

## OXYGEN UPTAKE RATE TESTS TO EVALUATE INTEGRATED FIXED FILM ACTIVATED SLUDGE PROCESSES

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### ABSTRACT

The combination of biofilm and suspended growth processes is, to date, relatively novel and there is a need to develop tools to monitor the performance of IFAS systems. The recent start-up of a full-scale demonstration Integrated Fixed Film Activated Sludge (IFAS) process in Ontario was monitored for approximately 100 days, providing an opportunity to investigate analytical tools to assess process performance.

The objective of this study was to understand the dynamic changes in physical and microbiological parameters in the process during and following plant start-up. More specifically, knowledge of the rate of biomass accumulation on the carriers, and the time to establish full nitrification activity was desired. Parameters such as total biofilm solids, in-basin nitrification rates, and batch nitrification rates were compared to an oxygen uptake rate (OUR) test modified by us for use with large polyethylene carriers. Samples were collected from both upstream and downstream ends of the plug flow aeration basin to enable profiling of the above parameters through the basin.

As observed in other IFAS installations, the modified OUR test determined that the biomass carriers performed greater than 87% of nitrification. Nitrification activity of the carriers was observed to follow different trends than biofilm total solids during process start-up. The process reached high nitrification rates within weeks whereas the biofilm total solids required more than 50 days to attain a quasi-steady-state. This study illustrated that parameters in addition to biofilm total solids are required to assess activity in nitrifying IFAS processes and oxygen uptake rates can be a useful tool in this regard.

### KEYWORDS

IFAS, Oxygen Uptake Rate, nitrification, biomass carriers

## INTRODUCTION

Many wastewater treatment plants in North America are now required to meet specific ammonia and total nitrogen effluent limitations. Real estate and infrastructure constraints have led to a growing interest in the Integrated Fixed Film Activated Sludge (IFAS) process. The combination of biofilm and suspended growth processes is, to date, relatively novel and there is a need to develop tools to monitor the performance of IFAS systems.

The recent start-up of a full-scale demonstration IFAS process in a single train at Lakeview Wastewater Treatment Plant (WWTP) in Ontario was monitored for approximately 100 days, providing an opportunity to investigate and develop analytical tools to assess process performance. The purpose of the upgrade was to achieve an ammonia effluent concentration less than 5 mg/L within the existing footprint of the plant. Figure 1 illustrates schematically the layout of the three pass IFAS train.

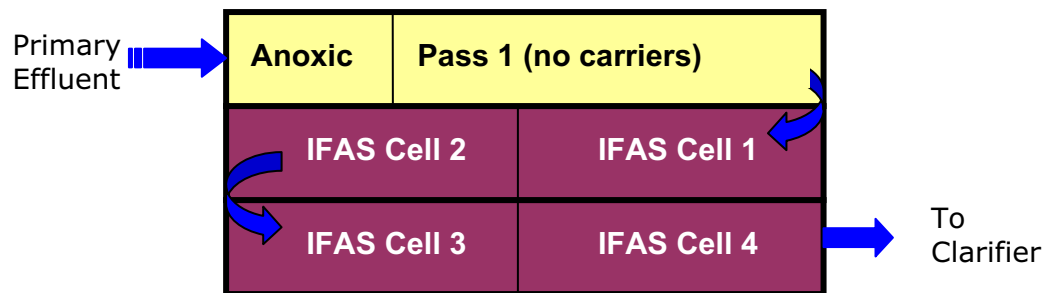


FIGURE 1. SCHEMATIC OF LAKEVIEW DEMONSTRATION IFAS TRAIN

The underlying objective of this study was to understand the dynamic changes in physical and microbiological parameters in the process during and following plant start-up. More specifically, knowledge of the rate of biomass accumulation on the carriers, and the time to establish full nitrification activity was desired. Parameters such as total biofilm solids, in-basin nitrification rates, batch nitrification rates, and oxygen uptake rates (OURs) of the carriers were analyzed on approximately a biweekly basis. Samples were collected from both upstream and downstream ends of the plug flow aeration basin to enable profiling of the above parameters through the basin. An important aspect of this work was the adaptation of an oxygen uptake rate protocol to facilitate biological activity analysis of large carriers.

## METHODOLOGY

*Experimental Setup.* The demonstration train at Lakeview WWTP was a three pass plug flow conventional activated sludge train that was upgraded to incorporate Hydroxyl-PAC biomass carriers (402 m<sup>2</sup>/m<sup>3</sup>; Hydroxyl Systems Inc., Victoria, BC, Canada) in the latter two passes. The two passes with carriers were further divided into four cells by in-basin screens. The aeration system consisted of a fine bubble aeration grid with coarse bubble air-knives located at each screen. The fill fraction of carriers in the media zones was approximately 46%.

*Analytical Methods.* Ammonium ( $\text{NH}_4^+$ ), total solids (TS), and total suspended solids (TSS) were measured according to Standard Methods (1995).

*Activity Tests.* The biological activity of the carriers and the suspended growth was monitored using oxygen uptake rate tests. A modified oxygen uptake rate protocol was adapted from methods previously reported for activated sludge and small biomass carriers (Villaverde *et al.*, 2000; Fdz-Polanco *et al.*, 2000; Ochoa *et al.*, 2002; Standard Methods, 1995).

The protocol for carriers consisted of first washing 40 carriers three times in tap water to remove suspended solids that were not attached to the carriers. The carriers were then immersed in tap water with a total volume of 800 mL, in a 1 L beaker at room temperature. The sample was aerated to saturation using a diffuser stone and compressed air, and a cover was placed on the beaker to minimize oxygen transfer. Stirring was then initiated using a magnetic stir bar and plate and the dissolved oxygen concentrations were recorded for 5 min. The OUR was performed under three different conditions in order to measure 1) endogenous OUR, 2) nitrogenous OUR due to nitrification of ammonia without carbon and finally 3) exogenous respiration with acetate as the carbon source. The quantities of acetate and ammonia added were selected to ensure non-limiting conditions (ammonia > 20 mgN/L; acetate > 100 mgCOD/L).

A similar procedure was employed for the mixed-liquor, with the exception of aerating the 800 mL sample of activated sludge for more than 12 hours prior to the OUR test. This protocol ensured the endogenous state had been achieved.

The nitrogenous oxygen uptake rate (NOUR) was determined by subtracting the endogenous OUR from the OUR measured with ammonia present. The NOUR units were then converted from  $\text{mgO}_2/\text{L}/\text{min}$  to  $\text{mgN}/\text{m}^2/\text{d}$  using a conversion factor of 4.57  $\text{gO}_2/\text{gN}$  (the conversion therefore included any small amounts of nitrogen that were assimilated for biological growth), and the carrier surface area used in the test (Metcalf & Eddy, 2006). The resulting units were termed NOUR-N and were selected because they are more readily comparable to observed nitrification rates in biofilm systems.

*Biofilm Total Solids.* Total biofilm solids on the carrier were measured by first drying duplicate samples that each consisted of 10 carriers at 105°C for 24 h. The dried carriers were then weighed and the solids removed by first mixing carriers in 0.25 N NaOH for 24 hours followed by sonication for 90 minutes. The carriers were then dried again for more than 2 hours at 105°C and re-weighed. The difference was used to determine the total solids concentration on the carriers.

*Batch Nitrification Tests.* Batch testing was performed on samples of carriers from each of the cells. The batch tests utilized 80 carriers in 7 L of tap water, in a cylindrical column equipped with aeration by compressed air. Dissolved oxygen levels were at saturation and water temperature ranged between (15 – 20 °C). Ammonia and phosphorus were added to the reactors and the ammonia-N was recorded with time. Rates were calculated using the linear portion of the curve and normalized to the total carrier surface area.

## RESULTS

### Operating Conditions

The average flow rate to the IFAS train during the monitoring period was 12,800 m<sup>3</sup>/d resulting in an average total hydraulic retention time of 6.5 h in the aeration basin. The average primary effluent BOD and TKN during the period were approximately 360 mg/L and 80 mgN/L, respectively. Mixed liquor concentrations were on average 3,500 mg/L during approximately the first 100 days of operation and the temperature was 15°C. The primary clarifier effluent ammonia concentrations, flow and basin temperature for the study period are presented in Figure 2.

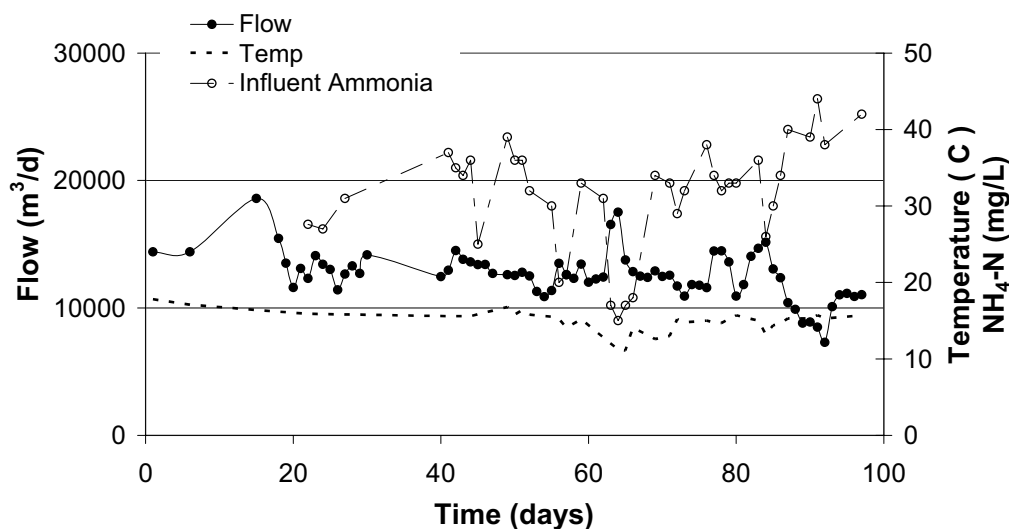


FIGURE 2. OPERATING CONDITIONS DURING THE FIRST 97 DAYS OF START-UP.

### Biofilm Development with Time

Total solids attached to the biomass carrier were monitored during start-up. The data presented in Figure 3 indicated that a quasi-steady-state total solids was reached in all cells at approximately 50 days. During the monitoring period the highest observed biofilm total solids was 24 g/m<sup>2</sup> in Cell 1. The average steady state total biofilm solids concentration in Cell 1 was approximately 8 g/m<sup>2</sup> higher than in Cell 4.

The OUR test was used to determine the biological activity on the carriers and the results were compared to the more traditional monitoring parameters. Figure 4 illustrates NOUR-N data that was obtained over the duration of the data collection program. Data is presented for both the upstream (Cell 1) and downstream (Cell 4) regions of the IFAS basin. Carriers in Cell 4 demonstrated higher ammonia removal rates than in Cell 1. Figure 4 also illustrates that higher ammonia removal rates were observed in Cell 3 than in Cell 4.

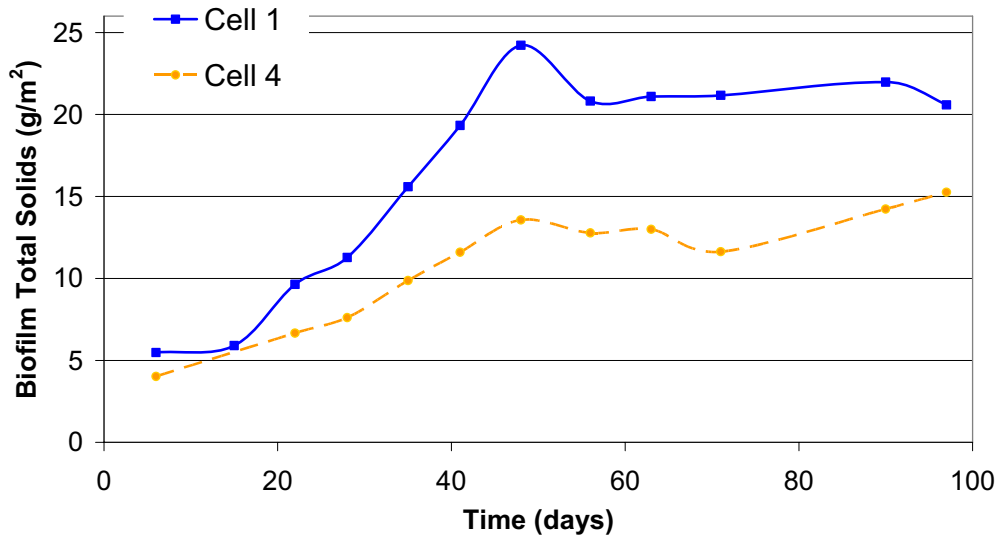


FIGURE 3. TOTAL BIOFILM SOLIDS IN CELLS 1 AND 4

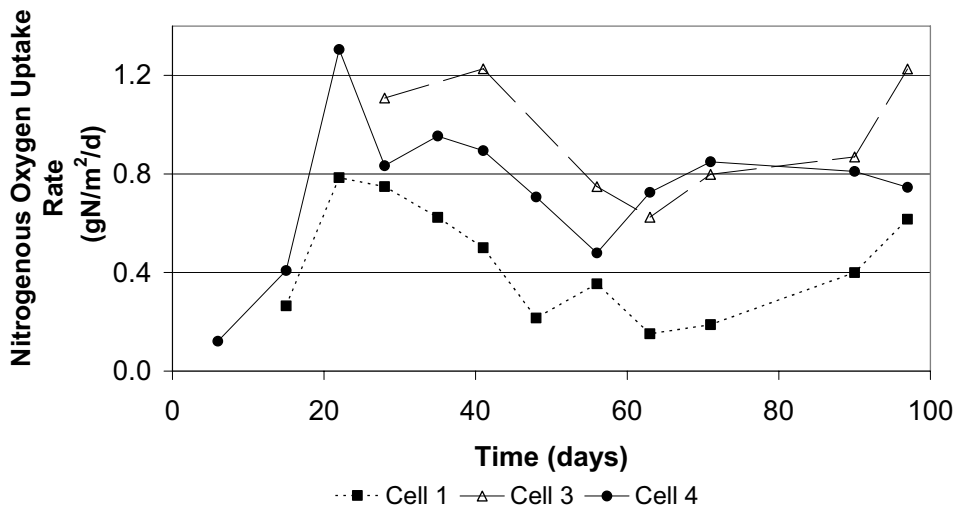


FIGURE 4. NITROGENOUS OXYGEN UPTAKE RATES IN THE IFAS TRAIN

### Nitrification Activity & OUR Validation

To further assess the nitrification activity throughout the IFAS train, and evaluate the OUR test, grab samples were collected in each of the cells to assist in evaluating the ammonia removal across each cell. This data was employed to determine the in-basin ammonia removal rates by first calculating the reduction in ammonia concentration across each cell. The removal rate of ammonia ( $\text{gN/m}^2/\text{d}$ ) was then determined using the reduction in ammonia concentration across the cell, the in-basin flows and carrier surface area in each cell.

The results for Cells 1 and 3, representing the lowest and highest ammonia removal rates respectively, are presented graphically in Figures 5 & 6 along with the measured nitrogenous oxygen uptake rates. There was a potential for error in the estimation of the ammonia removal across the cells as a result of the use of grab sampling as opposed to 24 h composite sampling. However, this data provided an additional point of reference and comparison for the oxygen uptake rate data. The in-basin rates represent a combined ammonia removal of both suspended and attached growth and also include ammonia removal as a result of assimilation in biomass whereas the NOUR-N's represent the carrier removal capacity only.

Figures 5 and 6 illustrate that the NOUR-N's corresponded well with the in-basin ammonia removal rates, given the inherent inaccuracies in measuring in-basin removal rates. Based on the NOUR-N results, Cell 1 appeared to have ammonia removal rates between 0.3 and 0.6  $\text{gN/m}^2/\text{d}$  at quasi-steady state while Cell 3 had much higher rates between 0.6 and 1.2  $\text{gN/m}^2/\text{d}$ . Both techniques illustrated similar patterns in ammonia removal rates with time.

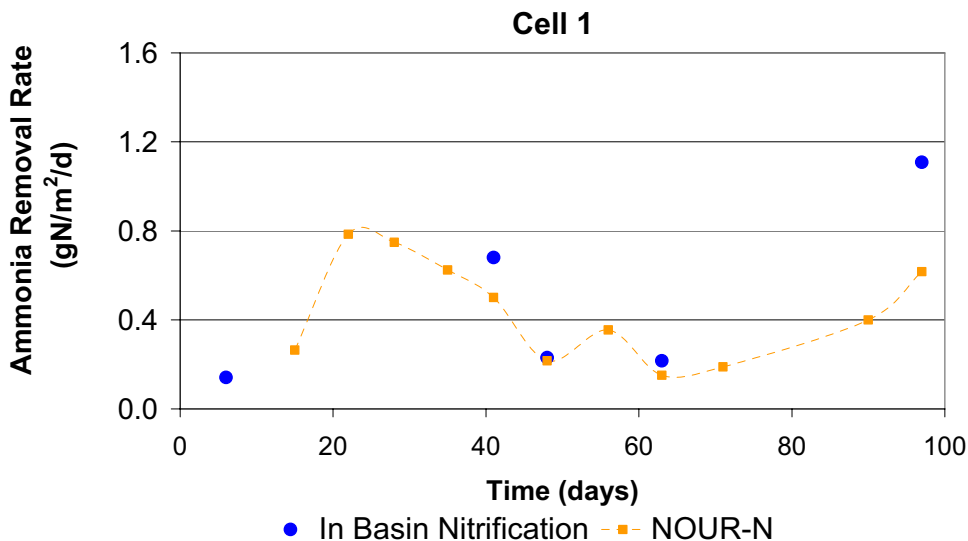


FIGURE 5. IN-BASIN AMMONIA REMOVAL RATES AND NITROGENOUS UPTAKE RATE ON THE CARRIERS FOR CELL 1.

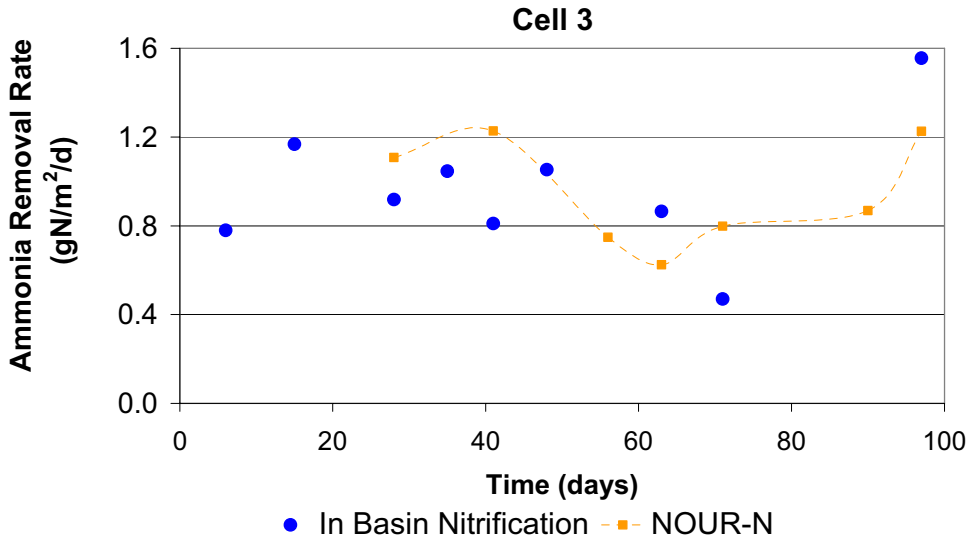


FIGURE 6. IN-BASIN AMMONIA REMOVAL RATES AND NITROGENOUS UPTAKE RATE ON THE CARRIERS FOR CELL 3.

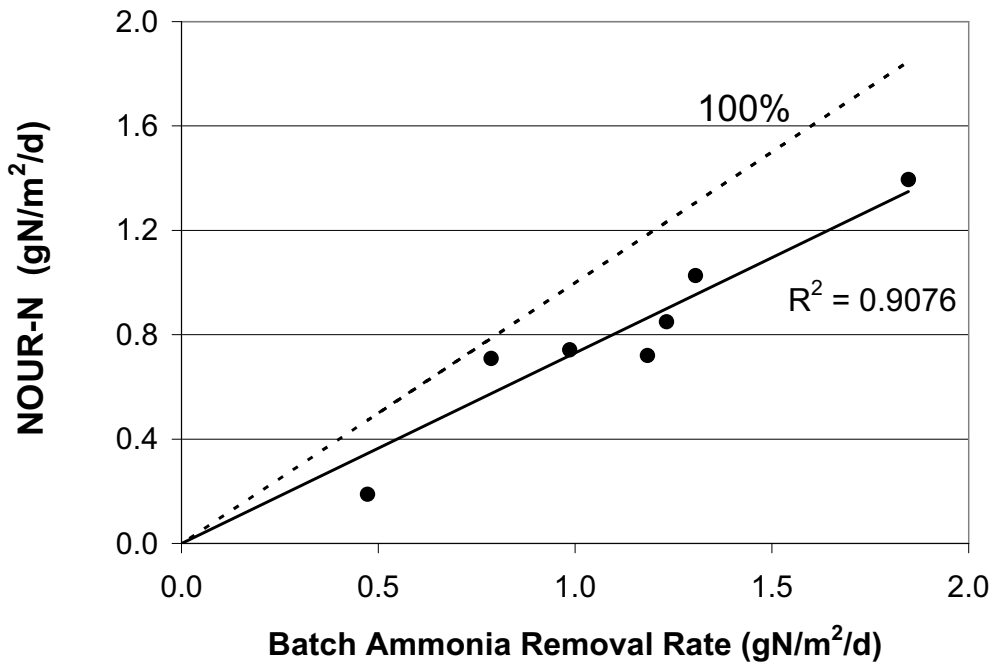


FIGURE 7. BATCH AMMONIA REMOVAL RATES COMPARED TO NOUR-N

As another comparison of NOUR-N to nitrification rate, batch testing was conducted on several samples of carriers. A summary of the findings is presented in Figure 7 which relates the batch ammonia removal rate to the NOUR-N. A strong correlation was observed between the two; however, the batch ammonia removal rates were higher than the NOUR-N equivalent rates.

## Suspended vs. Attached Growth

The oxygen uptake rate measurements enabled a comparison of nitrification activity on the carriers in different cells with that of the suspended growth. Table 1 illustrates the average NOUR-N values for the carriers and the mixed liquor in the IFAS train. The MLSS value accounts for nitrification in the entire train (all three passes). The mixed liquor nitrification rates were first normalized to 3,500 mgMLSS/L (dividing the observed rate by the measured MLSS value and multiplying by 3,500 mgMLSS/L). The resulting units were mgN/L/min for a mixed liquor concentration of 3,500 mg/L. The rates were then applied to the entire treatment train by multiplying the rate in mgN/L/min by the total volume, resulting ultimately in units of kgN/d.

**TABLE 1. AVERAGE NITROGENOUS OXYGEN UPTAKE RATES AT STEADY STATE**

MLSS	NOUR-N (kgN/d)				
	Cell 1	Cell 2	Cell 3	Cell 4	Total
40	36	56	95	78	306
<b>% Nitrification by Carriers</b>					<b>87%</b>

The carrier NOUR-N rates were converted from gN/m<sup>2</sup>/d to kg/d by multiplying by the total surface area of carriers in each cell. The mass removal rates in each cell were then summed to provide the total mass removal rates in the train that was contributed by the carriers. On average, the carriers contributed 87% of the nitrification and the suspended growth 13%.

## DISCUSSION

### Biofilm Development with Time

Biofilm development in each cell was influenced by the operating conditions present at each position in the plug flow basin. As would be expected, Cell 1 accumulated the greatest solids on the carriers achieving a quasi-steady state mass of approximately 21 g/m<sup>2</sup>. Cell 4, under much lower loaded conditions, reached a steady state total biofilm solids of approximately 13 g/m<sup>2</sup>.

Table 2 compares the findings of this study with previous studies on biofilm total solids. The results of the Lakeview study confirmed the findings of Shaw *et al.* (2003) which indicated that the steady state solids on IFAS carriers are dependent on the contaminant load experienced by the carrier. The range of total biofilm solids determined by Jones *et al.* (1999) (18-21 g/m<sup>2</sup>), for an almost identical carrier, corresponded well to the findings of this study.

TABLE 2. BIOFILM TOTAL SOLIDS

Study	Carrier	Location	Biofilm Total Solids <sup>1</sup> (g/m <sup>2</sup> )
Lakeview Demonstration	Hydroxyl-PAC	Upstream IFAS Reactor	21
Lakeview Demonstration	Hydroxyl-PAC	Downstream IFAS Reactor	13
Jones <i>et al.</i> (1999)	Conor-PAC	Single IFAS Reactor	18 - 21
Shaw <i>et al.</i> (2003)	Kaldnes K1	Upstream IFAS Reactor	13.2
Shaw <i>et al.</i> (2003)	Kaldnes K1	Downstream IFAS Reactor	7.6

<sup>1</sup>Techniques for analyzing total biofilm solids may vary between studies

The development of biofilm nitrification activity with time was also unique for each cell. With the exception of Cell 3, the nitrification activity on the carriers increased along the length of the basin. This observation was thought to be a result of both lower carbonaceous loading and also higher dissolved oxygen in the downstream cells, as similar observations have previously been noted in pure fixed film systems (Hem *et al.*, 1994). Cell 3 carriers had the highest nitrification activity on average, likely as a result of both the low carbonaceous loading and the concentration of ammonia creating conditions for elevated growth kinetics (as opposed to Cell 4 where the ammonia concentration may have become limiting).

The level of nitrification activity on the carriers appeared to be in a continual state of flux – as opposed to coming to a single steady-state condition. This suggested that the biofilm was continuously adapting to the variable influent loading and operating conditions that were experienced during the 100 day start-up period. Throughout the period of study, however, the relative nitrification activity of the carriers typically ascended in the order of Cell 1, Cell 2, Cell 4, Cell 3.

The oxygen uptake rate data indicated high nitrification rates were observed many weeks prior to the total solids steady-state (Figure 8 and 9). Nitrification rates therefore did not appear to correlate with biofilm total solids, a result which has been identified by others (Liu, 1997).

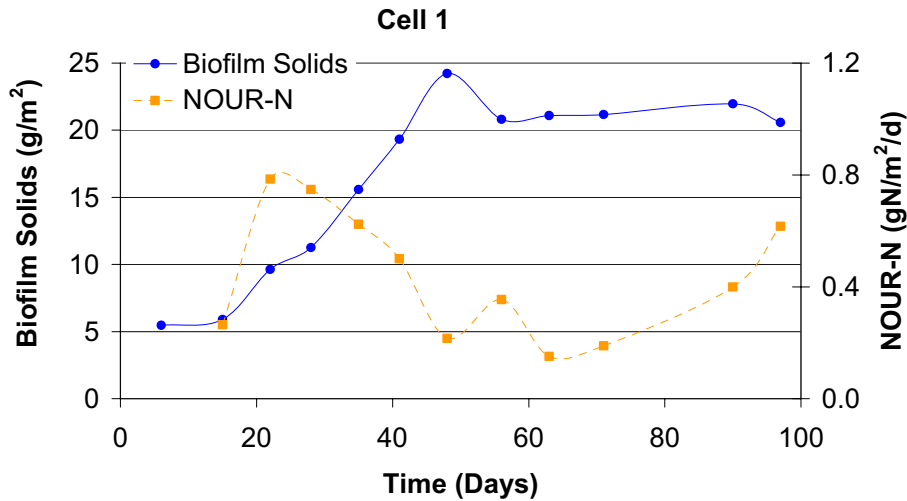


FIGURE 8. NITROGENOUS OXYGEN UPTAKE RATES (NOUR-N) AND BIOFILM SOLIDS IN CELL 1 OF THE IFAS TRAIN

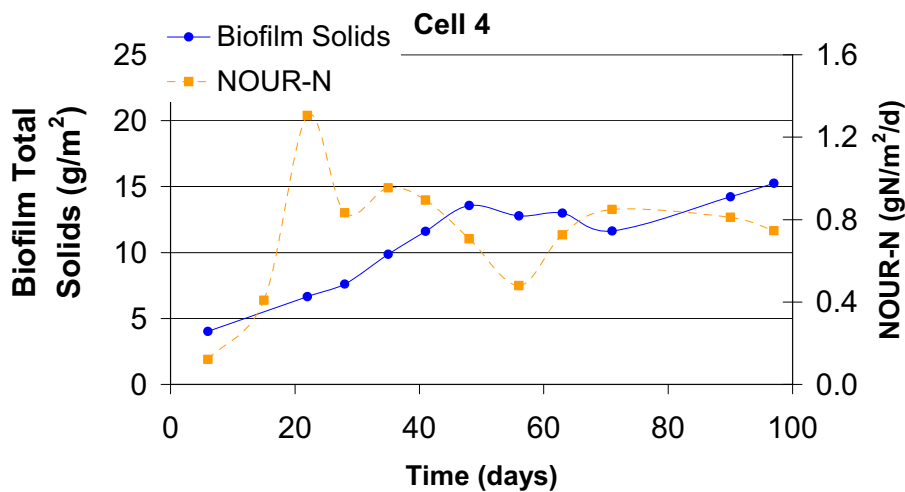


FIGURE 9. NITROGENOUS OXYGEN UPTAKE RATES (NOUR-N) AND BIOFILM SOLIDS IN CELL 4 OF THE IFAS TRAIN

This finding is likely indicative of a dynamic biofilm which adapts to different conditions. It seems likely that initially a thin biofilm is established where oxygen and substrates are not limiting; then as the biofilm increases in thickness, the autotrophic micro-organisms are forced to compete with heterotrophs for substrates and space. This pattern of growth, decline and subsequent adaptation to steady-state conditions can be observed in both Figures 8 and 9 for Cells 1 and 4 respectively.

This finding reinforces the notion that biofilm systems cannot be accurately assessed by the total biofilm solids alone, in contrast to a suspended growth system where solids may provide a good indication of the relative nitrification capacity.

### Nitrification Activity and OUR Validation

The OUR test, adapted for carriers, proved to be an effective technique for the assessment of the nitrification rate on carriers. The method is much more rapid than a batch ammonia removal test and does not require equipment for analysis of ammonia and/or nitrate. Despite the simplicity of the method, the OUR results correlated reasonably with both the nitrification rate batch tests and the in-basin ammonia removal rates. Discrepancies between batch nitrification testing and OUR testing may have been a result of differences in dissolved oxygen levels, different mixing regimes and/or water temperature that occurred as a result of utilization of different reactor configurations for the two tests. A recent improvement to the method has included use of the datalogging feature on the dissolved oxygen probe to improve the accuracy of OUR rates.

### Suspended vs. Attached Growth

The oxygen uptake rate results indicated that the carriers achieved approximately 87% of the total nitrification activity. This finding was anticipated given that the average suspended solids SRT during this period was 2.6 days which is very low for sustaining consistent nitrification. Table 3 outlines similar findings in other studies where the biomass carriers that achieved on average 80% of the nitrification in the IFAS plants.

TABLE 3. CARRIER FRACTION OF TOTAL NITRIFICATION

Study	Suspended Growth SRT (days)	Carrier Nit. Rate Fraction
Lakeview Demonstration	2.6	87%
Jones <i>et al.</i> (1999)	3	70 - 80%
Yerrell <i>et al.</i> (2001)	3 - 4	55 - 61%
Christensson & Welander (2003)	1.2 - 3.6	85%
Ochoa <i>et al.</i> (2002) <sup>1</sup>	3.7 - 8.0	95-99%

<sup>1</sup> Small pore size, high surface area carrier

## CONCLUSIONS

As observed in other IFAS installations, the OUR test indicated that the carriers performed the majority of nitrification in the system. Total biofilm solids and nitrification activity on the carriers were found to be dependent on operational conditions and contaminant load variation throughout the plug flow basin at quasi-steady state.

Nitrification activity of the carriers was observed to follow different trends than biofilm total solids during process start-up. The process began nitrifying almost immediately following start-up and reached high nitrification rates within weeks whereas the biofilm total solids required almost two months to attain a quasi-steady-state. This study illustrated that parameters in addition to biofilm total solids are required to assess activity in nitrifying IFAS processes and oxygen uptake rates can provide a useful tool in this regard.

A modified oxygen uptake rate methodology proved to be a simple method to analyze trends in biofilm nitrification activity for large polyethylene carriers. This methodology requires minimal analytical tools, is a rapid test and the resources to conduct such testing are typically available onsite at most wastewater treatment plants. OUR testing could be employed as a tool for process analysis and troubleshooting in IFAS plants.

## ACKNOWLEDGEMENTS

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