

Computer Program Development for the Design of IFAS Wastewater Treatment Processes

Tongchai Sriwiriyarat

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Clifford W. Randall, Ph.D., Chair

Daniel L. Gallagher, Ph.D.

John C. Little, Ph.D.

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By

Tongchai Sriwiriyarat

ABSTRACT

The Integrated Film Activated Sludge Process (IFAS) was developed to reduce the cost of additional facilities required to complete year round nitrification in the design of new or retrofit wastewater treatment plants. The purpose of this project was to develop a computer-based mechanistic model, called IFAS, which can be used as a tool by scientists and engineers to optimize their designs and to troubleshoot a full-scale treatment plant. The program also can be employed to assist researchers conducting their studies of IFAS wastewater treatment processes. IFAS enables the steady-state simulation of nitrification-denitrification processes as well as carbonaceous removal in systems utilizing integrated media, but this current version supports only sponge type media. The IFAS program was developed by incorporating empirical equations for integrated biofilm carbonaceous uptake and nitrification developed by Sen and Randall (1995) into the general activated sludge model, developed by the International Association on Water Quality (IAWQ, previously known as IAWRC), plus the biological phosphorus removal model of Wentzel et al (1989). The calibration and evaluation of the IFAS model was performed using existing data from both an IFAS system and a conventional activated sludge bench-scale plant operated over a wide range of Aerobic Mean Cell Residence Times (Aerobic MCRT's). The model developed provides a good fit and a reasonable prediction of the experimental data for both the IFAS and the conventional pilot-scale systems. The phosphorus removal component of the model has not yet been calibrated because of insufficient data and the lack of adequately defined parameters.

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CHAPTER 1

INTRODUCTION

Biological Nutrient Removal (BNR), i.e., the removal of nitrogen and phosphorus from wastewaters using biological mechanisms, is an advanced wastewater treatment technology that has been developed to reduce the impacts of nutrients on receiving waters. Eutrophication effects and algae blooms may be accelerated and stimulated in water bodies as a consequence of nutrient discharges. Every kilogram of phosphorus assimilated by algae ($C_{106}H_{263}O_{110}N_{16}P$) typically generates 111 kilograms of biomass, which is equivalent to 138 kg of COD. If the treatment plant discharges 5 mg/L of phosphorus, the potential COD formation is 690 mg/L, which substantially exceeds the 400 mg/L COD concentration of typical untreated USA municipal sewage. Also a kilogram of nitrogen could potentially produce 16 kilograms of algae, which is equivalent to 20 kilograms of COD (Randall et al., 1992). The typical treatment plant discharges about 18 mg/L Total Nitrogen (TN), which can produce 360 mg/L of COD as algae, and almost equal the COD of raw sewage. The COD thus produced accumulates in the bottom sediments of lakes, reservoirs, and estuaries when the algae die and settles. This increases the sediment oxygen demand and accelerates nutrient recycling and eutrophication.

Research and investigations have shown that algal growth in most North American estuaries is nitrogen limited (Randall et al., 1992 and STAC, 1986), and point source nitrogen controls are necessary to manage and restore water quality. At many wastewater treatment plants (WWTP), nitrification and nitrogen removal are seasonal and depends on the growth rate of the nitrifiers, which is lower in winter than in summer and fall. To obtain complete nitrification all through the year, the aerobic Mean Cell Residence Time (MCRT) of the biomass must be increased during winter to exceed the critical MCRT for nitrifiers. However, increasing the MCRT increases the mixed liquor suspended solids (MLSS) concentration and this may overload the secondary clarifiers. If so, either the activated sludge basin volume must be increased to reduce the MLSS concentration going to the clarifiers, or additional clarifier capacity must be added, unless an innovative approach is used. Recent full-scale and laboratory research has

demonstrated that a viable innovative technology is the integration of fixed film media into the aerobic zone of BNR activated sludge reactors (Sen and Randall, 1995). This technology, labeled the Integrated Fixed Film Activated Sludge (IFAS) system (Sen, 1995), enhances COD removal and denitrification, thus enabling year round nitrification and nitrogen removal in activated sludge systems that are otherwise undersized

Mechanistically-based mathematical models have been developed to account for the major reactions that occur in IFAS systems, to assist engineers or scientists in the development of optimized design and operation of wastewater treatment systems (Sen, 1995). This is desirable because IFAS systems are complicated and difficult to analyze because of the large number of biochemical reactions that occur in the different environmental zones, i.e., anaerobic, anoxic, and aerobic. Such models reduce the amount of time and the budget needed to explore the feasibility of the different process options.

The first version of a model called Multiple Cell Wastewater Treatment Plant (MCWTP) was developed to predict COD removal, nitrification, and denitrification in IFAS systems (Sen, 1995). This model can also be used to compare the performance of IFAS processes with both conventional BNR and traditional activated sludge processes. However, this version was developed on a spreadsheet program and for a University of Cape Town/ Virginia Initiative Project (UCT/VIP) plant configuration. The objectives of this research were to develop a second mathematical model and a computer program that is more useful and practical. The model was expected to be more user friendly, interactive, and simpler handling. To be able to characterize the complex system efficiently, the second version of the IFAS program integrated the empirical equations for substrate uptake by biofilm on supporting media into the International Association on Water Quality (IAWQ) general activated sludge model (Model No. 1). The empirical IFAS equations were modified so that they were compatible with the general model and were able to reasonably predict the behavior of the fixed film microorganisms. These changes should make the IFAS program easier to use for practicing design engineers and scientists, and make it possible to analyze a wide variety of plant configurations.

CHAPTER 2

LITERATURE REVIEW

2.1 NUTRIENT EFFECTS ON AQUATIC ECOSYSTEMS

Two primary sources of nutrients, point and non-point, typically contribute nutrients to receiving waters. An increase of algae and other photosynthetic aquatic life in the water bodies would be a consequence of increased nutrient inputs. These organisms and plants grow autotrophically, thus manufacturing organic matter, then eventually die and settle down to the bottom. Some of the nutrients are then released and recycled back to the water column for new growth. The algal organic remains can also be consumed by bacteria resulting in the depletion of dissolved oxygen (DO) in the lower layers of the water column. Also, ammonia-nitrogen formed by deamination of organic compounds can, for instance, be converted to nitrite and nitrate by nitrifying bacteria with the consumption of DO. The oxygen consumed by this process is typically referred to as Nitrogenous Oxygen Demand (NOD).

2.2 BIOLOGICAL NUTRIENT REMOVAL

Biological nutrient removal (BNR) can be used to reduce the impact of nutrient discharge on the oxygen content of the receiving water. It potentially can provide a more economical alternative of nutrient removal than conventional activated sludge treatment plants using physicochemical or chemical processes. Excess biological phosphorus removal (EBPR) eliminates or reduces chemical addition for phosphorus removal. Also, Randall (1991, 1992) reported that the aeration energy required for BOD stabilization is reduced due to some substrate utilization that occurs in the anaerobic during BPR. Biological nitrogen removal utilizing the wastewater BOD for denitrification can result in an aeration energy reduction of as much as 62.5% of the energy required for nitrification (Randall et al., 1992). Both EBPR and biological nitrogen removal will reduce the amount of sludge that must be processed for disposal, and

nitrogen removal will reduce or eliminate the need to add alkalinity for pH adjustment (Randall et al., 1992).

2.2.1 Biological Nitrogen Removal

Biological Nitrogen Removal consists of two separate sets of reactions to convert ammonia-nitrogen (NH_3N) to gaseous molecular nitrogen (N_2). The first set is the oxidation of the ammonia-nitrogen to nitrite and then to nitrate by *Nitrosomonas* spp. and *Nitrobacter* spp., respectively. Typically, the nitrite concentration found in the bulk solution is less than 0.2 mg/L because the rate of the over all process is limited by *Nitrosomonas* spp and nitrite is converted rapidly to nitrate. The second set of reaction involves the reduction of nitrate to molecular nitrogen. BOD is required for denitrification, which reduces the amount of DO that must be transferred by aeration if the wastewater BOD is used for this purpose. Denitrification also produces alkalinity and can restore up to 50 % of that which was destroyed during the nitrification process, 7.14 mg (as CaCO_3) alkalinity consumed per milligram $\text{NH}_3\text{-N}$ oxidized, 3.57 mg alkalinity produced per mg of nitrate reduced. Many microorganism species are capable of denitrifying nitrate in the anoxic zone, but the most commonly observed are *Pseudomonas* species. Münch et al.(1996) observed that the denitrification rate depends on the DO concentration and is accurately described by the switching functions presented in the IAWQ model. They also found that the denitrification rate decreased gradually with time during aeration periods in sequencing batch reactors (SBRs). It has been reported that some species may be able to nitrify and denitrify under aerobic conditions. Robertson et al.(1988) reported that *Thiosphaera pantotropha* are able to nitrify $\text{NH}_3\text{-N}$ and denitrify $\text{NO}_3\text{-N}$ using acetate as a carbon source under aerobic conditions with 30 % saturation of dissolved oxygen. However, no practical application has ever been demonstrated.

2.2.2 Biological Phosphorus Removal

The Excess Biological Phosphorus Removal (EBPR) method of wastewater treatment was developed after numerous observations of the accumulation of phosphorus in excess of typical activated sludge nutritional requirements were reported in the 1960s. Fuhs et al.(1975) concluded that the principal microorganism group mediating biological phosphorus removal was the *Acinetobacter* genus. These organisms take up short-chain fatty acids (SCFA) into their cells under anaerobic conditions and store them as poly- β -hydroxyalkanoates (PHA). The stored PHA is used for energy and growth under subsequent aerobic conditions, and excess energy is stored in polyphosphate bonds, resulting in phosphorus removal and storage. The cycle is completed when the energy stored in the polyphosphate as bonds is used to polymerize the SCFAs as PHAs under anaerobic conditions. This results in the release of phosphorus to the bulk solution. Therefore, the anaerobic zone of activated sludge is necessary for biological phosphorus removal process.

2.3 BIOFILM PROPERTIES

2.3.1 Competition in Biofilm

Studies of biofilm properties have shown that the heterotrophs, nitrifiers, and denitrifiers coexist in a unit volume of biofilm, increasing with the biofilm depth. Although the microorganism population increases with biofilm depth, the number of reactions taking place in the biofilm does not change. From studies, the dissolved oxygen flux was a key parameter determining the activity of these bacteria. High dissolved oxygen within biofilm increases the activity of nitrifiers and decreases the amount of denitrified nitrate (Masuda et al., 1991; Watanabe et al., 1992). Various models have been developed to characterize the behavior of competition microorganisms in biofilm as mentioned in the attached growth model section.

2.3.2 Simultaneous Nitrification and Denitrification

Masuda et al. (1991) observed the nitrogen loss from a Rotating Biological Contactor (RBC) plant and hypothesized that there were simultaneous nitrification and denitrification processes in the biofilm. This occurred when the oxygen transfer rate decreased enough to create a micro-aerophilic environment. They also demonstrated that the nitrogen removal efficiency correlated with the temperature, oxygen pressure, influent organic to ammonia ratio, and hydraulic loading.

Bang et al. (1995) investigated the denitrification process in the aerobic environment of the biofilm on a RBC. Polyvinyl alcohol (PVA) was used as a carbon source at 25 °C with an influent C/N ratio of 1.2. The net denitrification in the aerobic zone was about 78%. They also observed that the number of denitrifiers and PVA decomposing bacteria accumulating in the surface layer were higher than those in the middle and bottom layers, by up to 1 to 2 orders of magnitude. The nitrification efficiency was directly proportional to the oxygen flux. The denitrification efficiency, on the other hand, was indirectly proportional to the oxygen flux to the biofilm layers. They verified this experiment with a computer simulation. Adequate agreements between both results were obtained (Watanabe et al., 1992).

2.4 INTEGRATED FIXED FILM BIOLOGICAL PROCESS

The integrated fixed film activated sludge (IFAS) process was introduced to enhance carbonaceous and nitrogen removal. This technology combines the main advantages of the attached growth system and the suspended growth system, and minimizes their disadvantages. The attached growth system provides a high volumetric density of microorganisms accumulating by natural attachment as biofilm on the media. Shock load and toxic load problems can be minimized by this process due to the large amount of biomass on the integrated media. This increases the cell retention time without increasing the mixed liquor concentration in the system and overloading the secondary clarifier. These are potential problems with suspended growth biological system. However, suspended growth treatment systems are more flexible than fixed film systems for meeting higher effluent quality standards particularly nutrient removal. IFAS process, however, is a hybrid system which provides both stability and flexibility.

Researchers have reported that temperature has a primary impact on the kinetics of various biochemical conversions in the biological nutrient removal processes that result in substantially lower growth rates of the microorganisms. Large wastewater treatment plants located in the temperate zones of North America were observed and found that they fall in the range of 10-12 °C (Sen, 1995). McClintock et al. (1991,1993) also found that EBPR could not be completed at 5 days MCRT and 10 °C. More adverse effects on the performance of EBPR and nitrogen removal due to low temperature can be due to low MCRT. Mamais and Jenkins (1992) reported that EBPR functioned efficiently at 2.9 days aerobic MCRT for the temperature range investigated (13.5-20 °C). Temperature affected EBPR when the system MCRT was operated below 2.9 days. The growth rate of nitrifiers is dramatically lower at temperatures of 10-12 °C as in winter compared to summer when temperatures exceed 20 °C (Ekama and Marais, 1984). A primary thrust of the Chesapeake Bay Program is to incorporate BNR into the existing conventional activated sludge plants as economically as possible. To accomplish year round nitrification, it is necessary to increase the quantity of biomass maintained in smaller the aerobic zone. This can be done by increasing the Mixed Liquor Suspended Solid (MLSS) concentration, but this will result in higher sludge loadings to the clarifiers, and may exceed their capacity. Alternatively, the aeration basin volume can be increased. Therefore, larger aeration basins or clarifier tanks are required. Due to the constraints economic resources and space, the integrated fixed film activated sludge was an option which was evaluated and shown that can minimize the size needs of the aeration tank or clarifier. This is because a large amount of microorganisms can be maintained on the support media without substantially increasing loading to the clarifier.

2.5 MEDIA TYPES AND APPLICATIONS

Several types of media can be utilized in integrated fixed film activated sludge treatment systems. Ringlace[®], a rope type media, was installed in the wastewater treatment plant of the city of Geiselbullach, Germany to upgrade the wastewater treatment plant to achieve a year round nitrification. This purpose of this upgrading was to maintain nitrification throughout the year and improve sludge settling and it has successfully accomplished. (Lessel, 1991; Lessel, 1993). In the United States, Ringlace[®] IFAS was installed in the treatment plant of the city of Annapolis,

Maryland and operated as both a Modified Ludzack Ettinger (MLE) and a Step Feed BNR process. (Sen and et al., 1993; Sen and et al., 1994a; Sen, 1995; Randall and et al., 1996; and Randall, 1997). The data showed that the integrated Ringlace enhanced nitrogen removal. In both plant configurations, nitrification in the IFAS section was more than three times as much as in the control section without media. Also, the amount of aerobic denitrification was enhanced in the IFAS system when operation was changed from MLE to Step Feed BNR.

Sponge media was tested in the Geiselbullach, Germany by Lessel (1991), but was not selected as a biofilm media because of its anaerobic sludge production. Randall (1997) categorized applications of floating sponge media into three types. For the first type, the media zone was placed after primary sedimentation and operated without recycles before the activated sludge zone. This was used at Moundsville, West Virginia, USA by Golla et al.(1993) with Captor[®] as the sponge media. There was 70-75% nitrogen removal in the Captor[®] zone over a three-year monitoring period. The average ammonia nitrogen effluent was 5.4 mg/L with a standard deviation of 3.6 mg/L, and was below the effluent ammonia nitrogen standard. For the second type, Linpor-N[®], another floating sponge media designed to enhance nitrification, was installed as a last treatment step without subsequent clarification at Wyk, Germany (Morper and Wildmoser, 1989; Schonberger,1989). At least 50% nitrogen removal was achieved even at a temperature as low as 10 °C. For the last concept, the floating media was added directly to the aeration tank of the activated sludge process to enhance nitrification in winter. This system was successfully implemented by Sen and Randall (1994) at the Cox Creek Wastewater treatment plant, Maryland, USA. Also a bench-scale plant with sponge IFAS obtained almost complete nitrification while only 50% was obtained in a control system with no sponges. In Japan, Kondo (1992) conducted an experiment of porous media application in a domestic wastewater treatment plant. Effluent BOD and nitrogen concentrations of less than 20 and 15 mg/L were obtained over water temperature range of 13-31 °C could be achieved as long as the optimum pore size and pad dimensions were chosen. This plant was operated with only 1.5 hours of aeration and a subsequent 0.5 hours of agitation. Tsuno and et al., (1992) investigated the applicability of polyurethane foam cubes in the sewage treatment plant at Kyoto City, Japan. Polyurethane foam cubes of 8 cm³ were added into an aerobic reactor consisting of 6 cells that operated

without recycle. The nitrification rate could reached 0.33 mg N/hr-cube at a temperature of 15 °C.

Jensen (1995) found that freely floating media significantly increased nitrification at a temperature of 12 °C under operating conditions of low aerobic MCRT (3.4 to 1.7 days). Ringlace[®] did not perform nitrification as well as Captor[®] media. However, denitrification in the aerobic reactor was higher with the Ringlace[®] media (Mitta, 1994). Liu (1996) confirmed that nitrification could be maintained in the Captor[®] system at 12 °C at aerobic MCRTs as low as 1.7 days. There was at least 15 mg/L difference in effluent ammonia between the IFAS and the control system at the selected aerobic MCRT. It was shown that the IFAS system could maintain nitrification at an aerobic MCRT and temperature at which the control system would fail.

2.6 MATHEMATICAL MODELING

The complexity of activated sludge systems has expanded from system designed for carbonaceous compounds removal only to include nitrification, denitrification and excess biological phosphorus removal. Many biochemical reactions and compounds are involved in these processes. The computer model plays an important role in the simplification of the complexity of wastewater treatment processes for both full-scale and bench-scale systems. In full-scale operation, the model can be used to optimize the processes or troubleshoot the treatment systems. It can be applied at the bench-scale in research studies for testing results, optimizing processes, or selecting processes. The computer models mainly are divided into two categories according to the type of biological growth, i.e., suspended growth or attached growth.

2.6.1 Suspended Growth Model

A task group was formed by IAWQ (previously known as IAWPRC) in 1982 to facilitate the application of models for designing and operating activated sludge systems and many models have since been developed to describe various complex activated sludge systems. Grady (1986) initially presented a single-sludge system model, which

consisted of seven processes including carbon oxidation, nitrification, and denitrification, which was the outline for a model that was agreed on by the task group. The SSSP was developed to describe a single sludge system with the matrix approach proposed by IAWQ (Bidstrup, 1988). A preliminary model was evaluated by Dold and Marais(1986) and this led to the development of Activated Sludge Model No. 1 (ASM1) development. Modifications were made and adopted as a final version of ASM1 (Henze and et al., 1987). Subsequently, many other models have been developed building upon the ASM1 model. ASM1 does, however, not include the phenomenon of EBPR. Extension of ASM1 to include EBPR was proposed and developed by IAWQ and called ASM2. ASM2 includes both the excess biological phosphorus removal processes and chemical processes for phosphorus precipitation (Henze et al., 1994). Barker and Dold (1997) developed their general model, which includes 36 processes, among them, the EBPR component. The anoxic growth of poly-P microorganisms also has been incorporated in the model. Anoxic and anaerobic hydrolysis of slowly enmeshed biodegradable COD processes are incorporated into this model as well as the fermentation of readily biodegradable organic materials. The general model is based on the original ASM1 and the Wentzel Model (1989). Henze (1999) proposed ASM No. 2d that includes phosphorus removal by of poly-P microorganisms during denitrification. Gujer (1999) presented an ASM No. 3, which is a modification of ASM No. 1. A substrate storage process was introduced into this version as a new process and it is assumed that there is no COD flow from nitrifier decay. The modeling of heterotroph and autotroph decay processes were clearly separated in ASM3.

2.6.2 Attached Growth Model

Two factors have been raised when dealing with the modeling of fixed growth systems. First, the effects of diffusive resistance on substrate removal need to be incorporated into the model to accurately predict the performance of the system. Second, the heterogeneous nature and poor characterization of these conditions within the biofilm result in the difficulty of the biofilm modeling difficulties. Early mathematical models focused on substrate utilization in the biofilm. Substrate utilization was described as a

process of molecular diffusion and simultaneous biochemical reactions (Williamson and McCarty, 1976). Numerous steady state models have been developed, which vary from a single microorganism species to multiple-species and from a single substrate to multiple-substrates. Subsequently, a steady state biofilm model of a single substrate coupled with substrate flux into the biofilm has been developed by assuming neither net growth nor decay over time. A minimum substrate concentration in the bulk liquid must be maintained to achieve a steady state condition. The substrate flux and thickness are assumed to be zero when the substrate concentration is below this criteria. The Monod equations are used to describe biochemical reactions and Fick's law is used to describe diffusion equations, which combined together are the basic mechanisms in biofilms. Idealized biofilms have been described as having uniform cell density and uniform thickness. All nutrients required for growth are assumed to be in excess concentrations (Rittmann and McCarty, 1980a). The model was evaluated and the results showed that the model successfully predicted the substrate utilization rate and biofilm thickness.(Rittmann and McCarty, 1980b). Mass transport by diffusion is assumed to be one dimensional because the biofilms are typically very thin. Due to the possibility of extensive computational efforts, steady state mechanistic models with multiple-species with competition of substrate and space were developed. A multi-species model for COD removal and nitrification was proposed by Wanner and Gujer (1984), but this model was not verified with experimental data. Wanner and Gujer (1984) showed that given the competition for oxygen, the heterotrophs may be washed out at low substrate concentrations. In contrast, at high substrate concentrations, they may overgrow the slow-growing autotrophic organisms. The heterotrophs have a tendency to reside at the surface and autotrophs may accumulate more in the deeper layers. The biomass flux was used to simulate biomass growth. However, this model is not a true steady state model. Subsequently, Rittmann and Manem (1992) presented a steady state model that described multi-species behavior with multiple active species, inert biomass, substrate utilization, diffusion within the biomass, external mass transport, and the detachment phenomenon. This model was verified experimentally and its predictions agreed with the observed data in terms of space competition. Higher acetate concentrations resulted in NH_4^+N flux decrease because autotrophs were forced deeper into the biofilm by heterotrophs. Kissel

et al.(1984) proposed a dynamic model, allowing the volume of biomass to increase with time from V to $V+\Delta V$ at time t to $t+\Delta t$ when biomass increases due to positive net growth.

2.7 NUMERICAL SIMULATION APPROACH

The equations applied in the activated sludge model form a system of non-linear equations. Many numerical approaches are available from the literature to solve these equations. However, the approach that can be used to solve most conditions is preferred. The global convergence method was used since it is reported in the literature that it guarantees the convergence of these equations with any starting point (Press et al., 1992). Although more computational needs are required, the Modified Newton-Raphson method, combines the rapid local convergence of Newton's method and the global convergent strategy, it is a powerful method because it guarantees some degree of progression toward the solution at each iteration.

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Computer Program Development for the Design of IFAS Wastewater Treatment Processes

By T. Sriwiriyarat¹ and C.W. Randall²

Abstract : The Integrated Fixed Film Activated Sludge Model (IFAS) is a computer-based mechanistic model package that allows steady-state simulation of IFAS wastewater treatment processes. IFAS wastewater treatment systems are activated sludge biological nutrient removal processes that have been enhanced by the addition of biofilm support media into the aerobic zone of the system. This process is used to obtain year round nitrification in activated sludge systems that otherwise could not support it. The IFAS model was developed based on the IAWQ general model for activated sludge and empirical equations for COD uptake and nitrification on biofilm developed at Virginia Tech. The current version of the IFAS Model supports only sponge media; however, the model could be modified for other media if the appropriate equations and parameters are known. Data obtained from an IFAS sponge pilot scale plant treating a weak municipal wastewater supplemented by sodium acetate and phosphates were used to calibrate the model. The calibrated model was then verified with data obtained from experiments using other influent wastewater concentrations and different operating conditions. The model generated ammonia and soluble COD profiles that were insignificantly difference statistically from the experimental data. Enhanced biological phosphorus removal also has been incorporated into the model, but has not yet been verified. Verification studies are being planned and will be performed in the future. The IFAS Model satisfactorily predicts carbonaceous removal and nitrification, and has the potential to be a useful tool for scientists and engineers seeking to design and optimize either IFAS or conventional BNR activated sludge systems. It also could be used to troubleshoot full-scale treatment plants.

¹Graduate Student, Civil and Environmental Engineering Department,
418 NEB, Virginia Tech, Blacksburg, VA 24061.

²The C.P. Lunsford Professor, Civil and Environmental Engineering Department,
418 NEB, Virginia Tech, Blacksburg, VA 24061.

INTRODUCTION

The growth rate of nitrifiers in the winter, i.e., at low temperatures, is substantially lower than in the summer or fall, i.e., at higher temperatures. To obtain year round complete nitrification with conventional activated sludge systems in temperate zones, the amount of biomass maintained in the aerobic zones must be increased in the winter relative to what is required in the summer and fall. This is usually accomplished by increasing the solids retention time (SRT) of the mixed liquor suspended solids (MLSS) in the activated sludge reactors. This increases the MLSS concentration, which often overloads the secondary clarifiers. Then it is necessary to either increase the clarifier capacity so that more solids can be processed, or to increase the total reactor volume so that the MLSS concentration to the clarifiers is reduced. However, an alternative approach has been developed in recent years, the Integrated Fixed Film Activated Sludge (IFAS) process (Lessel, 1993, Sen and Randall, 1994, Randall and Sen, 1996). This technology integrates biofilm support media into activated sludge aerobic reactors to increase the biomass concentration and enhance nitrification. Experience has shown that it also enhances denitrification in the aerobic zone. The coexistence of suspended growth and attached growth enhances the amount of biomass in the reactor without contributing a substantial amount to the amount of sludge flowing forward to the secondary clarifier because the additional biomass remains attached to the support media, which is retained in the aerobic reactor.

Extensive pilot-scale studies of IFAS processes have been conducted by Virginia Tech researchers to evaluate different types of media, elucidate the fundamentals of the IFAS mechanisms, and determine the impacts of IFAS on biological nutrients removal systems (Mitta, 1994; Jensen, 1995, Sen, 1995, Liu, 1996). These studies evaluated both rope-like Ringlace[®] media and Captor[®] sponge media. Additionally, the Ringlace media was evaluated and utilized for the upgrade of the 37,850 m³/d Annapolis, Maryland Water Reclamation Facility, and the Captor[®] media was evaluated at the 56,775 m³/d Cox Creek Facility near Baltimore, Maryland (Sen, et al., 1993; Randall, 1996). All of these investigations showed that IFAS could be used to enhance both nitrification and denitrification in activated sludge systems without significantly increasing the solids loading to the secondary clarifiers.

Modeling tools that assist engineers or scientist to optimize their designs or to operate wastewater treatment plants (WWTP) are needed to predict the fate of components in the activated sludge system, as well as treated effluent. The models allow exploration through a simulation of alternative wastewater treatment plant configurations, inputs, and operational strategies. Once the model is calibrated to a particular wastewater, the model can be applied to screen the potential process designs and to eliminate the inefficient and uneconomic designs. The objective of this project was to develop, a user-friendly computer-based model that could be used to evaluate IFAS systems and compare them with conventional BNR and fully aerobic activated sludge systems. The goals were to develop a computer-based mechanistic and empirical IFAS model that would forecast the simultaneous COD removal, nitrification, and denitrification processes occurring in a properly functioning IFAS system, and enable comparison with non-IFAS activated sludge system.

MODEL DEVELOPMENT

The model developed was designed to provide the same benefits as the mechanistic general model for biological nutrient removal activated sludge systems, initially developed at the University of Cape Town, adapted by the International Association on Water Quality (IAWQ) as Activated Sludge Model No. 1 (ASM1), and subsequently modified by Barker and Dold (1997). The rate expressions used were a combination of those employed by Barker and Dold (1997) for their adaptation of the general model, and empirical IFAS equations developed by Sen (1995) and co-workers. The ASM1 model is a mechanistic model for carbonaceous organic removal, nitrification, and denitrification (Henze, 1987), which was subsequently modified to ASM2 by incorporating the excess biological phosphorus removal model developed by Wentzel, et al. (1989) at the University of Cape Town. The details of the general model will not be discussed in this paper, but the reader is referred to the literature cited above.

The amount of substrate uptake by biofilm on integrated media was established by the empirical equations developed by Sen and co-workers. The mass balance equations were then established with the appropriate rate expressions. The IFAS program solves these mass balance

equations simultaneously as a system of nonlinear equations using the Modified Newton techniques. Various assumptions were made to simplify the complex activated sludge system model, which are listed as follows:

- No diffusion of nitrate from the bulk solution into the biofilm. Therefore, the concentration of nitrate in the mixed liquor may be slightly higher than the true concentration in the aerobic zone because nitrate is not denitrified by the biofilm.
- No excess biological phosphorus removal will be accomplished by the biomass growth on the supporting media. Only normal phosphorus uptake for biofilm growth is incorporated into the equations.
- Sufficient alkalinity is assumed to be provided to the system in the simulation of the model. Therefore, the alkalinity component is not included in the mechanistic equations.
- No nitrite accumulation occurs in the system. All nitrite nitrogen is assumed to be rapidly converted to nitrate by *Nitrobactor* spp., except when DO is limiting.
- No biomass in the incoming influent wastewater. Therefore, no influent biomass effects on the performance of the system.
- pH is constant and near neutrality to ensure optimum biological activity.

Nitrification Rates for Biofilm on Sponge Cuboids

The maximum ammonium-nitrogen (NH_4^+ -N) uptake rate of the sponge biofilm ($q_{m,\text{Nitr},\text{sp}}$) was determined at low soluble biodegradable COD (SCOD_{bio}) levels to minimize nitrogen uptake by the heterotrophs (Sen, 1995; Sen et al., 1995). Ammonium-N levels, greater than 10 mg N/L, and dissolved oxygen (DO) above 7 mg/L were provided to achieve zero order nitrification rates with respect to ammonium-N and DO. It was established by Sen (1995) that the relationship between SCOD_{bio} and NH_4^+ -N was such that the NH_4^+ -N uptake rate was inhibited if the concentration of SCOD_{bio} was above 10 mg/L, as shown in Equation 1. A possible explanation is space competition pressure as defined by the multi-species biofilm theory (Rittmann and Manem, 1992, and Wanner and Gujer, 1985). The higher specific growth rate heterotrophs utilize SCOD_{bio}

and grow at the surface layer of the biofilm. The slow-growing nitrifiers are forced deeper into the biofilm layer and experience greater mass transport resistance, particularly an inadequate supply of DO.

$$q_{m, \text{Nitr}, \text{sp}} = \frac{A_{\text{NH}_4\text{-N}} K_{\text{SN}}}{K_{\text{SN}} + \text{SCOD}_{\text{bio}} - 10} \quad (1)$$

where $A_{\text{NH}_4\text{-N}} = 4.4 \text{ mg NH}_4^+\text{-N per sponge cuboid per day at } 12 \text{ }^\circ\text{C}$, and
 $K_{\text{SN}} = \text{Half saturation coefficient} = 9.4 \text{ mg/L SCOD}_{\text{bio}} \text{ at } 12 \text{ }^\circ\text{C}$

When the SCOD_{bio} is less than 10 mg/L, the nitrification rate is controlled by the $\text{NH}_4^+\text{-N}$ concentration in the mixed liquor. It is represented by Equation 2.

$$q_{m, \text{Nitr}, \text{sp}} = 1.055 \text{NH}_4^+ - \text{N} \quad (2)$$

COD Uptake Rate for Biofilm on Sponge Cuboids

Batch tests were carried out with sponge media and mixed liquor to determine a maximum COD uptake rate for sponge biofilm ($q_{m, \text{COD}, \text{sp}}$). The determination by Sen (1995) from the experimental data showed that the rate was related to the SCOD_{bio} in the mixed liquor as follows:

$$q_{m, \text{COD}, \text{sp}} = \frac{A_{\text{SCOD}_{\text{bio}}} \text{SCOD}_{\text{bio}}}{K_{\text{SM}} + \text{SCOD}_{\text{bio}}} + C \quad (3)$$

When $C = 0 \text{ mg SCOD/sponge/day}$, which was the best fit,

$A_{\text{SCOD}_{\text{bio}}} = 51.5 \text{ mg SCOD per sponge per day at } 12 \text{ }^\circ\text{C}$

$K_{\text{SM}} = \text{Half saturation coefficient} = 19.3 \text{ mg/L SCOD}_{\text{bio}} \text{ at } 12 \text{ }^\circ\text{C}$

The overall rate equation for nitrification was adapted from Barker and Dold, 1997, and the number relates back to their numbering system for rate equations. It combines nitrification in the mixed liquor and on the biofilm, and can be expressed as follows:

$$r_{16} = \mu_A \frac{NH_4-N}{K_{NH,SS} + NH_4-N} \left| \frac{DO}{K_{O,AUT,SS} + DO} \right| Z_A + \quad (4)$$

$$Y_{Aq_m, Nitr, sp} \frac{NH_4-N}{K_{NH, BF} + NH_4-N} \left| \frac{DO}{K_{O, AUT, BF} + DO} \right| S_{ponge}$$

The overall aerobic growth rate of heterotrophs with acetate as a carbon source and ammonium nitrogen as a nitrogen source is:

$$r_1 = \mu_H \frac{S_{BSA}}{K_{SH,SS} + S_{BSA}} \left| \frac{DO}{K_{O, HET, SS} + DO} \right| \frac{NH_4-N}{K_{NA,SS} + NH_4-N} \left| \frac{PO_4-P}{K_{GRO,SS} + PO_4-P} \right| Z_H +$$

$$Y_{Hq_m, COD, sp} \frac{S_{BSA}}{K_{SH, BF} + S_{BSA}} \left| \frac{DO}{K_{O, HET, BF} + DO} \right| S_{ponge} \quad (5)$$

The above growth rate is also applied for process rates using S_{BSC} as the substrate and NO_3^- as the electron acceptor (Barker and Dold, 1997).

At steady state, the biofilm detachment rate must be equal to the biofilm growth rate. Therefore, excess microorganisms from biofilm growth are detached to the mixed liquor. The degree of detachment depends on the turbulence in the mixed liquor. First order decay rates are used for both the suspended growth and the attached biomass.

PROGRAM DEVELOPMENT AND OPERATION

IFAS was written for IBM-PC compatible microcomputers in Borland C++ Builder suite. Borland C++ Builder package was chosen because it provides the visual productivity of Delphi while it permits work in a C++ environment. The system was designed for utilization with a 32

bit Windows based program. IFAS program was written and compiled on Windows 98 and is compatible with Windows 95/98 or Windows NT. Many functions were added to the program to make it user-friendly and interactive to users. IFAS allows the user to enter the specific operating and design data, in addition to the wastewater characteristics. The system MCRT is used instead of the aerobic MCRT because the system MCRT is a more general design parameter than aerobic MCRT. The user is able to select either an IFAS or a Conventional Activated Sludge system.

The CAS system of this program is a general activated sludge plant configuration without media integrated in the aerobic zone, and may be either a BNR process or a conventional fully aerobic process. Default kinetic and stoichiometric parameters are provided as well as switching function coefficients to allow simulations for investigative or educational purposes. All parameters must be modified for the specific wastewater characteristics and the mode of operation selected. The functions related to the IFAS process will be disabled if a conventional activated sludge system is selected. The process configuration can be defined by recycle flows, the mixed liquor DO concentration, and the number of reactors. The program allows simulation of tanks in series up to 12 activated sludge reactors in the treatment train. The volume of each reactor must be entered when the process configuration is defined. IFAS then utilizes all information to set up mass balances equations and simulates the fate of all defined components in the wastewater treatment plant. The sludge wastage rate is computed automatically based on the system MCRT. All particulate biomass and inert organic matters entering the secondary clarifiers are assumed to be returned to the process in recycle streams. It is assumed that there is no accumulation of solids with time and that no reactions occur in the clarifier. It also is assumed that there are no particles discharged in the effluent. After the wastage rate is known, the steady state equations are solved simultaneously by the Modified Newton technique using the globally convergent method.

The global technique converges a solution from almost any initial guess or starting point. The system MCRT is employed to compute the initial conditions based on a single complete mixed reactor without sponge media installed. However, the IFAS program will request that the MCRT be reentered with a value different than the MCRT for wastage flow calculation, if the solution does not converge. The results can be presented in several ways after the solution has

converged, i.e., as line or bar charts indicating the substrate profile, as a complete printable detailed report, and as a table of all substrate concentrations in each reactor. All results can be exported to different formats such as Excel and HTML to make them easier to manipulate. In other words, the data can be manipulated by different programs even if the computer does not have the IFAS program installed.

MODEL CALIBRATION AND EVALUATION

A large number of kinetic and stoichiometric parameters taken from the literature and experimental data were used to calibrate the IFAS model. Pilot plant experiments treating a weak municipal wastewater supplemented by sodium acetate and phosphates were conducted using pilot-scale systems located on the Blacksburg campus of Virginia Tech (Sen, 1995). Wastewater was pumped from an adjacent sewer, and then stored for 24 hours inside the small building containing the pilot systems. The 24 hour storage period was used to bring the wastewater to temperature equilibrium, accomplish removal of any DO and nitrates contained in the sewage, and to allow some fermentation of the organic compounds. Because the wastewater was weak in biodegradable fermentable organics, acetate was added until it was approximately 66 percent of the influent COD. This percentage of acetate was used to describe the influent wastewater characteristics in the model predictions.

The two pilot plant systems simulated the UCT/VIP process configuration. Sponges were added to the aerobic zone of one of the systems for IFAS evaluation, and the other was used as a BNR control. Both treatment trains consisted of two anaerobic tanks, two anoxic tanks, and three aerobic tanks in series. Experiments were carried out at different aerobic MCRTs and operating conditions. Data from these experiments were utilized to establish the yield coefficient (Y_H), the decay rate (b_H), the maximum substrate utilization rates by the MLSS and the biofilm (q_{mH}), and the half saturation constant (K_{SH}) for the heterotrophs. The maximum growth rate (μ_{max}) and Y_H determined from these experiments were converted to COD units to consistency with COD mass balance determinations and in conformance with the IAWQ models.

The influent wastewater in these experiments was fully characterized into COD, TKN, and TP fractions, i.e., biodegradable, nonbiodegradable, ammonia, nitrate, etc., for input into the program. Other kinetic, stoichiometric and switching function parameters for the three types of bacteria in BNR systems were taken from the general model (Barker and Dold, 1997). Some parameters were adjusted to obtain the best fit of the model to the experimental data. A single set of kinetic and stoichiometric parameters produced accurate predictions for both systems and five different aerobic MCRTs per system. The calibrated values of the stoichiometric, kinetic, and switching function parameters are listed in Table 1 to 3. The parameters associated with excess phosphorus removal are not presented in this paper.

Table 1. Stoichiometric parameters for the IFAS model

Symbol	Characterization	Value	Units
<i>Non-polyP Heterotrophs</i>			
Yhaer	Aerobic yield	0.582	mg cell COD yield (mg COD utilized) ⁻¹
Yhanx	Anoxic yield	0.440	mg cell COD yield (mg COD utilized) ⁻¹
Yhana	Anaerobic yield	0.440	mg cell COD yield (mg COD utilized) ⁻¹
Yac	Fermentation Sbsa yield	0.700	mg Sbsa COD (mg Sbsc COD) ⁻¹
Eanox	Anoxic hydrolysis efficiency factor	0.700	mg Sbsc COD (mg Senm COD) ⁻¹
Eana	Anaerobic hydrolysis efficiency factor	0.500	mg Sbsc COD (mg Senm COD) ⁻¹
Fnzh	Nitrogen content of active mass	0.085	mg N (mg COD active organisms) ⁻¹
Fnzezh	Nitrogen content of endogenous mass	0.085	mg N (mg COD endogenous residue) ⁻¹
Fpzh	Phosphorus content of active mass	0.021	mg P (mg COD active organisms) ⁻¹
Fpzezh	Phosphorus content of endogenous mass	0.021	mg P (mg COD endogenous residue) ⁻¹
Feph	Fraction of active mass remaining as endogenous residue	0.080	mg COD endogenous mass (mg COD active mass) ⁻¹
Fcvh	COD:VSS ratio	1.420	mg COD (mg VSS) ⁻¹
<i>Autotrophs</i>			
Ya	Yield	0.142	mg cell COD yield (mg N utilized) ⁻¹
Fnza	Nitrogen content of active mass	0.085	mg N (mg COD active organisms) ⁻¹
Fnzea	Nitrogen content of endogenous mass	0.085	mg N (mg COD endogenous residue) ⁻¹
Fpza	Phosphorus content of active mass	0.021	mg P (mg COD active organisms) ⁻¹
Fpzea	Phosphorus content of endogenous mass	0.021	mg P (mg COD endogenous residue) ⁻¹
Fepa	Fraction of active mass remaining as endogenous residue	0.080	mg COD endogenous mass (mg COD active mass) ⁻¹
Fcva	COD:VSS ratio	1.420	mg COD (mg VSS) ⁻¹

Table 2 Kinetic parameters for the IFAS model at 20 °C

Symbol	Characterization	Value	Units	θ_T
<i>Non-polyP Heterotrophs</i>				
μ_H	Maximum specific growth rate	6.423	d^{-1}	1.030
$K_{SH,SS}$	Half saturation coefficient for suspended solids growth	60.805	$mg\ COD\ L^{-1}$	1.030
$K_{SH,BF}$	Half saturation coefficient for biofilm growth	60.085	$mg\ COD\ L^{-1}$	1.030
B_H	Decay rate	0.064	d^{-1}	1.055
$\eta_{S,ANX}$	Anoxic solubilization factor	1.000		
$\eta_{S,ANA}$	Anaerobic solubilization factor	0.500		
η_{GRO}	Anoxic growth factor	0.496		
K_H	Maximum specific hydrolysis rate	4.450	d^{-1}	1.050
K_X	Half saturation coefficient for hydrolysis	0.150	$mg\ COD\ (mg\ COD)^{-1}$	1.000
K_C	Maximum specific fermentation growth rate	4.000	d^{-1}	1.029
$K_{S,ANA}$	Fermentation half saturation growth rate	5.000	$mg\ COD\ L^{-1}$	1.000
K_R	Ammonification rate	0.080	$L\ (mg\ COD.d)^{-1}$	1.029
$A_{SCODbio}$	Maximum utilization rate on sponge	65.239	$mg\ SCOD_{bio}(sponge.d)^{-1}$	1.030
K_{SM}	Half saturation coefficient for COD utilization	24.423	$mg\ SCOD\ L^{-1}$	1.030
<i>Autotrophs</i>				
μ_A	Maximum specific growth rate	0.545	d^{-1}	1.030
$K_{NH,SS}$	Half saturation coefficient for mixed liquor growth	1.495	$mg\ N\ L^{-1}$	1.060
$K_{NH,BF}$	Half saturation coefficient for biofilm growth	1.495	$mg\ N\ L^{-1}$	1.060
B_A	Decay rate	0.035	d^{-1}	1.060
A_{NH4-N}	Maximum nitrification rate on sponge	5.574	$mg\ NH_4N\ (sponge.d)^{-1}$	1.030
K_{SN}	Half saturation coefficient on sponge	14.982	$mg\ SCOD\ L^{-1}$	1.060

Table 3 Switching function parameters for the IFAS model

Symbol	Characterization	Value	Units
<i>Mixed Liquor Section</i>			
$K_{O,HET,SS}$	DO limit for heterotrophs in mixed liquor	0.700 mg O ₂ L ⁻¹	
$K_{O,AUT,SS}$	DO limit for autotrophs in mixed liquor	0.500 mg O ₂ L ⁻¹	
$K_{NA,SS}$	Ammonia limit in mixed liquor	0.005 mg N L ⁻¹	
$K_{NO,SS}$	Nitrate limit in mixed liquor	0.100 mg N L ⁻¹	
$K_{GRO,SS}$	Phosphate limit in mixed liquor	0.005 mg P L ⁻¹	
<i>Biofilm Section</i>			
$K_{O,HET,BF}$	DO limit for heterotrophs in biofilm	2.000 mg O ₂ L ⁻¹	
$K_{O,AUT,BF}$	DO limit for autotrophs in biofilm	3.000 mg O ₂ L ⁻¹	
$K_{NA,BF}$	Ammonia limit in biofilm	2.000 mg N L ⁻¹	

RESULTS AND DISCUSSION

Comparison of the experimentally determined substrate profiles with predicted values from IFAS showed that the IFAS model predictions produced accurate profiles for all systems and different operating conditions. Most estimated soluble COD and ammonium-N profiles fell within the range of values of the experimental data as shown in Figure 1, 2, 5, 6, 7, and 8. That is, the IFAS predictions were statistically insignificantly different from the experimental data. However, as expected, the predicted nitrate profiles were higher in the aerobic zones of the IFAS sponge system because it was assumed that no nitrate in bulk solution diffused to the biofilm. In fact, it is known that nitrates do diffuse into the biofilm and this results in substantial denitrification.

Figure 1 presents the soluble COD profiles in the IFAS system at 3.1 and 1.0 day aerobic MCRTs as were determined by experiment, and compares them with predictions by Sen's spreadsheet IFAS model, and the modified IFAS model of this research. A much better prediction of the soluble COD profile was obtained with the modified IFAS model compared to

Sen's spreadsheet model by incorporating a hydrolysis term for the particulate COD. The SCOD profiles in the control system for the same operating conditions are shown in Figure 2.

Figures 3 and 4 show the MLVSS profiles for both systems. It was noted that the predictions by both models for the last anoxic and first two aerobic reactors (Figure 4) did not quite agree with the experimental data. It is likely that there were analytical errors during the experiments that resulted in the observed differences.

In Figures 5, 6, 7, and 8, the predicted ammonium-nitrogen from IFAS program compared well with the experimental data. This was an improvement over the spreadsheet version, which included the biodegradable organic nitrogen in the profiles. In the IFAS predictions, all slowly biodegradable substrate and biodegradable organic nitrogen were accounted for by including them in the $SCOD_{bio}$ and NH_4^+-N profiles through hydrolysis processes. However, both versions can predict satisfactorily over the aerobic zones for both the SCOD and ammonium profiles because the fractions of particulate COD and organic nitrogen were quite low in the aerobic reactors. Further investigation of substrate profiles in the biofilm is needed to model the amount of nitrate denitrified in the biofilm.

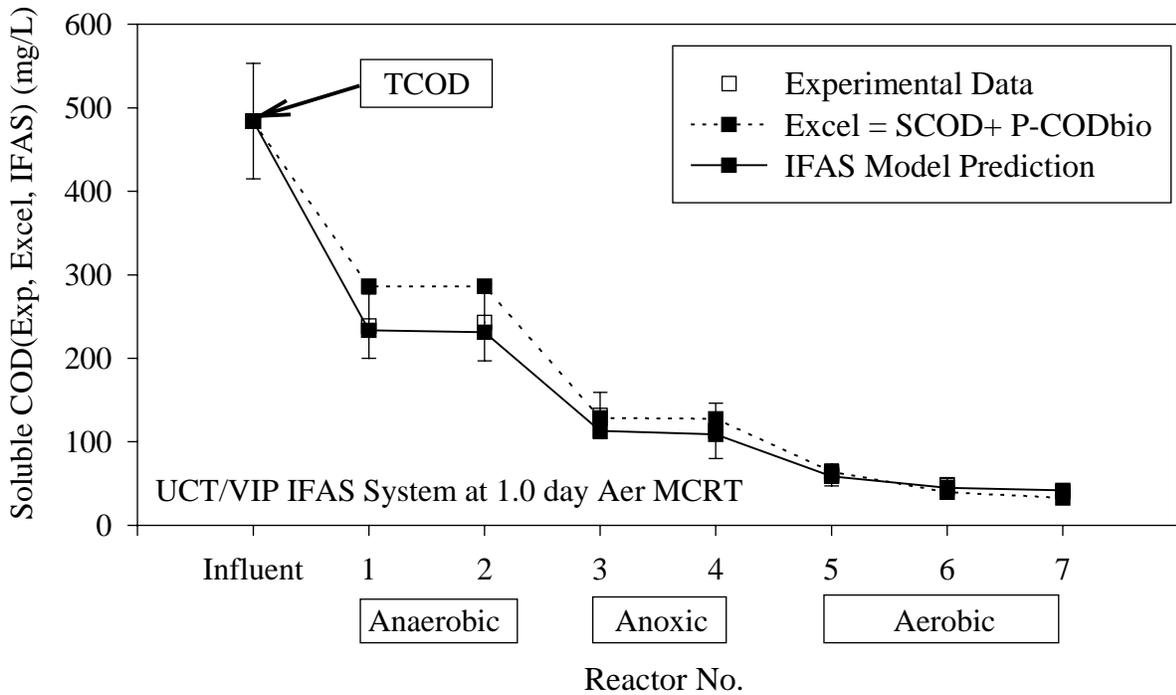
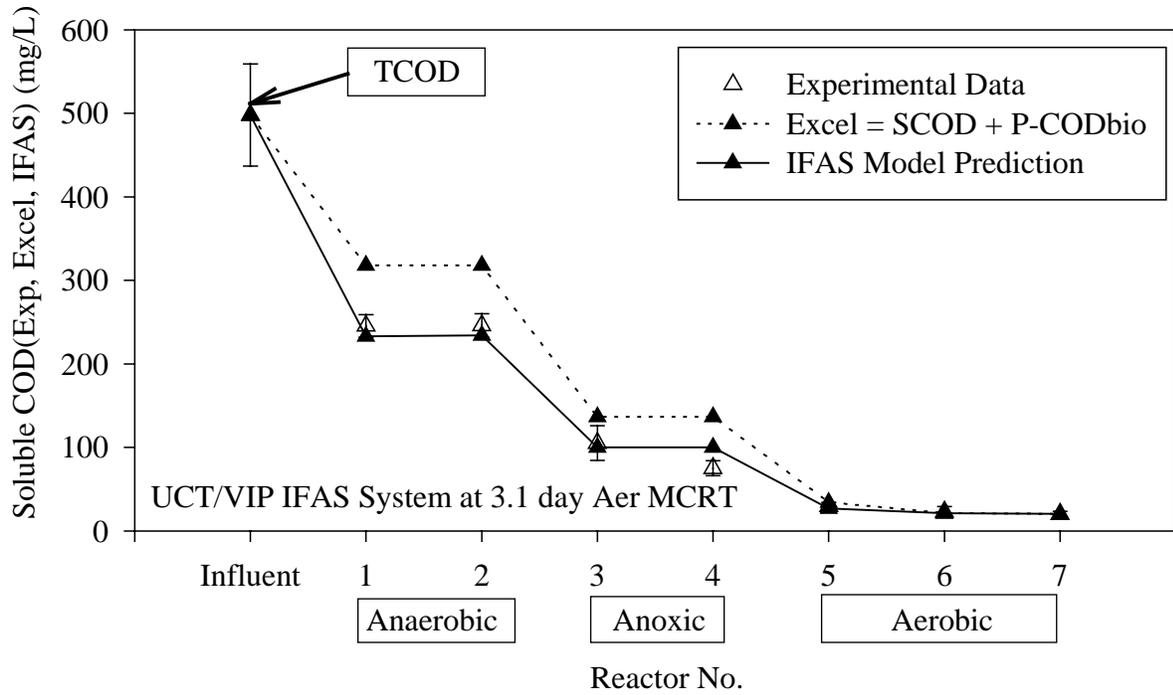


Figure 1. Experimental Data and Model Predictions for SCOD, IFAS-Sponge System at 12 °C

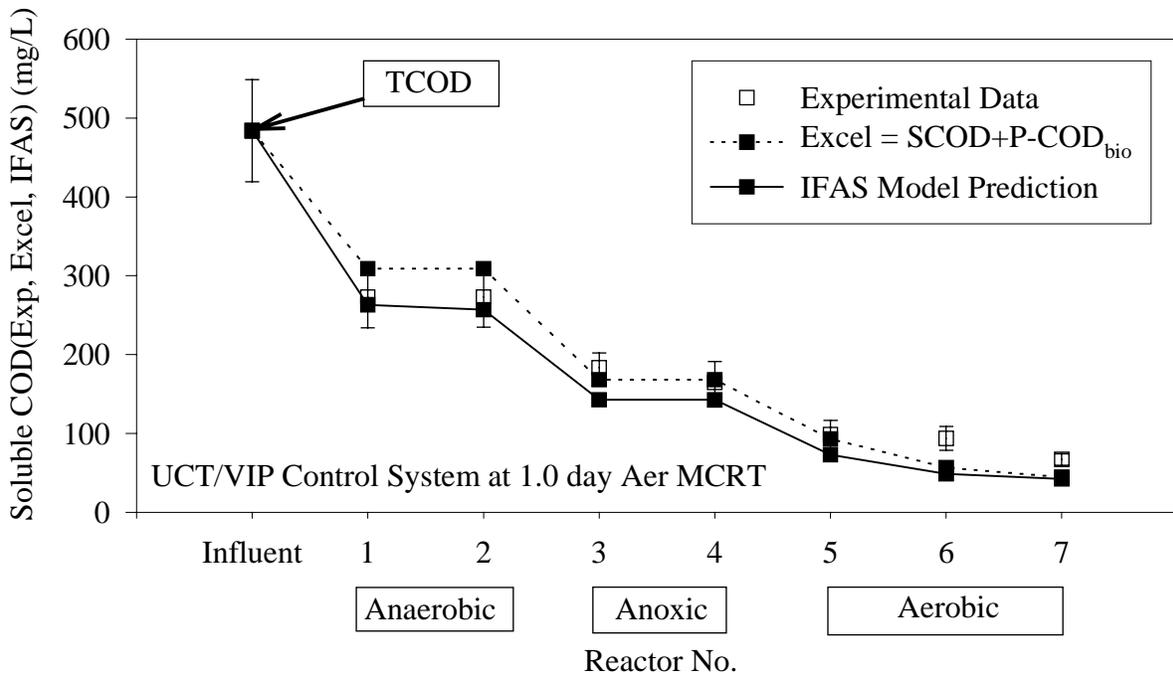
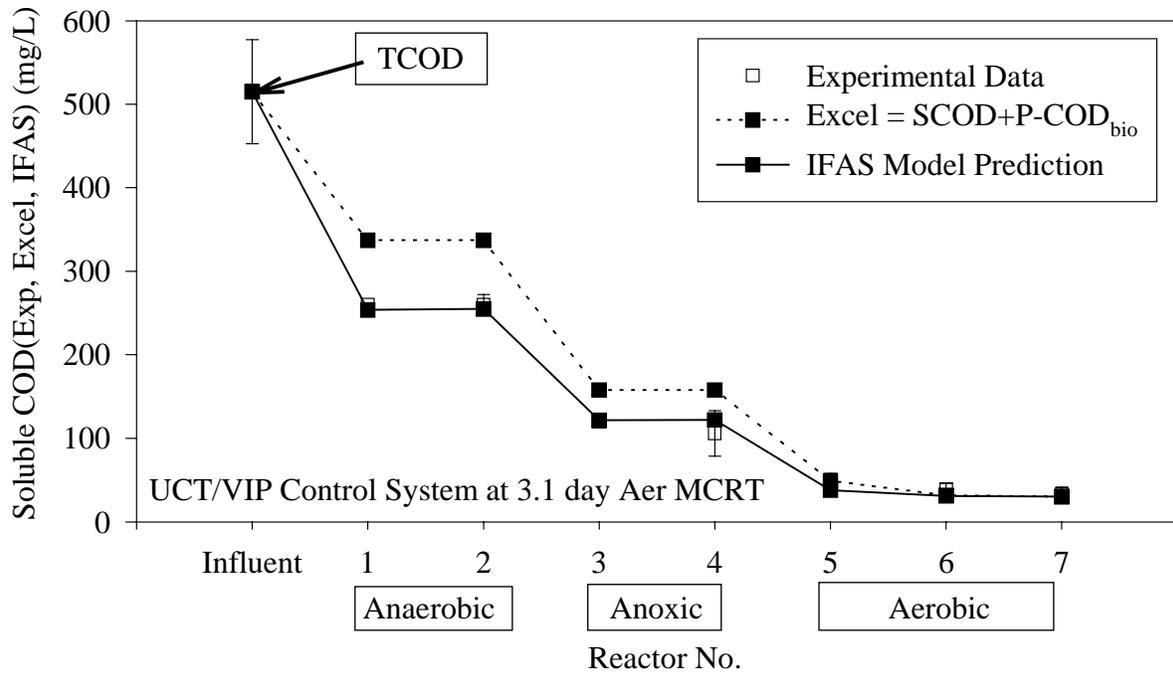


Figure 2. Experimental Data and Model Predictions for SCOD, Control System at 12 °C

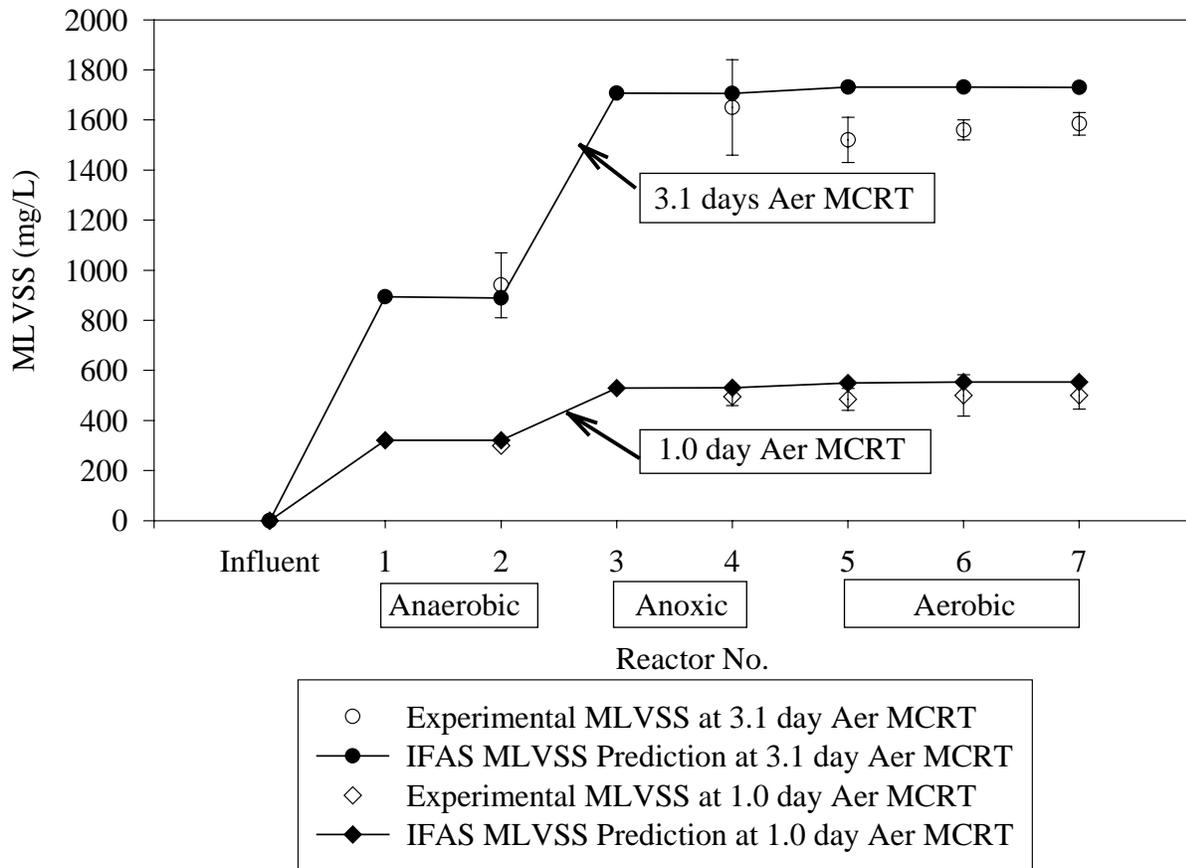


Figure 3. MLVSS Profiles of IFAS System with UCT/VIP Configuration at 12 °C

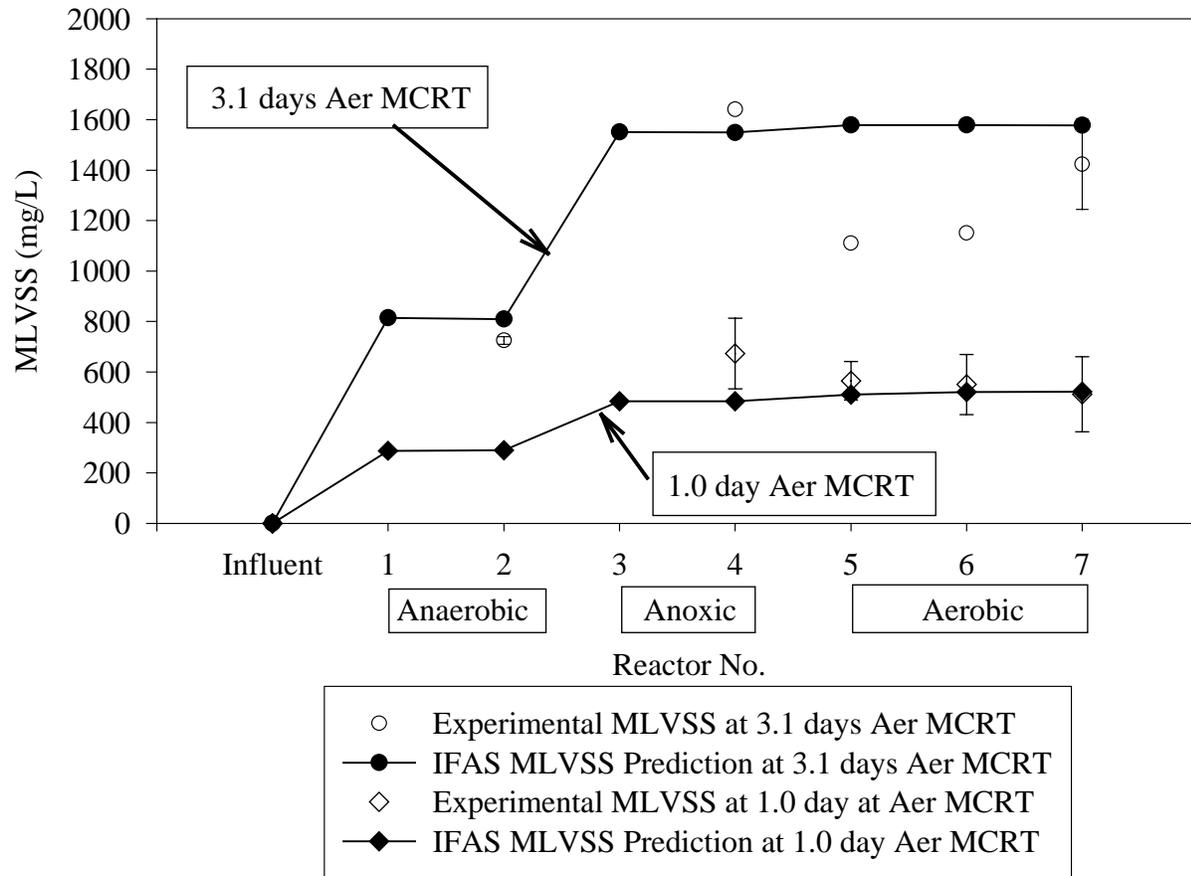


Figure 4. MLVSS Profiles of Control System with UCT/VIP Configuration at 12 °C

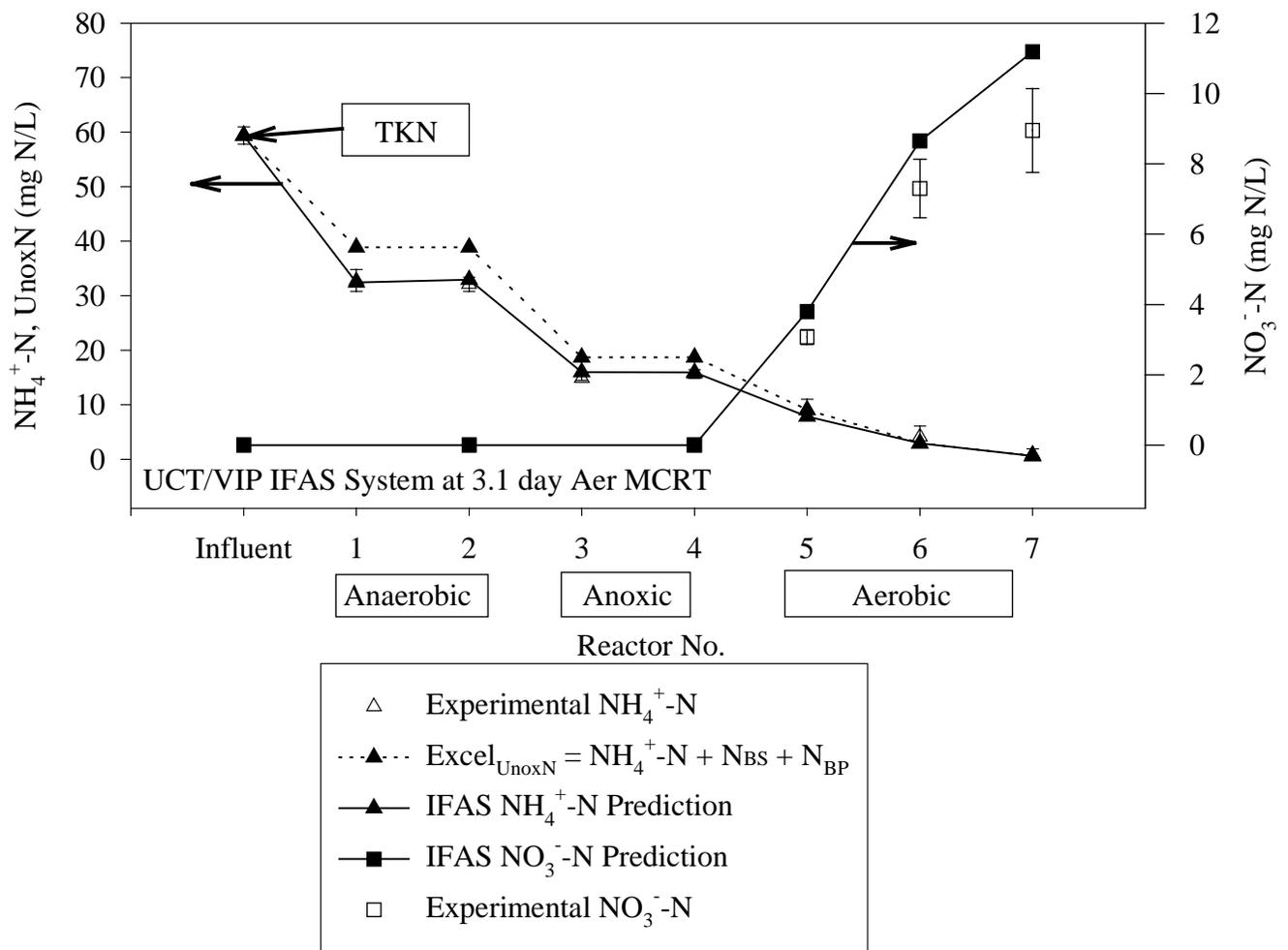


Figure 5. Experimental Data and Model Prediction for $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, IFAS-Sponge System at 12°C

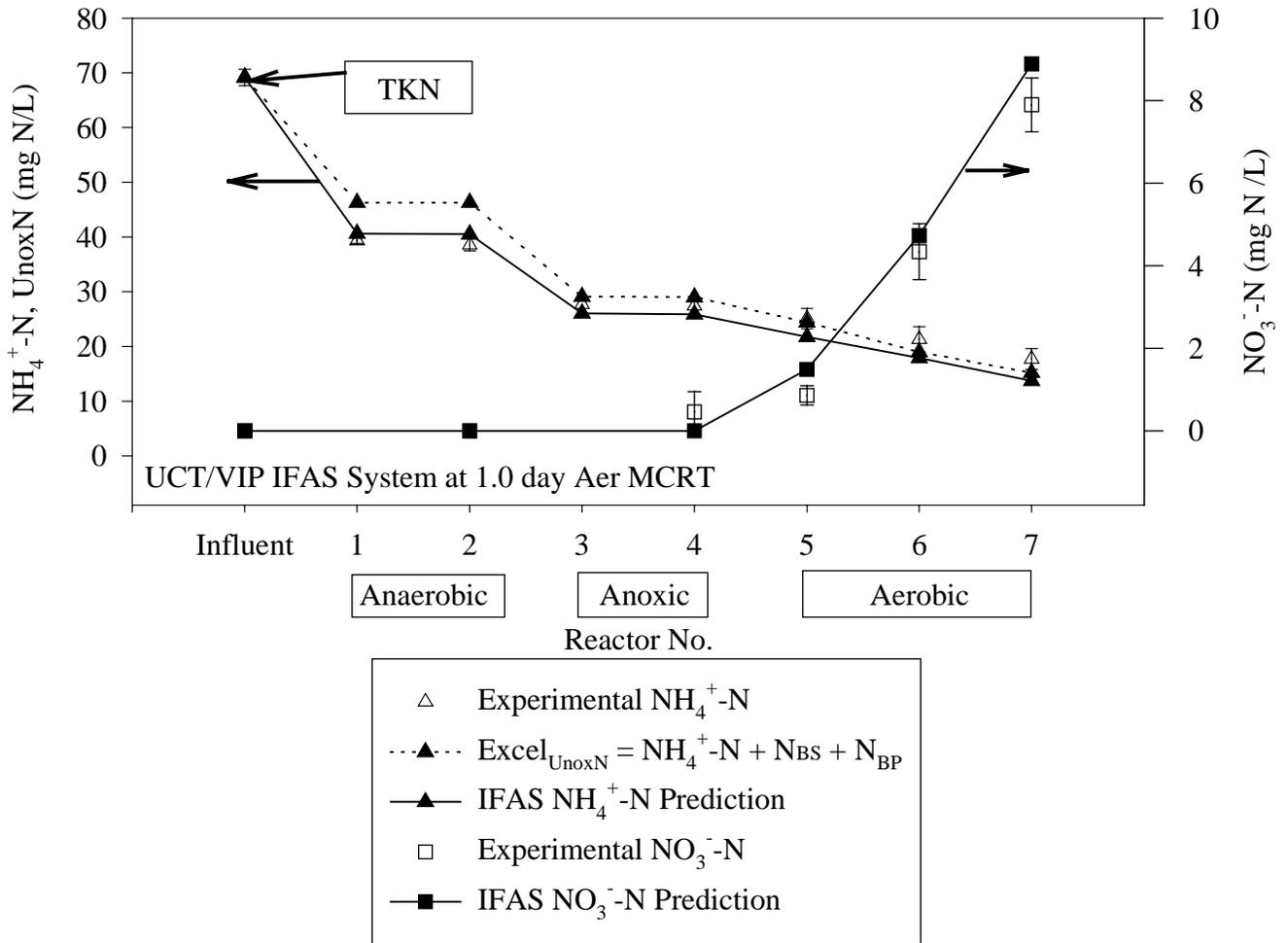


Figure 6. Experimental Data and Model Prediction for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$, IFAS-Sponge System at 12 °C

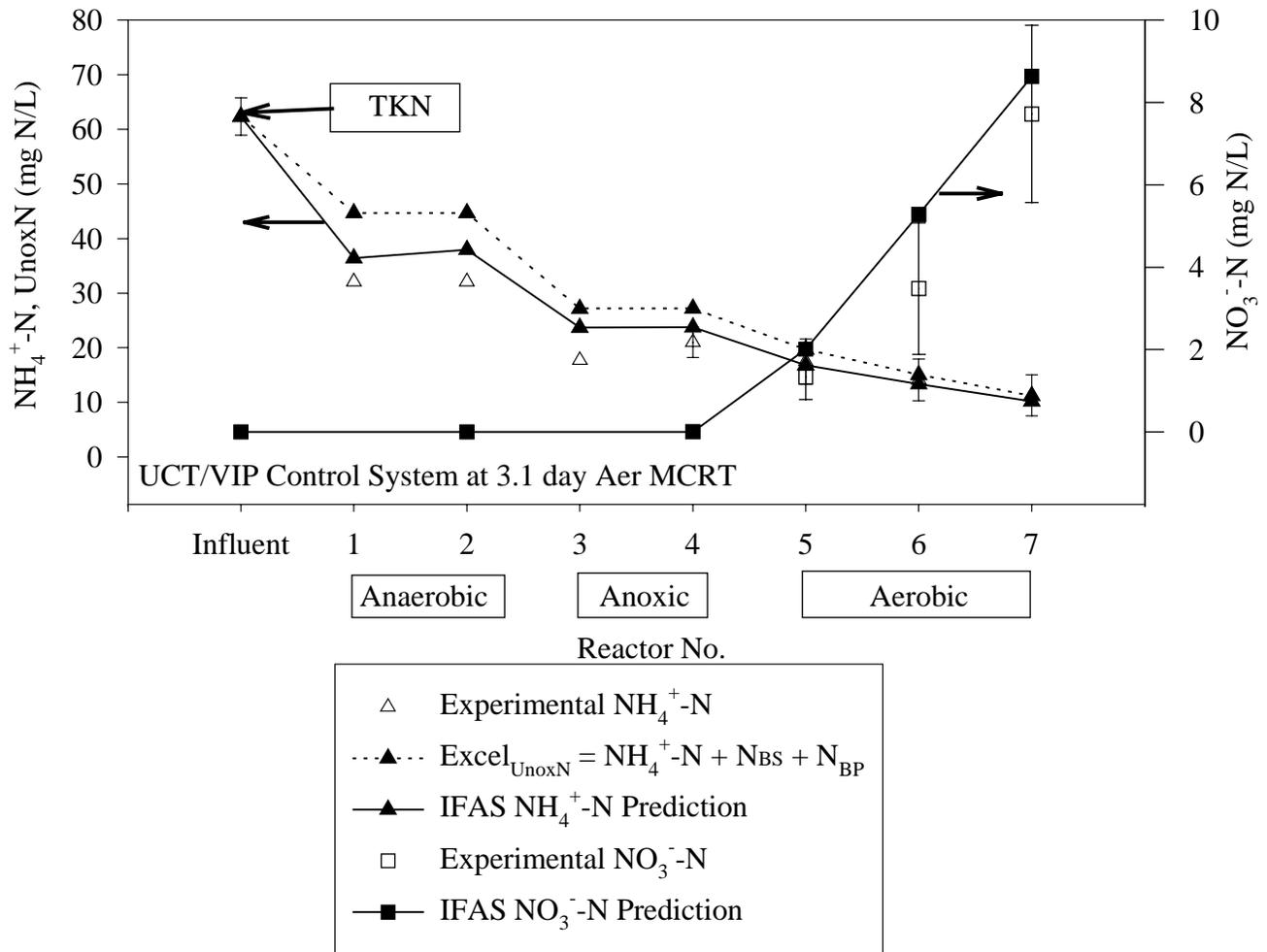


Figure 7. Experimental Data and Model Predictions for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$, Control System at 12 °C

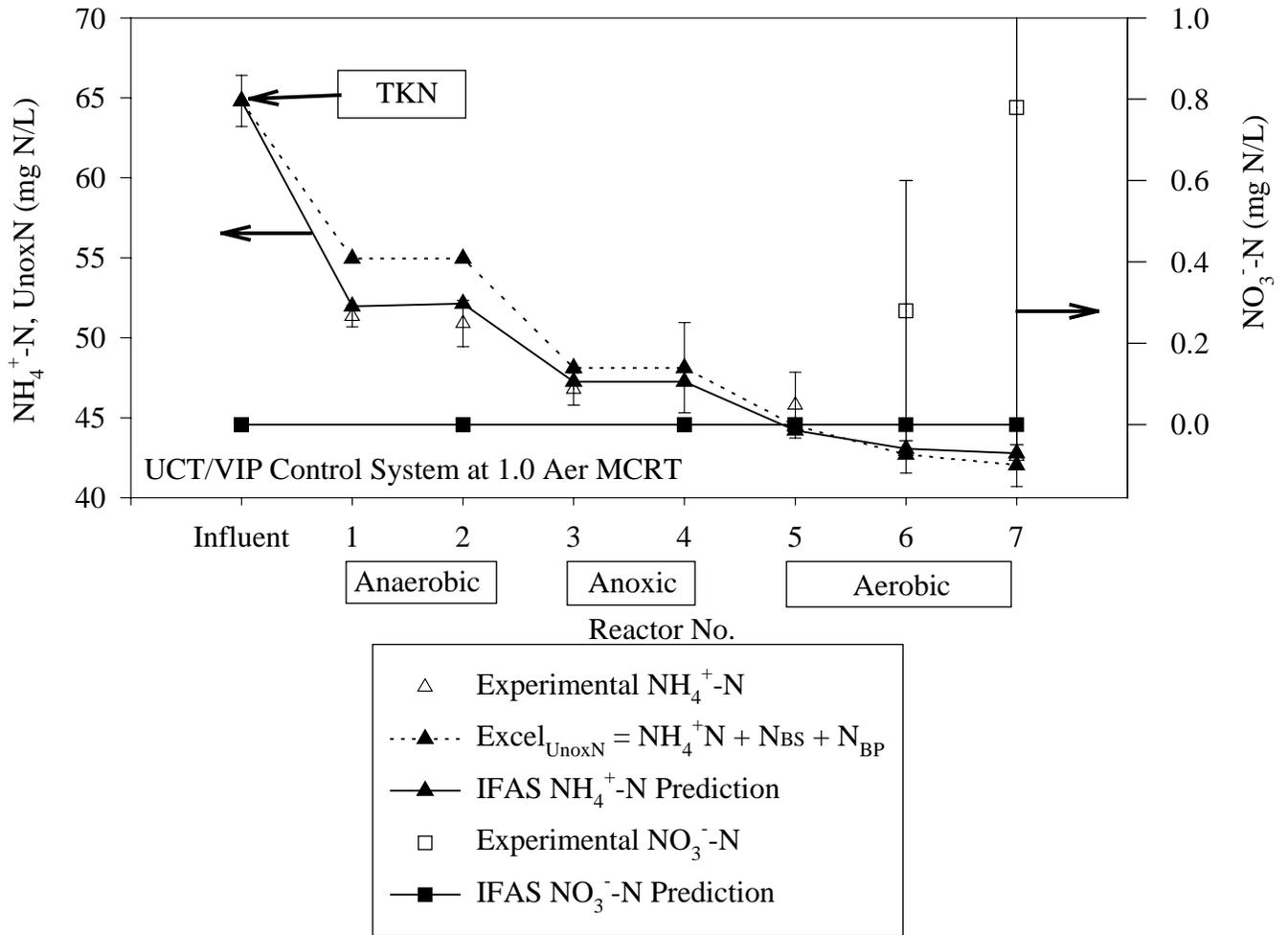


Figure 8. Experimental Data and Model Predictions for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$, Control System at 12 °C

CONCLUSION

An IFAS computer model package that predicts carbonaceous removal, nitrification, and denitrification at steady state conditions in activated sludge systems with either integrate sponge media (IFAS) in the aerobic zone or without integrated media was developed. The model is based on the general model of Barker and Dold (1997) integrated with empirical equations developed by Randall, Sen and co-workers at Virginia Tech from IFAS pilot-scale and full-scale studies. The model was calibrated using kinetic and stoichiometric coefficients from the literature and the experimental pilot plant studies. The model predictions agreed very well with the experimental data from the pilot studies. The soluble COD and NH_4^+ -N concentrations obtained using the IFAS program closely agreed with the observed results, which was a substantial improvement over the spreadsheet IFAS version developed by Sen (1995). The nitrate profiles could be further improved by incorporating the nitrate flux into the biofilm into the program, but further experimental work is required before this will be possible

The developed model has the potential to be a useful tool for engineers or scientists who desire to design or operate IFAS systems to obtain year round nitrification. The IFAS program also can be used to predict the location and amount of sponge media needed to optimize the design and operation of IFAS systems.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

Aer MCRT	= Aerobic MCRT (day)
DO	= Dissolved oxygen (mg O ₂ /L)
N _{BP}	= Particulate biodegradable organic nitrogen (mg N/L)
N _{BS}	= Soluble biodegradable organic nitrogen (mg N/L)
NH ₄ ⁺ -N	= Ammonium nitrogen (mg N/L)
NO ₃ ⁻ -N	= Nitrate nitrogen (mg N/L)
MLVSS	= Mixed Liquor Volatile Suspended Solids (mgCOD/L)
VSS	= Volatile Suspended Solids (mg MLVSS/L).
P-COD _{bio}	= Particulate biodegradable COD (mg COD/L)

PO ₄ -P	= Soluble orthophosphate (mg P/L)
SCFA	= Short Chain Fatty Acid (mg COD/L)
S _{BSA}	= Soluble readily biodegradable SCFA COD (mg COD/L)
S _{BSC}	= Soluble readily biodegradable complex COD, non-SCFA (mg COD/L)
SCOD	= Total Soluble COD = S _{BSA} + S _{BSC} + S _{US} (mg COD/L)
SCOD _{bio}	= Soluble biodegradable COD = S _{BSA} + S _{BSC} (mg COD/L)
Sponge	= Number of sponge cuboid (Sponge/L)
S _{US}	= Soluble unbiodegradable COD (mg COD/L)
TCOD	= Total COD (mg COD/L)
TKN	= Total Kjeldahl nitrogen (mg N/L)
UCT/VIP	= University of Cape Town/Virginia Initiative Project
UnoxN	= Unoxidized Nitrogen = NH ₃ -N/NH ₄ ⁺ -N + N _{BP} + N _{BS} (mg N/L)
Z _A	= Autotrophic organism mass (mg COD/L)
Z _H	= Non-polyP heterotrophic organism mass (mg COD /L)