retention times, Q_c^m, as calculated by Equation 16, to the experimental values determined using Equation 18 show the most diversity between actual and theoretical values. The minimum solids retention times (Equation 16) are substantially less than the actual retention times. The minimum solids retention times vary from 4.5 to 15.1 days with an average of 8.7 days. The average theoretical minimum solids retention time is approximately 43 percent less than the average actual solids retention time.

The design solids retention times, Q_c^d, (Equation 17) vary from 8.1 to 27.2 days with an average of 15.7 days. These values indicate that the retention times in the plant could be increased to improve nitrification.

However, all 4 of the previously-mentioned theoretical solid retention times are dependent upon the nitrifier growth rate (Equation 12) which, in turn is dependent upon the available ammonia-nitrogen concentration.

$$u_n =$$

$$0.47*[e**0.098(T-15)]*[DO/DO+1.3]*[1-0.833(7.2-pH)*[N/K_n+N] \quad (12)$$

where: N = effluent NH_4^+-N concentration, mg/l and

K_n = half-saturation constant, mg/l NH_4^+-N, mg/l,

= 10**0.051T-1.158 (1)

un = overall nitrifier growth rate, with consideration for nitrogen concentrations, (1/day).

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. In all of the sample runs, the available ammonia-nitrogen was less than 2.0 mg/l and the removal was greatly decreased in the third and fourth aeration basins. At these low concentrations and removals, the "multiplier" (u_n, nitrifier growth rate) for ammonia-nitrogen concentrations approaches a constant value of one and increases the required retention time substantially.

Paolini and Variali reported that nitrification began in their activated sludge system at a hydraulic detention time of 1.2 to 1.7 days.(25) This supports the experimental data represented herein which shows that the actual hydraulic detention times are greater than theoretically required, especially when considering the influent ammonia-nitrogen concentrations are so low initially.

Substrate Utilization Rates

Equation 19 is used to calculate the experimental substrate utilization rate, U, based on experimental ammonia-nitrogen removal and hydraulic detention time.

$$U = S_o - S / Q_h * X \qquad (19)$$

where: $Q_h = V/Q_f$ = hydraulic detention time, time.

Q_f = flow rate, mgd.

U = experimental substrate utilization rate, time-1.

S_o = influent soluble ammonia-nitrogen concentration, mg/l.

S = effluent soluble ammonia-nitrogen concentration, mg/l.

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. Since the influent soluble BOD_5 concentrations were so low entering the aeration basins, the experimental substrate utilization rates were calculated for ammonia-nitrogen removal only. These experimental substrate utilization rates are compared with the values developed using Equation 13 (ammonia oxidation rates, $q_{n,}$) and Equation 14 (nitrification rates, r_n).

$$q_n = u_n / Y_n \qquad (13)$$

where: q_n = ammonia oxidation rate, lb of NH_4^+-N oxidized per lb of VSS under aeration per day,

Y_n = organism yield coefficient, lb Nitrosomonas grown (VSS) /lb of NH_4^+-N removed.

$$r_N = q_n * f \quad (14)$$

where: f = nitrifier fraction of the mixed liquor solids,

r_N = nitrification rate, lb NH_4-N oxidized /lb/MLVSS/day.

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. The experimental substrate utilization rates were calculated based on overall performances only. Basin-by-basin performance was not determined due to the very low removals that occurred in each basin. Figure 17 includes the overall average experimental substrate utilization rates for each of the sample runs.

The actual experimental overall substrate removal rates, as shown in Figure 17, have values ranging from 0.012 to 0.027 lb's of NH_3-N removed / lb's of MLVSS / day. The overall average for all 5 of the runs was 0.019. The very low concentrations of ammonia-nitrogen entering into basins 3 and 4 for each of the runs caused the overall averages for each of the runs to be substantially lower than the others. Jenkins et al. reported a range of removal rates from 0.2 to 0.5 lb/MLVSS/day for an activated sludge system with a average mean cell residence time of approximately 10 days.(26)

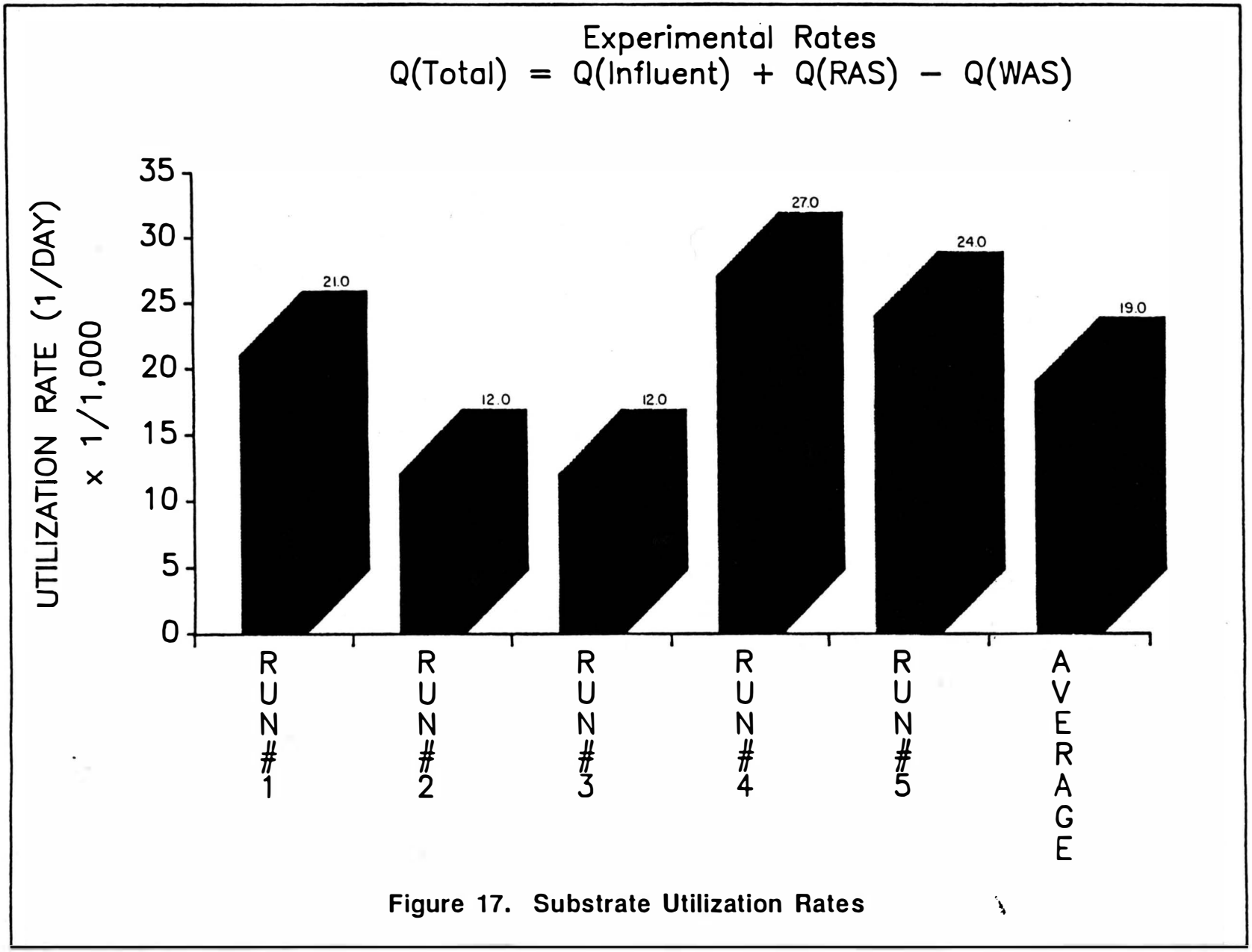


Figure 17. Substrate Utilization Rates

A graphical comparison of the different substrate utilization rates is presented in Figure 18. The 3 different substrate rates shown were obtained from Equation 13 for ammonia-oxidation (qn), Equation 14 for nitrification rate (rn) and the actual experimental removal rate as calculated using Equation 19. The comparison of the theoretical utilization rates (Equation's 13 and 14) with the actual utilization rate, (Equation 14) as shown in this figure reveals a drastic difference between the theoretical and actual values. The theoretical values are calculated taking into account pH, DO, temperature, effluent ammonia-nitrogen concentrations, typical yield coefficient (Yn) and an estimate of the nitrifier fraction of organisms in the mixed liquor.

A review of the parameters utilized for calculating the theoretical substrate utilization rates shows that all of the parameters are reproducible and documented thoroughly, with the exception of the yield coefficient and the nitrifier fraction. The nitrifier fraction estimate of 0.35, as discussed in the literature review section, is a conservative estimate and the large difference between theoretical and experimental values probably are not be linked to this parameter.

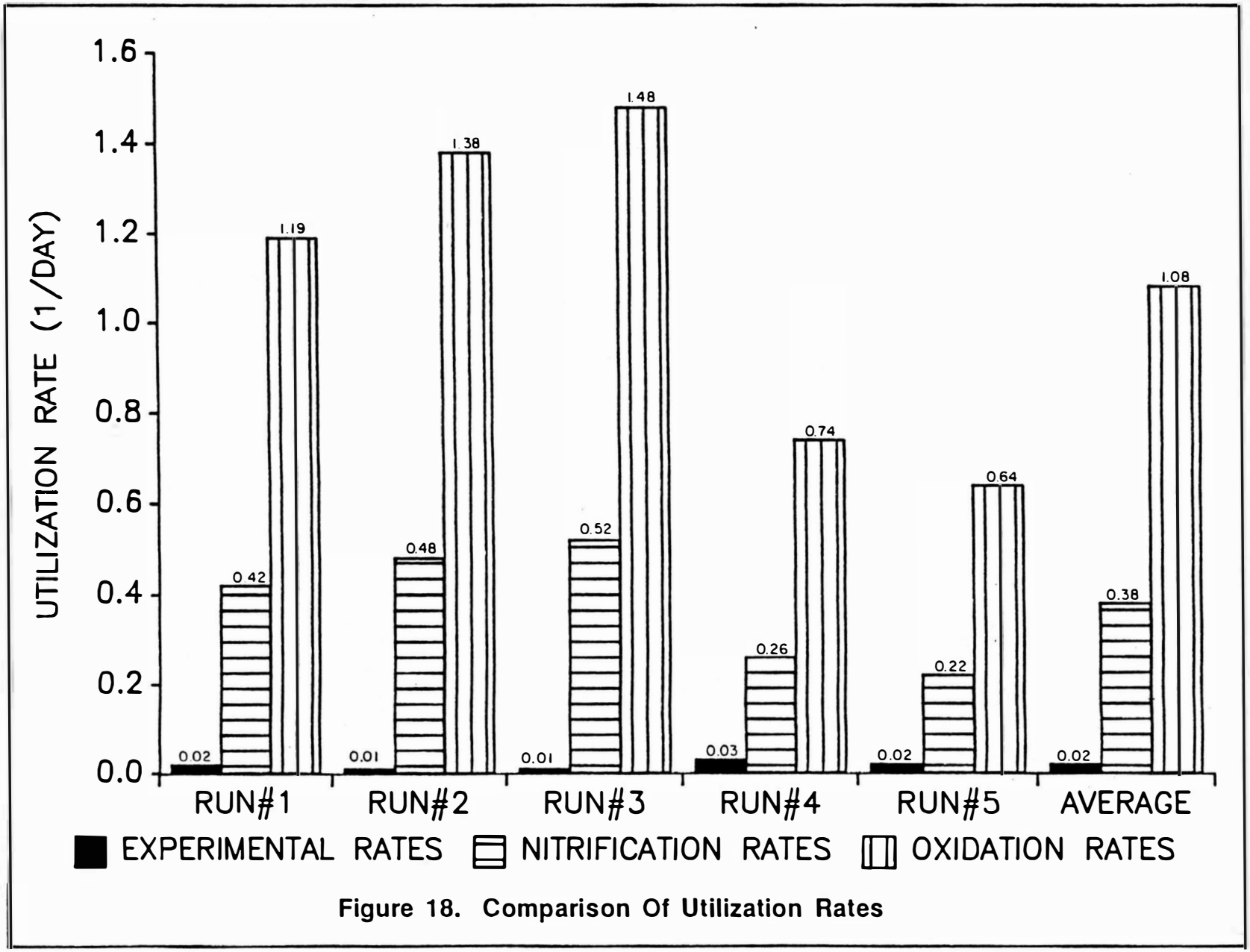


Figure 18. Comparison Of Utilization Rates

Therefore, by the process of elimination, the low experimental utilization rates might be associated with the organism yield coefficient, Y, lb VSS grown / lb NH_3-N removed. The large mass of solids that were under aeration could have produced yield coefficients higher than normal values because the pounds of VSS produced is falsely exaggerated where in fact, V.S.S. production is actually decreased by the carry-over of solids. Therefore, the large amount of solids under aeration competing for substrate are prohibiting the growth of new organisms (VSS) and thus forcing the substrate utilization rates to substantially lower-than-normal values.

BOD Removal Efficiencies

Equation 20 can be used to calculate the BOD removal efficiencies and the ammonia-nitrogen removal efficiencies.

$$E = [(S_o - S_e) / S_o] * 100 \qquad (20)$$

where: E = efficiency of BOD and ammonia-nitrogen removal, percent

S_o = influent BOD and ammonia-nitrogen concentration, mg/l

S_e = effluent BOD and ammonia-nitrogen concentration, mg/l

A sample calculation using data from Run 1, Basin 1 is shown in Appendix B. Figure 19 shows the influent (basin 1 influent) and effluent (basin 4 effluent) concentrations and overall activated-sludge BOD removal efficiencies.

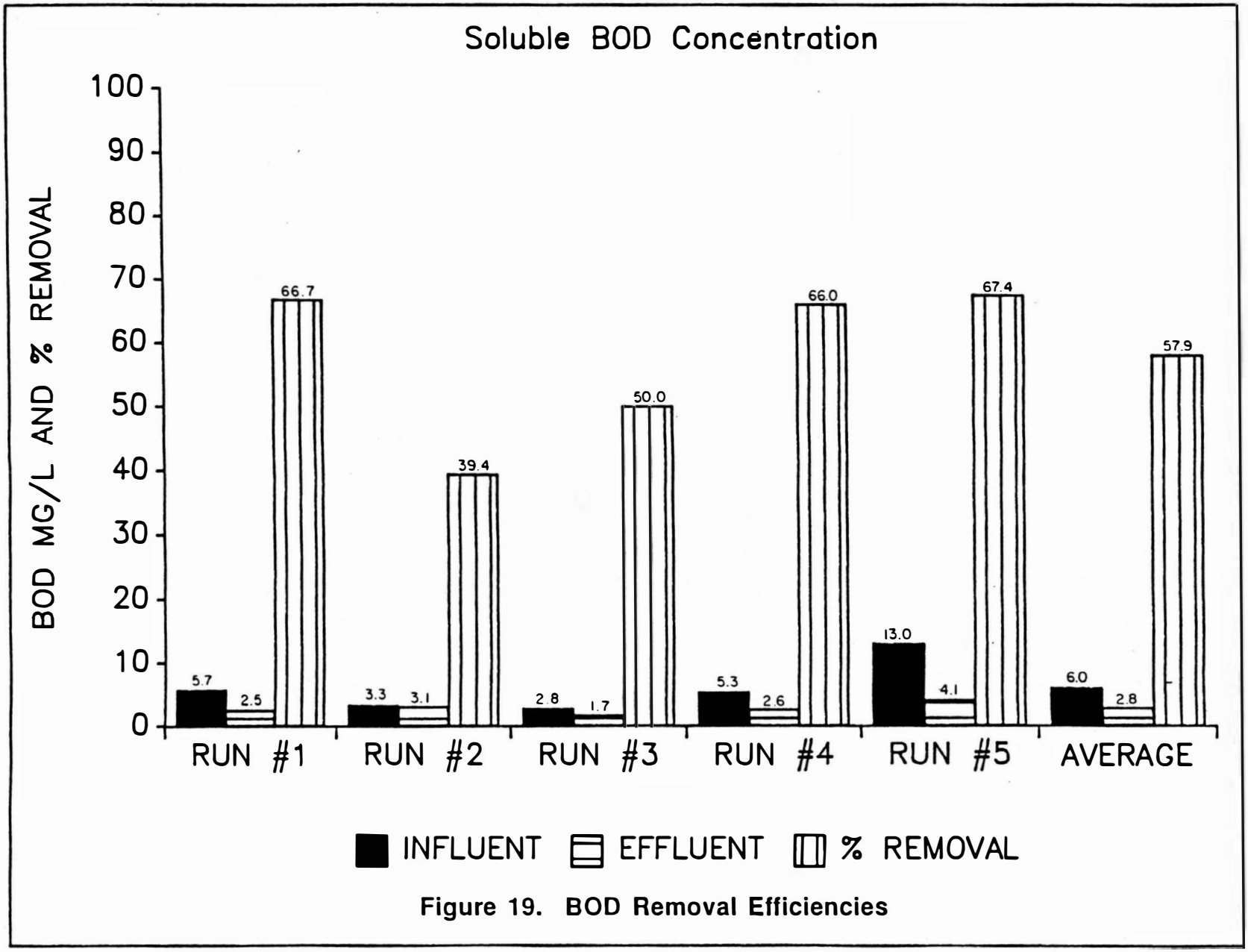


Figure 19. BOD Removal Efficiencies

Ammonia-Nitrogen Removal Efficiencies

Figure 20 shows the overall ammonia-nitrogen removal efficiencies calculated by utilizing Equation 20 and the influent and effluent ammonia-nitrogen concentrations. These ammonia-nitrogen removal efficiencies ranged from 93.3 to 98 percent with an average percent removal of 95.2. These values are fairly typical for an activated sludge system. However, the effluent ammonia-nitrogen concentrations in basins 3 and 4 are approaching or have reached the minimum ammonia-nitrogen concentration where removal can still be accomplished effectively. The low percent removal efficiencies experienced in the latter basins 3 and 4 tended to lower the overall average.

The BOD removal efficiencies ranged from 39.4 to 67.4 percent with an overall average of 57.9 percent. These values are substantially lower than expected for normal activated sludge systems. However, such low the influent BOD concentrations, higher removal efficiencies would be difficult to achieve.

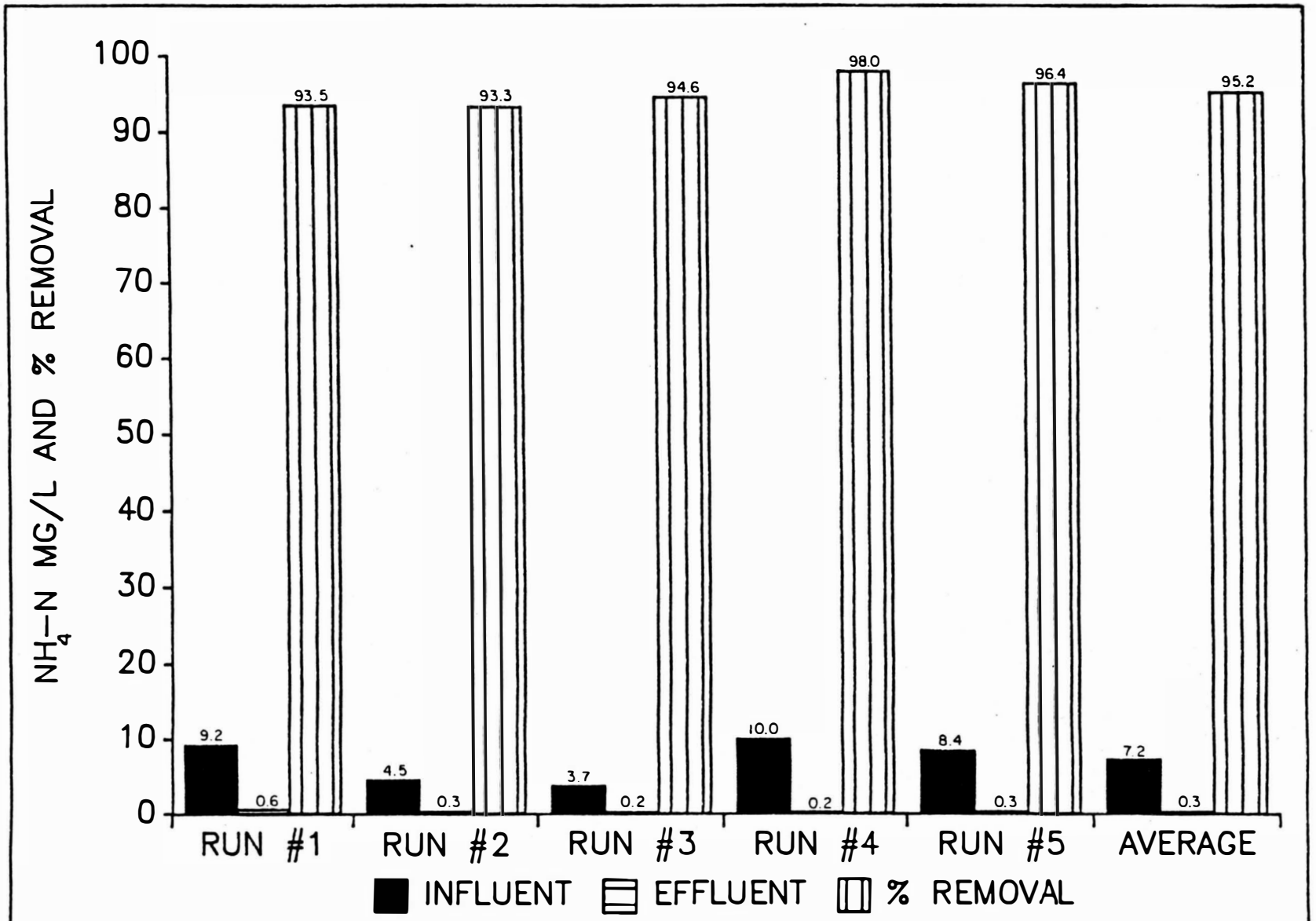


Figure 20. Ammonia-Nitrogen Removal Efficiencies

Food-to-Microorganism Ratios

Food-to-microorganism ratios (F/M) are used as both design and control parameters for activated sludge processes. The F/M ratio was defined in Equation 21. Figure 21 is a graph of the average F/M ratios for each of the 5 runs. Soluble BOD was used as an estimator of the food portion of the equation and the mixed liquor volatile suspended solids (MLVSS) concentration was utilized as an estimator for the microorganism concentration.

The F/M ratios in Figure 21, calculated from influent soluble BOD concentrations, ranged from 0.014 to 0.069 with an overall average of 0.039. Typical values for an extended aeration process range from 0.05 to 0.15.(4) A comparison of the actual experimental values to the typical values reveal that the experimental values are substantially lower. The low values can be attributed to both of the variables in the equation; low influent substrate concentrations and high suspended solids concentrations under aeration. The graph also indicates a declining trend in the ratios as the flow proceeds through the basins. This decline was very likely due to the decrease in the substrate concentrations from basin 1 to basin 4. It should be noted that the ratios were calculated using MLVSS concentrations. If MLSS concentrations had been used, even lower ratios would have resulted.

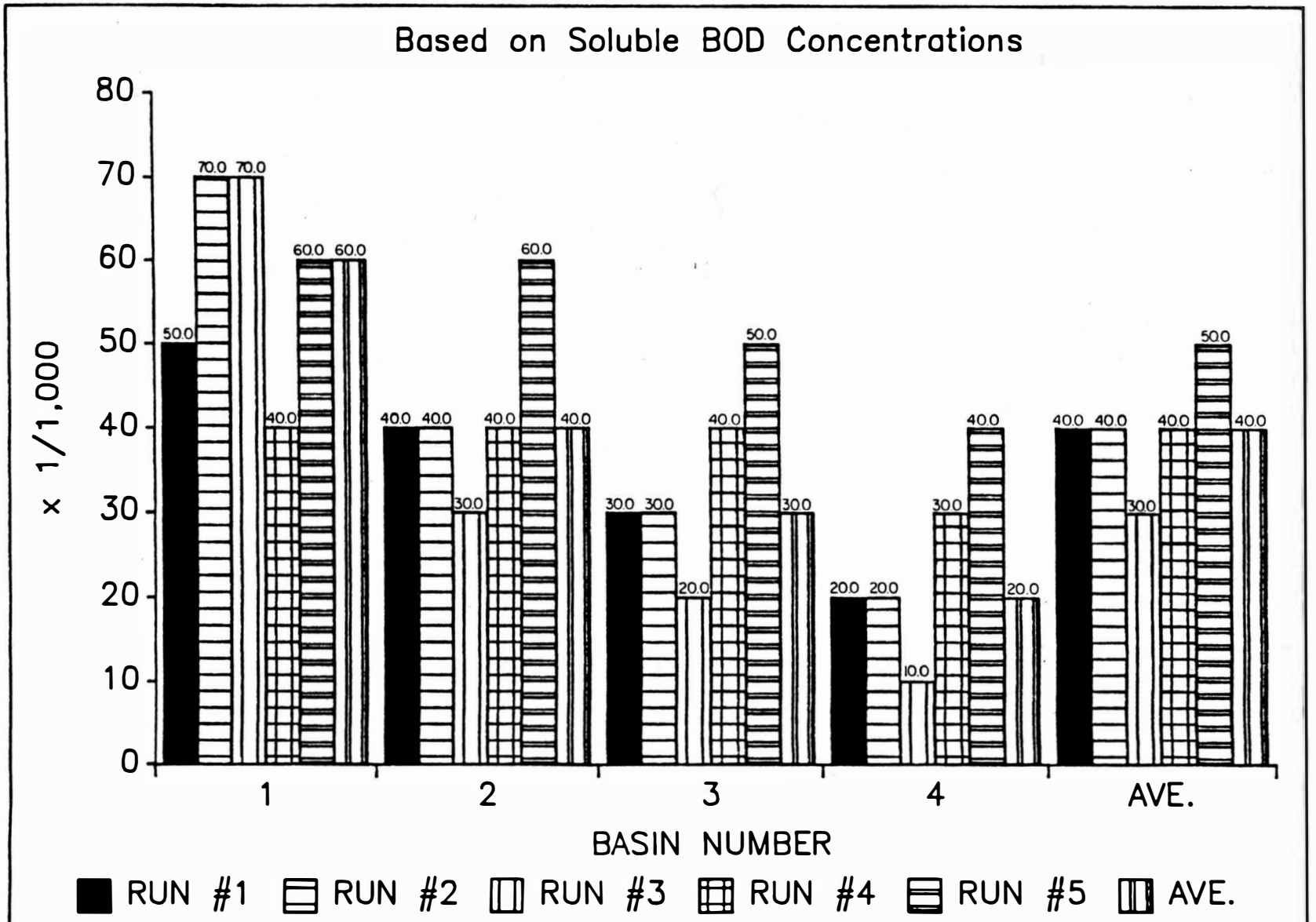


Figure 21. Food-To-Microorganism Ratios

Figure 22 is a graphical representation of F/M ratios based on ammonia-nitrogen as an estimator of food. These ratios, calculated using the influent soluble ammonia-nitrogen concentrations, are larger than the ratios obtained using soluble BOD concentrations (especially in basins 1 and 2). This is attributed to the larger substrate concentrations that the ammonia-nitrogen concentrations introduce into the system. Because most of the removable BOD has already been removed in upstream waste treatment processes, it seems appropriate to define the substrate portion of the F/M ratio as ammonia-nitrogen since it is the predominant constituent in the waste stream, the largest quantity of substrate removed, and the substrate of primary interest in the nitrification process.

Hydraulic Detention Times

Calculation of the theoretical hydraulic detention time, Q, can be accomplished using Equation 22.

$$Q = S_o - S \,/\, MLVSS * q_n \qquad (22)$$

The theoretical hydraulic detention time is dependent upon the influent ammonia-nitrogen concentration, MLVSS concentration and the substrate maximum removal rate. Both oxidation and nitrification maximum rates of ammonia-nitrogen removal were compared with the actual hydraulic detention time. Oxidation ammonia-nitrogen removal rates take into account temperature, pH, D.O. and effluent ammonia-nitrogen concentrations; whereas, nitrification removal rates accounts for the portion of the

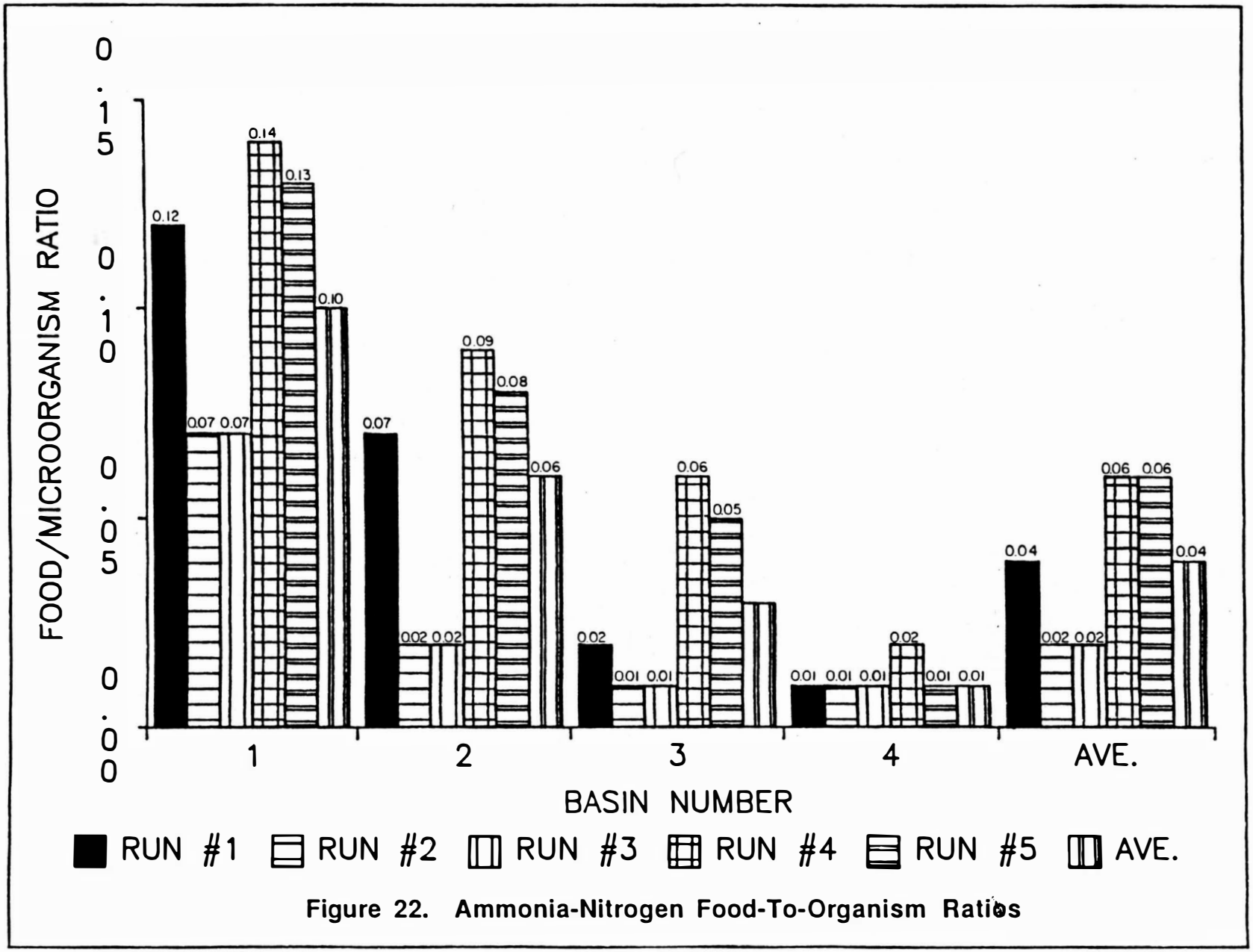


Figure 22. Ammonia-Nitrogen Food-To-Organism Ratios

microorganisms that are actually nitrifying bacteria.

Figure 23 contains a comparison of the theoretical hydraulic detention times calculated from oxidation rates and nitrification rates to the experimental hydraulic detention time. Theoretical hydraulic detention times calculated from oxidation rates ranged from 0.03 to 0.13 hours with an average of 0.06 hours. These detention times reflect removal rates based on optimum conditions of pH, D.O., and temperature and the assumption that the entire population of bacteria is nitrifiers. Of course, this assumption that 100 percent of the activated sludge bacteria are nitrifiers is not valid for most combined or separate stage activated sludge nitrification systems. Therefore, the fraction of bacteria that are nitrifiers (nitrification rate) must be approximated as previously described in discussing Equation 14. Theoretical hydraulic detention times, calculated from theoretical nitrification rates, yielded detention times varying from 0.12 to 0.25 hours with an average of 0.21 hours.

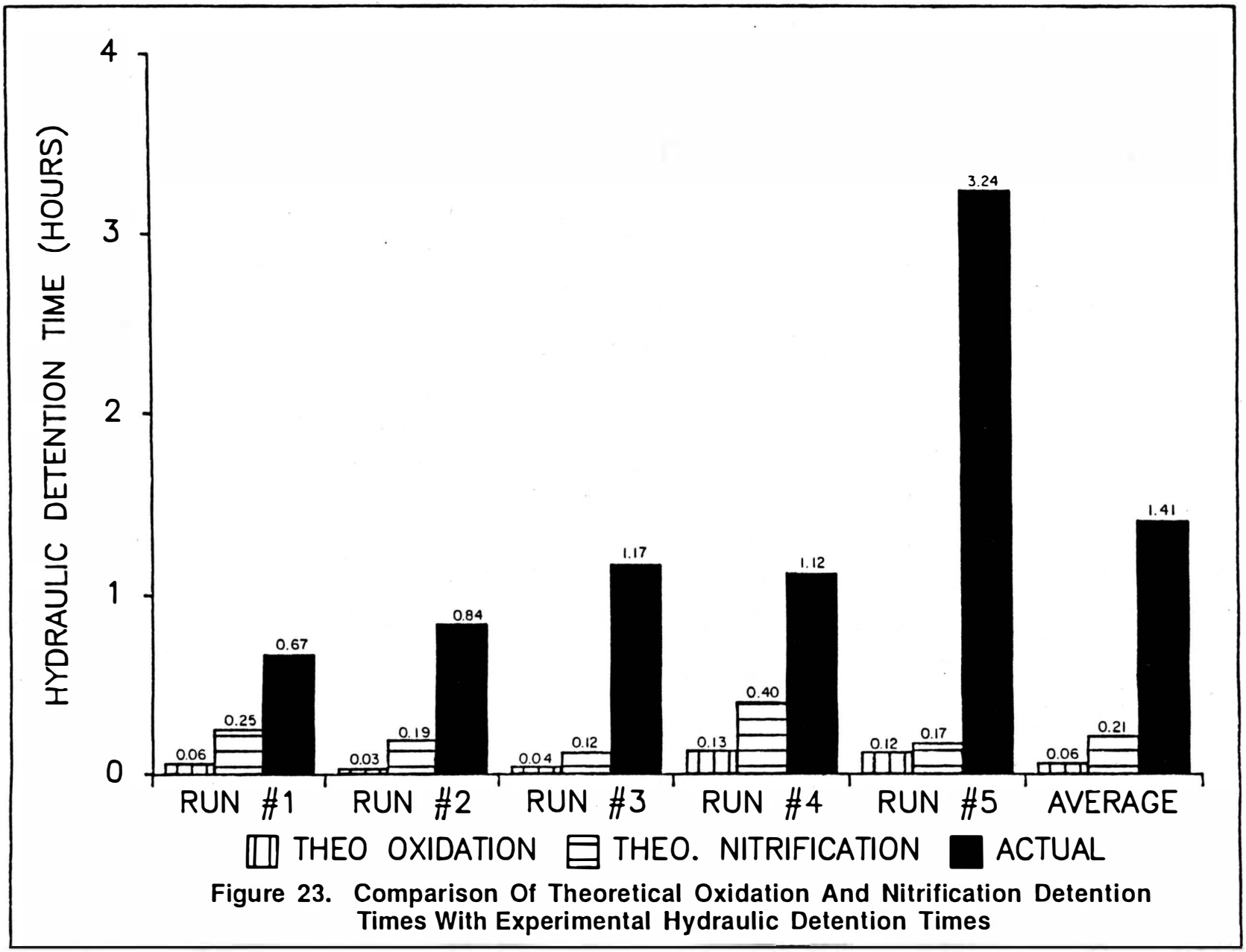


Figure 23. Comparison Of Theoretical Oxidation And Nitrification Detention Times With Experimental Hydraulic Detention Times

The experimental (actual) hydraulic detention times ranged from 0.67 to 3.25 hours with an average of 1.41 hours. Actual hydraulic detention times were calculated from the total volume of all 4 basins considered as a single unit. Clearly evident in Figure 23 is that the actual hydraulic detention times are substantially greater than theoretically required when considering the parameters of D.O., pH, temperature and ammonia-nitrogen concentrations. Actual hydraulic detention times could be reduced by removing a basin or basins from the treatment scheme. Taking the fourth basin out of the treatment train would be conservative also when considering the fact that all of the effluent ammonia-nitrogen concentrations from basin 2 were below the discharge permit concentration for all 5 sample runs.

Waste Activate Sludge Rates

Theoretical waste activated sludge rates (Equation 23) are dependent upon several parameters including final clarifier effluent flows, effluent volatile suspended solids concentrations, waste activated sludge concentrations, mixed-liquor volatile suspended solids concentrations and the minimum mean cell residence time (Equation 15).

$$Q_w = [((V*X)/Q_c^m)-(Q_e*X_e)]/X_w \qquad (23)$$

The minimum mean-cell residence time is calculated from the theoretical maximum nitrifier growth rate, which assumes the ammonia-nitrogen concentrations to be non-limiting. Figure 24 exhibits the theoretical waste activated sludge rates, actual waste activated sludge rates, difference

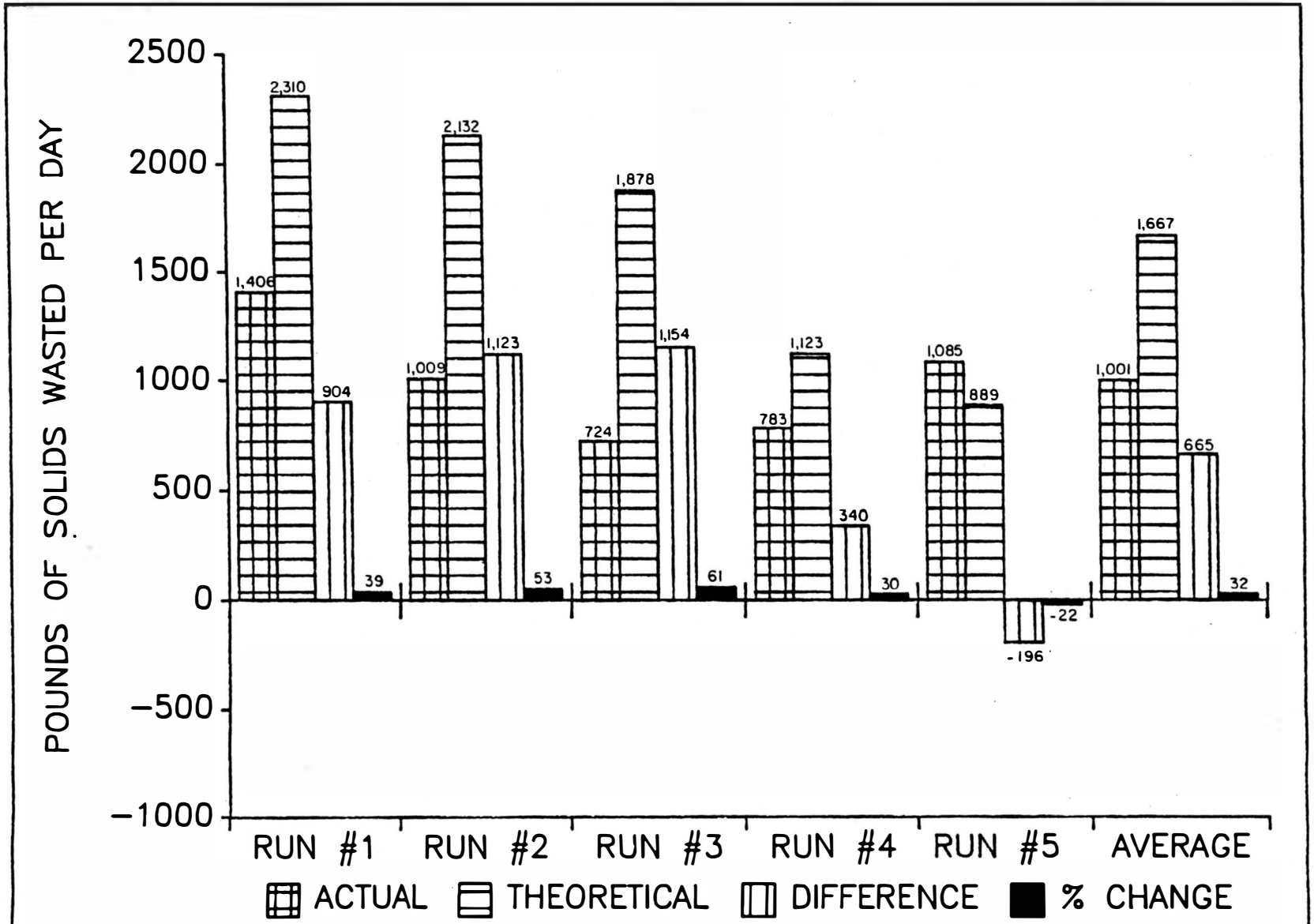


Figure 24. Waste Activated Sludge Wasting Rates

between theoretical and actual rates and the percent difference between the 2 rates.

The theoretical waste activated sludge rates spanned from 889 to 2310 pounds per day with an average of 1667. The actual wasting rates ranged from 724 to 1406 with an average rate of 1001 pounds per day. Thus, comparing averages, the theoretical rate is 32 percent higher than the actual wasting rate. An increase in the actual wasting rate would eventually result in a decrease in the aeration system MLVSS concentration which would also decrease the required wasting rate after the system achieved equilibrium.

SUMMARY

Table 7 is a summary of pertinent values discussed in this study.

Maximum nitrifier growth rates (Figure 7, non-limiting ammonia-nitrogen concentrations) for an average MLVSS activated sludge concentration of 2400 mg/l (see Appendix A, for MLVSS data) at 11^{o}C for this study ranged from 0.10 to 0.22 (1/day) with an average of 0.16. This average value is approximately 55 to 60 percent less than reported recommended values reported in the literature.

Maximum nitrifier growth rates (Figure 8, effluent ammonia-nitrogen utilized) at 2400 mg/l and 11^{o}C for this study ranged from 0.08 to 0.14 (1/day) with an average of 0.11 for each of the runs. This average is substantially less than values for typical nitrification systems reported in the literature at the temperatures encountered.

Table 7. Summary of Experimental Data

Parameter	Experimental Ave. Value	Theoretical Value	* % Diff.	Cited Value	Literature * % Diff.
Non-Limit. Nit. Grow. Rates (U_n) (Figure 7)	0.16 (1/day)	0.11<	+45	0.36(9) 0.40(1)	-55 -60
Solids Rention time (Q_c)(Figures 11- 16)	12.4 (days)	8.7@ 12.1#	+45 +03	15.7$	-21
Substrate Utilization Rates (U) (Figure 17)	0.02 (1/day)	1.08^ 0.38~	-98 -95	0.35(26) 0.29(1)	-94 -93
Substrate % Removal Efficiency (Figure 20)	57.9 (%)	95.2>	-39	N.A.	N.A.
F/M Ratios (Figure 21)	0.04	0.04+	0	0.10(4)	-60
Hydraulic Detention Time (Q_h) (Figure 23)	1.41 (Hours)	0.06^ 0.21~	+2250 +571	N.A.	N.A.
W.A.S. Wasting Rate (Q_w) (Figure 24)	1001 (lb/day)	1667	-40	N.A.	N.A.

< Calculated Accounting for Actual Ammonia-Nitrogen Concentrations

* Percent Difference From Experimental Value

@ Calculated Using Nitrifier Growth Rates Assuming Non-Limiting Ammonia-Nitrogen Concentrations (Equation 16).

\# Calculated Using Nitrifier Growth Rates Assuming Limiting Ammonia-Nitrogen Concentrations (Equation 15).

$ Design Residence Time, Calculated Using a Safety Factor = 1.8

^ Oxidation Rate, (q_n)

~ Nitrification Rate, (r_N)

\+ Calculated based on NH_4-N as a Food Source.

> Calculated based on NH_4-N for Substrate Removal

Actual solids retention times (Figure 15) varied from 11.4 to 16.8 days with an average of 12.4. Theoretical minimum solids retention times (Figure 13, non-limiting ammonia-nitrogen concentrations) ranged from 4.52 to 15.1 days with an average of 8.7. Maximum nitrifier growth rate values (Figure 12, limiting ammonia-nitrogen concentrations) resulted in theoretical solids retention times ranging from 7.6 to 22 days with an overall average of 12.1 days. Thus, the average experimental solids retention time was approximately 45 percent higher than theoretically required as calcultated for the condition present during sampling. Furthermore, the average experimental solids retention time was approximately 3 percent higher than theoretically required for optimum conditions. The average experimental solids retention time was approximately 21 percent less than the design mean cell residence time.

Actual (experimental) substrate utilization rates (Figure 17) obtained in this study ranged from 0.012 to 0.027 days with an average of 0.019. Theoretical utilization rates, calculated from nitrification and oxidation rates, resulted in substantially larger average rates, equal to 0.38 and 1.08 days respectively. Thus, the average actual utilization rate was approximately 97 percent less than the average theoretical nitrification and oxidation rates.

Experimental substrate percent removal efficiencies, as calculated from BOD concentrations (Figure 19), varied between 39.4 to 67.4 percent with an average of 57.9. Substrate percent removal efficiencies, calculated from ammonia-nitrogen substrate removal quantities, resulted in

values ranging from 93.3 to 98.0 percent with an average of 95.2. Thus, the BOD substrate removal efficiency is approximately 39 less than ammonia-nitrogen substrate removal quantities.

Actual (experimental) F/M ratios (Figure 21) ranged from 0.01 to 0.07 with an average of 0.04. F/M ratios calculated utilizing ammonia-nitrogen as a food source resulted in values ranging from 0.01 to 0.14 with an average of 0.04. Values reported in the literature review resulted in average value of 0.10 for a similiar nitrification system. Thus, the experimental F/M average ratio was approximately 60 percent less than the reported value.

Actual (experimental) hydraulic detention times varied between 0.67 and 3.24 hours with an average of 1.41. Theoretical average hydraulic detention times calculated from oxidation and nitrification rates resulted in average times of 0.06 and 0.21 hours respectively, resulting in detention times of 2250 and 571 percent higher than theoretically required as calculated from the average theoretical oxidation and nitrification rates.

Actual waste activated sludge wasting rates varied between 724 and 1406 with an average of 1001 pounds of dry weight solids wasted per day. Theoretical wasting rates as calculated from Equation 24 ranged from 889 to 2310 with an average of 1667 pounds of dry weight solids wasted per day, 40 percent below theoretical average wasting rates.

CONCLUSIONS

The following conclusions have been made from the investigations conducted at the nitrification facility at the BWWTP.

1. Based on the low BOD-to-ammonia-nitrogen ratios obtained, the treatment process seems to be operating as a seperate-stage nitrification activated sludge system.

2. The experimental average substrate utilization rate obtained was approximately 95 percent lower than that found in the literature review and as theoretically calculated.

3. Substrate percent removal efficiency, as calculated from BOD removal quantities, was approximately 39 percent less than the substrate removal efficiency as calculated from ammonia-nitrogen removal quantities.

4. Average nitrifier growth rate, determined in this experiment assuming non-limiting ammonia-nitrogen conditions, was approximately 55 percent less than those found in the literature.

5. Average actual (experimental) solids retention time was approximately 45 percent greater than theoretically required for the concentrations of process parameters that were present at the time of sampling for this study.

6. Average actual (experimental) hydraulic time was approximately 570 percent greater than required as determined by the theoretical nitrification rate.

7. Average actual (experimental) waste-activated sludge wasting rate was approximately 40 percent less than theoretically required.

8. Process control and monitoring can be accomplished by utilizing a F/M ratio based on ammonia-nitrogen in lieu of BOD concentrations. The ratio of food-to-microorganism of 0.8, which is the average of the ratios in basins 1 and 2, should be used for establishing optimimum ammonia-nitrogen removal conditions.

RECOMMENDATIONS FOR FUTURE STUDIES

The following recommendations are made for future studies involving similar research objectives.

1. An attempt should be made to establish the minimum influent ammonia-nitrogen concentration at temperatures less than $15^{o}C$ where ammonia-nitrogen limits nitrifier growth rates and nitrification rates in the treatment system.

2. The phenomenon in which high solids retention times have been observed to prevent low temperatures from effecting nitrifier growth rates should be studied to determine the retention time at which temperature effects are eliminated.

3. The effect of higher carbonaceous BOD loadings to the aeration system should be studied to determine the effect exerted on the nitrification treatment process.

4. Bench-scale reactor studies should be conducted at various MLVSS and ammonia-nitrogen (substrate) concentrations to establish precise yield coefficients for nitrifiers in low-temperature environments.

5. Data should be collected to substantiate reports that in separate-stage nitrification systems, the ratio of organic matter to nitrogen is the major factor in determining if biological nitrification is effectively possible.

6. The feasibility of using basin 4 (and perhaps basin 3) for denitrification should be studied.

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APPENDIX A

EXPERIMENTAL DATA

Table A1. Data From Run 1

12/27/83 1:00 p.m.

	COD (MG/L)	BOD (MG/L)	AMMONIA (MG/L)	SS (MG/L)	VSS (MG/L)	DO (MG/L)
RBC Left Effluent	50.2	16.9	16.0	67.0	56.0	5.1
RBC Right Effluent	39.6	17.7	17.3	98.0	74.0	4.8
Aeration Basin Influent	26.5	5.7	9.2	3880.0	3070.0	3.6
Aeration Basin 1 Effluent	25.3	3.8	6.4	4820.0	3400.0	0.9
Aeration Basin 2 Effluent	28.8	3.9	2.7	3740.0	2870.0	0.6
Aeration Basin 3 Effluent	21.2	2.4	0.7	2550.0	1980.0	4.3
Aeration Basin Effluent	21.6	2.5	0.6	3560.0	2700.0	3.9
Final Clarifier Effluent	23.7	1.9	0.1	15.0	9.0	5.2

Plant Influent pH = 7.55
Plant Influent Temperature = 11.7^{o} C
Plant Inflluent Flow = 2.28 MGD
Waste Activated Sludge Flow = 32 GPM
Return Activated Sludge Flow = 1.65 MGD
Return Activated Sludge V.S.S. = 7940.0 MG/L
L.- R.B.C. Flow = 1.65 MGD
R.- R.B.C. Flow = 1.08 MGD
Aeration Room Temperature = 2^{o} C
Outside Air Temperature = 13^{o} F
Plant Effluent pH = 7.28

Table A2. Data From Run 2

12/29/83 1:00 p.m.

	COD (MG/L)	BOD (MG/L)	AMMONIA (MG/L)	SS (MG/L)	VSS (MG/L)	DO (MG/L)
RBC Left Effluent	33.5	7.3	7.4	39.0	30.0	6.1
RBC Right Effluent	34.3	5.1	7.4	38.0	29.0	5.6
Aeration Basin Influent	27.3	3.3	4.5	1640.0	1240.0	2.6
Aeration Basin 1 Effluent	21.2	3.4	1.3	2510.0	1880.0	0.7
Aeration Basin 2 Effluent	24.8	3.1	0.3	3350.0	2510.0	6.3
Aeration Basin 3 Effluent	24.5	3.3	0.3	4260.0	3100.0	7.5
Aeration Basin Effluent	24.4	3.1	0.3	3220.0	2380.0	6.7
Final Clarifier Effluent	20.0	2.0	0.1	10.0	10.0	6.8

Plant Influent pH = 7.55
Plant Influent Temperature = 11.2^{o} C
Plant Influent Flow = 1.95 MGD
Waste Activated Sludge Flow = 31 GPM
Return Activated Sludge Flow = 7.97 MGD
Return Activated Sludge V.S.S. = 10220.0 MG/L
L.- R.B.C. Flow = 1.45 MGD
R.- R.B.C. Flow = 0.90 MGD
Aeration Room Temperature = 4^{o} C
Outside Air Temperature = 5^{o} F
Plant Effluent pH = 7.27

Table A3. Data From Run 3

1/3/84 1:00 p.m.

	COD (MG/L)	BOD (MG/L)	AMMONIA (MG/L)	SS (MG/L)	VSS (MG/L)	DO (MG/L)
RBC Left Effluent	34.3	6.3	6.6	64.0	48.0	5.1
RBC Right Effluent	31.9	5.5	7.2	53.0	40.0	4.9
Aeration Basin Influent	26.1	2.8	3.7	1030.0	790.0	6.5
Aeration Basin 1 Effluent	22.2	2.2	1.4	1600.0	1240.0	2.7
Aeration Basin 2 Effluent	21.4	1.6	0.2	2340.0	1740.0	3.0
Aeration Basin 3 Effluent	24.2	1.8	0.2	2810.0	2190.0	7.8
Aeration Basin Effluent	22.0	1.7	0.2	2670.0	2040.0	7.3
Final Clarifier Effluent	19.8	1.4	0.1	21.0	17.0	6.9

Plant Influent pH = 7.56
Plant Influent Temperature = 11.1^{o} C
Plant Influent Flow = 1.62 MGD
Waste Activated Sludge Flow = 26 GPM
Return Activated Sludge Flow = 1.70 MGD
Return Activated Sludge V.S.S. = 6940.0 MG/L
L.- R.B.C. Flow = 1.20 MGD
R.- R.B.C. Flow = 0.67 MGD
Aeration Room Temperature = 4^{o} C
Outside Air Temperature = 12^{o} F
Plant Effluent pH = 7.11

Table A4. Data From Run 4

1/11/84 1:00 p.m.

	COD (MG/L)	BOD (MG/L)	AMMONIA (MG/L)	SS (MG/L)	VSS (MG/L)	DO (MG/L)
RBC Left Effluent	45.4	12.3	17.8	87.0	63.0	4.30
RBC Right Effluent	45.4	13.0	17.2	79.0	59.0	4.1
Aeration Basin Influent	26.3	5.3	10.0	5290.0	3820.0	4.6
Aeration Basin 1 Effluent	23.9	2.8	7.1	3410.0	2500.0	0.6
Aeration Basin 2 Effluent	20.9	3.0	5.9	3170.0	2310.0	0.2
Aeration Basin 3 Effluent	22.1	3.0	2.2	2370.0	1680.0	0.7
Aeration Basin Effluent	21.5	2.6	0.2	3270.0	2320.0	1.9
Final Clarifier Effluent	22.7	1.8	0.1	10.0	7.8	2.9

Plant Influent pH = 7.53
Plant Influent Temperature = 12.3^{o} C
Plant Influent Flow = 2.44 MGD
Return Activated Sludge Flow = 1.67 MGD
Return Activated Sludge V.S.S. = 2745.0 MG/L
L.- R.B.C. Flow = 1.60 MGD
R.- R.B.C. Flow = 1.16 MGD
Aeration Room Temperature = 4^{o} C
Outside Air Temperature = 12^{o} F
Plant Effluent pH = 7.41

Table A5. Data From Run 5

1/18/84 1:00 p.m.

	COD (MG/L)	BOD (MG/L)	AMMONIA (MG/L)	SS (MG/L)	VSS (MG/L)	DO (MG/L)
RBC Left Effluent	42.0	8.8	15.8	60.0	44.0	5.7
RBC Right Effluent	40.4	7.5	15.8	56.6	43.4	5.3
Aeration Basin Influent	27.9	4.6	8.4	4170.0	2940.0	4.9
Aeration Basin 1 Effluent	27.2	4.2	6.0	3400.0	2530.0	2.9
Aeration Basin 2 Effluent	25.2	3.8	4.7	2790.0	2170.0	0.3
Aeration Basin 3 Effluent	26.4	4.5	1.4	3010.0	2220.0	0.6
Aeration Basin Effluent	24.0	4.1	0.3	3740.0	2790.0	0.2
Final Clarifier Effluent	26.0	1.5	0.1	13.0	11.0	2.3

Plant Influent pH = 7.82
Plant Influent Temperature = 11^{o} C
Plant Influent Flow = 3.00 MGD
Waste Activated Sludge Flow = 29.0 GPM
Return Activated Sludge Flow = 1.80 MGD
Return Activated Sludge V.S.S. = 7390.0 MG/L
L.- R.B.C. Flow = 1.75 MGD
R.- R.B.C. Flow = 1.20 MGD
Aeration Room Temperature = 1^{o} C
Outside Air Temperature = -10^{o} F
Plant Effluent pH = 7.18

Table A6. BOD To COD Ratios

	RUN 1 BOD TO COD	RUN 2 BOD TO COD	RUN 3 BOD TO COD	RUN 4 BOD TO COD	RUN 5 BOD TO COD	AVERAGE BOD TO COD
RBC Left Effluent	0.337	0.218	0.184	0.271	0.210	0.244
RBC Right Effluent	0.447	0.149	0.172	0.286	0.186	0.248
Aeration Basin Influent	0.215	0.121	0.107	0.202	0.165	0.162
Aeration Basin 1 Effluent	0.150	0.160	0.099	0.117	0.154	0.136
Aeration Basin 2 Effluent	0.135	0.125	0.075	0.144	0.151	0.126
Aeration Basin 3 Effluent	0.113	0.135	0.074	0.136	0.170	0.126
Aeration Basin Effluent	0.116	0.127	0.077	0.121	0.171	0.122
Final Clarifier Effluent	0.080	0.100	0.071	0.079	0.058	0.078

Table A7. Pounds of Soluble BOD Per 1000 Cubic Feet of Tank Volume Per Day Based On Effluent Flows of R.B.C.'S Only (No RAS Flow Included)

	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5
Aeration Basin No. 1	6.42	3.90	2.32	5.53	6.43
Aeration Basin No. 2	4.57	3.32	1.54	3.48	5.12
Aeration Basin No. 3	2.98	2.61	1.10	2.88	4.25
Aeration Basin No. 4	1.94	2.18	0.95	2.24	3.67

Table A8. Pounds of Volatile Suspended Solids

	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5
Aeration Basin No. 1	3399.47	1639.31	1066.60	3320.65	2874.05
Aeration Basin No. 2	3754.55	2628.78	1784.46	2880.29	2814.42
Aeration Basin No. 3	3630.30	4199.16	2941.66	2986.57	3285.98
Aeration Basin No. 4	4203.66	4922.23	3799.46	3592.87	4500.07

Table A9. Sludge Age In Days Based On MLSS

Calculated With R.B.C Effluent Flows and R.A.S Flow

Equation = Pounds of S.S. in Basin / Pounds of S.S. Into Basin

	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5
Aeration Basin No. 1	1.52	1.70	0.79	1.49	1.72
Aeration Basin No. 2	1.70	2.73	1.36	1.29	1.61
Aeration Basin No. 3	1.56	4.44	2.21	1.35	1.88
Aeration Basin No. 4	1.82	5.23	2.83	1.65	2.63

APPENDIX B

EXPERIMENTAL CALCULATIONS

Experimental Calculations

A. Nitrifier Growth Rates, Non-Limiting Ammonia-Nitrogen Conditions:

$$u^*_n = 0.47*[e**0.098(T-15)]*[DO/DO+1.3]*[1-0.833(7.2-pH)] \quad (11)$$

where: u^*_n = nitrifier (Nitrosomonas) growth rate, 1/day with no NH_4-N limitations.

$$u^*_n = 0.47*[e**0.098(11.7-15)]*[0.9/0.9+1.3]*[1]]$$

$$u^*_n = 0.13 \text{ 1/day}$$

B. Nitrifier Growth Rates, Limiting Ammonia-Nitrogen Conditions:

$$u_n = 0.47*[e**0.098(T-15)]*[DO/DO+1.3]*[1-0.833(7.2-pH)*[N/K_n+N] \quad (12)$$

where: N = effluent NH_4^+-N concentration, mg/l and

K_n = half-saturation constant, mg/l NH_4^+-N, mg/l,

= 10**0.051T-1.158 (1)

un = overall nitrifier growth rate, with consideration for nitrogen concentrations, (1/day).

$$u_n = 0.47*[e**0.098(11.7-15)]*[0.9/0.9+1.3]*[1]*[6.4/((10**((0.051*11.7)-1.158)+6. 4))] \quad (12)$$

= 0.13 1/day

C. Ammonia Oxidation Rate:

$$q_n = u_n / Y_n \quad (13)$$

where: q_n = ammonia oxidation rate, lb of HN_4^+-N oxidized per lb of VSS under aeration per day,

Y_n = organism yield coefficient, lb Nitrosomonas grown (VSS) /lb of NH_4^+-N removed.

$q_n = 0.13 / 0.15$

$= 0.87$ lb of NH_4-N / lb VSS / day

D. Nitrification Rate:

$$r_N = q_n * f \quad (14)$$

where: f = nitrifier fraction of the mixed liquor solids,

r_N = nitrification rate, lb NH_4-N oxidized lb / MLVSS / day.

$r_N = 0.87 * 0.35$

$= 0.30$

E. Minimum Solids Retention Time, Limiting Ammonia-Nitrogen Conditions:

$$Q_c^m = 1 / u_n \quad (15)$$

where: Q_c^m = minimum solids retention time, days, for nitrification with corrections for pH, temperature, ammonia-nitrogen and DO.

$Q_c^m = 1 / 0.13$

$= 7.6$ days

F. Minimum Solids Retention Time:

$$Q_c^m = 1 / [(Y_n * q_n) - k_d] \quad (16)$$

where: k_d = endogenous decay coefficient, time -1

q_n = average of run 1

$Q_c^m = 1 / [(0.15 * 0.87) - 0.05]$

= 12.4 days

G. Design Solids Retention Time:

$$Q_c^d = S.F. * Q_c^m \quad (17)$$

where: Q_c^d = solids retention time of design, days,]

S.F. = safety factor.

$Q_c^d = 1.8 * 6.44$

= 11.6 days

H. Actual Solids Retention Time:

$$Q_c = V * X / [(Q_w * X_w) + (Q_e * X_e)] \quad (18)$$

where: Q_c = MCRT based on the aeration tank volume, day,

V = total aeration tank volume, mg

X = volatile suspended solids in the aeration tank, mg/l,

Q_w = waste sludge flowrate, mgd,

X_w = volatile suspended solids in the waste stream mg/l,

Q_e = treated effluent flowrate, mgd,

X_e = volatile suspended solids in the treated effluent mg/l.

$Q_c = 0.64 * 2737.0 / [(0.05 * 2870) + ((2.73 - 0.05) * 9.0)]$

$= 10.4$ days

I. Experimetal Substrate Utilization Rates:

$$U = S_o - S / Q_h * X \quad (19)$$

where: $Q_h = V/Q_f$ = hydraulic detention time, time.

Q_f = flow rate, mgd.

U = experimental substrate utilization rate, time-1.

S_o = influent soluble ammonia-nitrogen concentration, mg/l.

S = effluent soluble ammonia-nitrogen concentration, mg/l.

$U = 9.2 - 0.6 / ((0.64 / (2.73 + 1.65 - 0.05)) * 2737)$

$= 0.021$ 1/day

J. Experimental Removal Efficiencies (Ammonia-Nitrogen)

$$E = [(S_o - S_e) / S_o] * 100] \quad (20)$$

$$= [(9.2 - 0.6) * 100] / 2.5 \; 9.2$$

$$= 93.5\ \%$$

K. Theoretical Hydraulic Detention Time, Based on Theoretical Nitrification Rates.

$$Q = S_o - S / MLVSS * q_n \quad (22)$$

$$= [9.2 - 0.6 / 2737 * 0.30] * 24$$

$$= 0.25 \text{ hours}$$

L. Theoretical Waste Activated Sludge Wasting Rates:

$$Q_w = [((V*X)/Q_c^m)-(Q_e*X_e)]/X_w \quad (23)$$

$$= [((0.64 * 2737 / 6.5) - ((2.68 * 9.0)] / 2870$$

$$= 0.0855 \text{ mgd} * 8.34 * 2870$$

$$= 2310 \text{ lb's / day}$$