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DEPARTMENT OF CIVIL ENGINEERING
Water Quality Engineering

MEng Thesis:

Design of an integrated fixed-film activated sludge (IFAS) system for possible application at the Borcherds Quarry WWTW.

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Abstract

Nitrification can be seen as the weakness of a conventional activated sludge (CAS) process employing biological nutrient removal (BNR). Suspended nitrifiers only grow in the aerobic zone of the biological reactor but are subjected to anaerobic and anoxic conditions where no nitrifier growth takes place. To establish a nitrifier population that consistently produces low effluent ammonia concentrations, long sludge ages are required (about 15 to 25 days) in South African BNR wastewater treatment plants. This results in relatively large biological reactors. Integrated Fixed-Film Activated Sludge (IFAS) systems have been used extensively in European and Scandinavian countries. This process entails the addition of moving-bed biofilm carriers in certain zones of an activated sludge system to establish biofilm growth. The most successful application has been the addition of these carriers in the aerobic zones of activated sludge plants to facilitate the growth of nitrifiers on the biofilm. This allows nitrifiers to grow independently from the suspended sludge age since it remains stationary on the biofilm in the aerobic tank. The system is thereby relieved from the requirement of a long suspended sludge age. For the University of Cape Town (UCT) process commonly employed in South Africa, it is shown that a suspended sludge age of 5 to 7 days is adequate to meet final effluent standards when converted to an IFAS process. As a result, an UCT-IFAS process can treat 50% to 70% more wastewater in an existing process volume or reduce the size required for a new installation by 30% to 40% when compared to a conventional UCT process with a minimum wastewater temperature of 14°C. The intricacies and challenges associated with designing an IFAS process are unpacked in this thesis to gain a better understanding of what is required to harvest the potential benefits.

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1 Table of Contents

Abbreviations

ADWF	Average dry weather flow
ANO	Ammonia nitrifying organisms
AOR	Actual oxygen requirement
ASM	Activated sludge model
BNR	Biological nutrient removal
BNRAS	Biological nutrient removal activated sludge
BO	Biodegradable organics
BOD	Biochemical oxygen demand (synonymous to BOD_5)
BPO	Biodegradable particulate organics
BSO	Biodegradable soluble organics
C	Carbon
CAS	Conventional activated sludge
COD	Chemical oxygen demand
DO	Dissolved oxygen
DSVI	Diluted sludge volume index
EBPR	Enhanced biological phosphate removal
FBDA	Fine bubble diffused aeration
FSA	Free and saline ammonia
IFAS	Integrated fixed-film activated sludge
SFAS	Separated Fixed-film activated sludge
ISS	Inert suspended solids
JHB	Johannesburg (Process)
MBBR	Moving bed bioreactor
MLE	Modified Ludzack-Ettinger
MLSS	Mixed liquor suspended solids
N	Nitrogen
NDEBPR	Nitrifying denitrifying excess biological phosphate removal
NOO	Nitrite oxidizing organisms
OHO	Ordinary heterotrophic organisms
OP	Ortho-phosphate
OUR	Oxygen utilization rate
P	Phosphorous
PAO	Poly-accumulating organisms
PDWF	Peak dry weather flow
PST	Primary settling tank
PWWF	Peak wet weather flow
RAS	Return activated sludge
RBC	Rotating biological contactor
RBCOD	Readily Biodegradable COD
SF	Safety Factor for Nitrification (SRT/SRT_m)
S_f	Safety factor applied to max specific growth rate of nitrifiers (μ_{AmT})
SHC	Solids handling criteria
SOTE	Standard oxygen transfer efficiency
SRT	Solids retention time (same as sludge age)
SRT_m	minimum sludge age required for nitrification

SST	Secondary settling tank
TKN	Total Kjedahl Nitrogen
TOD	Total oxygen demand
TP	Total phosphorous
TSS	Total suspended solids
UCT	University of Cape Town
UO	Unbiodegradable organics
UPO	Unbiodegradable particulate organics
USO	Unbiodegradable soluble organics
VFA	Volatile Fatty Acids
VSS	Volatile suspended solids
WAS	Waste activated sludge
WUL	Water use license
WW	Wastewater
WWTW	Wastewater treatment works

SECTION A: IFAS LITERATURE REVIEW

1 Introduction

The activated sludge process has been used for treating municipal wastewater for more than a century. The process is generally well understood but by no means stale. Researchers across the world are continuously working to gain a better understanding of the mechanics of the process and to translate this understanding into improved wastewater treatment plant design. In the last 40 years biological nitrogen and phosphorus removal in a conventional activated sludge (CAS) process has been the preferred technology (Ekama, 2014). This preference is well deserved since an effectively designed biological nutrient removal activated sludge (BNRAS) plant can remove more than 90% Nitrogen and Phosphorous from typical domestic wastewater streams. Consequently, the bulk of recent research has not been focused on achieving better effluent quality, instead the focus has been on increasing capacity of existing plants or reducing the space footprint of new plants (Ekama, 2014). The current consensus seems to be that these objectives are best achieved by focusing on

i. Improving N removal, especially the nitrification step of N removal;
ii. Improving phase separation of sludge and effluent.

The focus on improving nitrogen removal stems from the known weakness of the activated sludge process, namely the facilitation of the growth of nitrifiers. Nitrifiers are essential for converting ammonia into nitrites and ultimately nitrate, i.e. nitrification. However, they are the slowest growing organisms of interest in an activated sludge plant and therefore a long sludge age is required to establish a population of nitrifiers. In fully aerobic conditions nitrification takes place at sludge ages of 2 to 5 days depending on temperature and the maximum specific growth rate of the nitrifiers (μ_{Am20}) which is considered a wastewater characteristic rather than a kinetic attribute of the process.

The activated sludge process is based on selection principles, where organisms with beneficial functions are selected in certain parts of the process by creating conditions that will cause these organisms to outcompete others to the extent that they can perform their beneficial function. Nitrifiers are obligate aerobes and are only able to grow in aerobic zones of a system (Ekama & Wentzel, 2008), although endogenous mass loss of the nitrifiers takes place in both aerobic and unaerated conditions. The unaerated zones (anaerobic and anoxic) required to achieve P removal and denitrification in a BNRAS system therefore negatively affects the growth of nitrifiers. As a result, an even longer sludge age is required to establish a population of nitrifiers. Figure 1.1 shows the minimum sludge age required for nitrification at various unaerated mass fractions and maximum specific growth rates for nitrifiers (μ_{Am20}).

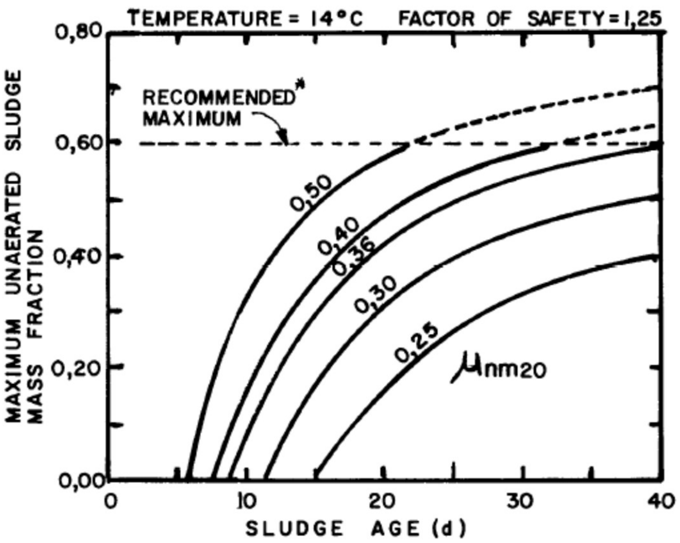


Figure 1.1: Maximum unaerated sludge mass fraction as a function of the sludge age and the maximum specific growth rate of the nitrifiers at a temperature of 14°C and a factor of safety for nitrification of 1.25 (Ekama & Wentzel, 2008).

The minimum sludge age required for nitrification is calculated as follows (Ekama & Wentzel, 2008):

Equation 1.1: Minimum sludge age required for nitrification

$$SRT_m = \frac{S_f}{(1 - f_{xt})\mu_{AmT} - b_{AT}S_f}$$

To illustrate the implication of the slow growth of the nitrifiers, consider a BNRAS reactor with an unaerated mass fraction of 40% with μ_{Am20} = 0.45, S_f = 1.25 and a minimum temperature of 14 °C (*note 14°C is an assumed or example minimum wastewater temperature and not derived from data from a particular plant*). Such a system requires a minimum sludge age of 13.5 days for stable nitrification. If the unaerated mass fraction is 45% a minimum sludge age of 15.4 days is required. At the same temperature of 14°C, all the biodegradable COD would be converted to biomass at a sludge age as low as 4 days.

Since heterotrophs (that utilize COD) and autotrophs (that nitrify ammonia) are mixed in the biomass, the sludge ages of the organism groups cannot be decoupled. Hence heterotrophs, which produce more than 97% of the activated sludge mass, are automatically subjected to long sludge ages. This has some benefits, for example the reduction of the active fraction and volume of the sludge wasted, but it comes at a price in the form of a larger biological reactor and increased aeration requirements.

There is great potential in decoupling the sludge age of heterotrophs and nitrifiers (autotrophs). However, this is not possible in a purely suspended activated sludge reactor. Attached growth systems such as trickling filters or moving bed bioreactors (MBBR's) are not primarily designed or operated according to sludge age, since the biomass is retained on the media and excess sludge is scoured or sloughed and wasted in a largely uncontrolled manner. 'Sludge age' in these systems is a description of how long organisms grow on the biofilm before it is scoured or sloughed due to excessive biofilm thickness. These ‘sludge ages’ are typically much longer than that of the suspended sludge. This makes attached growth systems particularly suitable for accommodating nitrifiers. The integrated fixed-film activated sludge process (IFAS) is an attempt to combine the best properties of suspended activated sludge and attached growth systems. Fixed or moving media (carriers) are added to strategic zones in the activated sludge reactor and thereby two distinct sludge ages are obtained; one for the suspended biomass and one for the attached growth biomass.

Through careful design of an IFAS system the sludge ages of heterotrophs and nitrifiers could potentially be decoupled (to be independent). It is possible to have a suspended biomass sludge age for heterotrophs of about 5 days that is sufficient for complete biodegradable COD utilization while hosting a much longer sludge age for nitrifiers on the fixed media, where the only form of sludge wasting is scouring and sloughing. By maintaining nitrifiers in the aerobic zone of the reactor only, it also grows faster than it would in suspended biomass where it is exposed to unaerated zones. At face value the IFAS system holds the potential to reduce the required reactor volume by about 50% for a BNRAS system, simply by reducing the suspended sludge age from about 15 days to about 5 days at 14°C. Or inversely 50% more flow (COD load) can be treated through an existing reactor upgraded to the IFAS process. Therein lies the potential benefit of an IFAS reactor, if it could achieve such a significant increase in capacity economically and without compromising the system in other ways.

Other quoted advantages of the IFAS system include:

i. That it produces a better settling sludge (lower DSVI) (Odegaard, et al., 2014). This could allow operation of the reactor at a higher MLSS concentration which increases the system’s capacity;
ii. Increased resistance to toxicity shocks that is typical of industrial effluent (Odegaard, 2014) ;
iii. Better removal of micropollutants, a particularly valuable attribute where wastewater reclamation to potable standard is considered (Odegaard, 2014);

These possible advantages are considered secondary attributes of an IFAS system and are not the primary focus of this report. As promising as the IFAS process seems at face value, there are also several complexities to the integration of fixed-film and activated sludge systems that require careful consideration in order to harvest the benefits.

This thesis comprises of two parts. *Section A* is a desktop study of the IFAS process and an attempt to unpack its intricacies, challenges and design considerations. This in turn forms the foundation for *Section B*, namely the design of an IFAS process for application at the refurbished A-Works at the Borcherds Quarry WWTW. Ultimately a comparison is drawn between the performance of CAS treating raw wastewater (WW), CAS treating settled WW, IFAS treating raw WW and IFAS treating settled WW at the existing Borcherds Quarry WWTW A-Works. Since biological nutrient removal (BNR) processes have been preferred in South

Africa for decades, this study considers the feasibility of IFAS in BNR systems. The UCT process is used as a departure point and converted to an UCT-IFAS process. The sensitivity of the steady state UCT- IFAS model to certain variables is also explored.

2 Brief History of the IFAS Process (Odegaard, et al., 2014)

The possibility of intensifying the activated sludge process by using cell support systems was pointed out before 1980. Fixed-film reactors (such as trickling filters) and activated sludge reactors have been used independently for over a century and at times the processes were combined, but not often integrated in a single reactor. Biofilm growth within an activated sludge reactor has been facilitated in several ways over the years. The biofilm media used includes:

i. Fixed plastic media in the tank;
ii. Partly submerged rotating biological contactor (RBC);
iii. Cords or rope hanging in the tank (Ringlace^{TM});
iv. Suspended carriers that move freely in the tank.

The early attempts at IFAS reactors have been plagued with various issues that has prevented widescale implementation. Examples of these issues are clogging of fixed media, mechanical failures of RBC units (shafts) due to uneven and heavy biofilm growth and excessive biofilm thickness in rope carriers that limits oxygen diffusion to nitrifiers. Suspended carriers have proved to be the most successful. The Linpor^{TM} system was developed in Germany in the 1980's and comprised 1 cm^3 polyurethane foam cubes added to conventional activated sludge reactors. Results were not convincing although the sludge settleability improved. The foam carriers were light and accumulated at the top of the last reactor. The breakthrough for the IFAS system came after the MBBR process was introduced by Odegaard in the 1990's. Odgeaard was the designer of plastic MBBR carriers and the main author of design criteria for such systems over the past 2 decades. Plastic carriers with a density similar to that of water move freely in a reactor under the turbulence caused by diffused aeration. The carriers are retained in the reactor through cylindrical sieves. Since MBBR carriers have been applied in IFAS processes many of the previous determining issues were resolved and the technology has gained more favour in the market. Today there are more than 600 full-scale IFAS plants operational in the world (Odegaard, 2015).

3 Description of the IFAS Process

In its broadest sense the IFAS process is a combination of an activated sludge process and a fixed-film process, although many other processes adhere to this definition e.g.:

i. External Nitrification, using trickling filters;
ii. Rotating Biological Contactors (RBC);
iii. High Rate MBBR process;

A further differentiator is whether the suspended biomass and the fixed film media are in contact or separated. External Nitrification is an example of a separated fixed-film activated sludge (SFAS) process (Odegaard, et al., 2014). The integrated fixed-film activated sludge (IFAS) process can therefore be loosely defined as a wastewater treatment system comprising suspended activated sludge and fixed-film biomass that are in contact with each other.

An IFAS process is most commonly a retrofit or departure from a conventional activated sludge plant where media is placed in the aerobic zone to facilitate biofilm growth. The media can be fixed media such as AccuFAS^{TM}, Bio-Blok^{TM}, or suspended rope Ringlace^{TM} (Ekama, 2014). The media can also be suspended, floating, or moving such as Kaldness^{TM} carriers or ABC^{TM} carriers. The different types of media are discussed in more detail in Section 11. This report focusses mainly on the use of moving bed media in the IFAS reactor, also called the MBBR-IFAS process.

The IFAS process could be an effective and non-disruptive way to increase the capacity of existing activated sludge plants. Upgrades can be done without any increase in footprint and in most cases with only minor modifications. This option is especially attractive in dense urban areas where space for expansion is limited.

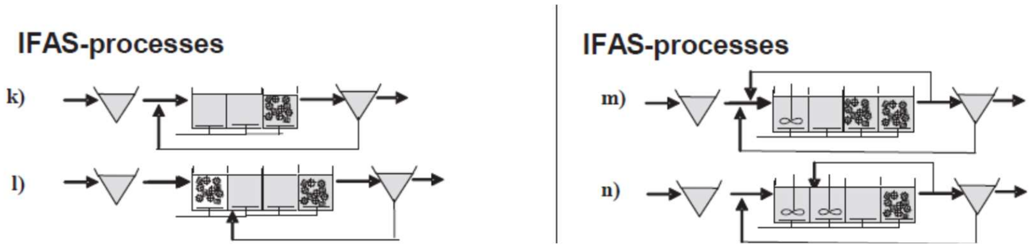


Figure 3.1: Typical IFAS configurations (Odegaard, 2014)

Various configurations of the IFAS process exists as can be seen in Figure 3.1. No process consideration prevents the addition of IFAS media in the anaerobic and anoxic zones of a BNRAS reactor. Both denitrification and P-removal can be facilitated in biofilms. However, P-removal and denitrification are strengths of the activated sludge process, which produces relatively low and predictable effluent concentrations at low sludge ages. This study therefore considers placing the biofilm carriers only in a strategic portion of the aerobic zone so that nitrification is enhanced. This way the strengths of the two supplementary processes are exploited and a more economical solution is achieved. The UCT process configuration is preferred in the Western Cape province of South Africa as well as some other parts of the world. The UCT configuration was also selected for the upgrades at the Borcherds Quarry A-Works, with IFAS being a likely retrofit. Figure 3.2 therefor shows the configuration considered for the remainder of this report. A deviation from the configurations proposed in Figure 3.1 is that carriers will only be placed in the middle (50%) of the aerobic tank. This creates pre-IFAS and post-IFAS zones, each being 25% of the aerobic volume. The pre-IFAS zone has the main function of reducing the organic load to the biofilm carriers. Adding carriers to this zone will have limited benefits since high organic (COD) loading inhibits nitrification on biofilm carriers. The post-IFAS zone facilitates nitrification in the MLSS through nitrifiers scoured from the carriers. It also facilitates flocculation with less intense aeration and a reduced dissolved oxygen (DO) concentration prevents oxygen being recycled to the anoxic zone. It will be shown later in this report that concentrating the IFAS carriers in a smaller zone decreases aeration requirements and therefore saves energy.

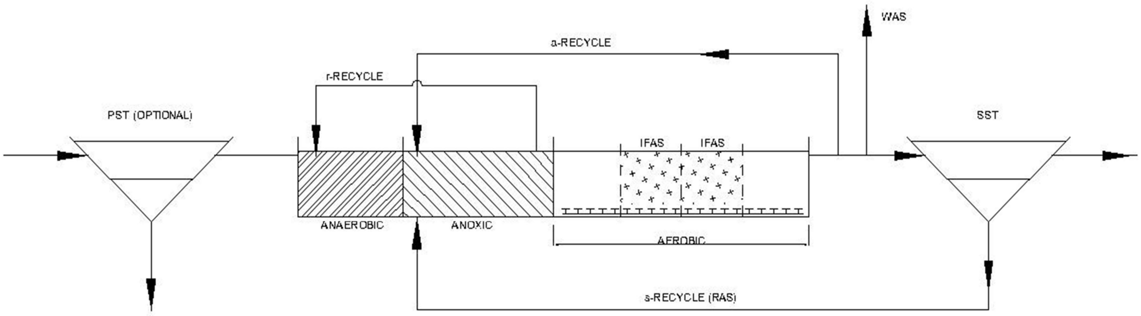


Figure 3.2: Schematic Layout of the UCT-IFAS process that includes anaerobic and anoxic zones for biological nutrient removal. The middle section of the aerobic zone is the IFAS zone which includes biofilm carriers. This is the assumed layout for the discussions included in this report.

The gains sought when converting an activated sludge reactor to an IFAS reactor may be any one or combination of the following:

i. Nitrification at a lower sludge age and therefore increased treatment capacity for a given process volume;
ii. More stable nitrification, especially at low temperatures;
iii. Reduced fluctuation of effluent ammonia concentration;
iv. Better sludge settleability resulting in the option to increase reactor MLSS concentration and thereby increase plant capacity;
v. More protection of the biomass against toxicity shocks;
vi. Better removal of micropollutants.

Key challenges that need to be addressed in the design of an IFAS system are the following:

i. The modelling and prediction of the nitrification rate in the IFAS zone is complex with several factors weighing in on the process;
ii. The nitrification rate decreases with an increase in organic loading (Ekama, 2014). Therefore, an important design objective is to ‘protect’ the IFAS nitrification zone from high organic loadings;
iii. The aerobic IFAS zones, as with any biofilm process, needs to be operated at DO concentrations of typically 3 to 6 mgO/l. This is significantly higher than for activated sludge aerobic zones which are typically operated at a DO concentration of 2 mgO/l;
iv. Practical considerations such as the screening or retaining of the carriers in the designated zones and maintenance of the diffused aeration network below the carriers.

4 The fate of COD in an IFAS Reactor

The biofilms on suspended media can utilize COD effectively. MBBR plants are typically designed as flow-through plants with no recycle. This is possible since all the biomass is retained on the media and a suspended biomass sludge age is not sought. In such plants the biodegradable soluble organics (BSO) are utilized although the biodegradable particulate organics (BPO) that does not get enmeshed and adsorbed (and is not hydrolyzed) in the media will pass through the system. Settleable BPO will settle out in the secondary settling tank (SST) from where it is typically wasted in MBBR systems. Non-settleable BPO will escape with the final effluent.

At high COD loading rates (around 30 gCOD/m^{2}d) compact bacterial biofilms are formed on the media while at moderate loading rates (around 10-15 gCOD/m^{2}d) promotes a more ‘fluffy’ biofilm with a rich variety of ciliated protozoa. Low loading rates (<5 gCOD/m^{2}d) promotes a biofilm dominated by stalked ciliates (Odegaard, 2014).

In an IFAS reactor designed to achieve primarily nitrification on the biofilm carriers, COD removal on the biofilms is not the objective since the activated sludge utilizes COD well enough. In fact, COD utilization on the biofilm should be avoided since the compact heterotrophic biofilms that form inhibits nitrification. At high bulk phase COD concentrations, the heterotrophic biofilm is oxygen limited rather than substrate limited. This means that oxygen cannot diffuse through the heterotrophic film to the slower growing and therefore deeper lying autotrophic film. Hence autotrophic growth and nitrification cannot take place. Therefore, an important objective in an IFAS system is to keep biodegradable COD away from the nitrifying IFAS zone.

For the purposes of this report it is assumed that the same fraction of COD is unbiodegradable for both activated sludge and fixed-film biomass. Unbiodegradable soluble organics (USO) escapes with the final effluent while unbiodegradable particulate organics (UPO) gets enmeshed in the biomass and becomes part of the reactor volatile suspended solids (VSS).

The biodegradable COD entering the reactor comprises a soluble (BSO) and a particulate (BPO) fraction. The BSO (readily biodegradable COD) is typically utilized within the first 2-3 hours of introduction to the biomass. In a UCT process this means that the BSO is mostly taken up in the anaerobic zone by poly-p accumulating organisms (PAO's) or utilized in the anoxic zones for denitrification before it reaches the aerobic zone.

BPO COD on the other hand is not readily biodegradable. Due to its particulate nature, it needs to be hydrolyzed before it can be utilized. This hydrolysis is the rate-limiting step in the utilization of BPO and can take up to 4 days (at 14°C) in an activated sludge reactor (Ekama & Wentzel, 2008). Since the hydraulic retention time of an activated sludge reactor is typically not more than 24 hours, this means BPO may not be utilized during its first cycle through the reactor. Instead it gets enmeshed in the biomass and settles out in the secondary settling tank before it is recycled back to the reactor. The BPO therefore has a mean residence time in the reactor equal to the sludge age. This is also the main reason why activated sludge reactors for COD removal typically do not have sludge ages below 4 to 5 days.

In an IFAS system a significant portion of the BPO is expected to reach the IFAS zone. For raw wastewater a much higher BPO load is expected on the IFAS zones than for settled wastewater. The carriers and the biofilm will inevitably trap some of the BPO in its irregularities, where it will remain until it is hydrolyzed and utilized (Odegaard, 2014). Since organic loading is an inhibiting factor to the nitrification rate in biofilms, this is an unwanted incidence that should be avoided or reduced with careful design. To estimate the BPO load that reaches the IFAS reactor, one would have to consider the enmeshment, adsorption, hydrolysis and utilization rate of the BPO by the suspended biomass. Adsorption and hydrolysis would be the rate limiting steps, with utilization occurring within 2-3 hours after hydrolysis. The steady state activated sludge model does not consider this rate since it assumes that all BSO and BPO are transformed to ordinary heterotrophic organism (OHO) VSS mass at sludge ages longer than 4 days (Ekama & Wentzel, 2008).

The BPO hydrolysis gradient through the aerobic zones becomes an important factor to understand in order to design the IFAS zones optimally. Since COD inhibits biofilm nitrification, it is important to understand what the BPO COD loading on each of the four aerobic zones are. Modelling was done using UCTOLD software, where one anoxic tank preceded four equally sized aerobic tanks. The model was run at 14°C with sludge ages ranging between 5 and 15 days and anoxic mass fractions of 0.4 to 0.5. It was found in each case that BPO COD hydrolysis (and therefore utilization) was evenly spread throughout the four aerobic tanks. In other words, in each of the tanks about 25% of the BPO COD was utilized. This assumption is carried forward to the IFAS model and allows for simplified calculation of the C/N ratio in each tank and the influence this has on nitrification.

Table 4.1 shows a typical South African domestic wastewater COD fractionation.

Table 4.1: Typical South African wastewater COD fractions [adapted from (Wentzel & Ekama, n.d.)]

	Raw	**Settled**
UPO	(13%) 130 mgCOD/l	(4%) 27 mgCOD/l
USO	(7%) 70 mgCOD/l	(11%) 70 mgCOD/l
BPO	(60%) 600 mgCOD/l	(54%) 353 mgCOD/l
BSO	(20%) 200 mgCOD/l	(31%) 200 mgCOD/l
Total COD	(100%) 1000 mgCOD/l	(100%) 650 mgCOD/l

PST's typically remove 40% of the BPO load to the reactor. This is beneficial for nitrification in the IFAS process since it reduces the inhibiting COD load to the IFAS nitrification zone. The BPO load to the IFAS zones for settled wastewater systems may in some cases be low enough to make installation of biofilm carriers in the pre-IFAS zone feasible for high TKN/COD wastewater.

5 Nitrification Theory

Nitrification is the biological process whereby free and saline ammonia (FSA) is oxidized to nitrite and nitrate (Ekama & Wentzel, 2008).

5.1 Microbiology

Nitrification is mediated by specific autotrophic organisms. These organisms obtain their carbon (anabolism) from dissolved CO_2 while their energy for biomass synthesis (catabolism) is obtained from oxidizing ammonia to nitrite and nitrite to nitrate (Ekama & Wentzel, 2008). The first step, oxidation of ammonia, is mediated by ammonia nitrifying organisms (ANO's) while the oxidation of nitrite to nitrate is mediated by nitrite oxidizing organisms (NOO's). Nitrosomonas and Nitrobacter were originally thought to be the only mediators of nitrification, but recent studies have revealed that there are several genera of nitrifying organisms (Ekama & Wentzel, 2008).

5.2 Nitrification in conventional activated Sludge

The rate of the two-step nitrification process is governed by the rate of the slower step, namely the oxidation of ammonia to nitrite by the ANO's. Once this step is complete, nitrites are virtually immediately oxidized to nitrate by the NOO's. This is the reason why nitrite concentrations in municipal wastewater treatment plants are generally very low (<1mgN/l). As a simplification for steady state models only the rate limiting step is considered and it is assumed that ANO's convert ammonia directly to nitrate (Ekama & Wentzel, 2008).

The rate of nitrification has been successfully formulated in terms of the Monod equation in 1964 by Downing et al. (Ekama & Wentzel, 2008). According to Monod:

i. The mass of organisms generated is a fixed fraction of the mass of substrate (ammonia) utilized and
ii. The specific growth rate (rate of growth per unit mass of organisms per unit time) is related to the concentration of substrate surrounding the organisms.

From (i)

Equation 5.1: Mass of ANO's generated (Monod)

$$M\Delta X_{BA} = Y_A M\Delta N_a$$

Where;

$M\Delta X_{BA}$ = mass of nitrifiers generated (mgVSS)

$M\Delta N_a$ = mass of ammonia as N utilized (mgFSA-N)

Y_A = nitrifier yield coefficient (mgVSS/mgN)

From (ii) The Monod equation is shown below:

Equation 5.2: Monod Equation for nitrifier growth

$$\mu_A = \frac{\mu_{Am} N_a}{K_{nT} + N_a}$$

Where;

μ_A	specific growth rate at ammonia concentration (1/d) N_a
μ_{Am}	maximum specific growth rate of nitrifiers (1/d)
K_{nT}	half saturation constant, i.e. the concentration at which $\mu_A = \frac{1}{2}\mu_{Am}$ (mgN/l)
N_a	bulk liquid ammonia concentration (mgN/l)

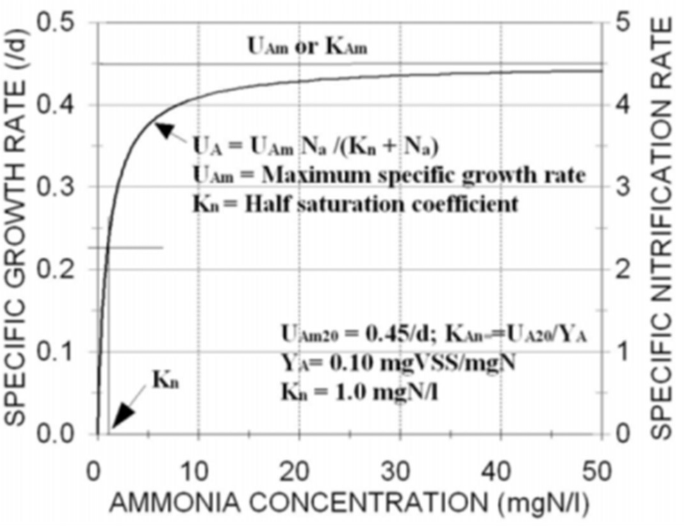


Figure 5.1: The Monod specific growth rate equation for nitrification at 20°C (Ekama & Wentzel, 2008)

Monod growth kinetics require that three constants be known, namely the yield coefficient Y_A, maximum specific growth rate μ_{Am} and the half saturation coefficient K_n. For the activated sludge process these constants are shown in Table 5.1.

Table 5.1 Kinetic constants and their temperature sensitivity for ANO's (Ekama & Wentzel, 2008)

Kinetic Constant	Symbol	Unit	At 20°C	θ
Yield coefficient	Y_A	mgVSS/mgFSA	0.10	1.00
Endogenous respiration rate	b_A	/d	0.04	1.029
Half saturation coefficient	K_n	mgFSA/l	1.0	1.123
Max specific growth rate	μ_{Am}	/d	varies	1.123

Monod growth kinetics have proved to be extremely effective in describing nitrifier growth in the activated sludge process and consequently nitrification in the activated sludge process is well understood (Ekama & Wentzel, 2008). The biggest cause of uncertainty is μ_{Am}, considered a wastewater characteristic rather than a kinetic constant, since it varies for different wastewaters.

For nitrifiers to be sustained in an activated sludge system, the growth rate of the nitrifiers (less endogenous respiration) should be higher than the rate at which nitrifiers are removed from the system through sludge wastage. The minimum sludge age calculated in Equation 5.3 defines the maximum sludge wastage rate that maintains nitrifiers in the system. Since nitrifiers are obligate aerobes that do not grow in unaerated zones, the specific growth rate is adjusted for by ($1-f_{xt}$), where f_{xt} is the total unaerated mass fraction.

Equation 5.3: Minimum sludge age required for nitrification

$$SRT_m = \frac{S_f}{(1 - f_{xt})\mu_{AmT} - b_{AT}S_f}$$

If a system is operated at a sludge age higher than the minimum required sludge age for nitrification, near-complete nitrification will take place. The steep slope of the Monod growth curve for nitrifiers (or the small value of K_a) ensures that nitrification proceeds at almost maximum rate for ammonia concentrations > 5 mg/l, but it is difficult to achieve very low ammonia concentration (<1 mgN/) as can be seen in Figure 6.10. If the system nitrifies the ammonia concentration towards the end of the reactor will be low (<2.0 mgFSA/l) which will cause the nitrifier growth rate to reduce rapidly. For this reason, effluent ammonia concentrations of zero is not achievable.

The effluent ammonia concentration is sensitive to dynamic flow conditions. The greater the diurnal flow variation, the higher the peak and average effluent ammonia concentration. The purpose of the safety factor S_f (typically 1.1 to 1.4) is to accommodate such dynamic flow variations. The higher the S_f, the lower the peak and average ammonia concentrations, but the higher the sludge age. This again results in a larger biological reactor.

5.3 °Comparison of suspended sludge and fixed film nitrification kinetics

Table 5.2 is a comparison between the nitrification kinetics in conventional activated sludge and fixed film (MBBR-IFAS), and aids to better understand the similarities and differences of these systems. The table comprises of two sections namely Nitrifier Growth and Nitrification Rate, owing to the governing nitrification dynamics in activated sludge and fixed-film reactors respectively.

Table 5.2: Comparison of the nitrification kinetics in suspended activated sludge and biofilms.

	Activated Sludge (Ekama & Wentzel, 2008)	**Attached Growth MBBR-IFAS**
NITRIFIER GROWTH		
Max Specific Growth Rate	The kinetic constant μ_{Am20} has been observed to vary considerably for different wastewaters. Therefore, μ_{Am20} is classified as a wastewater characteristic rather than a process kinetic. Values between 0.3 and 0.75 have been observed. The cause of the variation seems to be of an inhibitory nature due to undefined chemicals in the influent. Industrial wastewater therefore typically causes a lower growth rate than domestic wastewater.	The nitrifier growth rate is not a design parameter for attached growth systems, probably since the nitrifiers have an indefinite period in which to grow. Detachment of the biomass needs to happen before it gets wasted with the suspended WAS and typically detachment only happens once a prolific biomass has formed. Therefore, the attached growth system controls its own sludge age that is by implication long enough to ensure nitrifier growth has taken place (if conditions are conducive to nitrifier growth). Hydrodynamics, and in this case the turbulence and shear caused by fine bubble aeration and contact between carriers have a significant effect on the sloughing rate and biofilm sludge age.
Endogenous Respiration Rate	b_{n20} is considered constant for all municipal wastewater at 0.04/d. Its effect is quite small. Endogenous respiration of nitrifiers takes place in aerobic and unaerated zones.	This is not an important design parameter since nitrifier growth is not considered as discussed above. Since nitrifiers are not exposed to unaerated zones (where no growth takes place, but endogenous respiration still occurs) it has a growth advantage over the suspended nitrifiers.
Half-Saturation Coefficient	K_{n20} is considered constant for all municipal wastewater at 1.0 mgFSA-N/l. It is indicative of the steep slope of the Monod growth curve for nitrification and is the reason why nitrification happens to near-completion when conditions are favorable for nitrifiers. It is also the reason why effluent ammonia concentration below 1.0 mgFSA-N/l is hard to achieve. When the ammonia concentration is low nitrifier growth and nitrification is substrate limited and slows down dramatically.	Not an important design parameter since nitrifier growth is not considered as discussed above. Since the nitrification capacity of system defined by system parameters such as DO, organic load and surface area, nitrification does not continue to “completion” as readily as in activated sludge. As with MLSS the low value of K_{n20} is the reason why effluent ammonia concentration below 1.0 mgFSA-N/l is hard to achieve.
Temperature	Nitrifier growth kinetics are very sensitive to temperature. $$\mu_{AmT} = \mu_{Am20}(1.123)^{(T-20)}$$ $$K_{nT} = K_{n20}(1.123)^{(T-20)}$$	An IFAS process is less sensitive to temperature than CAS. Although nitrifier growth (μ_{AmT}) may be equally slow for both systems, the nitrifiers in the biofilm are not subjected to short sludge ages and have more time to grow. When a nitrifier population on a biofilm is established

	Activated Sludge (Ekama & Wentzel, 2008)	**Attached Growth MBBR-IFAS**
	$b_{AT} = b_{A20}(1.029)^{(T-20)}$ For every 6°C drop in temperature the μ_{AmT} value halves which means the minimum sludge age for nitrification doubles.	the nitrification rate is not as susceptible to temperature variations. In an IFAS system it is typically observed that during winter the attached biomass is significantly more than in summer. A typical example of this was observed at Broomfield WWTW in Colorado where an IFAS process was operated at sludge ages between 4 and 7 days with temperatures between 12°C and 23°C (Rutt, et al., 2006). See Figure 6.8. The most likely explanation is that the suspended biomass nitrifies the ammonia in summer months due to more favorable nitrifier growth kinetics at warmer temperatures. This leaves less ammonia available for the attached growth nitrifiers and the population is reduced therefore. During winter months the less favorable growth kinetics of the suspended nitrifiers causes nitrification in the suspended biomass to cease or become unstable. More ammonia is available for the attached growth nitrifiers and the biofilm proliferates.
Unaerated Zones	Nitrifiers are obligate aerobes and only grow in the aerobic zone of a reactor while endogenous respiration takes place in both aerobic and unaerated zones. The effect of this dynamic is that the growth rate of nitrifiers is reduced with the same fraction as the unaerated mass fraction of the system. This increases the minimum sludge age for nitrification by 40% to 100% for f_{xt} between 0.3 and 0.5.	Unlike the suspended biomass, the biofilm on the carriers remains in the aerobic zone of the reactor. The nitrifier growth is therefore not hindered by exposure to unaerated portions of the reactor. As mentioned earlier nitrifier growth rate is not determining for nitrification in biofilms.
Safety Factor for nitrifier growth rate (S_f)	Nitrification is unstable near the minimum sludge age (or max unaerated fraction), especially with cyclic flow and load conditions. To ensure consistent nitrification a factor of safety S_f is applied that reduces the maximum specific growth rate (μ_{Am20}) of the nitrifiers. S_f = 1.25 to S_f = 1.35 is typically used.	S_f is not used in biofilm processes. It will be shown however in Section 6.7 that the operational sludge age over the minimum (SF) required sludge age for nitrification in the MLSS has a significant effect on whether nitrification takes place in the biomass or MLSS in an IFAS system. (Note that this SF is applied directly to sludge age and not to the nitrifier growth rate) $SF = {}^{SRT}/_{SRT_m}$
Minimum Sludge age for nitrification	The minimum sludge age required for nitrification captures the effects of all the considerations above and defines the conditions at which nitrifiers will be sustained in the system: $SRT_m = \dfrac{S_f}{(1-f_{xt})\mu_{AmT} - b_{AT}S_f}$	Detachment of the biomass needs to happen before it gets wasted with the suspended WAS and typically detachment only happens once a prolific biomass has formed. Therefor the attached growth system controls its own sludge age that is by implication long enough to ensure nitrifier growth has taken place (if conditions are conducive to nitrifier growth). Hydrodynamics, and in this case the turbulence and shear caused by fine bubble aeration and contact between carriers have a significant effect on the sloughing rate and biofilm sludge age.

	Activated Sludge (Ekama & Wentzel, 2008)	**Attached Growth MBBR-IFAS**
NITRIFICATION RATE		
Nitrification Rate	The nitrification rate is directly related to the specific growth rate for nitrifiers as can be seen on the two parallel axis of the Monod growth curve (Figure 5.1). KAm ranges from 3.0 mgFSA-N/mgANOVSS.d to 7.5 mgFSA-N/mgANOVSS.d as µAm20 ranges between 0.3 d-1 and 0.75 d-1. This direct correlation stems from the fact that the yield coefficient is assumed to be constant at 0.10 mgANOVSS formed per mg FSA-N nitrified. Evidence that Y_A is not constant has been presented in the 1960's however Downing et al. stated that different Y_A values that can be observed at different VSS concentrations are inconsequential since μ_{Am} is experimentally derived from the maximum specific nitrification rate K_{Am} observed. $K_{Am} = \mu_{Am}/Y_A$ The nitrification rate is virtually at its maximum if the bulk liquid ammonia concentration is above 2 mgN/l. The maximum nitrification rate in an activated sludge system is directly coupled to μ_{Am20} which is deemed to be a wastewater characteristic rather than a process kinetic. At bulk liquid ammonia concentration below 2.0 mgN/l the nitrification rate slows down rapidly and therefore zero effluent ammonia is not readily achieved.	The nitrification rate can be predicted using the following model (Odegaard, et al., 2014): $r_n = k(Sn)^n$ where r_N = nitrification rate (gNH_4-N/m^2d) k = reaction rate coefficient, dependant on organic load (C/N ratio) and temperature. n = reaction order constant, estimated 0.7 Sn = rate-determining ammonium concentration, mgNH4-N/l (can be estimated at Sn = (DO_{bulk} – 0.5)/3.2) With essentially all BOD removed upstream of nitrification zone k may be set at 0.75. Alternatively, k may be estimated, varying from 0.7 at 0.5 $gBOD_5$/ gNH_4-N influent C/N ratio to 0.5 at C/N = 4.5 $gBOD_5$/ gNH_4-N (Odegaard, et al., 2014). The nitrification rate is linearly dependent on DO concentration. A feasible control philosophy would be to do ammonia concentration measurement in the aerobic zone and vary the DO in the IFAS zone between 3 and 6 mgO/l to achieve the desired nitrification rate and effluent ammonia concentration.
Surface Area of Carriers	Nitrifiers are part of the volatile suspended solids (VSS) mass and no carriers are used.	It has been demonstrated that biofilm area is the key parameter in design and the nitrification rate is based on the effective carrier area ($g/m^2_{carrier}$ area.d) (Odegaard, et al., 2000)
Steady state Influent Ammonia Concentration vs. **Nitrification capacity**	Influent ammonia concentration is not determining for effluent ammonia concentration. If the system nitrifies, it does so effectively and almost to completion as is shown in Figure 6.8. The influent ammonia concentration is immaterial to the minimum sludge age required for nitrification. The nitrification capacity of activated sludge is very large (almost indefinite), provided that the system has enough time to respond (grow enough ANOVSS).	Influent ammonia concentration is determining for effluent ammonia concentration. Nitrification rate and available media surface area defines system nitrification capacity. Nitrification capacity of system defined by system parameters: i. DO concentration; ii. Organic load (C/N ratio); iii. Temperature. If nitrification capacity of system is exceeded high effluent ammonia concentrations can be expected.

	Activated Sludge (Ekama & Wentzel, 2008)	**Attached Growth MBBR-IFAS**
DO Concentration	Nitrification rates are not significantly affected for DO rates up to 33 mgO/l. Floc size and mixing intensity/turbulence plays a role in oxygen diffusion to nitrifiers at center of floc. In most cases a DO concentration of 2 mgO/l at the reactor surface ensures that nitrification can take place without impairment.	The nitrification rate is linearly dependent upon the oxygen concentration up to more than 10 mgO_2/l. Normally one designs for DO concentrations of 4 to 6 mgO_2/l at peak load. The linear relationship between oxygen concentration and nitrification rate can be used favorably for process control (Odegaard, 2014). In the last section the oxygen concentration may be low since the nitrification rate is not oxygen limited but ammonium limited. In Section 6.7 the apportionment of nitrification to the biofilm and suspended biomass is discussed. It is observed than when conditions are favorable for nitrification in the suspended biomass (i.e SRT > SRT_m), nitrification tends to happen in the MLSS rather than on the biofilm. The hypothesis for this phenomenon is that nitrifiers in the MLSS have relatively unrestricted access to oxygen whereas the biofilm require oxygen to diffuse through the surface to the nitrifiers deeper in the biofilm. This is the most likely reason why the MLSS nitrifiers 'outcompete' the biofilm nitrifiers for substrate. It also explains why biofilms require higher DO concentrations than MLSS for nitrification.
Bulk liquid Ammonia Concentration	For bulk liquid ammonia concentrations above 2 mgFSA-N/l the nitrification rate is virtually at its maximum. At concentrations below 2 mg FSA-N/l the nitrification rate rapidly declines to zero. The implication thereof is that when nitrification takes place, the process is completed rapidly, but the ammonia concentration cannot readily be reduced to 0 mgFSA/l.	As long as the ammonia concentration is above 0.5 - 1.5 mgNH4-N/l (depending on oxygen concentration, see figure 7) the nitrification rate will not be limited by ammonium but by oxygen (Odegaard, 2014). The ammonia concentration cannot readily be reduced to 0 mgFSA/l.
Organic Loading	The organic loading or TKN/COD ratio is not known to have an effect on nitrification in an activated sludge system. Since nitrifiers are free swimming, diffusion of oxygen and substrate are not limiting factors. Where aerobic granules and large flocs are present a degree of diffusion limited nitrification may occur.	Organic load has a determining influence on the nitrification rate in attached growth systems. The inhibiting influence of organic loading on nitrification arises due to prolific heterotrophic growth on the media from COD utilization. Oxygen cannot diffuse through the heterotrophic layer to the ANO's beneath. Nitrification is first order with respect to organic loading. This means aerobic zone should be subdivided to gain benefit of lower organic loads in latter reactors.
Cyclic Flow and Load	The nitrification efficiency of an activated sludge reactor decreases with cyclic flow and load conditions in comparison with the results found in steady state conditions. During peak loads the nitrifier population cannot respond (grow) quickly enough to oxidize the excess ammonia. The excess	The nitrification rate is linearly dependent on DO concentration. A feasible control philosophy would be to do ammonia concentration measurement in the aerobic zone and vary the DO in the IFAS zone between 3 and 6 mgO/l to achieve the desired nitrification rate and effluent ammonia

	Activated Sludge (Ekama & Wentzel, 2008)	**Attached Growth MBBR-IFAS**
	ammonia is discharged with the effluent which in turn reduces the mass of nitrifiers formed. The safety factor for nitrification S_f, (at S_f of 1.1 to 1.4) compensates somewhat for this by effectively increasing the system sludge age. Significant diurnal variation of the effluent ammonia concentration can still be expected for an influent ammonia load amplitude of 0.25 or higher.	concentration. This may assist to reduce diurnal variations in effluent ammonia concentrations. It is likely that additional surface area to that required in a steady state calculation may improve diurnal variation of the effluent ammonia concentration.
pH and alkalinity	μ_{AmT} Is adversely affected if the reactor pH falls outside the 7.0 to 8.5 range. Within this range optimal nitrification rates are expected with sharp declines outside this range. Nitrification consumes alkalinity at 7.14 mg alkalinity (as $CaCO_3$) per mgFSA-N nitrified. Denitrification restores 3.57 mg alkalinity (as CaCO3) per mg NO3-N denitrified. The reactor alkalinity should be maintained above 40 mg/l in order to maintain a pH above 7.	Expected to be similar to activated sludge.

6 Modelling IFAS Nitrification

The IFAS process is not a simple process to model. The activated sludge system is well understood, and fairly accurate models are used daily across the world to simulate the processes. This includes steady state models and dynamic models such as Activated Sludge Model No. 1 (ASM1), ASM2, ASM2d etc. Attached growth systems on the other hand have proven to be more challenging from a modelling perspective. Biofilm growth is multifaceted and intricate, making it very hard to model from 'first principles'. Although activated sludge models are also based on observations of the behavior of a large variety of organisms, the combined kinetics thereof has, to date, been more predictable than that of biofilms. The root of uncertainty may at least in part be attributed to the uncontrolled nature of the thickness and density of a biofilm, the micro mechanics that causes or prevents sloughing and diffusion kinetics of electron donors and acceptors through a diverse organism groups. IFAS adds even more complexity in that there may be interaction between the suspended biomass and the biofilm.

In this report the activated sludge steady state model is used as a departure point. The biofilm on the carriers are only modelled according to their intended purpose, i.e. nitrification. Nitrification in IFAS reactors has been observed to take place simultaneously in suspended sludge and carriers under certain conditions. An attempt is made to model this interaction and thereby predict the combined and respective contributions of the activated sludge and biofilms to nitrification.

6.1 Nitrification in MLSS

The nitrification model used in the activated sludge system was discussed in Section 5.2. The observation was made that the growth rate of the nitrifiers is an extremely important parameter and a long enough sludge age to maintain nitrifiers in the system is paramount. It was also observed that nitrification will happen very effectively and produce low effluent ammonia if the minimum sludge age requirement is adhered to.

To compare the sludge age requirements of IFAS plants with that of activated sludge plants Johnson (Odegaard, et al., 2014) compared the design sludge age and temperatures of various IFAS plants in the US with the (German) ATV design curve for nitrification and presented Figure 6.1 below.

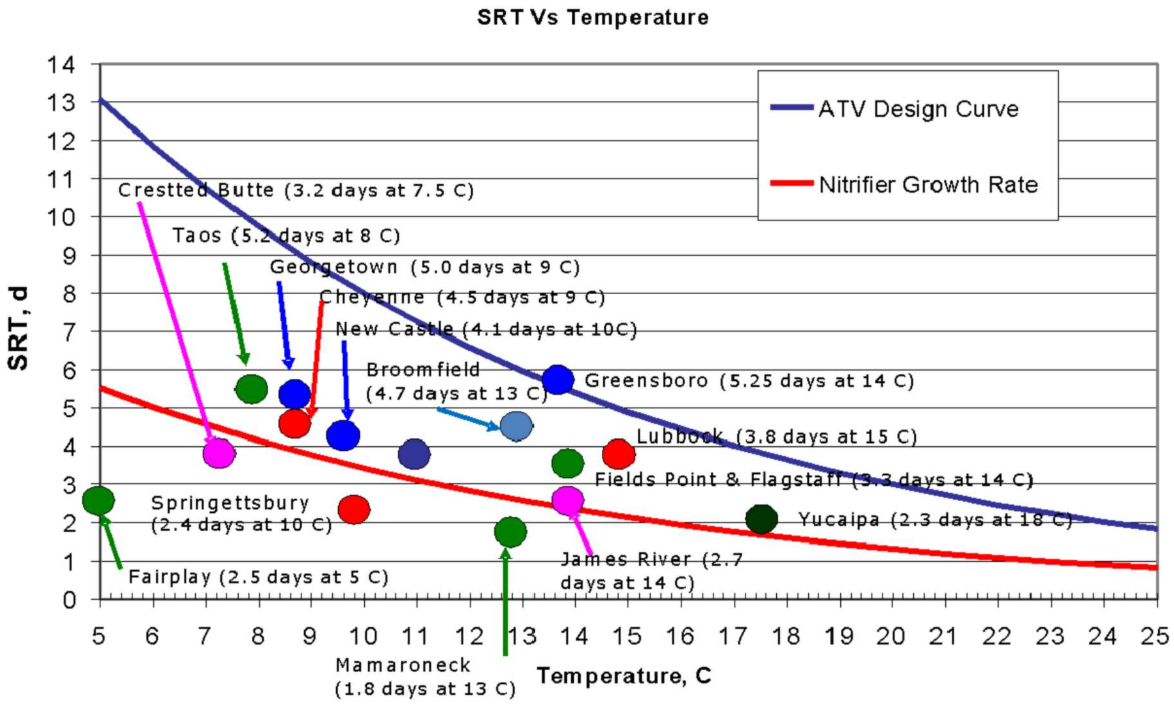


Figure 6.1: Suspended solids retention time (SRT) vs. wastewater temperature for various IFAS wastewater treatment plants (red line) compared to the ATV suspended activated sludge SRT vs temperature guideline for nitrification (blue line). (Ekama, 2014)

It is evident that IFAS plants can be operated at sludge ages well below that proposed by the ATV design curve. Ekama (2014) simulated the average performance of these plants (red line) by applying the activated sludge calculation for the minimum required sludge age (SRT_m) for nitrification. That is $SRT_m = 1/\{\mu_{Am20}(\theta_\mu)^{(T-20)} - b_{A20}(1.03)^{(T-20)}\}$. The best fit was given by $\mu_{Am20} = 1.10/d$ and $\theta_\mu = 1.143$. The best fit for the (blue) ATV design curve is given by $\mu_{Am20} = 0.545/d$ and $\theta_\mu = 1.148$. The conclusion drawn is that the biofilm on the IFAS media has at least halved the required sludge age for nitrification.

This approach is valuable to portray the potential benefit of an IFAS reactor although it may not be accurate enough for modelling purposes. An underlying assumption in Figure 6.1 when deriving nitrifier growth rates from the ATV design curve and from the red line, is that the systems are fully aerobic. If one were to model IFAS performance by using $\mu_{Am20} = 1.10/d$ and $\theta_\mu = 1.143$ in an activated sludge model and adjusting for the fact that no nitrifier growth happens in the unaerated mass fractions the model would still predict relatively high sludge age requirements at low temperatures. This is not accurate since an IFAS reactor designed for nitrification on the biofilm is not negatively affected by a large unaerated mass fraction. The biomass is stationed in the aerobic zone and can grow uninterrupted, since it does not pass through unaerated zones. Also, the trend of a higher required suspended sludge age at lower temperatures does not make sense as a requirement for nitrification in an IFAS reactor, since the autotrophic biomass on the media are not subjected to the suspended sludge age and can grow for extended periods until it is sloughed from the media.

Perhaps the most important deduction from Figure 6.1 is that all the IFAS plants shown could nitrify at suspended sludge ages below 6 days regardless of the temperature or the unaerated mass fraction. The suspended sludge age in an IFAS reactor is not of primary importance for nitrification in an IFAS reactor, it is instead selected to ensure hydrolysis of all the slowly biodegradable COD, to ensure stable aerobic P uptake, to achieve a certain volume and stability of WAS sludge and to improve biomass flocculation.

6.2 Nitrification in IFAS Biofilm

Nitrification in the biofilm of an IFAS reactor may be modelled using the empirical equation developed for the pure MBBR process (Odegaard, et al., 2014). The nitrification rate (r_N) is estimated as follows:

Equation 6.1: Area-specific nitrification rate expression

$$r_N = k(S_n)^n$$

r_N = *nitrification rate* ($gNH_4\text{-}N/m^2.d$)

k = *reaction rate coefficient*

n = *reaction order constant, can be estimated at* $n = 0.7$

Sn = *rate-determining ammonia concentration,* $mgNH_4\text{-}N/l$*; can be estimated as*

$Sn = (DO_{bulk} - 0.5)/3.2$ *when ammonia concentration is above 1.5* $mgNH_4\text{-}N/l$.

Figure 6.2 below shows that for bulk liquid ammonia concentration above 1.5 mgFSA-N/l the DO concentration, and not ammonia is rate determining.

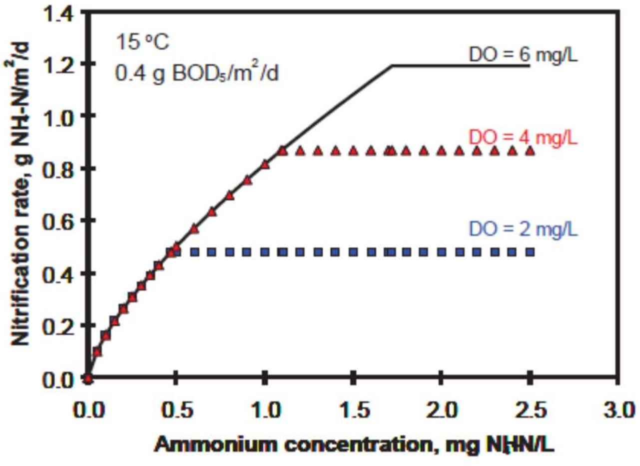


Figure 6.2: The area-specific nitrification rate in MBBR processes at various dissolved oxygen and bulk liquid ammonia concentrations. (Ekama, 2014)

Odegaard et al. (2014) states that the k value is dependent on the influent wastewater C/N ratio (BOD_5/NH_4-N). He goes on to state that the k value may be set at 0.75 if (essentially all) BOD is removed in a suspended sludge or IFAS reactor upstream. Unfortunately, the literature that presents data for the inhibition of nitrification due to the presence of organic material only refers to BOD, rather that COD and its various components, which makes it difficult to integrate the activated sludge and biofilm nitrification models. It is unclear whether Odegaard is referring to slowly biodegradable (particulate) organics as well as readily biodegradable (soluble) organics. This is an important distinction for an IFAS process, since unlike pure MBBR processes, an IFAS process retains and recycles BPO long enough for it to be hydrolyzed and available for utilization by OHO's on the biofilm. A worthwhile research topic (out of the scope of this thesis) would be to determine through laboratory work how nitrification is inhibited on biofilm due to heterotrophic growth in response to BSO and BPO separately. BSO is very rapidly utilized and so can cause fast overgrowth of nitrifiers on the carriers. In contrast BPO is utilized slowly and so results in a much slower overgrowth of nitrifiers. Since a fraction of BPO may be enmeshed and hydrolyzed in the MLSS it would be interesting to know to what degree this BPO is available for the OHO's on the biofilm and how nitrification is inhibited by it.

Odegaard et al. (2014) presents the following curve to describe the influence of C/N ratio on the nitrification rate coefficient (k) in an IFAS system. He describes the C/N ratio in terms of BOD_5 and ammonia.

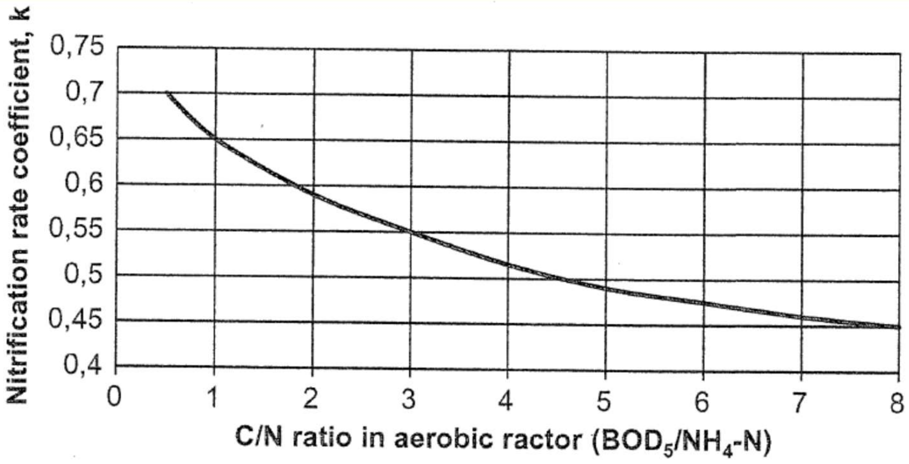


Figure 6.3: The nitrification rate coefficient, k, as a function of the C/N ratio of influent to the bioreactor. (Odegaard, et al., 2014)

To incorporate the IFAS model into the CAS model it was necessary to express the C/N ratio in terms of COD. An estimation was made that the COD/BOD_5 ratio is approximately 2.0 and Figure 6.4 was produced to show the relationship between COD and the nitrification rate coefficient k. Since unbiodegradable COD (USO + UPO) is believed to have no influence on biofilm growth, it was further decided to express the k-value as a function of biodegradable organics (BPO + BSO) only. A typical biodegradable COD (BCOD) fraction of 0.85 was used and the C/N ratio is expressed as $BCOD/NH_4$. The ammonia concentration used is the influent-equivalent nitrification capacity of the system after sludge production. A polynomial trendline was used to express the curve as a function and allow for automatic calculation of k in the spreadsheet.

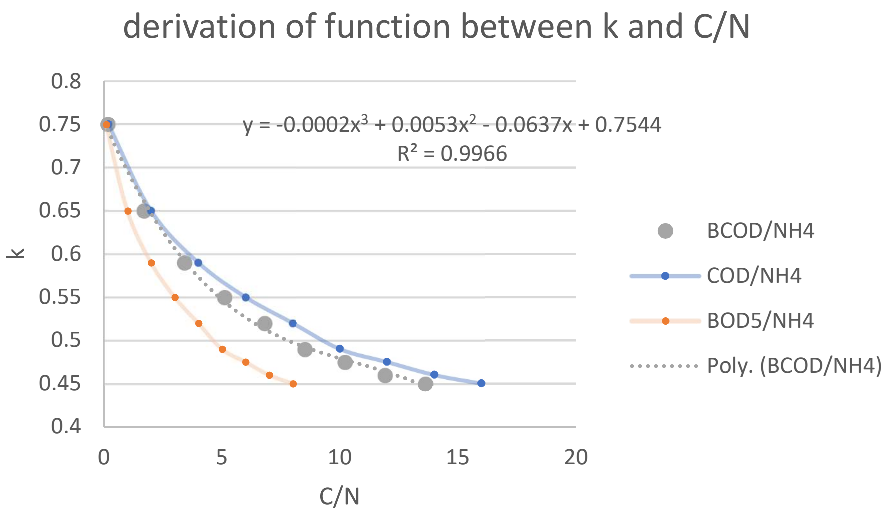


Figure 6.4: The nitrification rate coefficient, k, as a function of the C/N ratio of influent to the bioreactor converted from BOD_5/NH_4 to biodegradable COD to ammonia ($BCOD/NH_4$).

The sensitivity of the nitrification rate r_N in relation to the bulk liquid DO concentration and the C/N ratio is shown in Figure 6.5. Once the IFAS system is designed and the available surface area for biofilm growth has been fixed, both the DO concentration and the COD load (or C/N ratio) in the IFAS zones will be determining parameters for the system nitrification rate and capacity.

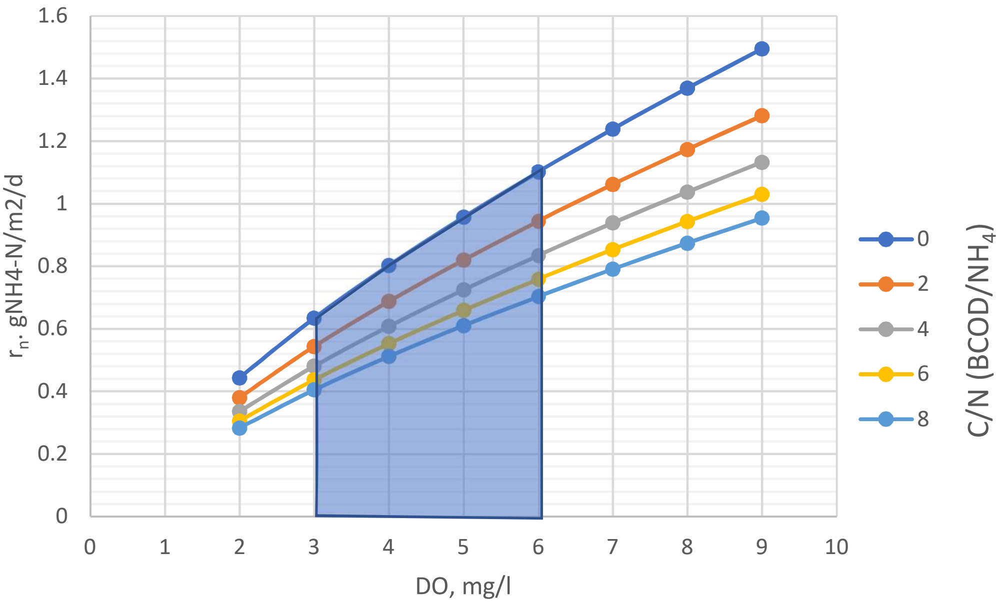


Figure 6.5: The sensitivity of the area-specific nitrification rate (r_n) to the dissolved oxygen concentration and the influent C/N ratio.

It is clear from Figure 6.5 that a near-linear relationship exists between the DO concentration and the nitrification rate when the bulk liquid ammonia concentration is sufficient (> 2 mgN/l). The DO concentration can be manipulated operationally between 3 mgO/l and 6 mgO/l at the reactor surface. The lower limit of the DO concentration will be governed by the requirement for keeping the carriers mixed and suspended and to ensure that oxygen can diffuse to the nitrifiers in the biofilm. The upper limit is an economical consideration due to increased aeration costs. The target DO concentration is the lowest possible value that will keep the carriers in suspension and also allow sufficient DO diffusion through the OHO biofilm to the ANO's to produce a nitrification rate that will result in low (<2mgN/l) effluent ammonia concentration. A rational operational strategy would be to install inline ammonia metering instrumentation and to automate control of the aeration in the IFAS zones to meet the target effluent ammonia concentration. The pre- and post-IFAS aerobic zones can be operated at conventional DO concentrations around 2 mgO/l.

The sensitivity of the nitrification rate r_N in relation to the C/N ratio at a typical IFAS DO concentration of 4 mgO/l is shown in Figure 6.6.

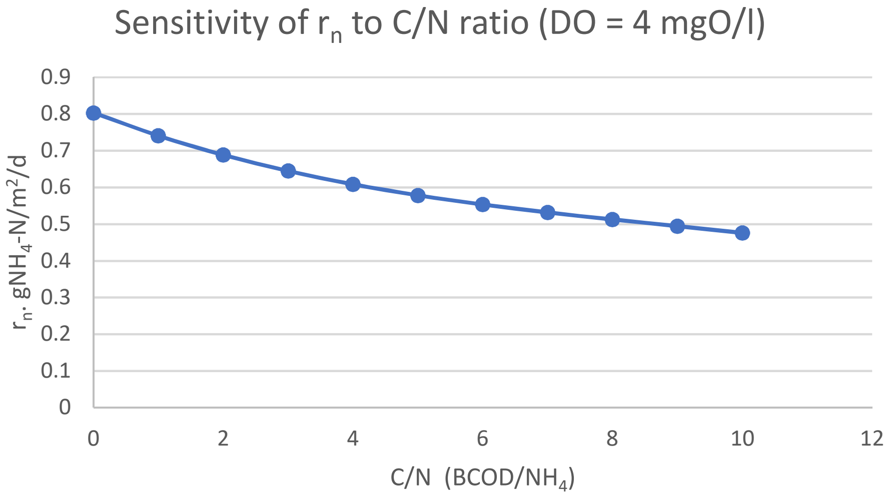


Figure 6.6: The sensitivity of r_N to the influent C/N ratio at a DO concentration of 4 mgO/l.

An important objective in the design of an IFAS system is for maximum biodegradable COD to be utilized upstream of the IFAS zone to reduce the C/N ratio and ensure nitrification at the highest rate. In biological nutrient removal plants, especially in NDEBPR plants, the BSO is often completely utilized in the anaerobic and anoxic zones. The BPO is hydrolyzed and partly utilized in all the zones of the reactor and will contribute to a higher C/N ratio in the IFAS zone.

When PST's are installed upstream that removes a large fraction (about 40%) of the BPO, it will reduce the C/N ratio to the IFAS zone and result in an improved nitrification rate.

6.3 Effect of Temperature on Biofilm nitrification

Biofilm nitrification in an IFAS process is far less sensitive to temperature than nitrification in MLSS. Although nitrifier growth (μ_{AmT}) may be equally slow for both systems, the nitrifiers in the biofilm are not subjected to short sludge ages and have more time to grow. When a nitrifier population on a biofilm is established, the nitrification rate is not as susceptible to temperature variations. The influence of temperature on biofilm nitrification does not even feature in the design procedure presented by Odegaard in Hybrid Systems (Odegaard, et al., 2014).

Since the DO concentration has a big effect on nitrification rate the temperature may have an indirect effect on the nitrification rate. The wastewater temperature will affect the oxygen transfer rate and consequently the nitrification rate. This aspect is related to the fact that the nitrification process is highly influenced by oxygen diffusion and, in a biofilm process, diffusion increases when the temperature decreases, as oxygen solubility is higher with lower temperatures. Since oxygen diffusion is improved at lower temperatures this may, to a degree, counter slower nitrifier growth rates at low temperatures to make IFAS systems even more resilient to temperature variations (Metcalf & Eddy, 2004).

It will be shown in the following section that biofilm nitrification is affected by temperature, primarily due to the influence temperature has on the MLSS. The nitrification (or lack thereof) that takes place in the MLSS determines how much substrate (ammonia) is available for nitrification in the biofilm. Nitrification will shift between MLSS and the biofilm due to temperature variations, but the complete IFAS system is much less susceptible to temperature variations and should give more stable nitrification performance in comparison to CAS.

6.4 Carrier surface Area

The biofilm carrier surface area is one of the most important design variables for an IFAS system (Odegaard, et al., 2000) as can be derived from the fact that the nitrification rate calculations are expressed as a per m^2 value. Operational conditions such as the C/N ratio and DO concentration determine the area specific nitrification rate, but the total carrier surface area available for biofilm growth sets the nitrification capacity for the system. For example, a DO concentration of 4.0 mgO/l and a C/N ratio of 4.0 will result in a nitrification rate of 0.6 gFSA-N/m^2d. A total carrier surface area of 1 000 000 m^2 in a reactor will result in a nitrification capacity of 600 kgFSA-N/d. 800 m^2/m^3 Carrier area per (dry storage) volume occupied results in a bulk carrier volume of 1250 m^3. At a filling fraction of 50% these carriers would fit into a reactor volume of 2500 m^3.

There is a trade-off between operational DO concentration and the carrier surface area supplied. One may opt to operate at a high DO concentration to improve the nitrification rate and provide less carriers, however it is foreseen that the increased aeration costs would make this irrational. The DO level should be chosen around the lower limit (3-4 mgO/l) for design purposes and adequate carriers be provided to achieve the required nitrification capacity at these DO levels.

It would also be good practice to design for a filling fraction of about 55%. If for any reason the system does not perform as desired or the load on the reactor increases, the filling fraction may be increased to the maximum practical limit of 65%. Filling fractions higher than 65% prevents free movement of the carriers (Odegaard, 2014).

6.5 Reactor and SST sizing green fields

The volume occupied by the biofilm carriers needed to achieve the required nitrification capacity, can become considerable and limiting for the reactor volume/capacity, especially if low surface area carriers are used. The sludge age and maximum unaerated mass fraction for an IFAS system is also calculated differently from a CAS system. For a green fields system, where the reactor volume relative to the SST area can be manipulated, the optimum IFAS design is achieved as follows:

i. Choose the operational sludge age as the minimum required for BPO hydrolysis, good biological flocculation and stable EBPR. At a temperature of 14°C, 6 days should be adequate;
ii. Determine the TSS mass in the reactor at the chosen sludge age;
iii. Choose a reactor concentration through cost minimization where reactor volume and SST area are traded off to achieve the minimum overall cost as shown in Figure 6.7 (Ekama & Wentzel, 2008);
iv. Determine the reactor and SST sizes;
v. Determine the unaerated (anaerobic + anoxic) mass fraction that would produce compliant effluent phosphate and nitrate concentrations.
vi. Determine whether the available volume is sufficient for the biofilm carriers;
vii. If the available volume is not adequate, reduce the reactor concentration until the volume is sufficient to house the biofilm carriers;
viii. Alternatively use a higher surface area carrier or increase the reactor filling fraction;
ix. Recalculate reactor and SST sizes;

If the reactor concentration is decreased (resulting in a larger reactor) to create space for the carriers, the SST's can be made smaller due to a lower MLSS concentration in the reactor. In this way only a slightly higher cost than the minimum may be achieved because the minimum cost extends over a TSS concentration range of about 2 kgTSS/m^3 as can be seen in Figure 6.7.

For a green fields IFAS system the optimum capacity is achieved when, at the chosen sludge age, the (cost-minimized) reactor concentration loads the SST to its solids loading rate while the IFAS zone of the reactor volume is large enough to house biofilm carriers with adequate surface area to achieve the required nitrification capacity.

For a green fields project CAS system, the reactor and SST sizes are functions of the selected reactor TSS concentration. The most economical concentration is selected based on cost minimization of the complete system as shown in Figure 6.7.

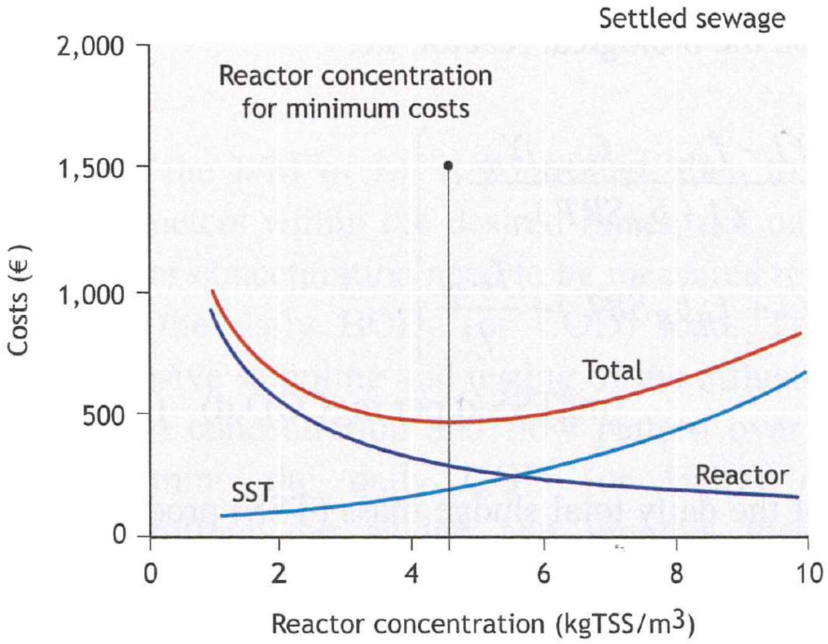


Figure 6.7: An example of a cost optimization output where the most cost effective reactor TSS concentration is selected to give the minimum total cost of the system (Ekama & Wentzel, 2008).

For an IFAS reactor, designed for a short sludge age of about 6 days, the same procedure will be followed, however the space required in the reactor for carrier media may result in larger reactors than the cost minimization exercise indicates. This will result in a maximum allowable design concentration, purely to create enough space for the carrier media. The volume required for carrier media may be a determining factor when one or several of these conditions exist:

i. The influent wastewater has a high TKN/COD ratio (>0.10);
ii. A low surface area carrier is used (<800 m^2/m^3);
iii. A low filling fraction is used (<60%);
iv. Large pre- and post IFAS aerobic zones are included.

Or one of the following conditions necessitates a smaller reactor size in relation to SST size:

v. Low wastewater strength (COD concentration);
vi. High Peak flow factors (PWWF/ADWF);
vii. Poor settling sludge.

6.6 IFAS retrofit capacity calculation

When existing reactors and SST’s are used, and the relative sizes thereof cannot be altered during an IFAS retrofit, the WWTW capacity calculation follows the following steps:

i. Choose the operational sludge age as the minimum required for BPO hydrolysis, good biological flocculation and stable EBPR. At a temperature of 14°C, 6 days should be adequate;
ii. Determine the mass of sludge produced in the reactor at the selected sludge age and an estimated ADWF rate;
iii. Determine the resultant TSS concentration in the reactor;
iv. Use a peaking factor (f_q) and determine the estimated PWWF from the ADWF;
v. Determine whether the SST solids loading rate is exceeded according to the flux theory;
vi. Iterate the ADWF rate and TSS concentration until the PWWF loads the SST to its capacity and the required reactor volume meets the available reactor volume;
vii. Determine the unaerated (anaerobic + anoxic) mass fraction that would produce compliant effluent phosphate and nitrate concentrations.
viii. Calculate the volume required for the biofilm carriers to achieve the required nitrification capacity, allowing for pre- and post IFAS zones of 25% of the aerobic volume each;
ix. If the reactor volume is insufficient to accommodate the carriers, try increasing the carrier filling fraction, or using higher surface area carriers. If conditions for biofilm nitrification are favorable in pre- or post IFAS zones, consider also placing carriers in either of these zones;
x. If the reactor volume is still insufficient, reduce the ADWF capacity to match the nitrification limit of the carriers. The option then exists to increase the MLSS sludge age beyond 6 days to utilize the extra capacity in the system.

6.7 Simultaneous Nitrification in biofilm & MLSS (substrate apportionment)

In an IFAS reactor nitrification activity will be present in the MLSS and on the biofilm. This was observed at the Broomfield Kaldness Hybas Plant as shown in Figure 6.8 (Rutt, et al., 2006). The biofilm growth during winter months is more prolific than in summer, also in the second reactor where nitrifier growth on the biofilm is inhibited by OHO growth to a lesser degree.

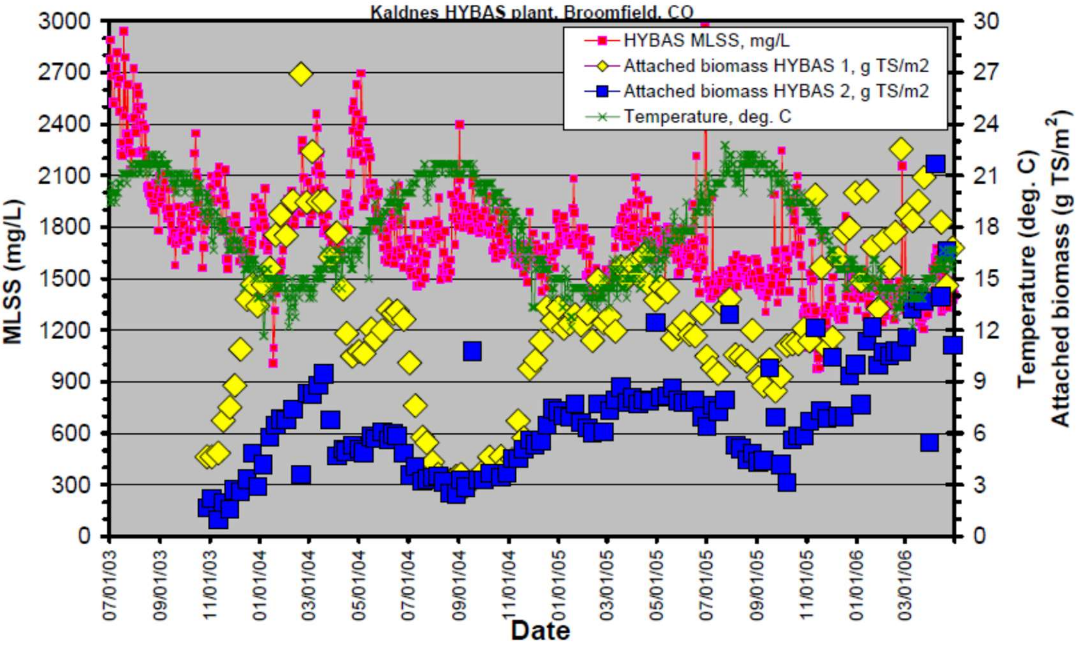
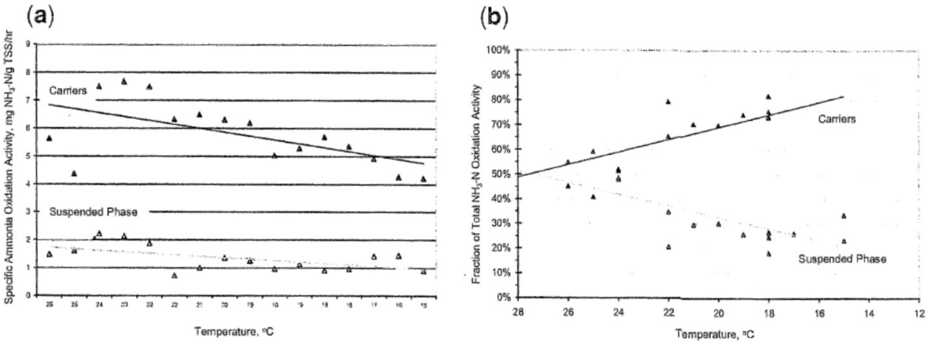


Figure 6.8: A comparison of the attached (biofilm) biomass and suspended biomass vs. the wastewater temperature at the Broomfield WWTW IFAS plant (Rutt, et al., 2006).

McQuarrie and Thomas (Odegaard, et al., 2014) considered the specific ammonia oxidation activity in the MLSS and on the biofilm and also noticed trends in the interaction. They found a larger fraction of the total nitrification in the system takes place on the biofilm carriers as the temperature declines.



Specific nitrification activity in attached and suspended biomass versus temperature

Fraction of NH_3-N oxidation activity in attached and suspended biomass versus temperature

Figure 6.9: Distribution of nitrification activity in the attached and suspended biomass as a function of temperature (Odegaard, et al., 2014).

Odegaard (2014) observed that the location for nitrification (MLSS or biofilm) is related to the sludge age of the MLSS. Since nitrification in the MLSS is wholly dependent on the minimum sludge age for nitrification (SRT_m) requirement, it makes sense that this impacts on the location for nitrification.

Odegaard proposes a correction factor K to assign the nitrification to either the attached biomass or the MLSS (Odegaard, et al., 2014). At 2 days aerobic sludge age he sets K = 1, meaning all nitrification takes place on the biofilm. At 8 days aerobic sludge age K = 0.2, meaning only 20% of the nitrification takes place on the biofilm and the remainder takes place in the MLSS. This observation makes sense, but it is expected that this will not be accurate for all IFAS reactors, since SRT_m is dependent on various factors including temperature, the unaerated mass fraction and the maximum specific growth rate of the nitrifiers. Instead of the specific sludge age values proposed by Odegaard it may be more appropriate to apportion nitrification as a function of the minimum sludge age for nitrification (SRT_m), and the safety factor (SF) associated with it.

When conditions are conducive for nitrification in the MLSS, i.e. the SRT_m requirement is met, nitrification takes place primarily in the suspended MLSS, but also in the biofilm. This is probably because the suspended MLSS flocs are small and oxygen diffusion to nitrifiers in the flocs is not a problem, whereas oxygen diffusion to nitrifiers in the biofilm is more challenging. Therefore, if the suspended sludge age is higher than the minimum sludge age for nitrification requirement, most of the ammonia will be nitrified in the suspended MLSS.

McQuarrie (2010) confirmed this by stating that if the Safety Factor for Nitrification (SF) in the MLSS is higher than 2.0, the CAS system will not benefit from the addition of carriers, since the autotrophs population in the MLSS will be stable and nitrify sufficiently (Odegaard, et al., 2014). McQuarrie also proposed various approaches for the design of IFAS systems based on SF, where nitrification in the MLSS is not considered for SF below 1.0, and nitrification in the biofilm is used only for nitrification stability for SF between 1.0 and 2.0.

Although nitrification in the MLSS system happens either ‘completely’ or not at all, depending on the sludge age as shown in Figure 6.10, one expects the apportionment of nitrification between the biofilm and MLSS to happen more gradually. In other words, at sludge ages slightly below or above SRT_m, nitrification will be more equally divided between the MLSS and biofilm.

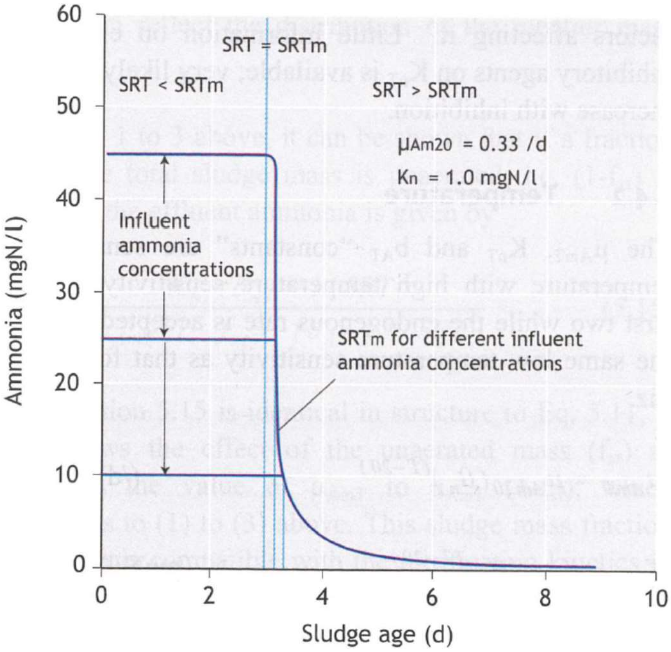


Figure 6.10: Effluent ammonia as a function of the suspended sludge age (Ekama & Wentzel, 2008)

From the observations by Odegaard and McQuarrie (Odegaard, et al., 2014), and from the principles of the CAS model for nitrification, the following ammonia (substrate) apportionment is proposed:

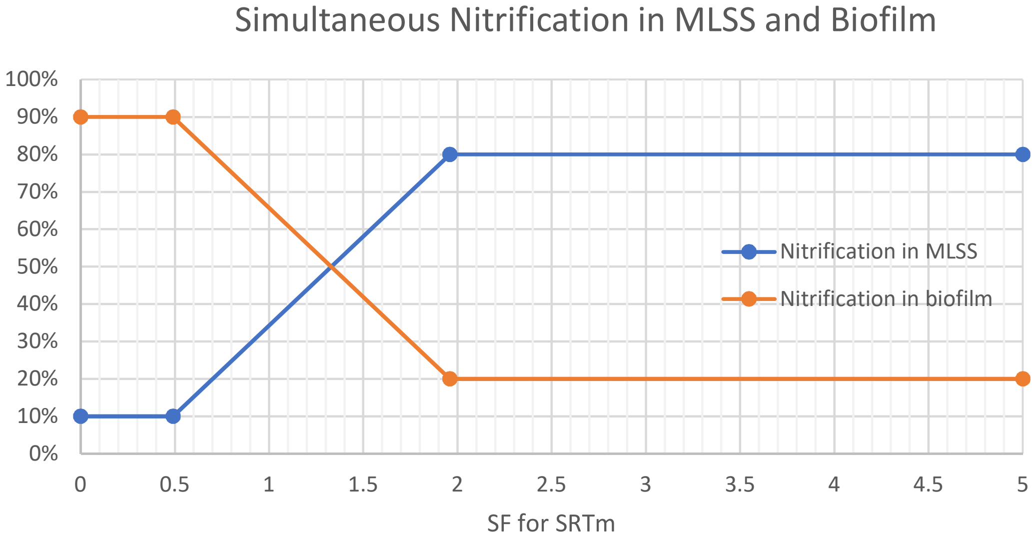


Figure 6.11: A switching function allocating substrate (ammonia) to the MLSS or biofilm, depending on the safety factor for nitrification (SF).

i. From SF = 0.5 to SF = 2.0, nitrification shifts linearly from the biofilm to the MLSS;

ii. At SF about 1.3 the amount of ammonia nitrified in the biofilm and in the MLSS is similar;

iii. At SF < 0.5 nitrification takes place in the biofilm primarily. 10% of the ammonia is nitrified by the MLSS, although this is only due to seeding of autotrophs sloughed from the biofilm to the MLSS;

iv. At SF > 2 nitrification takes place primarily in the MLSS although about 20% of the ammonia is nitrified in the biofilm;

Although more testing and laboratory work is proposed to refine this hypothesis, it successfully describes the observed effect seasonal temperature variations have on nitrification in an IFAS system. Figure 6.13 shows how the location for nitrification changes due to seasonal temperature changes. The effect of two different chosen sludge ages (4 days and 6 days) is also clear. For this example, $\mu_{Am20} = 0.50$ and $f_{xt} = 0.4$ was used.

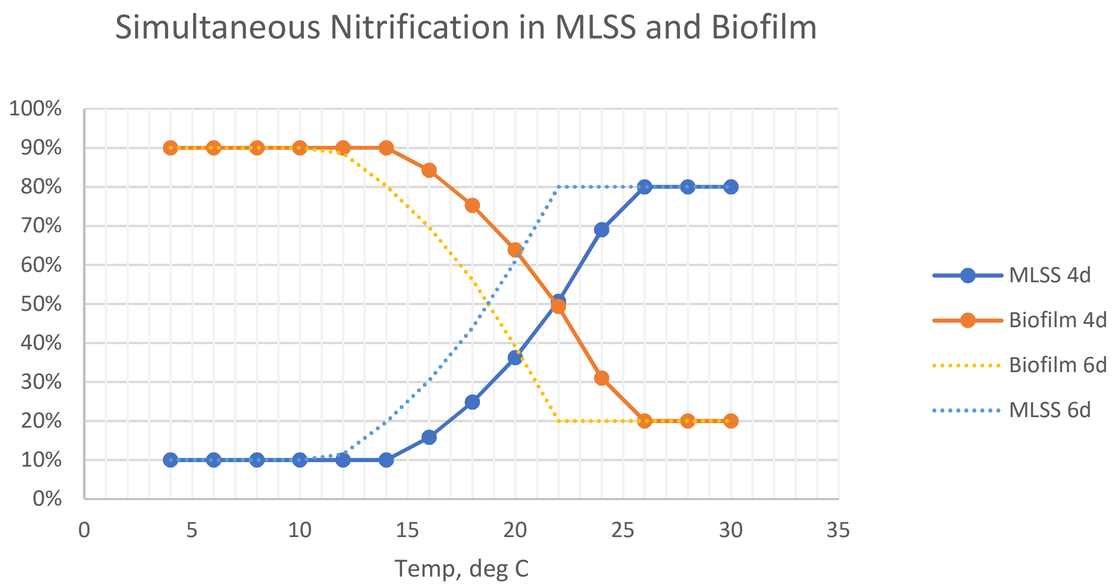


Figure 6.12: An example of how nitrification switches between the MLSS and biofilm as a function of the wastewater temperature. For this example, $\mu_{AMT} = 0.50$ *and* $f_{xt} = 0.4$*. The effect of the selected suspended sludge age can also be seen.*

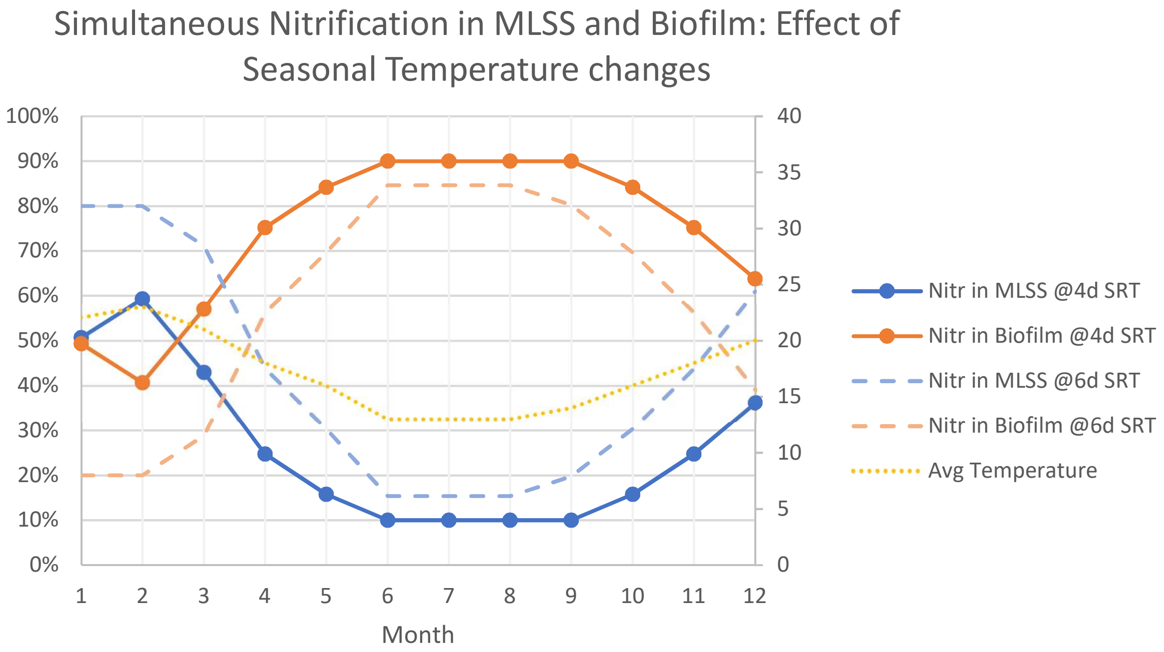


Figure 6.13: The seasonal change in the site for nitrification can be seen.

Two factors that have a big impact on the minimum sludge age for nitrification and therefore on the location for nitrification are the maximum growth rate for the nitrifiers μ_{AmT} and the unaerated mass fraction f_{xt}. In the figures below T = 20 °C and the sludge age is 5 days:

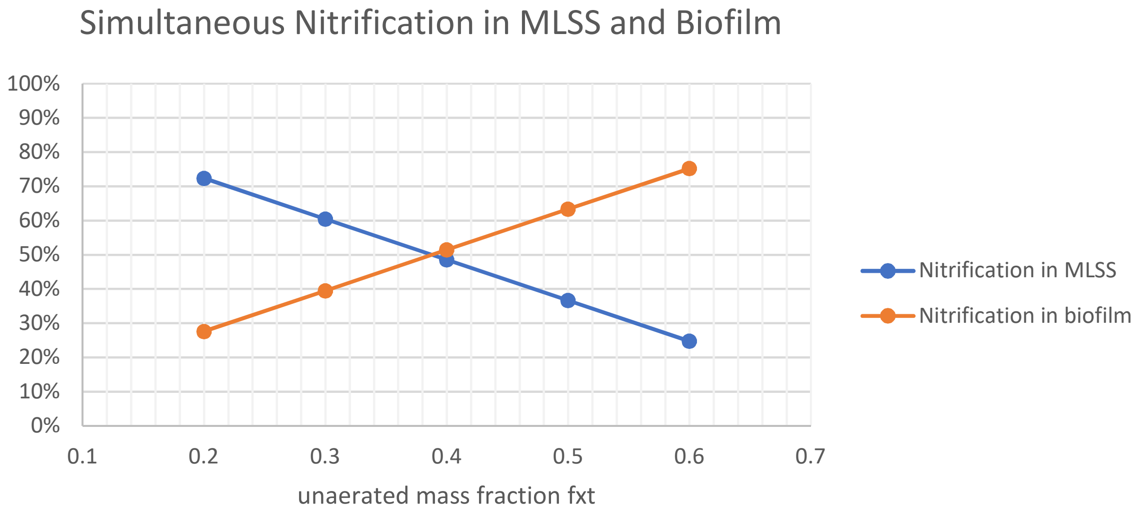


Figure 6.14: The location of nitrification as a function of the unaerated mass fraction.

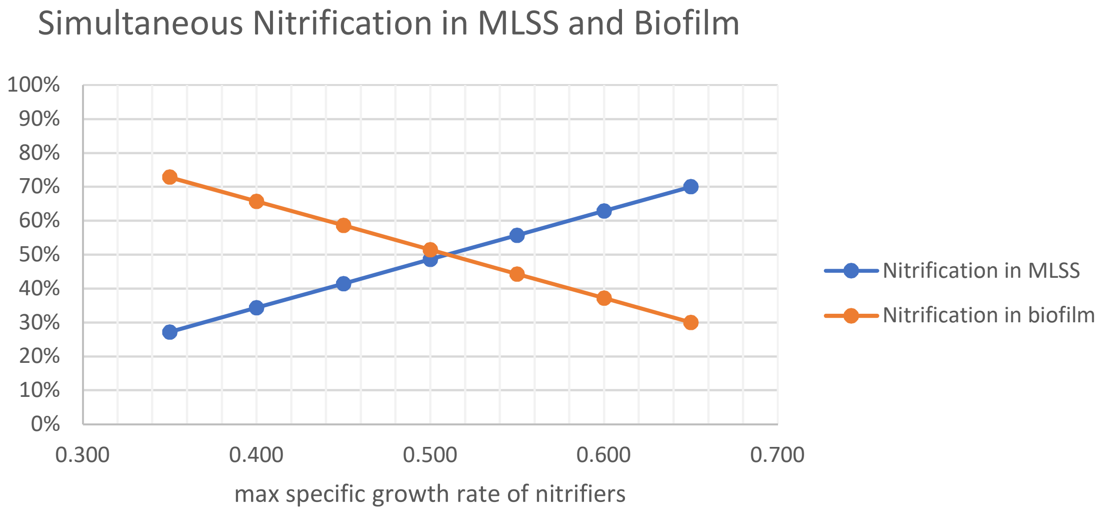
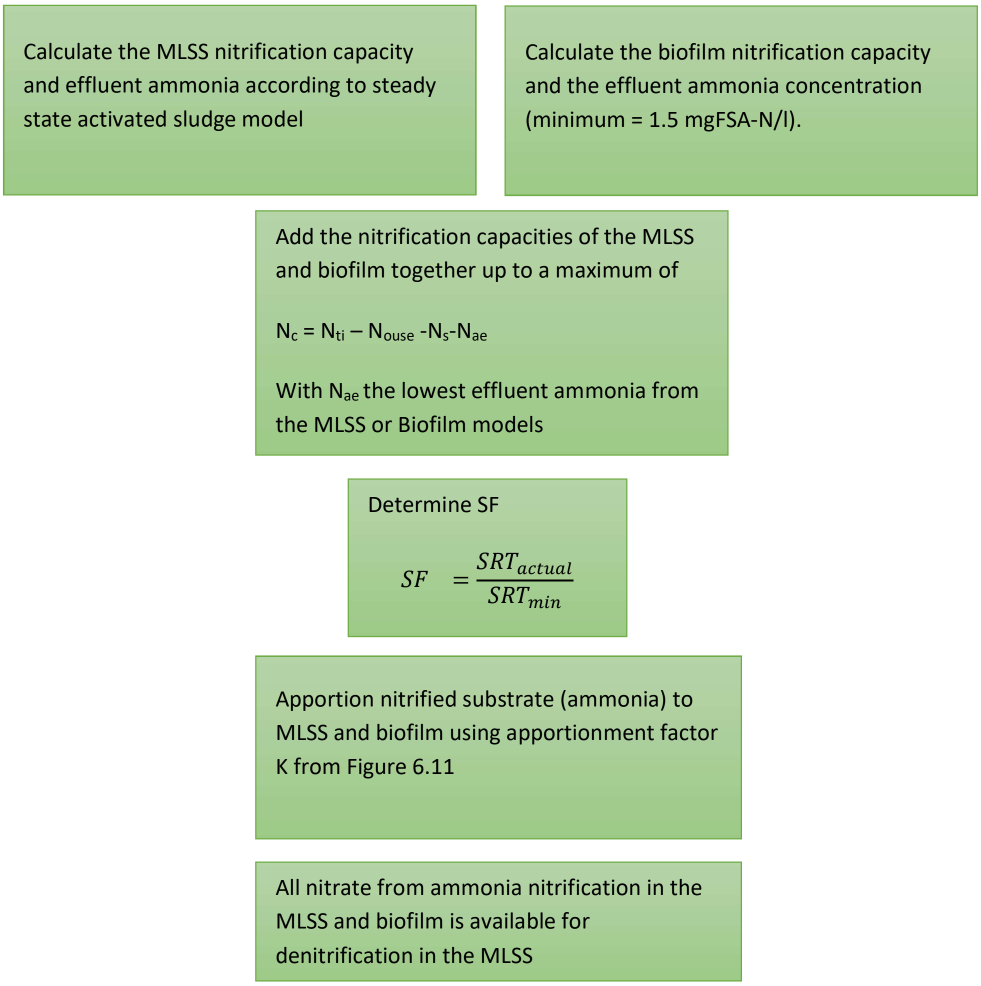


Figure 6.15: The location of nitrification as a function of the maximum specific growth rate for nitrifiers. State assumptions.

The flow-chart below summarizes the steps for calculating biofilm and MLSS nitrification:



Calculate the MLSS nitrification capacity and effluent ammonia according to steady state activated sludge model

Calculate the biofilm nitrification capacity and the effluent ammonia concentration (minimum = 1.5 mgFSA-N/l).

Add the nitrification capacities of the MLSS and biofilm together up to a maximum of

$N_c = N_{ti} – N_{ouse} - N_s - N_{ae}$

With N_{ae} the lowest effluent ammonia from the MLSS or Biofilm models

Determine SF

$$SF \quad = \frac{SRT_{actual}}{SRT_{min}}$$

Apportion nitrified substrate (ammonia) to MLSS and biofilm using apportionment factor K from Figure 6.11

All nitrate from ammonia nitrification in the MLSS and biofilm is available for denitrification in the MLSS

Figure 6.16: Flow chart for nitrification modelling and substrate apportionment in an IFAS reactor.

7 Denitrification in IFAS

Denitrification in the an IFAS reactor, as considered in this thesis, occurs predominantly in the anoxic zone of the reactor. Since the suspended OHO biomass does well at denitrification it does not seem like an economical option to include biofilm carriers in the anoxic zone. If prolific biomass growth occurs on the biofilm carriers in the aerobic zone, some anoxic zones may form deep in the biofilm where oxygen cannot diffuse through the entire biofilm. Since the objective of the biofilm carriers in an IFAS reactor is nitrification, thick biofilm growth is avoided and DO concentrations are deliberately high to ensure sufficient diffusion of oxygen through the biofilm. Hence denitrification in the aerobic zone biofilm carriers should be negligible.

Denitrification by suspended OHO's in the anoxic zone is predicted as per the CAS model (Ekama & Wentzel, 2008). The nitrate available for denitrification is the total from the ammonia nitrified in both the MLSS and the biofilm. Nitrate is returned to the anoxic zone through the a- and s-recycle streams in an UCT-IFAS system. Hence the calculations of the denitrification remains the same as for suspended CAS systems provided that the shorter sludge age of the system is used for denitrification calculations.

Since nitrification in an IFAS reactor is less susceptible to the unaerated mass fraction it is possible for high TKN/COD wastewater, to increase the size of the anoxic zone so that the unaerated mass fraction is higher than in CAS, especially where a low sludge age is used. This will produce lower effluent nitrate than CAS and protect P-Removal. The unaerated mass fraction should still however not exceed 0.45 since BPO degradation becomes minimized as discussed in Section 9.

8 P-removal in IFAS system

As for denitrification, there is no apparent benefit or significant influence that adding biofilm carriers to the reactor will have on P-removal. Carriers in the anaerobic zone do not seem beneficial, since PAO's cannot remain stationary to perform their function. PAO's need to be exposed to anaerobic conditions for VFA uptake and aerobic conditions to complete the P-removal cycle.

As for denitrification, if prolific biomass growth occurs on the biofilm carriers in the aerobic zone, some anaerobic zones may form deep in the biofilm where oxygen and nitrate cannot diffuse through the entire biofilm. Since the objective of the biofilm carriers in an IFAS reactor is nitrification, thick biofilm growth is avoided and DO concentrations are deliberately high to ensure sufficient diffusion of oxygen through the biofilm. Hence P-removal due to anaerobic layers the aerobic zone biofilm carriers should be negligible.

9 Sludge Age and Unaerated Mass Fraction

In a conventional BNR process such as the UCT process the sludge age is chosen based on the minimum sludge age required for nitrification and a safety factor to ensure stable nitrification during cycling flow and load conditions. Nitrifier growth in suspended activated sludge is strongly temperature sensitive and low temperatures increase the minimum sludge age required for nitrification. The minimum sludge age required for nitrification is directly coupled to the unaerated mass fraction since nitrifiers only grow in aerobic conditions. For a given sludge age a maximum unaerated sludge mass fraction exists.

IFAS presents the possibility to negate these limiting requirements by maintaining nitrifiers in the aerobic zone as biofilm on fixed media. There is therefore no minimum sludge age or maximum unaerated fraction required that pertains to nitrifier growth. The potential benefits are significant, but the question arises; what other processes or kinetics within the UCT-IFAS process then determines the minimum required sludge age and the maximum unaerated fraction.

A sludge age of 3 days is the limit of validity for steady state activated sludge model since the assumption that all biodegradable COD is utilized is not valid at lower sludge ages (Ekama & Wentzel, 2008). At sludge ages below 5 days predatory activity of protozoan organisms on free swimming bacteria is limited which decreases the flocculation achieved in the suspended biomass (Ekama & Wentzel, 2008). The flocculation and settleability of sludge may be a valid reason to maintain a minimum sludge age of 5 days for the suspended biomass.

To ensure stable EBPR and prevent PAO washout an aerobic SRT of about 3 days is required at a temperature of about 15°C. (note lower temperature requires higher aerobic SRT). Assuming f_{xt} = 0.5 a minimum sludge age of 6 days is required (see Figure 9.1).

It would seem that the sludge age for a UCT-IFAS process should not be selected below **5 days** in any event. The governing requirement, in many instances and particularly at low temperatures or when the unaerated mass fraction f_{xt} is large, will be the sludge age required to ensure stable EBPR. Figure 9.1 shows the minimum required aerobic sludge age for different temperatures.

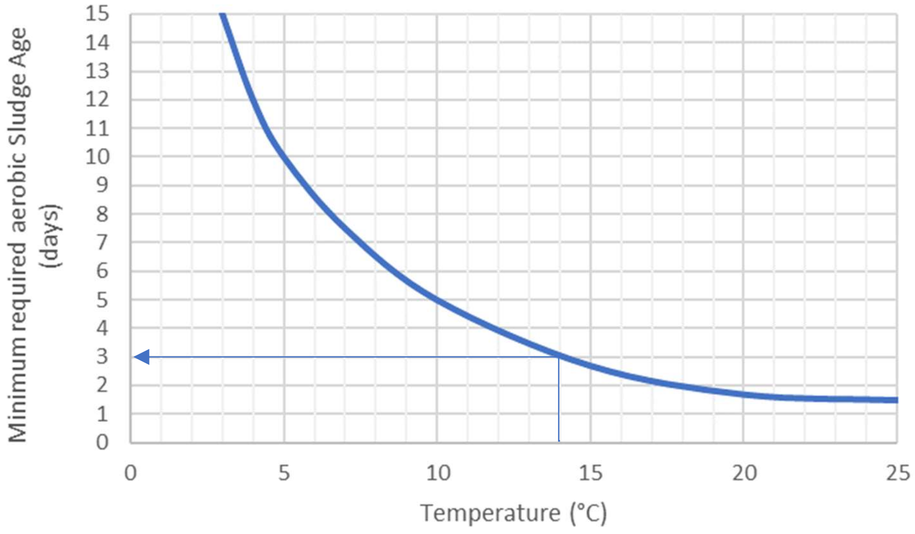


Figure 9.1: The minimum required aerobic sludge age to ensure stable EBPR as a function of temperature. [Simplified from: (Wentzel, et al., 2008)]

The comparison of the minimum required sludge ages at which conventional activated sludge (CAS) plants and IFAS plants can be operated comes down to two different requirements:

i. In a CAS (UCT) system the minimum sludge age is that required to sustain adequate nitrifiers in the system to ensure near-complete nitrification (SRT_m);
ii. In an UCT-IFAS system, the minimum sludge age is determined by the minimum aerobic sludge age required to ensure stable EBPR and near complete utilization of BPO;

The example comparison in Figure 9.2 assumes $\mu_{Am20} = 0.45$ and $S_f = 1.3$. A significant reduction in sludge age is possible for an IFAS process over a CAS process. The benefit of an IFAS process increases as the temperature decreases.

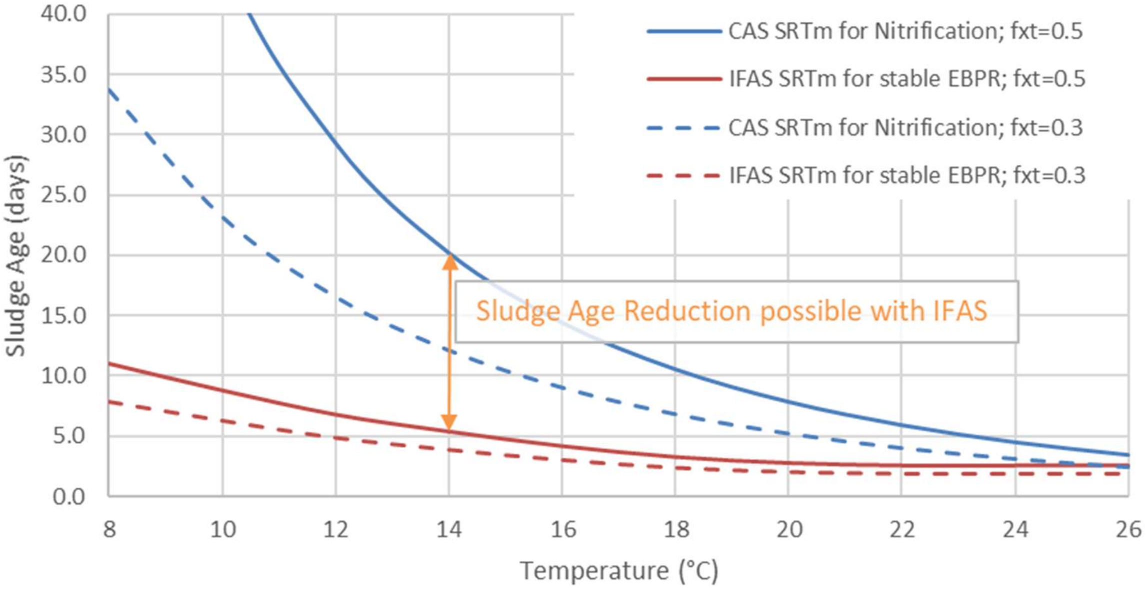


Figure 9.2: The possible sludge age reduction when comparing a conventional activated sludge BNR system with an IFAS BNR system as a function of temperature. The governing requirement for CAS is the minimum sludge age required for nitrification, while the governing requirement for IFAS is the minimum sludge age required for stable EBPR. The effect of the unaerated mass fraction can also be seen. Assumptions: μ_{AmT} *= 0.45/d;* S_f *= 1.3.*

The unaerated mass fraction has another limitation that may not be accurately modelled in steady state models. Steady state activated sludge models assumes that the sludge age would be long enough to ensure complete utilization of BPO COD, even with large unaerated mass fractions, since the sludge age required for nitrification is longer than that required for BPO utilization in CAS systems. Here, the UCT-IFAS process approaches the limit of validity of steady state activated sludge models.

When a low sludge age is chosen in combination with a high unaerated mass fraction, the sludge is not exposed to adequate aerobic conditions to ensure that BPO is enmeshed, adsorbed and utilized. This causes a build-up of enmeshed and adsorbed BPO in the system which are not utilized. In this condition sludge production rates increase sharply, and oxygen utilization decreases. The reactor starts performing as a contact stabilization tank with bio-flocculation occurring, rather than utilization (Ekama & Wentzel, 2008). The UCTOLD activated sludge model (Dold, et al., 1991) was used to determine when this condition arises.

In the UCTOLD model simulation results shown in Figure 9.3 different unaerated mass fractions and sludge ages were applied. It shows how virtually all the enmeshed and adsorbed BPO COD is utilized when the unaerated mass fraction (f_{xt}) is 0.4 for sludge ages above 5 days. Enmeshed BPO is not adsorbed and causes a build-up of non-degraded organics when the unaerated mass fraction (f_{xt}) is 0.6 or higher.

The UCTOLD Model was run several times for sludge ages between 5 and 15 days and at various unaerated mass fraction to determine the maximum unaerated mass fractions that should be used for an IFAS process at a minimum temperature of 14°C.

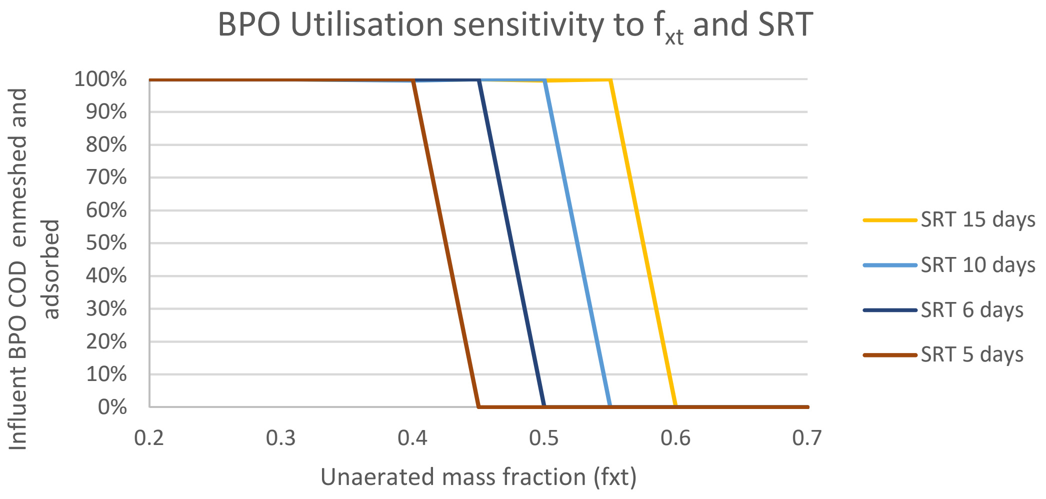


Figure 9.3: BPO utilization at different unaerated mass fractions and sludge ages at 14°C.

Table 9.1: UCTOLD results for biological reactor operated at various sludge ages and unaerated mass fractions in order to determine what the maximum unaerated mass fraction is that low sludge age UCT-IFAS reactors can function at. The Temperature was set at 14°C.

UNAERATED MASS FRACTION (f_{xt})	**SLUDGE AGE**				
	5 days	6 days	7.5 days	10 days	15 days
0.60	BPO build-up	BPO build-up	BPO build-up	BPO build-up	BPO build-up
0.50	BPO build-up	BPO build-up	BPO build-up	BPO utilized	BPO utilized
0.45	BPO build-up	BPO utilized	BPO utilized	BPO utilized	BPO utilized
0.40	BPO utilized	BPO utilized	BPO utilized	BPO utilized	BPO utilized

It can be seen from Table 9.1 and Figure 9.3 that the maximum unaerated sludge mass fraction for IFAS reactors that operate at sludge ages below 10 days is **0.45**.

This limitation is not inherently due to the IFAS process. It arises from the low sludge age and high unaerated sludge mass fraction selected. For CAS the sludge age would typically be selected higher for nitrification requirements which then automatically meets the virtually-complete BPO utilization requirement. The low sludge age of an UCT-IFAS reactor causes it to test the limits of validity of steady state activated sludge models that assume that all the BPO COD is utilized. Table 9.1 can be used as a guideline to determine whether this assumption is still valid (at 14 °C).

10 Oxygen Demand and Aeration Requirements

IFAS and CAS processes have different oxygen requirements. The nitrogenous oxygen demand of the two systems are very similar since virtually all the ammonia is nitrified in both cases and denitrification happens to a similar extent. The key difference in oxygen demand is due to the different operating sludge ages. An IFAS EBPR system can operate at a sludge age of 5 to 6 days while CAS typically operates at 15 to 25 days. Figure 10.1 below shows how the total oxygen demand and waste sludge volumes are affected.

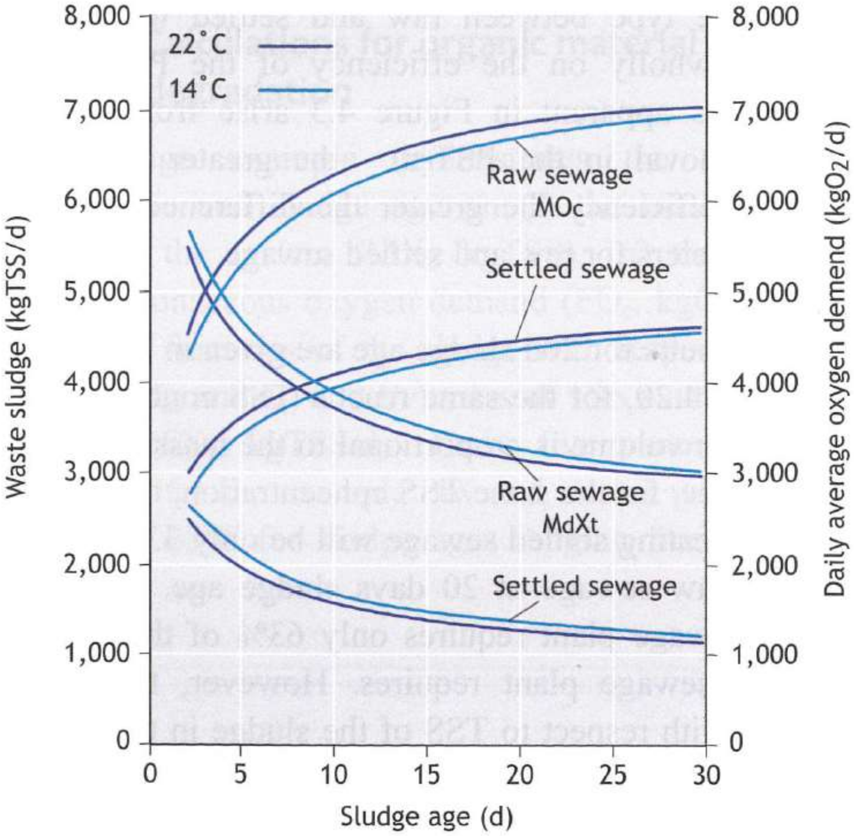


Figure 10.1: A comparison of the oxygen requirements and waste sludge produced for systems operating at different sludge ages. (Ekama & Wentzel, 2008)

The energy savings associated with a lower sludge age can be credited to an IFAS system, but one needs to consider what is done with the increased volume of waste activated sludge (WAS) that is produced. At a low sludge age, the WAS also has a higher active fraction (more trapped energy). If aerobic digestion of WAS is done this counteracts the energy saving gained through a lower operating sludge age. If anaerobic digestion (with struvite recovery for EBPR) is done the lower sludge age is even more energy efficient due to higher methane production being possible from the waste sludge with a higher active fraction.

Even though the nitrogenous oxygen demand in an IFAS process is similar to that of CAS, a higher DO concentration is required for IFAS aerobic zones. The DO is typically operated at 3 mgO/l to 6 mgO/l to allow oxygen to diffuse to the nitrifiers in the biofilm. This increases the aeration requirements for an IFAS system. In clear water at standard conditions the oxygen transfer is affected by DO as shown in Figure 10.2. The power requirement increases exponentially as the DO concentration is increased and approaches saturation. This is due to a reduction in oxygen transfer efficiency as the dissolved oxygen concentration increases towards saturation and the driving force for oxygen transfer reduces.

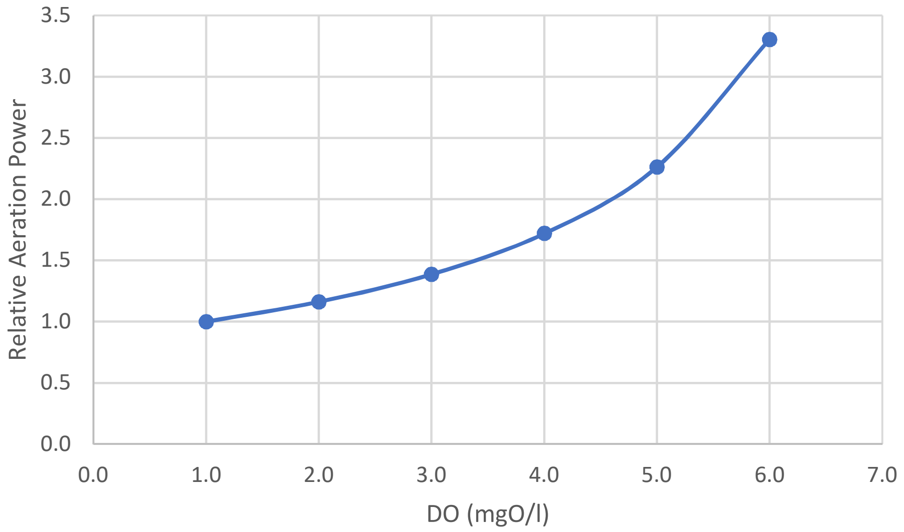


Figure 10.2: The effect of the operational dissolved oxygen concentration on the aeration power required.

Since the biofilm carriers trap rising air bubbles (or increase their flow path) from a diffused aeration system, it has been suggested that the oxygen transfer in a reactor with carriers is higher than a reactor without. Odegaard states that the oxygen transfer rate at standard conditions (SOTR) is high when the filling fraction is above 50%, even when medium-bubble diffusers are used, due to the presence of the carriers (Odegaard, et al., 2014).

Medium-bubble aeration has been preferred over fine-bubble aeration in IFAS systems due to the relatively high maintenance requirements for fine bubble diffusers. The presence of the carriers makes it difficult to replace or repair fine bubble diffusers, that typically require replacement every 10 to 15 years due to ageing of the rubber compounds and plastic pipe networks. Medium-bubble aeration systems are entirely made of stainless steel with relatively large orifices (±4mm). These systems are also not prone to fouling and have proven to operate effectively for over 20 years without any maintenance in some cases (Johnson & Boltz, 2013).

The other quoted reason for selecting medium bubble diffusers over fine bubble diffusers is the improved mixing that larger bubbles provide. Fine bubbles give less agitation and is therefore not as effective in mixing carriers. For a given air flow rate it could be said that medium bubble diffusers will cause less oxygen transfer (lower DO) and more mixing while fine bubble diffusers will cause more oxygen transfer (higher DO) but with less mixing. This balance needs to be found for every type of carrier and associated filling fraction.

It may be possible to install fine bubble diffusers to achieve the required dissolved oxygen concentration and then place mechanical mixers in the aerobic zone to aid the moving of carriers. This approach may have lower energy costs than coarse or medium bubble diffused aeration, but more frequent diffuser replacements will be required. A detailed life cycle cost analysis of the options may reveal the best option, although the simplicity of medium bubble diffusers for this application remains attractive.

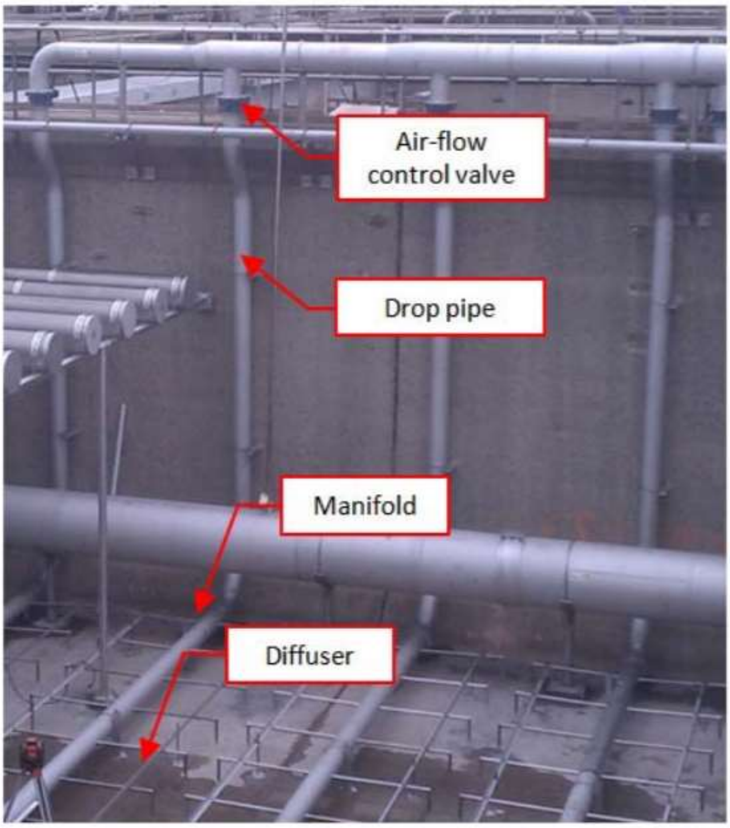


Figure 10.3: Photo of the aeration elements typically employed in an IFAS aerobic zone (Johnson & Boltz, 2013).

An aeration system for an IFAS reactor needs to adhere to the following requirements (Johnson & Boltz, 2013):

i. Can deliver the required airflow to meet process oxygen requirements;
ii. Should not require significantly more airflow than a fine-bubble diffuser aeration network;
iii. Promotes a rolling water circulation pattern for uniform carrier distribution;
iv. Can structurally withstand the weight of biofilm covered carriers on the diffusers when the tank is emptied;
v. Is not prone to orifice clogging and does not require frequent maintenance.

Items (iv) and (v) are the determining factors for why robust medium-bubble systems have been preferred over fine-bubble aeration systems for IFAS systems in industry.

A distinguishing parameter when comparing diffused aeration systems in industry is the standard oxygen transfer efficiency (SOTE) expressed as a % per m submergence value. This parameter is only slightly affected by the diffuser density and total submergence of the installation yet serves as an all-encompassing parameter that describes the efficiency of a diffuser network. Fine bubble diffused aeration systems typically have oxygen transfer efficiencies of 6% to 8% per meter submergence for dome diffusers. Diffuser manufacturers are continuously trying to improve the efficiencies and some suppliers claim that up to 10%/m can be achieved.

Course- and medium-bubble diffusers have a lower oxygen transfer efficiency than fine-bubble diffusers. Due to the larger bubble size more of the oxygen escapes to the reactor surface without contact/interaction with the wastewater. It seems a logical derivation that the oxygen transfer would improve somewhat due to the presence of carriers that block, divert or break up bubbles. It also seems logical that a higher filling fraction would do this to a higher degree.

Pham et al. (2008) did tests in a 2.1m deep test tank (1.2m x 1.2m wide) and found the SOTE with coarse-bubble aeration and no carriers to be 2.35%/m (Johnson & Boltz, 2013). When the tank was filled to a fill fraction of 25% the SOTE increased to 3.20%/m. The fill fraction was again increased to 50%, but the SOTE dropped to 2.60%/m, apparently due to poorly configured diffuser layout which resulted in poor mixing of the carriers. In these tests the carriers had no biofilm growth. Unfortunately, oxygen transfer in IFAS systems is poorly understood, particularly the effects the type of carriers, filling fractions and biofilm growth have on the SOTE is worth testing further.

It has been observed that the presence of carriers can have a negligible or negative effect on the oxygen transfer efficiency when fine bubble diffusers are used (Pham, et al., 2008). This may be due to coalescence of the fine bubbles in the presence of carriers. More research is required to determine the optimal diffuser type for each type of carrier and an associated filling fraction.

The SOTE value used for the stainless steel medium bubble diffused aeration systems with 4 mm orifices most widely employed in IFAS systems to date is 3.45% per meter submergence, regardless of the fill fraction. As discussed above one would expect variation due to the fill fraction, but the extent is unknown. One can however, quickly derive that the efficiency is about half of fine-bubble diffused aeration systems (without carriers). The difference is somewhat recovered over time since stainless steel medium bubble diffusers are assigned a fouling factor of 1 where EPDM fine-bubble diffusers have a typical fouling factor of 0.9 due to lost efficiency as the diffusers get older. The reduced efficiency of medium bubble diffusers potentially has a significant impact on the overall aeration and energy costs of the plant. One sensible way in which this effect can be lessened is to only place medium-bubble aeration in the IFAS zones of the aerobic tank and install fine-bubble diffusers in the pre- and post IFAS aerobic zones.

Lothman et al. (2011) studied the oxygen transfer and aeration requirements in two parallel reactors at the T.Z Osborne Water Reclamation Facility in Greensboro, NC (USA). The first reactor was a CAS reactor in an MLE configuration. The second reactor was an IFAS reactor in the exact same configuration but with AnoxKaldness carriers in the first half of the aerobic zone. The carrier supplier recommended that course bubble diffusers be installed in the IFAS zones with carriers to ensure adequate mixing. The IFAS zones were operated at DO concentrations of 3.6 to 3.8 mgO/l. Table 10.1 indicates the results of a comparison between the two reactors.

Table 10.1: Summary of relative process performance in terms of air use, blower power requirements and energy footprint at the T.Z Osborne Water Reclamation Facility in Greensboro, NC (USA), (Lothman, et al., 2011)

	Process Inflow Rate	**Oxygen Demand**	**Air Flow**	**Air Flow per oxygen demand**	**Blower Power per oxygen demand**
$\left(\frac{IFAS}{CAS}\right)_{winter}$	2.06	1.97	3.33	2.08	2.00
$\left(\frac{IFAS}{CAS}\right)_{summer}$	1.99	1.34	2.20	2.11	2.09

The IFAS reactor treated double the volume of wastewater in the same volume than that treated by the CAS reactor and therefore had an oxygen demand that was approximately double that of the CAS reactor. The airflow to the IFAS reactor was up to 3.33 times higher than the CAS reactor due to the increased aeration requirements for mixing and the higher dissolved oxygen requirement. When this was normalized to the theoretical oxygen demand ($\Delta COD + \Delta NH_4^+$) for each reactor it was found that the IFAS reactor required double the amount of air (and blower power) per oxygen demand (and per volume treated) than the CAS reactor.

It will be shown in Section 29 that the theoretical design applied to Borcherds Quarry WWTW A-Works indicated that the aeration power required per unit of wastewater treated in the IFAS reactor was 56% and 28% higher for raw and settled sewage respectively than the aeration power required per unit of wastewater treated in a CAS reactor.

11 Types of carriers

Different types of biofilm carriers have been used in MBBR-IFAS applications. Key considerations for selecting the type of biofilm carrier include:

i. Specific surface area of the carrier, i.e. available area for biofilm growth. This is the most important consideration since it is determining for the nitrification capacity of an IFAS tank. The specific area is measured as m^2/m^3 bulk storage volume. Carriers typically have specific surface areas ranging from 500 m^2/m^3 to 1200 m^2/m^3 (Odegaard, 2014). At a maximum filling fraction of 70% the maximum achievable net (in-tank) specific area is 840 m^2/m^3. Whether high surface area carriers are used at a lower filling fraction or vice versa is immaterial to the process. Carriers with higher surface area (>3000 m^2/m^3) such as the Mutag Biochip^{TM} are also available on the market.

ii. Biofilm growth control: The carrier should provide protection of biofilm growth so that it is not sloughed too easily, but the biofilm should not be too protected so that the growth does not become too dense. This will favour OHO growth while nitrifiers in the deeper layers of the biofilm will be starved of oxygen.

iii. The carriers should be free-moving and able to rotate freely above the diffused aeration system. Carriers should not be able to get stuck into one another since this will prevent the carriers from moving and it will become stationary, with air short-circuiting around stationary zones. Air should be able to flow to all parts of the carriers.

iv. The density of the carriers should be similar to that of water. High density polyethylene has become the material of choice, partly due to its density (0.95g/cm^3).

v. High density polyethylene is also favoured for its chemical resistance, mechanical strength and UV resistance. If lesser quality materials are used, it may disintegrate over time, requiring cumbersome and expensive replacement.

vi. The carrier size and shape should be such that it can easily be retained with sieves. For this reason, larger carriers are favoured since this allows larger sieve-openings which in turn causes less clogging due to wastewater constituents such as solids, rags and fibrous materials. It also reduces the headloss across the sieves.

Figure 11.1 shows various types of carriers available on the market. The 1200 m^2/m^3 carriers are proposed for the Borcherds Quarry A-Works due to its high specific area and relatively large size which makes retaining of the carriers easier.

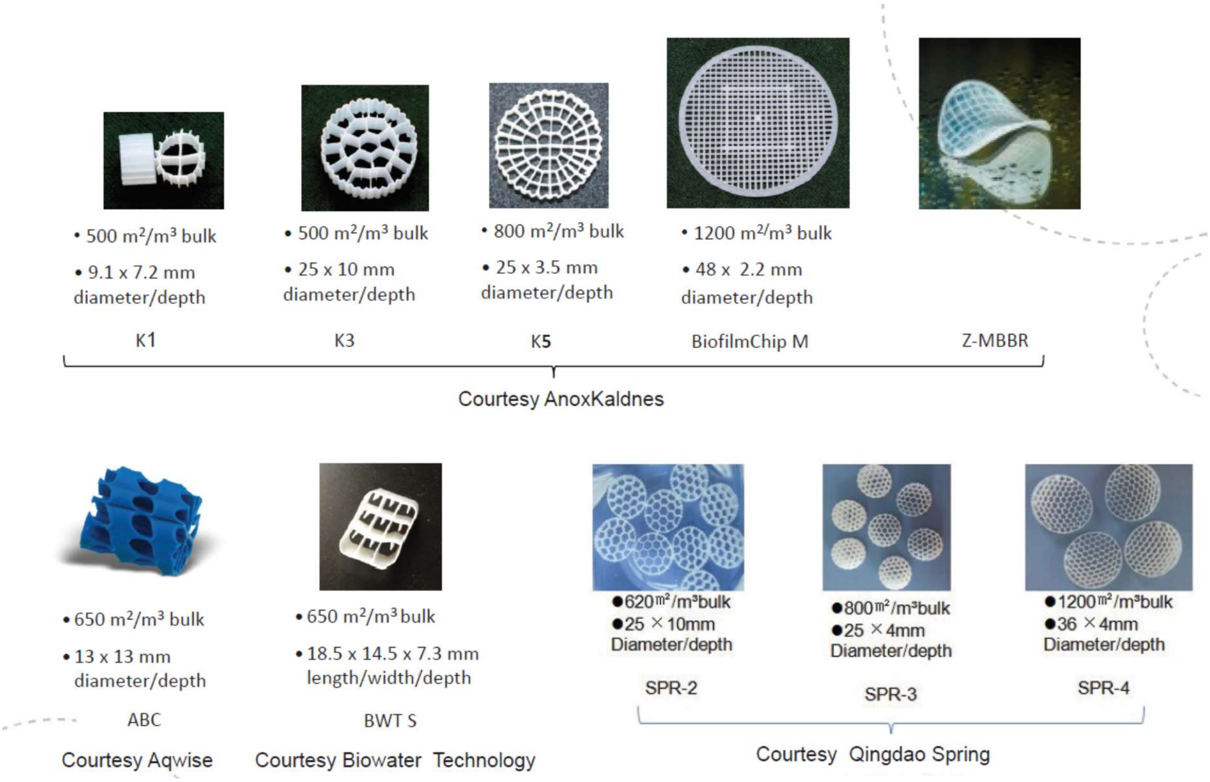


Figure 11.1: Various types of MBBR biofilm carriers available on the market (Odegaard, 2014).

12 Retaining carriers

For carriers to remain in the designated IFAS zones, sieves need to be installed between zones. The apertures of the sieves need to be smaller than the carriers and designed in a shape that will prevent carriers from attaching and accumulating on the sieves. An important parameter for preventing carriers from attaching to sieves is the velocity through the apertures. A low velocity (carrier specific) is recommended and as such a high surface area of sieves is required. Vertical sieves with air knives (coarse bubble filtration for scouring sieves) are sometimes used although perforated pipes extending over the diffusers are employed more commonly.

The incorporation of sieves necessitates a review of the inlet works. The apertures used at the inlet works should be equal or smaller than that of the carrier sieves to reduce the potential for fouling of the sieves. It seems logical that perforated screens at the inlet works such as step screens or drum screens will be a better option than vertical bar screens such as front raked or back raked screens since vertical bar screens only screens in one dimension as opposed to two-dimensional screening by perforated screens.

Unless a wastewater treatment works is already equipped with reliable fine screening at the inlet works there is real benefit for using larger biofilm carriers. The sieves in the reactor and the inlet works are thereby relieved from the need for very fine screening and the risk of fouling of the sieves is significantly reduced.

Figure 12.1: Retaining sieves for biofilm carriers that prevents loss of carriers. The sieves require a large surface area to keep approach velocities to a minimum, preventing fouling of the sieves by carriers.

SECTION B: IFAS DESIGN APPLIED TO BORCHERDS QUARRY WWTW

13 Existing Infrastructure

The A-Works at Borcherds Quarry WWTW is the oldest part of the Borcherds Quarry WWTW and was constructed in the early 1970's. It consisted of a fully aerobic biological reactor and a single SST. Another SST and additional surface aerators were later included. When the B-Works and C-Works were completed in the 90's the A-Works was initially used for WAS stabilization but was soon abandoned. The flow to the Borcherds Quarry WWTW has gradually increased to the point where the B-Works and C-Works can no longer cope with the incoming wastewater load. The City of Cape Town then proceeded to investigate reinstating the A-Works as a cost-effective alternative to expanding the works. To make a worthwhile impact on the overall plant capacity, the A-Works needed to be 'stretched' to the maximum capacity achievable in the existing infrastructure.

Figure 13.1: Aerial view of the Borcherds Quarry A-Works before being upgraded.

Figure 13.2: Aerial view of the Borcherds Quarry A-Works after being upgraded.

The existing infrastructure comprises of the following:

1. Inlet Works serving A-, B- and C-Works;
2. PST's serving B- and C-Works. The PST's have enough capacity to serve the A-Works as well and therefore options exist to feed the A-Works with raw or settled sewage;
3. A 5240 m^3 Biological Reactor without any internal walls. Existing aerator platforms and walkways were demolished;
4. Two SST's, one with a 20 m diameter and the other with a 30 m diameter. Both SST's have a side wall depth of 3.0 m.
5. Return activated sludge (RAS) Pump Station.

It was decided to convert the A-Works reactor into a UCT BNRAS system with diffused aeration. IFAS is to be investigated as a possible retrofit and the design should allow for this possibility as far as practicable.

14 Wastewater Characteristics

Two-hourly sampling of the raw wastewater was done over a 72-hour period by A.L Abbott & Associates from 16 August 2016 to 19 August 2016. The samples were settled in an Imhoff cone to simulate the effect of a PST and filtered through 0.45 µm filter paper to determine the soluble fractions. The data was mathematically flow-weighted using Simpson's Rule. The flow weighted averages are shown below:

Table 14.1: Wastewater characteristics of influent at Borcherds Quarry WWTW

Incoming flow	COD	VFA	TKN	FSA	TP	OP	TSS	ISS
Raw WW	1594	-	113	-	12	-	541	25
Settled WW	878	-	83	-	8.7	-	270	11
0.45µm membrane filtered WW	451	80	73	70	7	6.7	-	-

Filtered Effluent Concentrations	COD	VFA	TKN	FSA	TP	OP	TSS	ISS
Raw WW	47.82	-	3.5	0.5	2.5	2.5	0	0
Settled WW	47.82	-	4.0	1.0	1.8	1.8	0	0

Wastewater characterization was done using block diagrams as shown in Appendix A. One can see that the influent at Borcherds Quarry WWTW has high wastewater strength. The high COD and TKN concentrations are due to the stercus facility on site that receives night soil buckets from informal settlements, hence some of the sewage is not diluted with flushing water. Tanker waste from landfill and other sources is also discharged at Borcherds Quarry WWTW.

The raw and settled TKN/COD ratios measured 0.071 and 0.091 respectively, while the TP/COD ratios measured 0.0075 and 0.0099 respectively. Settling increases the TKN/COD ratio due to a considerable fraction of COD being removed in PST's, while TKN is removed to a lesser degree. The raw and settled wastewater IFAS performance will be discussed more in Section 30, but some generalized influences this ratio has on IFAS design are listed here:

i. At higher TKN/COD ratios the inhibition of biofilm nitrification due to organic load is reduced;
ii. At higher TKN/COD ratios the space available for biofilm carriers may become limiting (due to larger unaerated mass fractions for denitrification) and higher specific area carriers or larger carrier filling fractions are needed for near-complete nitrification;
iii. Higher TKN/COD ratios will result in larger unaerated mass fractions and a higher minimum sludge age for MLSS nitrification. This means a larger fraction of nitrification would take place on the biofilm for an IFAS system operated at a low sludge age.

The wastewater temperatures at Borcherds Quarry WWTW was assumed to vary between 14 °C and 24 °C. This is not based on actual data from the plant. It is recommended that extensive testing be done to determine the actual temperature range before IFAS is considered for implementation.

15 Effluent Standard

The Borcherds Quarry WWTW is licensed by the Department of Water and Sanitation (DWS) and the final effluent must comply with the conditions as set out in the Water Use License (WUL). The WUL stipulates the following effluent standards:

Table 15.1: Effluent Standard according to the Borcherds Quarry WWTW Water Use Licence

Variable	Limit
COD	75 mgCOD/l
Ammonia (as N)	2.0 mgN/l
Ortho-Phosphate (as P)	1.0 mgN/l
Nitrate (as N)	6.0 mgN/l
TSS	25 mg/l

The low effluent Ammonia standard necessitates the need for nitrification in the A-Works. Similarly, the low effluent nitrate and phosphate requirements necessitate the need for denitrification and EBPR. Biological phosphate removal could be substituted by ferric dosing but this is expensive and irrevocably binds the phosphate so that it cannot easily be used as a nutrient or fertilizer again. Also, the impact of co-precipitation with iron on the nitrifier biofilm on the carriers is not known.

The nitrate standard is particularly stringent for a biological process with high influent TKN/COD ratio. It will be seen in the A-Works model that this standard is slightly exceeded with CAS and IFAS processes. The standard is only achievable if COD dosing is done, if EBPR is substituted by ferric dosing or excessively high recycle ratios are used. None of these options are desirable and it would be advisable to apply for a relaxation of this limit.

For a conventional BNR there is little to choose between the UCT and Johannesburg (JHB) configurations. While the JHB system can carry a larger mass of sludge in its reactor due to the high TSS concentration in the pre-denitrification reactor, this does not give a higher capacity because this advantage is cancelled by its balanced sludge age being 2 days longer than for the UCT system (Ekama, 2017). Because the sludge age of an IFAS system is set by different criteria (not the balanced SRT), the JHB (IFAS) configuration may have a slightly higher capacity than the UCT system with IFAS. However, the disadvantage of the JHB system is that nitrate discharge to the anaerobic reactor starts at a lower influent TKN/COD ratio than the UCT system. Because the Borcherds Quarry WWTW has a high influent TKN/COD ratio the UCT-IFAS configuration was selected for evaluation.

The UCT process is effective in ensuring good P-Removal and low effluent nitrate concentrations over a wide range of influent TKN/COD ratios without the need for additional COD dosing as required in secondary anoxic reactors of some other process configurations. Options of treating raw and settled wastewater with or without IFAS biofilm carriers are investigated in this thesis.

16 Sludge Handling

The primary sludge and waste activated sludge (WAS) produced at the A-Works will be combined with that of the B-Works and C-Works. There are existing sludge handling facilities that comprise belt press dewatering and sludge storage. Dewatered sludge is trucked to a landfill site. Currently this facility does not distinguish between primary sludge and WAS and the two products are mixed.

In future anaerobic digestion may be practiced at the centralized sludge handling facility to generate better quality sludge and produce energy. Mixing primary sludge and WAS has several disadvantages when energy recovery for anaerobic digestion is considered (Ekama 2017). For the short and medium term, the only consideration for WAS at the A-Works is the mass of sludge produced since it directly affects the cost of transporting sludge to the central facility. The active fraction is of little importance until a more comprehensive sludge utilization strategy is in place.

17 Proposed Reactor Configuration

The proposed A-Works Reactor configuration is shown in Figure 17.1.

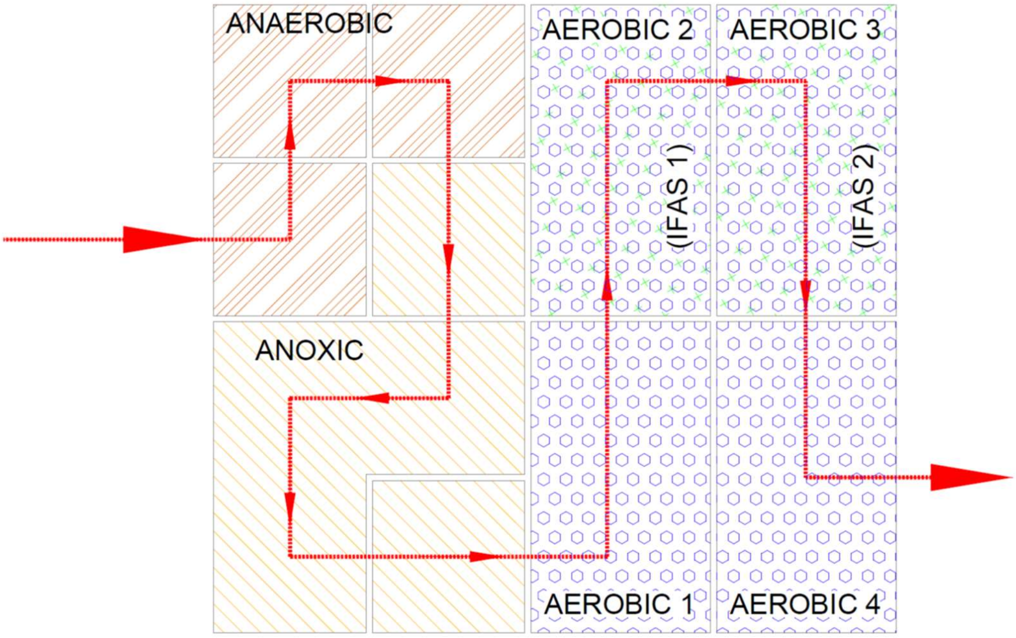


Figure 17.1: Layout of the Borcherds Quarry A-Works Reactor

The following considerations weighed in on the proposed reactor layout:

i. The reactor had existing inlet and outlets that dictated the layout;
ii. The reactor has a volume of 5240 m^3. The outer walls are existing, but internal walls can be replaced to establish the desired zone mass fractions;
iii. The anaerobic reactor was subdivided to benefit from the first order kinetics of readily biodegradable COD hydrolysis to VFA for P-removal;
iv. There are swing zones between anaerobic and anoxic zones as well as between anoxic and aerobic zones whereby the mass fractions of the respective zones could be altered. This flexibility is not discussed in more detail in this thesis, but is included in the design to accommodate future changes in wastewater characteristics;
v. For the reactor performance optimization, the anaerobic reactor mass fraction was set to 0.10 to ensure stable P-removal. The aerobic and anoxic mass fractions were considered variable, with the maximum allowable unaerated max fraction of the UCT-IFAS process set at 0.45 (see Section 9) and the maximum allowable unaerated mass fraction for a CAS UCT system set at 0.55;
vi. The aerobic reactor is subdivided in 4 zones. Table 17.1 describes the functions and operating conditions of the 4 aerobic zones:

Table 17.1: Aeration conditions for each of the 4 Aerobic Zones

	Aerobic Zone1 (Pre-IFAS)	**Aerobic Zone 2 (IFAS 1)**	**Aerobic Zone 3 (IFAS 2)**	**Aerobic Zone 4 (Post-IFAS)**

Fraction of Aerobic	25%	25%	25%	25%
Biofilm carriers	No	Yes	Yes	No
Main purpose	Reduce COD concentration and Hydrolyze BPO	Nitrification	Nitrification	Nitrification in MLSS by seeding Flocculation Reduce DO before recycle to anoxic zone COD removal/ hydrolysis
Diffuser type	FBDA	Stainless steel medium-bubble	Stainless steel medium-bubble	FBDA
DO concentration	2.0 mg/l	4.0 mg/l	3.0-6.0 mg/l	2.0 mg/l
DO control	Constant	Constant	Varied to effluent ammonia, using inline ammonia measurement	Constant

18 Suspended Sludge Age

As described in Section 9 the minimum sludge age is not dictated by the nitrifier growth rate for an IFAS system. Instead there are other (lesser) requirements according to which the sludge age is chosen. For the A-Works the minimum aerobic sludge age for stable EBPR is determining. From Figure 9.1 can be seen that an aerobic sludge age of 3 days is required to ensure stable EBPR. An aerobic mass fraction of 0.550 was selected and as a result the overall sludge age is calculated as shown:

Equation 18.1

$$\begin{aligned} R_S &= Aerobic\ Rs\ \div (1 - f_{xt}) \\ &= 3\ \div (1 - 0.450) \\ &= 5.45\ days \end{aligned}$$

The sludge age was therefore chosen as 6 days.

Note: All calculations shown are for the optimized ***Settled wastewater UCT-IFAS process****. The summarized results for the CAS Raw and Settled wastewater and Raw UCT-IFAS process are shown in Section 30.*

19 Influent Flow Rates

The objective of the A-Works refurbishment is to maximize the capacity of the existing infrastructure while complying with the effluent standards. Through an iterative optimization process as described in Section 6.6 the ADWF capacity of the A-Works operated as a Settled UCT-IFAS process is 12.7 Ml/d.

The diurnal peaking factor is 1.5 and the maximum rainwater/groundwater infiltration to the sewer system is estimated at 25% of PDWF. Therefore:

Equation 19.1

$$\begin{aligned} PDWF &= ADWF \times 1.5 \\ &= 12.65 \times 1.5 \\ &= 19.0\ Ml/d \end{aligned}$$

Equation 19.2

$$\begin{aligned} PWWF &= PDWF \times 1.25 \\ &= 19.0 \times 1.25 \\ &= 23.7\ Ml/d \qquad (= 1.875\ \times ADWF) \end{aligned}$$

20 Division of influent BSO between PAO's and OHO's

Through an iterative process (Wentzel, et al., 2008) the flux of biodegradable organic COD obtained by the OHO's and PAO's respectively was calculated.

Table 20.1: COD obtained by OHO's and PAO's respectively

Flux BO COD obtained by OHO's	**62%**	**6136**	**kgCOD/d**	485	mgCOD/l influent
BO used by OHO's for denitrification	47%	4706	kgCOD/d	372	mgCOD/l influent
BO used by OHO's in aerobic zone	14%	1429	kgCOD/d	113	mgCOD/l influent
Flux BO COD obtained by PAO's	**38%**	**3811**	**kgCOD/d**	301	mgCOD/l influent
Check total BO COD		9946	kgCOD/d	786	mgCOD/l influent

This is of importance since it affects the mass of sludge produced in the reactor. PAO's have a lower endogenous respiration rate (0.04 d^{-1} at 20°C) and higher endogenous residue fraction (0.25) than OHO's and therefore affects the mass of sludge differently from OHO's. The biodegradable organics (BO) available to the OHO's in the aerobic zone is important to calculate the inhibitory effect of COD on the nitrification rate.

21 Mass of sludge in the reactor

At the minimum temperature of 14°C, a sludge age of 6 days and the maximum flow rate of 12.7 Ml/d, the mass of sludge produced in the reactor was calculated. The detailed calculations are not described in this report but were completed as set out by Wentzel et al. (2008). The contributing components to the TSS in the reactor are shown in Table 21.1.

Table 21.1: Summary of the activated sludge masses that contribute to the TSS concentration in the reactor.

Activated Sludge Masses			
OHO VSS			
Ordinary Heterotrophic Organisms VSS	MX_{OHO}	7486	kgVSS
Endogenous Residue VSS OHO	$MX_{E,OHO}$	1816	kgVSS
PAO VSS			
Polyphosphate Accumulating Organisms VSS	MX_{PAO}	8559	kgVSS
Endogenous Residue VSS PAO	$MX_{E,PAO}$	433	kgVSS
Unbiodegradable Organic VSS	MX_{Iv}	2250	kgVSS
Total VSS	MX_V	20543	kgVSS
ISS from influent		835	kgISS
ISS of OHO's		1123	kgISS
ISS of PAO's		1766	kgISS
ISS	MX_{IOi}	3724	kgISS
TSS	MX_t	24267	kgTSS
VSS/TSS ratio		0.847	kgVSS/kgTSS

The TSS mass of 24267 kgTSS is then apportioned according to the chosen sludge mass fractions and the concentration in each zone is calculated. In a UCT process the anaerobic reactor operates at a concentration of r/(1+r) times the concentration chosen for the anoxic and aerobic zones. In this case the r-recycle ratio is chosen as 1 times ADWF and therefore the anaerobic zone concentration is half of the anoxic and aerobic zone concentrations.

Table 21.2: Volume requirements of the respective zones of the reactor

	Anaerobic	Anoxic	Aerobic	Total
Sludge mass fraction	0.100	0.350	0.550	1.000
Sludge mass (kgTSS)	2427	8493	13347	24267
Concentration TSS (kgTSS/m^3)	2.55	5.09	5.09	4.63
Volume (m^3)	**953**	**1667**	**2620**	**5240**

The concentration in the aerobic zone is 5.09 kgTSS/m^3 as optimized through an iterative process whereby the ADWF rate and TSS concentration are adjusted until the PWWF loads the SST to its capacity and the required reactor volume meets the available reactor volume.

22 SST flux calculation

By assuming that the recycle ratios of the SST's are high enough to ensure that SHC II governs the SST performance, the ADWF that loads the SST to its capacity at PWWF can be calculated as follows:

Equation 22.1: SST ADWF limit based on flux theory

$$Q_{ADWF,SST_{Limit}} = \frac{SST\ Area\ \times\ V_0 \times e^{-nX_T} \times f}{\left(\frac{PWWF}{ADWF}\right)}$$

Where;

i. f is the flux rating of the SST's, chosen as 0.7 for the A-Works SST's since both have side wall depths of only 3.0m;
ii. V_0 and n were estimated as 7.97 m/h and 0.343 m^3/kgTSS from and expected DSVI of 100 ml/g;
iii. The PWWF/ADWF factor for Borcherds Quarry WWTW is 1.875 as shown in Equation 19.2.

Hence;

$$
\begin{aligned}
Q_{ADWF,SST_{Limit}} &= \frac{1021\ \times\ 7.97 \times e^{-0.343(5.09)} \times 0.7}{(1.875)} \\
&= 530\ m^3/hr \\
&= 12.7\ Ml/d
\end{aligned}
$$

The ADWF capacity of the reactor and SST's was therefore optimized at 12.7 Ml/d at a concentration of 5.09 kgTSS/m^3. The flux curves and design and operation chart confirm that the SST is loaded to its solids loading capacity. The required recycle can be read from the D&O chart as 0.8 times the PWWF. This is 0.8 x 1.875 = 1.5 times the ADWF which equates to 1.5 x 12.7 = 19 Ml/d.

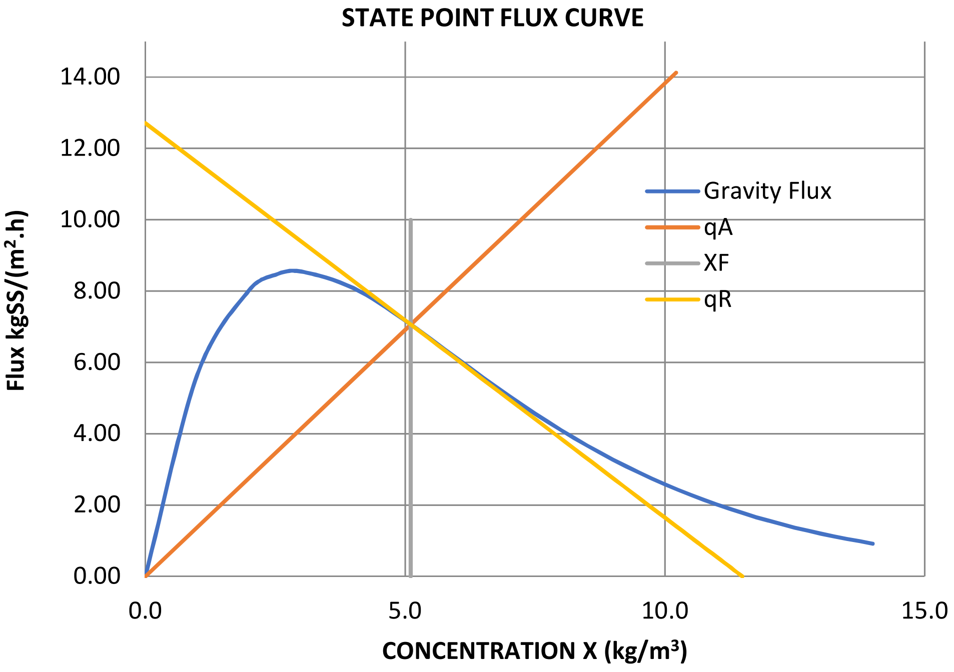


Figure 22.1: State Point flux curve used for SST design

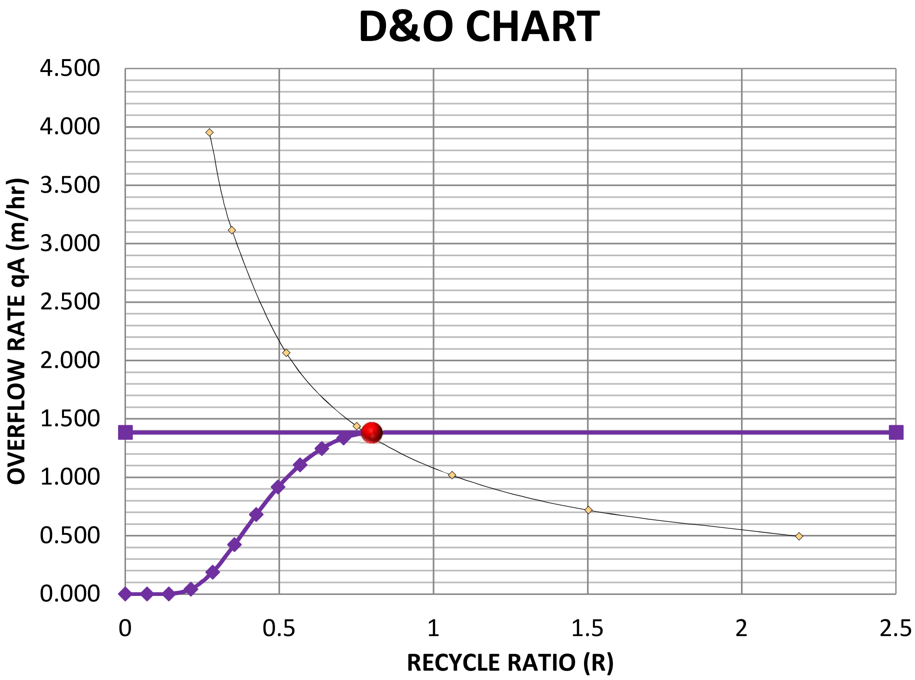


Figure 22.2: Design and Operating Chart indicating that the SST is loaded to capacity and the recycle ratio is optimal.

23 Mass fractions

In a CAS system the maximum unaerated mass fraction is primarily governed by the impact it has on nitrifier growth. Since nitrifiers only grow in the aerobic zone the unaerated mass fraction slows down nitrifier growth. This means that longer sludge ages are required for nitrification due to the unaerated mass fraction as shown in Figure 1.1. In practice unaerated mass fractions above 0.5 are seldom used, since designers want to ensure nitrification takes place and fear bulking sludge that may be more prevalent at high unaerated mass fractions.

In an IFAS system nitrification is not sensitive to the unaerated mass fraction. The maximum unaerated mass fraction is however limited to about 0.45 to ensure BPO utilization as discussed in Section 9.

For an UCT-IFAS system the mass fractions are chosen in the following order:

i. Anaerobic mass fraction is chosen to ensure complete EBPR. In this report this was fixed as 0.10. For IFAS systems with low sludge ages this is a conservatively high anaerobic mass fraction, since P-Removal improves significantly with lower sludge ages;

ii. The anoxic mass fraction is chosen to achieve the lowest possible effluent nitrate concentration at a maximum practical recycle ratio of 6 times the ADWF. To keep the total unaerated mass fraction below 0.45 the maximum anoxic mass fraction used in this thesis is 0.35;

iii. The aerobic mass fraction is the remainder i.e 1- f_{anaer} – f_{anoxic}, with a minimum value of 0.55 for IFAS systems in this thesis.

For the A-Works settled wastewater UCT-IFAS configuration the anaerobic mass fraction of 0.10 was adequate to achieve complete P-removal. The optimized (and balanced) anoxic mass fraction at a sludge age of 6 days and a maximum practical a-recycle ratio was calculated as 0.384. However, since the anoxic mass fraction cannot be higher than 0.35 as discussed in (ii) above, it was set to 0.35. The a-recycle ratio required to load the anoxic zone to its denitrification potential was calculated as 3.55 x ADWF. The remaining aerobic mass fraction is 0.550.

This produces an effluent nitrate concentration of 8.51 mgN/l, which is slightly higher than the effluent standard. It will be seen that the CAS UCT process also cannot comply with the effluent nitrate standard of 6 mgN/l due to the high incoming TKN/COD ratio.

24 MLSS Nitrification

The minimum sludge age required for nitrification in the MLSS is calculated from Equation 1.1 for the minimum temperature of 14°C:

$$SRT_m = \frac{S_f}{(1 - f_{xt})\mu_{AmT} - b_{AT}S_f}$$

$$= \frac{1.3}{(1 - 0.45) \times 0.224 - 0.0337 \times 1.3}$$

$$= 16.33\ days$$

Since the sludge age was chosen as 6 days no nitrification will happen in the biomass, save the nitrification due to seeding of nitrifiers that are sloughed from the biofilm carriers. The system will rely solely on the biofilm for nitrification during winter. At the maximum temperature of 24°C however, nitrification will occur:

$$SRT_m = \frac{1.3}{(1 - 0.45) \times 0.716 - 0.0448 \times 1.3}$$

$$= 3.88\ days$$

This means that nitrification will shift between the biofilm and MLSS due to seasonal temperature variations. The expected seasonal variation of wastewater temperatures is shown in Figure 24.1. By determining for each month what the SF (= SRT/SRT_m) value is a prediction is made of how much of the nitrification will take place on the MLSS and how much will take place on the biofilm. At Borcherds Quarry WWTW it is expected that nitrification will take place in the MLSS predominantly from December to March, while for the rest of the year the biofilm will facilitate nitrification.

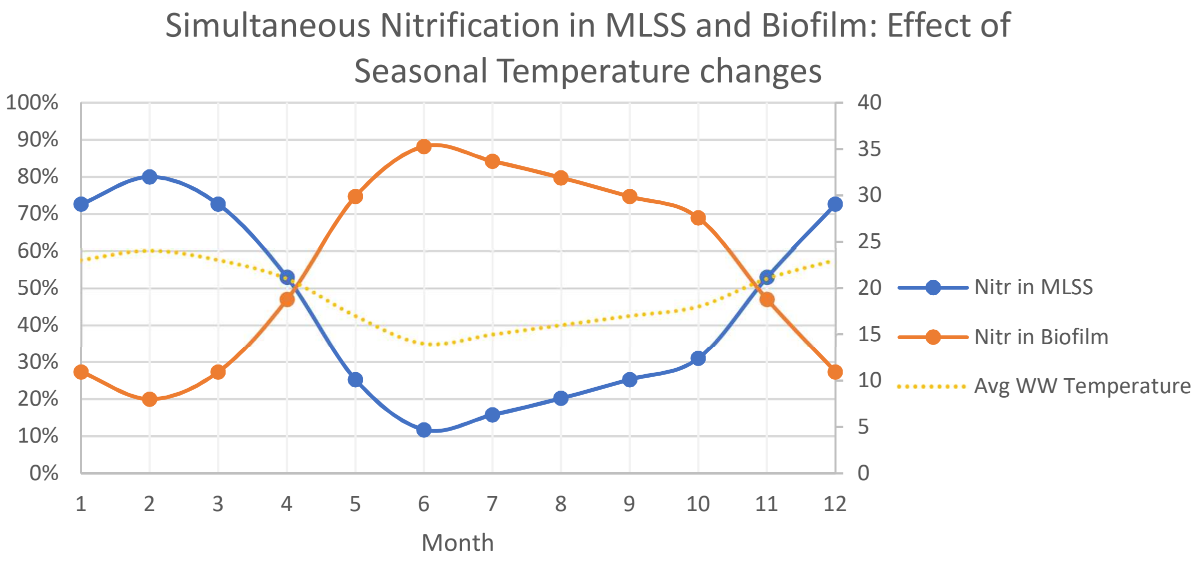


Figure 24.1: The effect of seasonal temperature variations on the site for nitrification at the Borcherds Quarry WWTW A-Works using a hypothetical seasonal wastewater temperature range between 14°C and 24°C.

25 Biofilm Nitrification

The required nitrification capacity (ammonia available to be nitrified) of the system can be calculated as follows:

Equation 25.1: Calculation of system nitrification capacity

$$N_c = N_{ti} - N_{te} - N_s$$

$$= N_{ti} - (N_{ouse} + N_{ae}) - N_s$$

Where;

N_{ti} is the influent TKN;

N_{te} is the soluble effluent TKN;

And N_s is the concentration of influent TKN incorporated in the sludge wasted.

Hence;

$$N_c = 83 - (3.0 + 1.5) - 27.1$$

$$= 51.4\, mgN/l\ influent$$

For biofilm nitrification calculations it is assumed that no nitrification takes place in the MLSS and all the nitrification takes place in the biofilm.

25.1 Nitrification in Aerobic Zone 1 (pre-IFAS)

Since no biofilm carriers are placed in this zone and no nitrification takes place in the MLSS at the minimum temperature, the ammonia concentration is unchanged. The influent-equivalent ammonia concentration is:

Equation 25.2: Influent ammonia concentration to pre-IFAS zone

$$\begin{aligned} N_a &= N_c + N_{ae} \\ &= 51.4 + 1.5 \\ &= 52.9\ mgN/l\ influent \end{aligned}$$

The influent-equivalent COD concentrations obtained by the OHO’s and PAO’s are summarized in Table 20.1.

The biodegradable COD available for heterotrophic growth in the aerobic zone is 113 mgCOD/l_{influent}. The function of the pre-IFAS zone is to reduce this as much as possible to prevent prolific OHO biofilm growth that prevents oxygen diffusion to nitrifiers in the biofilm. In most cases the COD to the aerobic zones will be BPO, with nearly all BSO utilized in anaerobic and anoxic zones. As derived from the UCTOLD models and discussed in Section 4 the BPO COD is reduced by 25% in each of the four aerobic zones.

The outflow BO COD concentration from Aerobic Zone 1 is 113mgCOD/l less 25%, which gives 84.8mgCOD/l influent.

25.2 Nitrification in Aerobic Zone 2 (IFAS zone 1)

The influent C/N ratio (BCOD/NH_4) is 84.8/52.9 = 1.6 mgCOD/mgFSA-N. The nitrification rate coefficient k can then be calculated from Figure 6.4, in this case k = 0.67.

The DO concentration in this zone is kept constant at 4 mgO/l. Since the ammonia concentration is still high, the nitrification rate determining ammonia concentration can be estimated as follows:

Equation 25.3:

$$
\begin{aligned}
S_n &= {}^{(DO-0.5)}/_{3.2} \\
&= {}^{(4.0-0.5)}/_{3.2} \\
&= 1.09\, mgFSA - N/l
\end{aligned}
$$

The nitrification rate achievable in IFAS zone 1 is then calculated as follows:

Equation 25.4: Nitrification rate

$$
\begin{aligned}
r_N &= k(S_n)^n \\
&= 0.67(1.09)^{0.7} \\
&= 0.708\, gNH_4 - N/m^2.d
\end{aligned}
$$

The volume of this zone is 720.5 m^3. Biofilm carriers with a specific area of 1200 m^2/m^3 was chosen and the required filling fraction was calculated based on the nitrification rate achieved. Figure 25.1 shows the nitrification potential of the carriers with different filling fractions. A filling fraction of 54% was found to be adequate for the settled wastewater UCT-IFAS system. This gives a net specific surface area of 649 m^2/m^3.

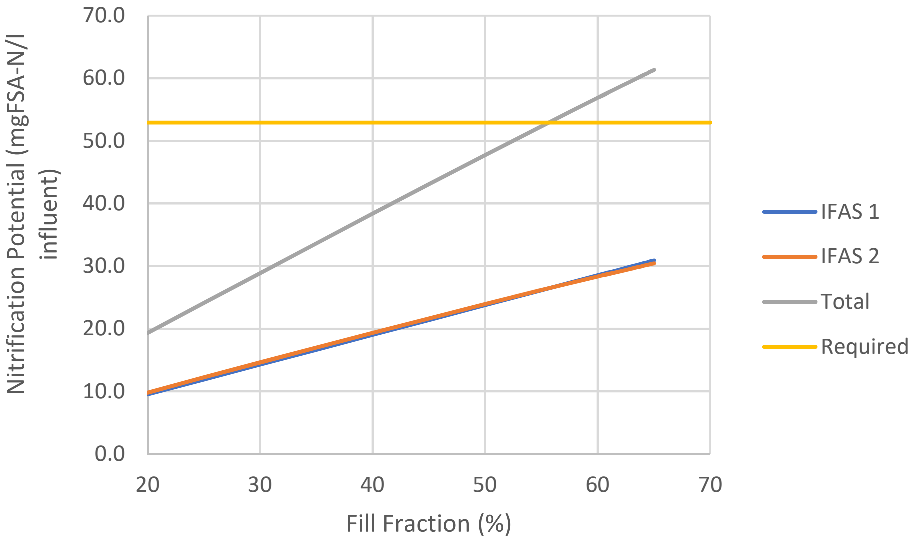


Figure 25.1: Nitrification potential of the IFAS System as a function of the carrier fill fraction.

The total surface area available in this zone is therefore:

Equation 25.5: Carrier surface area

$$
\begin{aligned}
Area &= Vol\ \times net\ specific\ carrier\ Area \\
&= 720.5 \times 649
\end{aligned}
$$

$$= 467612\ m^2$$

The influent-equivalent nitrification potential of this IFAS zone can now be calculated as follows:

Equation 25.6: Nitrification capacity of biofilm

$$N_{c,biofilm} = \frac{r_n \times carrier\ Area}{ADWF \times 1000}$$

$$= \frac{0.708 \times 467612}{12.65 \times 1000}$$

$$= 26.1\ mgN/l\ \ influent$$

The ammonia concentration exiting IFAS zone 1 is therefore 52.9-26.1 = 26.8 mgFSA-N/l influent.

25.3 Nitrification in Aerobic Zone 3 (IFAS zone 2)

The influent C/N ratio (BO COD/Nitrification capacity) is 56.5/26.8 = 2.1 mgCOD/mgFSA-N. The nitrification rate coefficient k can then be calculated from Figure 6.4, in this case k = 0.64.

The DO concentration in this zone is automatically controlled between 3 mgO/l and 6 mgO/l by monitoring the effluent ammonia concentration. To determine the nitrification capacity of the zone a DO of 4 mgO/l is used. Since the ammonia concentration is still high, the nitrification rate can be rate determining ammonia concentration can be estimated as follows:

Equation 25.7

$$S_n = {}^{(DO - 0.5)}/_{3.2}$$

$$= {}^{(4.0 - 0.5)}/_{3.2}$$

$$= 1.09\ mgFSA - N/l$$

The nitrification rate achievable in IFAS zone 1 is then calculated as follows:

Equation 25.8

$$r_N = k(S_n)^n$$

$$= 0.64(1.09)^{0.7}$$

$$= 0.683\ gNH_4 - N/m^2.d$$

The volume of this zone is 720.5 m^3. Biofilm carriers with a specific area of 1200 m^2/m^3 was chosen and a filling fraction of 54% was used. This gives a net specific surface area of 649 m^2/m^3. The total surface area available in this zone is therefore:

Equation 25.9

$$Area = Vol \times nett\ specific\ carrier\ Area$$

$$= 720.5 \times 649$$

$$= 467612\ m^2$$

The influent-equivalent nitrification potential of this IFAS zone can now be calculated as follows:

Equation 25.10

$$N_{c,biofilm} = \frac{r_n \times carrier\ Area}{ADWF \times 1000}$$

$$= \frac{0.683 \times 467612}{12.65 \times 1000}$$

$$= 25.3\ mgN/l\ \ influent$$

The ammonia concentration exiting IFAS zone 2 is therefore 26.8-25.3 = 1.5 mgFSA-N/l influent. This optimization was found by iterating the carrier fill fraction until adequate nitrification takes place to produce this effluent ammonia concentration of 1.5 mgFSA-N/l.

25.4 Nitrification in Aerobic Zone 4 (post-IFAS)

The biofilm nitrification model does not attribute any nitrification to the last zone of the reactor. In this zone the remaining biodegradable COD concentration is low (or zero) but the ammonia concentration will also be low. It is not economical to place carriers in this zone since the low ammonia concentration limits the nitrification rate. This zone may facilitate nitrification in the MLSS due to sloughing of biofilm from the carriers and thereby help to achieve low effluent ammonia concentration more consistently.

The model considers the effluent ammonia unchanged from the IFAS zone outlet:

Equation 25.11: Effluent ammonia concentration

$$N_{ae} = 1.5\ mgFSA - N/l$$

26 Total Nitrification

The total nitrification capacity is calculated as the sum of the MLSS nitrification capacity and the biofilm nitrification capacity to a limit of:

Equation 26.1: Max possible nitrification capacity

$$\begin{aligned} N_{c,max} &= N_{ti} - (N_{ouse} + 1.5) - N_s \\ &= 83 - (3.0 + 1.5) - 27.1 \\ &= 51.4\, mgN/l\ influent \end{aligned}$$

where the lowest achievable effluent ammonia concentration was set to 1.5 mgFSA-N/l.

Since the MLSS has no nitrification capacity at the selected sludge age and minimum temperature and the biofilm has a nitrification capacity of 51.4 mgN/l, the combined nitrification capacity is equal to the maximum possible nitrification capacity.

27 Denitrification

The ammonia nitrified in the system, i.e. the combined nitrification capacity of the biofilm and MLSS, is available for denitrification in the anoxic zone.

A conventional UCT system is balanced when the sludge age and influent TKN/COD ratio in which $f_{x,anaer} + f_{x,anoxic} = f_{x,m}$ and $a_{opt} = a_{prac}$ (say 6:1) so that a_{prac} loads the anoxic reactor exactly to its denitrification potential.

The procedure for ‘balancing’ an UCT-IFAS system to find the most economical solution is similar but differs in some regards. In a CAS system f_{xm} and sludge age are interdependent which requires that the sludge age is iterated until the minimum sludge age allowed which sets $f_{x,anaer} + f_{x,anoxic} = f_{x,m}$ is found. In a UCT-IFAS system f_{xm} is not directly related to the sludge age. The sludge age is chosen as the minimum required for EBPR and BPO utilization while f_{xm} is selected to ensure low effluent nitrate while not compromising BPO utilization.

Therefore, an UCT-IFAS system is balanced when, at the pre-selected sludge age and average influent TKN/COD ratio, with $a_{opt} = a_{prac}$ (say 6:1), the unaerated mass fraction ($f_{x,anaer} + f_{x,anoxic} \leq 0.45$) is selected so that a_{prac} loads the anoxic reactor exactly to its denitrification potential. In this case only $f_{x,anoxic}$ is iterated (and not sludge age) to match the denitrification potential to the recycled nitrate load. If the balanced f_{xt} is required to be more than 0.45, the a-recycle ratio is adjusted downward to regain a balanced system with f_{xt} set to 0.45.

The denitrification potential of the anoxic tank is the sum of the denitrification potential due to readily biodegradable COD (RBCOD) (that occurs rapidly) and the denitrification potential due to slowly biodegradable COD.

Equation 27.1: Denitrification potential attributable to RBCOD

$$\begin{aligned} D_{p1,RBCOD} &= S_{F,ANn}(1+r)(1-f_{cv}Y_{OHO})/2.86 \\ &= 46.7(1+1)(1-1.481\times 0.45)/2.86 \\ &= 10.9 mgN/l\ influent \end{aligned}$$

Equation 27.2: Denitrification potential attributable to SBCOD

$$\begin{aligned} D_{p1,SBCOD} &= \frac{f_{AX1}K'_{2T}(COD_{b,i}-S_{s,PAO})Y_{OHO}SRT}{(1+b_{OHO,T}SRT)} \\ &= \frac{0.35\times 0.1607\times(786-301)\times 0.45\times 6}{(1+0.2022\times 6)} \\ &= 33.3\ mgN/l\ influent \end{aligned}$$

$$\begin{aligned} D_{p1} &= 10.9+33.3 \\ &= 44.2\ mgN/l\ influent \end{aligned}$$

The effluent nitrate concentration from the reactor can be calculated as follows when the nitrate concentration in the outflow from the anoxic reactor is zero:

Equation 27.3: Effluent nitrate concentration

$$\begin{aligned} S_{NO_3,e} &= N_c/(a+s+1) \\ &= 51.4/(3.55+1.5+1) \\ &= 8.5\ mgN/l \end{aligned}$$

The optimum a-recycle ratio can be calculated from the following expression:

Equation 27.4: Optimal a-recycle ratio

$$a_{opt} = \left[-B + \sqrt{B^2 - 4AC}\right] /(2A)$$

Where:

$$A = S_{O_2,a}/2.86$$

$$= 1.0/2.86$$

$$= 0.35$$

$$B = N_c - D_{p1} + [(s+1)S_{O_2,a} + s\,S_{O_2,s}]/2.86$$

$$= 51.4 - 44.2 + [(1.5+1) \times 1.0 + 1.5 \times 0]/2.86$$

$$= 8.14$$

$$C = sN_c - (s+1)(D_{p1} - s\frac{S_{O_2,s}}{2.86})$$

$$= 1.5 \times 51.4 - (1.5+1)(44.2 - 0)$$

$$= -33.3$$

$$a_{opt} = \left[-8.14 + \sqrt{8.14^2 - 4 \times 0.35 \times (-33.3)}\right] /(2 \times 0.35)$$
$$a_{opt} = 3.55$$

Since the size of the anoxic zone was limited by the requirement for BPO utilization the optimal a-recycle ratio was found to be less than 6. Figure 27.1 shows that the lowest possible effluent nitrate concentration was achieved for an a-recycle ratio of 3.55 times the ADWF. This is the a-recycle ratio that loads the anoxic zone exactly to its denitrification potential. Lower or higher recycle rates will result in a higher effluent nitrate concentration since the minimum effluent nitrate concentration is either recycle limited or kinetics limited.

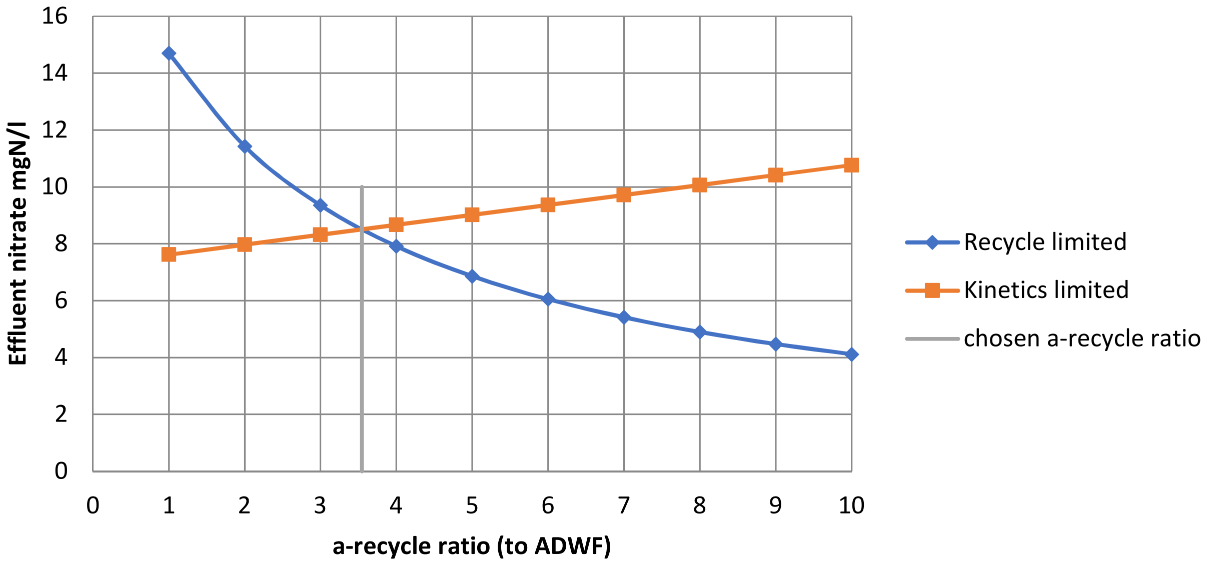


Figure 27.1: Prediction of effluent nitrate at various a-recycle ratios. The chosen a-recycle ratio of 3.55 produces the lowest possible effluent nitrate concentration.

28 TKN Mass balance

A TKN mass balance was done to confirm that all nitrogen entering and leaving the system is accounted for.

Table 28.1: TKN mass balance

N Mass balance		
TKN in (influent)	**1049.95**	**kgN/d**
TKN out	**1049.95**	**kgN/d**
N_{te}	154.22	kgN/d
N_{waste}	352.7	kgN/d
$N_{denitrified}$	543.0	kgN/d

29 Oxygen utilization & Aeration

The oxygen demand of the settled wastewater UCT-IFAS system is summarized in Table 29.1.

Table 29.1: Oxygen Demand of UCT-IFAS System

Carbonaceous Oxygen flux OHO's	FO_{OHO}	3840	kgO/d
Carbonaceous Oxygen flux PAO's	FO_{PAO}	1591	kgO/d
Carbonaceous Oxygen flux	FO_c	5431	kgO/d
Nitrogenous Oxygen flux	FO_N	2973	kgO/d
Oxygen demand recovered by denitrification	FO_D	1553	kgO/d
Total Oxygen Demand ($FO_C + FO_N - FO_D$)	FO_T	6851	kgO/d
Oxygen utilisation rate	O_T	109.0	mgO/(l.h)

The amplitude of the TOD influent (TOD_{peak}/TOD_{avg}) is 1.0. Since there are PST's upstream of the reactor, the TOD wave is dampened by 25%, which reduces the amplitude to 0.75.

The oxygen utilization rate (OUR) by the biomass does not respond directly to the influent TOD wave, instead it has been proven that the amplitude of the OUR is approximately 28% of the TOD amplitude for BNR systems (Musvoto, et al., 1992). The OUR amplitude is therefore 0.75 x 0.28 = 0.21.

The peak OUR can therefore be calculated as follows:

Equation 29.1: Peak oxygen utilization rate

$$\begin{aligned} OUR_{peak} &= OUR_{avg} \times (1 + amp) \\ &= 109 \times (1 + 0.21) \\ &= 131.8\, mgO/(l.h) \end{aligned}$$

The peak actual oxygen requirement (AOR) is therefore:

Equation 29.2: Peak actual oxygen requirement

$$\begin{aligned} AOR_{peak} &= OUR_{peak} \times Vol_{Aer} \\ &= 131.8 \times 2620/1000 \\ &= 345\, kgO/hr \end{aligned}$$

As discussed in Section 10 the pre- and post- IFAS zones are equipped with fine bubble diffusers with a higher SOTE. These zones also operate at a conventional DO concentration of

2.0 mgO/l. The IFAS zones are equipped with more robust stainless-steel medium-bubble diffusers that require less maintenance but have lower SOTE's. The IFAS zones are operated at a DO concentration of 4 mgO/l.

Table 29.2: Aeration Requirements of Aerobic Zones

	Zone 1 [Pre-IFAS]	**Zone 2 [IFAS]**	**Zone 3 [IFAS]**	**Zone 4 [Post-IFAS]**	**Total**
Airflow Fraction	25%	33%	30%	12%	100%
Airflow Fraction [kgO/hr]	86	114	104	41	345
DO [mgO/l]	2.0	4.0	4.0	2.0	
Type of diffusers	fine	medium	medium	fine	
SOTE [%/m submergence]	7.0%	3.5%	3.5%	7.0%	
Submergence (m)	4.2	4.2	4.2	4.2	
SOTE total	29.4%	14.5%	14.5%	29.4%	
Fouling Factor	0.90	1.00	1.00	0.90	
Standard Airflow [m^3/hr]	2626	8519	7745	1260	20150
Power required [kW]	42	126	115	19	301
Power required per Ml/d capacity [kW/(Ml/d)]					23.8
Power required per Ml treated [kWh/Ml]					572
Power required per oxygen demand [kWh/kgO]					0.87

The aeration requirements of the respective zones are summarized in Table 29.2. For a typical CAS UCT system, the oxygen utilization spread to four equal zones is approximately 33%;25%;21%;21%. Since the MLSS does not nitrify the nitrogenous oxygen demand is concentrated in the IFAS zones. This is estimated to change OUR spread for the settled UCT-IFAS system to 25%;33%;30%;12% amongst the four zones.

The IFAS zones require considerably more aeration than the other zones due to the reduced diffuser efficiency and higher operating DO concentration. The power consumed by typical modern centrifugal blowers was also calculated and presented in Table 29.2. The aeration power required per Ml/d capacity for the settled wastewater UCT-IFAS system is 23.8 kW/(Ml/d). For every Ml treated the power consumed is 572 kWh. The power required (at site conditions) per oxygen demand was calculated as 0.87 kWh/kgO.

30 Performance comparison /Super Summary

A detailed comparison of the CAS system treating raw and settled wastewater and the IFAS system treating raw and settled wastewater was done. The comparison of the results can be seen in the 'Super Summary' shown in Table 30.1.

Table 30.1: Performance comparison / Super summary for Borcherds Quarry WWTW A-Works

	CAS RAW	**CAS SETTLED**	**IFAS RAW**	**IFAS SETTLED**	
ADWF Capacity	5.7	7.4	9.3	12.65	Ml/d
ADWF Capacity Comparison i.t.o CAS Raw	**100%**	131%	**164%**	224%	
ADWF Capacity Comparison i.t.o CAS Settled	76%	**100%**	125%	**171%**	
Influent COD Concentration	1594	878	1594	878	mgCOD/l
Influent COD Load	9.0	6.5	14.7	11.1	tCOD/d
Influent TKN Concentration	113	83	113	83	mgN/l
Influent TP Concentration	12	8.7	12	8.7	mgP/l
PWWF	10.6	13.9	17.3	23.7	Ml/d
Sludge Age	12.0	16.4	5.0	6.0	days
Temperature	14.0	14.0	14.0	14.0	°C
Reactor TSS Concentration	7459	6641	6025	5094	mgTSS/l
SST flux ADWF limit	5.6	7.5	9.2	12.7	Ml/d
TKN/COD ratio	0.071	0.095	0.071	0.095	
Anaerobic Mass Fraction	0.100	0.100	0.100	0.100	
Anoxic Mass Fraction	0.221	0.350	0.243	0.350	
Aerobic Mass Fraction	0.679	0.550	0.657	0.550	
Portion of aerobic zone that has carriers	0%	0%	50%	50%	
Media filling fraction	0%	0%	49%	54%	by vol
Media specific surface area			1200	1200	m^2/m^3
Net specific surface area			592	649	m^2/m^3
Total Carrier Surface Area			1020170	935224	m^2
Carrier Surface Area per TKN Load			976	891	$m^2/(kgN/d)$
SF (SRT/SRT_m)	1.4	1.5	0.57	0.54	
IFAS zone 1 nitrification rate potential			0.515	0.708	$gNH_4\text{-}N/m^2d$
IFAS zone 1 nitrification rate actual			0.515	0.708	$gNH_4\text{-}N/m^2d$
IFAS zone 1 DO concentration	2.0	2.0	4.0	4.0	mgO/l
IFAS zone 2 nitrification rate potential			0.460	0.683	$gNH_4\text{-}N/m^2d$
IFAS zone 2 nitrification rate actual			0.460	0.683	$gNH_4\text{-}N/m^2d$
IFAS zone 2 DO concentration	2.0	2.0	4.0	4.0	mgO/l
Effluent Ammonia concentration	1.65	1.64	1.50	1.50	mgFSA-N/l
Effluent Nitrate concentration	7.33	6.66	7.75	8.51	$mgNO_3\text{-}N/l$
Effluent Total P concentration	0.0	0.0	0.0	0.0	mgP/l
Mass TSS wasted	2961	1929	5740	4045	kgTSS/d
Carbonaceous Oxygen flux	4883	3760	6802	5431	kgO/d
Nitrogenous Oxygen flux	1609	1915	2272	2973	kgO/d
Oxygen demand recovered by denitrification	888	1057	1217	1553	kgO/d
Total Oxygen Demand (FOC + FON - FOD)	5604	4617	7857	6851	kgO/d
Peak Aeration Power Requirement	138	138	352	301	kW
Aeration Power required per Ml	**585.4**	**447.0**	**914.3**	**571.5**	kWh/Ml
Aeration Power required per Oxygen Demand	0.46	0.46	0.84	0.87	kWh/kgO

The most significant comparison is that of the ADWF capacity. The raw wastewater IFAS system had 64% more capacity than the raw wastewater CAS system. The settled wastewater system had 71% more capacity than the settled wastewater CAS system. The effluent results were very similar. An important consideration is the increased energy consumption and therefore, operational cost that is required for the IFAS system due to the higher DO concentrations and lower efficiency of medium bubble diffusers.

31 Sensitivity Analysis and Applicability of the IFAS System

31.1 Model Applied to alternative site

To test whether the results obtained for the Borcherds Quarry A-Works are unique or more widely applicable, the model was applied to the Athlone WWTW. The comparison of results found for Athlone WWTW is shown in Table 31.1.

Table 31.1: Performance comparison / super summary for Athlone WWTW

	CAS RAW	CAS SETTLED	IFAS RAW	IFAS SETTLED	
ADWF Capacity	57.5	75.1	92.2	116.2	Ml/d
ADWF Capacity Comparison i.t.o CAS Raw	**100%**	131%	**160%**	202%	
ADWF Capacity Comparison i.t.o CAS Settled	77%	**100%**	123%	**155%**	
Influent COD Concentration	996	744	996	744	mgCOD/l
Influent TKN Concentration	58.9	55.8	58.9	55.8	mgN/l
Influent TP Concentration	8.01	7.18	8.01	7.18	mgP/l
PWWF	143	187	230	290	Ml/d
Sludge Age	12	12	5	5	days
Temperature	14	14	14	14	°C
Reactor TSS Concentration	5339	4727	4262	3729	mgTSS/l
SST flux ADWF limit	57.7	75.2	92.1	116.1	Ml/d
TKN/COD ratio	0.0591	0.075	0.0591	0.075	
Anaerobic Mass Fraction	0.1	0.1	0.1	0.1	
Anoxic Mass Fraction	0.2	0.21	0.14	0.23	
Aerobic Mass Fraction	0.7	0.69	0.76	0.67	
Portion of aerobic zone that has carriers	0	0	50%	50%	
Media filling fraction	0	0	59.1%	56.5%	by vol
Media specific surface area			1200	1200	m^2/m3
Net specific surface area			708.6	677.8	m^2/m3
Total Carrier Surface Area			12372391	10459769	m^2
Carrier Surface Area per TKN Load			2278	1613	m^2/(kgN/d)
SF (SRT/SRT_m)	1.48	1.46	0.683	0.584	
IFAS zone 1 nitrification rate potential			0.337	0.540	gNH_4-N/m^2d
IFAS zone 1 nitrification rate actual			0.337	0.540	gNH_4-N/m^2d
IFAS zone 1 DO concentration	2	2	4	4	mgO/l
IFAS zone 2 nitrification rate potential			0	0.136	gNH_4-N/m^2d

IFAS zone 2 nitrification rate actual			0	0.136	gNH_4-N/m^2d
IFAS zone 2 DO concentration	2	2	4	4	mgO/l
Effluent Ammonia concentration	1.46	1.52	1.55	1.50	mgFSA-N/l
Effluent Nitrate concentration	3.34	4.34	3.86	3.80	mgNO_3-N/l
Effluent Total P concentration	0	0	0	0	mgP/l
Mass TSS wasted	18605	16473	35649	31027	kgTSS/d
Carbonaceous Oxygen flux	31168	32336	42197	42629	kgO/d
Nitrogenous Oxygen flux	7459	11915	9522	16160	kgO/d
Oxygen demand recovered by denitrification	4119	6524	4940	8849	kgO/d
Total Oxygen Demand (FOC + FON - FOD)	34509	37727	46779	49940	kgO/d
Peak Aeration Power Requirement	848.7	848.7	2097.9	2195.7	kW
Aeration Power required per Ml	**354.3**	**271.2**	**546.1**	**453.5**	kWh/Ml
Aeration Power required per Oxygen Demand	0.461	0.461	0.841	0.872	kWh/kgO

31.2 TKN/COD Ratio

It was found that the benefit for installing IFAS carriers in a raw wastewater or settled wastewater process produced capacity increases of 55% to 71% at TKN/COD ratios between 0.059 and 0.095 at a minimum temperature of 14°C as shown in Figure 31.1. The UCT-IFAS process was found to be beneficial over a wide range of influent TKN/COD ratios.

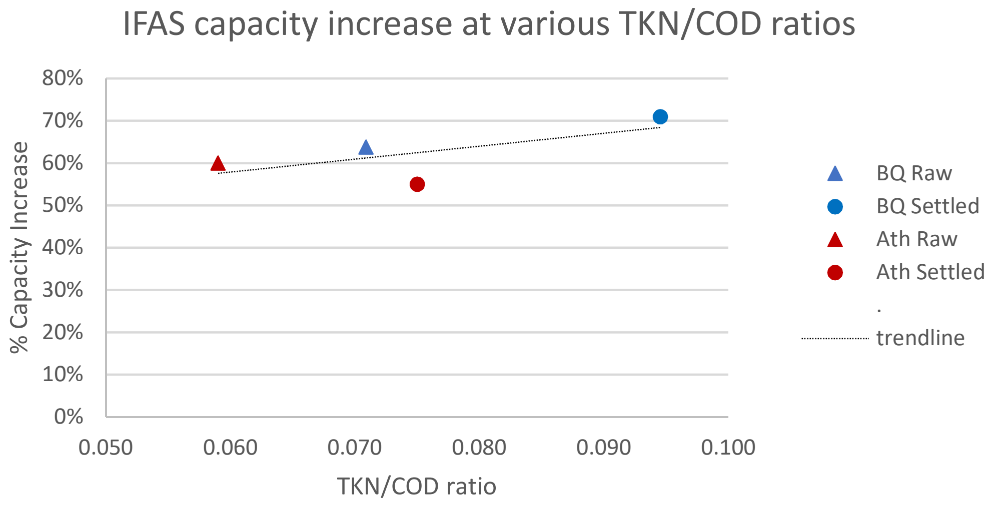


Figure 31.1: The capacity increases achievable with IFAS compared to CAS at two wastewater plants within the City of Cape Town operating at different TKN/COD ratios at an assumed minimum temperature of 14°C.

31.3 Carrier Surface Area per TKN Load for different TKN/COD ratios

The influent TKN/COD ratio has a significant impact on the nitrification rate achieved on the IFAS carriers and consequently on the number of carriers required to achieve near complete nitrification. Figure 31.2 indicates how the required carrier surface area reduces with increased TKN/COD ratio.

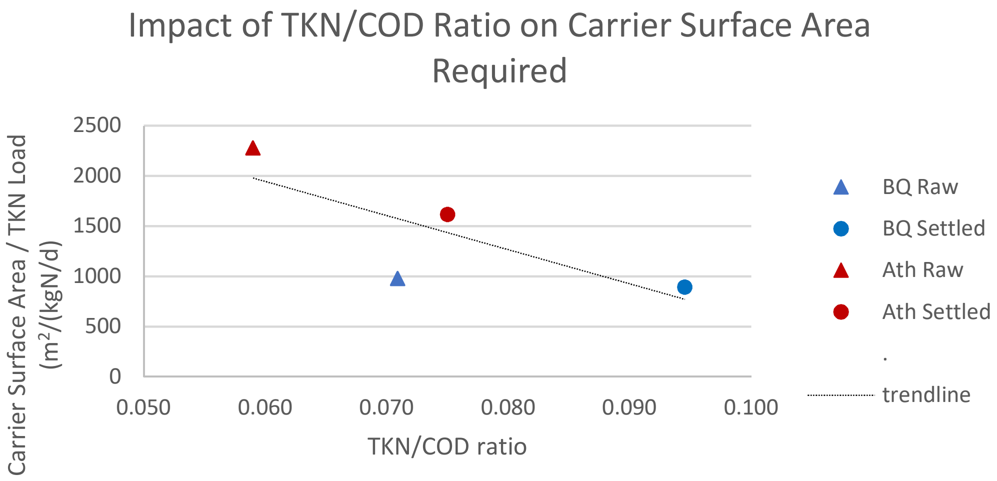


Figure 31.2: The Impact of TKN/COD ratio on the required carrier surface area for near-complete nitrification (normalized to the influent TKN load)

31.4 Aeration Power per Megalitre

Due to the less efficient oxygen transfer efficiency of medium bubble diffusers that are used in the IFAS zones as well as the high operating DO levels, the UCT-IFAS system requires more aeration and therefore energy than CAS to treat a volume of wastewater. The power consumed per megaliter treated was compared in Figure 31.3.

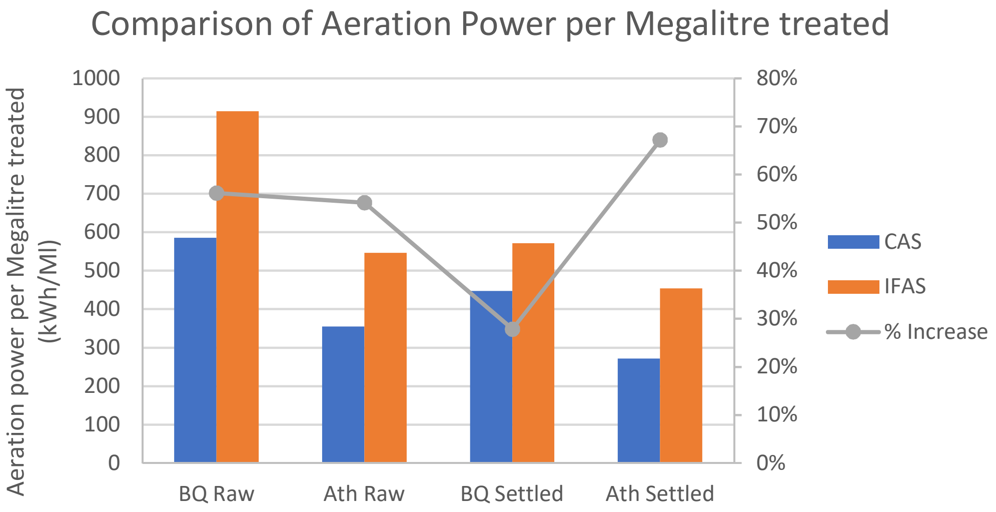


Figure 31.3: Comparison of the aeration power required for CAS and IFAS systems at Borcherds Quarry and Athlone WWTW's for both raw and settled wastewater.

31.5 Efficiency of Oxygen Transfer

While Figure 31.3 considers that the reduced sludge age of the IFAS system results in a reduced oxygen requirement, one can compare the oxygen transfer efficiency of the systems by normalizing the aeration power required using the peak oxygen demand. This reveals, as shown in Figure 31.4, that the IFAS system is 80% to 90% less efficient at transferring oxygen to the water. This is purely attributable to the lower oxygen transfer efficiency of medium bubble diffusers and the higher operating DO concentration of IFAS systems that decreases the driving force for oxygen transfer.

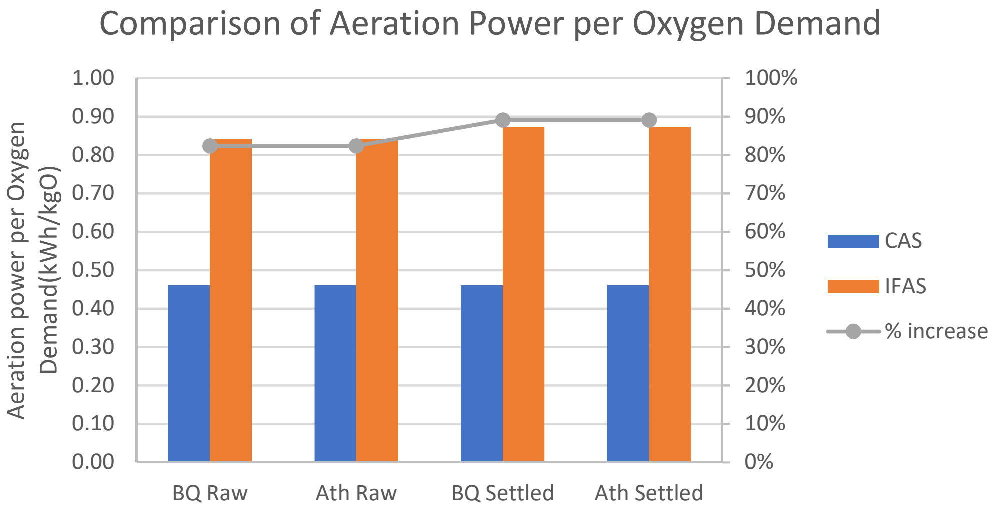


Figure 31.4: Comparison of the oxygen transfer efficiencies of CAS and IFAS systems for Borcherds Quarry and Athlone WWTW's.

31.6 Reactor MLSS Concentration

It was shown in this thesis that a reactor MLSS concentration above 5000 mgTSS/l for a low sludge age (6 days) still provided sufficient volume for the carriers required to achieve near-complete nitrification. High surface carriers (1200 m^2/m^3) were used in the calculations and a high filling fraction (54%) was still required.

If one wants to use lower surface carriers or operate at lower filling fractions it would be beneficial to design the system at relatively low concentrations. This will result in larger reactors but smaller SST's and can ensure that the reactor has sufficient space for the carriers required.

It should be noted that it was recommended in this thesis that only the middle portion of the aerobic zone be equipped with carriers. The option remains to populate more of the aerobic zone with carriers, but in doing so one has to accept that the nitrification rate achieved in those areas may be reduced and the benefit of the added cost reduces.

Although not in the scope of this thesis, the impact of a limited concentration for IFAS systems due to the space required for carriers may have a bearing on the design of an UCT-IFAS membrane bioreactor (MBR) system. Membrane bioreactors are characterized by high MLSS concentrations which allows for smaller reactor footprints. It seems logical that conversion of an UCT-MBR system to IFAS would be less beneficial than for UCT-CAS since the volume required for carriers may become limiting.

31.7 Hydraulic Design of Works

When retrofitting IFAS in a CAS system, the capacity of the system increases as discussed in this thesis. For capacity increases quoted in this thesis both the capacity of the reactor and the SST's were considered in combination with the flux theory applied to the SST's. For the calculations in this thesis a fixed ratio of PWWF/ADWF was used. Hence where it is found that the capacity of a system increases through conversion to IFAS it is important to consider whether the rest of the system can handle the higher hydraulic load. In some cases, there may be adequate capacity already, in other cases it may be necessary to modify piping, channels or weirs to accommodate the increased hydraulic load.

31.8 Aeration Capacity of Works

Since IFAS systems require more aeration than CAS, a retrofit may require an upgrade to the aeration system. This may include providing new or additional blowers and replacing fine bubble diffusers with medium bubble diffusers. In some cases, vertical shaft aerators will need to be replaced with medium bubble diffused aeration systems. IFAS systems employing medium bubble diffused aeration is still more energy efficient than vertical shaft aerators.

31.9 Simplified Cost Comparrison between IFAS and CAS

The feasibility and lifecycle cost comparison of IFAS and CAS will be unique for each installation. To determine in broad strokes the attractiveness of an IFAS system in comparison to CAS the following basic example is used.

CAS wastewater treatment plants (excluding inlet works and sludge treatment) in South Africa cost about R14 million per Ml/d capacity to install. Of this cost the aeration system costs about R4 million per Ml/d capacity.

If an IFAS system can increase the capacity by 60% that reduces the unit cost to R8.75 million per Ml/d capacity excluding IFAS carriers and sieves and additional aeration capacity required. Adding R1 million per Ml/d for carriers and sieves and R1.5 million per Ml/d for the extra aeration equipment brings the total unit capital cost to R11.25 million per Ml/d capacity.

The only major difference in operational costs is the extra energy required for aeration in IFAS systems. Using an 50% higher aeration power required for IFAS compared to CAS (see Figure 31.3), roughly 200 kWh per Ml additional aeration will be required each day. At R1.20 per kWh the added operational cost is R240 per day or R87 600 per year.

The difference in capital cost between CAS and IFAS is then R14 million – R11.25 million = R2.75 million per Ml/d capacity. The difference in capital cost will only be recovered in R2.75 million / R87 600 per year =31 years.

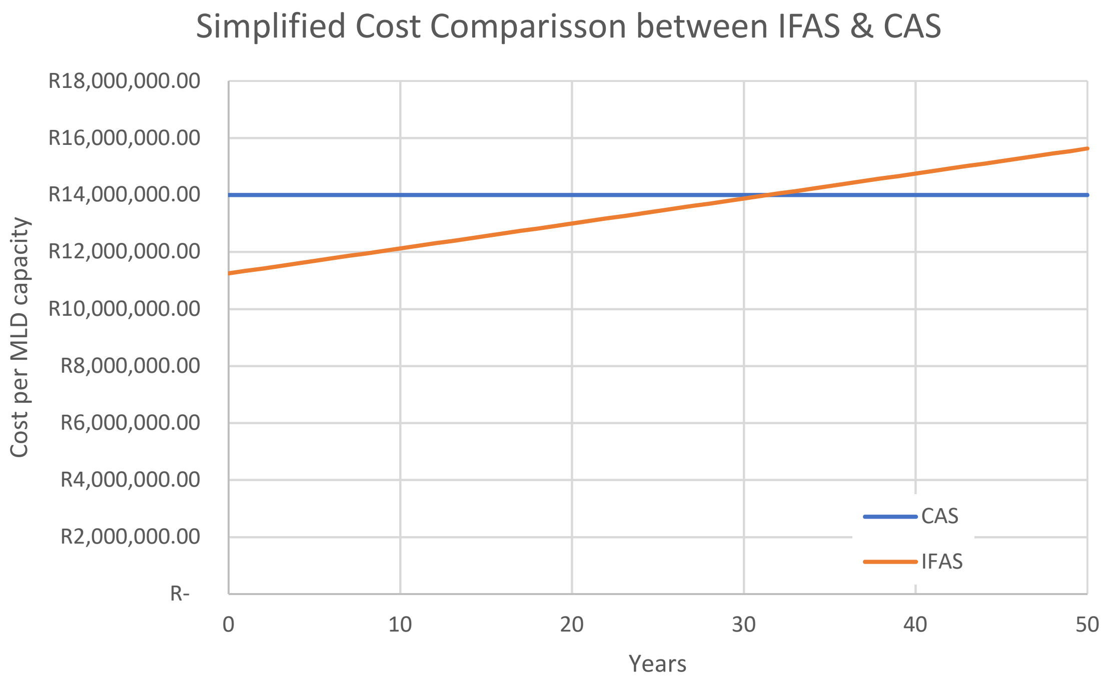


Figure 31.5: Simplified cost comparison between IFAS and CAS where the Capital cost per MLD is compared and the operational cost of the CAS system is set to zero and the additional aeration cost for IFAS is considered. For a period over 33 years CAS will be more cost effective. (Note inflation and discount rates considered equal, i.e. no preference is given to earlier or later expenditure)

This shows that IFAS will be a very attractive option where large capital expenditure is not possible or preferable. It also indicates why IFAS is such an attractive option for retrofitting existing CAS systems, especially where land availability, space or capital budget are constraints. From the example rates used here it can be derived that if existing CAS infrastructure worth R14 million per Ml/d capacity is in place, only R2.5 million per Ml/d capacity (18%) needs to be spent to unlock 60% extra capacity.

31.10 UCT-IFAS Range of Application

Although this thesis only looked at two wastewater treatment works within the City of Cape Town, it did provide the means to compare the impact of TKN/COD ratios and different wastewater strengths on the design and performance. It is apparent from the results that the UCT-IFAS process would perform well for most South African domestic wastewaters. The benefit of an IFAS system is much reduced if the actual minimum wastewater temperatures are above 20°C.

The effluent quality produced from an IFAS system is at least equal to that of an CAS system even at much higher wastewater loads. The IFAS system requires more aeration energy which results in higher operating costs than CAS. The capital cost of an IFAS system is however significantly less than a CAS system for the same capacity. A lifecycle cost analysis is required in each application to determine which option is most attractive for stakeholders.

32 Conclusion & Recommendations

i. Placing biofilm carriers in the aerobic zone of a UCT configuration to create a UCT-IFAS process allows nitrification to take place in the biofilm. This makes it possible to operate at a sludge age, much lower than that required for nitrification in the suspended MLSS.

ii. The minimum sludge age in an UCT-IFAS process is selected to ensure a long enough aerobic sludge age to achieve stable EBPR and near complete BPO utilization by OHO's. At 14°C and an unaerated mass fraction of 0.45 a minimum sludge age of 6 days is required to ensure stable EBPR and near-complete BPO utilization.

iii. PST's remove a significant portion (30% to 40%) of the influent COD while typically around 15% TKN is removed. This increases the TKN/COD ratio of the wastewater and prevents high organic loading on the carriers and thereby prevents inhibition of nitrification. Better nitrification rates are therefore achieved on carriers in a settled wastewater IFAS application.

iv. The removal of slowly biodegradable particulate organics (BPO) by PST's is particularly beneficial since BPO, unlike biodegradable soluble organics (BSO), may not be taken up or utilized in upstream anaerobic and anoxic tanks nor in a pre-IFAS zone.

v. The anaerobic and anoxic zones of an UCT-IFAS process facilitates uptake or utilization of organics prior to IFAS zones which prevents prolific OHO growth on the carriers and is therefore beneficial for the nitrification rate.

vi. In this report it was proposed to have a 25% pre-IFAS zone and 25% post-IFAS zone with two 25% IFAS zones in the aerobic tank. When the model shows that a carrier filling fraction below 60% gives adequate nitrification, one may choose to increase the pre-IFAS volume fraction so that the IFAS zones are filled to 60% exactly. This will ensure that the COD load to the IFAS zone is as low as possible and therefore the nitrification rate will be as high as possible. Similarly, if the space in the reactor (IFAS zones) are not sufficient for the volume of carriers required the pre- and post-IFAS zones can be made smaller or even eliminated if the C/N ratio is low enough in these zones.

vii. It was found that biofilm nitrification can be done effectively in different sections of the aerobic zone and it is not necessary to place carriers specifically in the middle section. The subdivision of the aerobic zone is more important to take advantage of the increased bulk liquid ammonia concentration in the upstream aerobic zones and the increase in nitrification rate that this leads to.

viii. Placing IFAS carriers only a concentrated part of the reactor saves energy since the remainder of the aerobic zone can be equipped with fine bubble diffusers and be operated at a DO concentration of 2 mgO/l.

ix. The biofilm nitrification model used in this thesis shows that the best nitrification rate will be achieved by moving the IFAS zone as far downstream in the aerobic zone as possible due the the lower C/N ratio achieved. It is still advisable to keep a post-IFAS aerobic zone operated at a lower DO concentration since the less turbulent aeration will allow for better flocculation of the MLSS and it will also prevent high DO concentrations being recycled to the anoxic zone through the a-recycle.

x. The aeration costs for an IFAS system are 28% to 67% more per unit treated than for CAS with fine bubble diffused aeration (FBDA) if one assumes that medium bubble diffusers are installed in IFAS zones and FBDA in pre- and post- IFAS zones.

xi. It will be worthwhile to design robust FBDA networks that do not require frequent maintenance, or to design means by which carriers can be removed and reintroduced to the reactor easily. FBDA as opposed to medium bubble aeration can reduce the overall aeration requirement of the IFAS system by about 60% to 70%, to make it even more energy efficient than CAS with FBDA. A combination of FBDA and mechanical mixing can also be employed to meet the mixing requirement of the carriers. At this stage the simplicity and reliability of medium bubble diffusers that require much less maintenance remains an attractive option, even at higher aeration energy costs.

xii. High surface area carriers have several benefits:
   a. Less carriers are required to nitrify the same load of ammonia;
   b. The IFAS zone can be smaller, which makes it possible to create a larger pre-IFAS zone to remove more COD upstream of the carriers and thereby improve the nitrification rate;
   c. A smaller IFAS zone enables a larger part of the aerobic zone to be operated at a lower DO Concentration (2 mgO/l) with FBDA, as opposed to the IFAS zone where 4 mgO/l DO is required and medium bubble diffusers are probably installed. The aeration requirement can therefore indirectly be reduced by using higher surface area carriers.

xiii. Large carriers have several benefits:
   a. Larger carriers allow for larger apertures in retaining sieves which reduces nuisance clogging of retaining sieves and reduces the headloss over the sieves;

   b. The sieve aperture size should be larger than that of the inlet works screens to prevent frequent clogging of the sieves. With larger carriers and sieve apertures the requirement for fine screens at the inlet works is alleviated.

xiv. Nitrification will shift between the MLSS and biofilm due to temperature variations as temperature affects the minimum sludge age required for nitrification in the MLSS. When nitrification occurs in the MLSS, it reduces the nitrification rate on the biofilm, since the biofilm and MLSS are competing for substrate (ammonia). During winter the biofilm will perform a larger portion of the nitrification.

xv. The benefit of IFAS reduces with increasing wastewater temperature. At a minimum (winter) wastewater temperature of 20°C IFAS would have very little benefit. This is because the MLSS nitrification is much improved at such high temperatures and the reduction of the sludge age possible with IFAS is less significant.

xvi. The anaerobic, anoxic and aerobic mass fractions required in IFAS and CAS systems are similar, which makes retrofitting an IFAS installation to a CAS system more feasible.

xvii. The IFAS system requires more aeration energy which results in higher operating costs than CAS. The capital cost of an IFAS system is however significantly less than a CAS system for the same capacity. A lifecycle cost analysis is required in each application to determine which option is most attractive for stakeholders.

xviii. The table below describes how Raw and Settled systems are affected differently by applying an IFAS process:

Table 32.1: Effect of IFAS on raw and settled wastewater treatment systems

	Raw IFAS	Settled IFAS
Nitrification Rate	Lower due to lower TKN/COD ratio	Higher due higher TKN/ COD ratio
Carriers required	More carriers required per unit treated, due to lower nitrification rate	Fewer carriers required per unit treated, due to higher nitrification rate
Zones with carriers	Need pre-IFAS zone to reduce COD load on biofilm	May be able to eliminate pre-IFAS zone since influent COD is much lower
Sludge Age Benefit	Reduced, since raw wastewater CAS requires shorter sludge age due to	Increased, since settled wastewater CAS requires long sludge age due to

	smaller unaerated mass fraction	larger unaerated mass fraction.

xix. More research is required to determine the impact of organic load on the nitrification rate due to OHO growth on the biofilm. In this thesis the inhibition of nitrification due to organic loading was calculated using a k factor proposed by Odegaard (2014). This factor was expressed as a function of the influent C/N ratio as BOD/NH_4. No distinction was made between slowly biodegradable and readily biodegradable COD. It would be worthwhile to determine, through laboratory work, how the nitrification rate is affected differently due to rapid OHO growth from readily biodegradable soluble COD and slower OHO growth from slowly biodegradable particulate COD.

33 References

Dold, P., Wentzel, M., Billing, A. & Marais, G., 1991. *Activated Sludge Simulation Programs: Nitrification and Nitrification/Denitrification Systems, Version 1,* s.l.: WRC Report No TT 52/91.

Ekama, G. A., 2014. *Recent Developments in Biological Nutrient Removal.* s.l., Water SA.

Ekama, G. A. & Wentzel, M. C., 2008. Nitrogen Removal. In: M. Henze, M. C. van Loosdrecht, G. A. Ekama & D. Brdanjovic, eds. *Biological Wastewater Treatment Principles, Modelling and Design.* London: IWA Publishing, pp. 87-138.

Ekama, G. A. & Wentzel, M. C., 2008. Organic Material Removal. In: M. Henze, M. C. van Loosdrecht, G. A. Ekama & D. Brdanjovic, eds. *Biological Wastewater Treatment Principles Modelling and Design.* London: IWA Publishing, pp. 53-86.

Ekama, G. & Takacs, I., 2014. Modeling. In: D. Jenkins & J. Wanner, eds. *Activated Sludge - 100 Years and Counting.* London: IWA Publishing, pp. 271 - 291.

Johnson, C. & Boltz, J. P., 2013. *Aeration system design in integrated fixed-film activated sludge (IFAS).* Chicago, WEFTEC.

Lothman, S. et al., 2011. *Comparison of Oxygen Transfer and uptake Between an Integrated Fixed-Film Activated Sludge (IFAS) Process and a Conventional Activated Sludge Process (ASP),* North Carolina: Water New Zealand.

Metcalf & Eddy, 2004. *Wastewater Engineering Treatment & Reuse.* Fourth ed. New York: McGraw-Hill.

Musvoto, E. et al., 1992. *Calculation of Peak Oxygen Demand in the Design of Full Scale Nutrient Removal Activated Sludge Plants,* Cape Town: City of Cape Town.

Odegaard, H., 2014. *Compact Wastewater Treatment with MBBR.* Hong Kong, SET.

Odegaard, H., 2015. *Advances on MBBR and IFAS Systems.* Palermo, Scandinavian Environmental Technology.

Odegaard, H., Christensson, M. & Sorensen, K. K., 2014. Hybrid Systems. In: D. Jenkins & J. Wanner, eds. *Activated Sludge - 100 Years and Counting.* London: IWA Publishing, pp. 293 - 318.

Odegaard, H., Gisvold, B. & Strickland, J., 2000. *The Influence of Carrier Size and Shape in the Moving Bed Biofilm Process,* Trondheim: IWA Publishing.

Pham, H., Viswanathan, S. & Kelly, R., 2008. *Evaluation of Plastic Carrier Media Impact on Oxygen Transfer Efficiency with Coarse and Fine Bubble Diffusers,* s.l.: Water Environment Federation.

Rutt, K., Seda, J. & Johnson, C. H., 2006. *Two Year Case Study of Integrated Fixed Film Activated Sludge (IFAS) at Broomfield, CO WWTP,* Brromfield: WEFTEC.

Wentzel, M. C. et al., 2008. Enhanced Biological Phospherous Removal. In: M. Henze, M. C. van Loosdrecht, G. A. Ekama & D. Brdanjovic, eds. *Biological Wastewater Treatment Principles, Modelling and Design.* London: IWA Publishing, pp. 155-220.

Wentzel, M. & Ekama, G., n.d. *Characterization of Municipal Wastewater,* Cape Town: Water Research Group UCT.

APPENDIX A

Borcherds Quarry WWTW Settled Wastewater Characterization Block Diagrams

COD SETTLED SEWAGE

Flow **13.94** **Ml/d**

Total COD (Sti)
878.0 mgCOD/l

Soluble (Ssi)
451.0 mgCOD/l

Particulate (Spi)
427.00 mgCOD/l

Biodegradable (Sbi)
786.3 mgCOD/l

Biodeg Soluble (Sbsi)	**403.2**	mgCOD/l
Fermentable (Sbsfi)	323.2	mgCOD/l
Fatty Acids (Sbsi,a)	80.0	mgCOD/l

fcm,bso 1.450 mgCOD/mg
FBSO mass 222.9 mg/l

Biodeg Partic (Sbpi)	**383.1**	mgCOD/l
BPO VSS	229.4	mgVSS/l

fcv,bpo 1.670 mgCOD/mgVSS

Unbiodegradable (Sui)
91.7 mgCOD/l

Unbiodeg Soluble (Susi)	**47.8**	mgCOD/l

fcm,uso 1.50 mgCOD/mg
mass 31.9 mg/l

Unbiodeg Partic (Supi)	**43.9**	mgCOD/l
UPO VSS	29.6	mgVSS/l

fS'up 0.05000
fcv,upo 1.481 mgCOD/mgVSS

Total Susp Solids (Set+Non-Set) conc =	270.0	mgTSS/l
Inorganic Susp Solids (Set + Non-Set) conc =	11.0	mgTSS/l
Volatile Suspended Solids (Set + Non-Set) =	259.0	mgVSS/l
Unbiodegradable VSS (from fcv Sup) =	29.6	mgVSS/l
Biodegradable VSS (total -unbio) =	229.4	mgVSS/l

TKN SETTLED SEWAGE

Total TKN (Nti)
83.0 mgN/l

check
83.0

Organic N (Noi)
13.0 mgN/l

Soluble (Ns)
73.0 mgN/l

FSA (Nai)	**70**	mgN/l

Particulate (Np)
10.00 mgN/l

Biodegradable (Nb)
7.0 mgN/l

Biodeg Soluble (Nobsi)	**0.0**	mgN/l

fnm,bso 0.0000 mgN/mg
mass 222.9 mg/l

Biodeg Partic (Nobpi)	**7.04**	mgN/l
BPO VSS	229.4	mgVSS/l

fn,bpo 0.0307 mgN/mgVSS

Unbiodegradable (Nu)
6.0 mgN/l

Unbiodeg Soluble (Nousi)	**3.00**	mgN/l

fnm,uso 0.0941 mgN/mg
mass 31.9 mg/l

Unbiodeg Partic (Noupi)	**3.0**	mgN/l
UPO VSS	29.6	mgVSS/l

fn,upo 0.10 mgN/mgVSS

TP SETTLED SEWAGE

Total P (Pti)
8.70 mgP/l

check
8.70

Organic P (Poi)
2.00 mgP/l

Soluble (Ps)
7.00 mgP/l

O-P (Pai)	**6.7**	mgP/l

Particulate (Pp)
1.70 mgP/l

Biodegradable (Pb)
1.3 mgP/l

Biodeg Soluble (Pobsi)	**0.30**	mgP/l

fpm,bso 0.0013 mgP/mg
mass 222.9 mg/l

Biodeg Partic (Pobpi)	**0.96**	mgP/l
BPO VSS	229.4	mgVSS/l

fp,bpo 0.0042 mgP/mgVSS

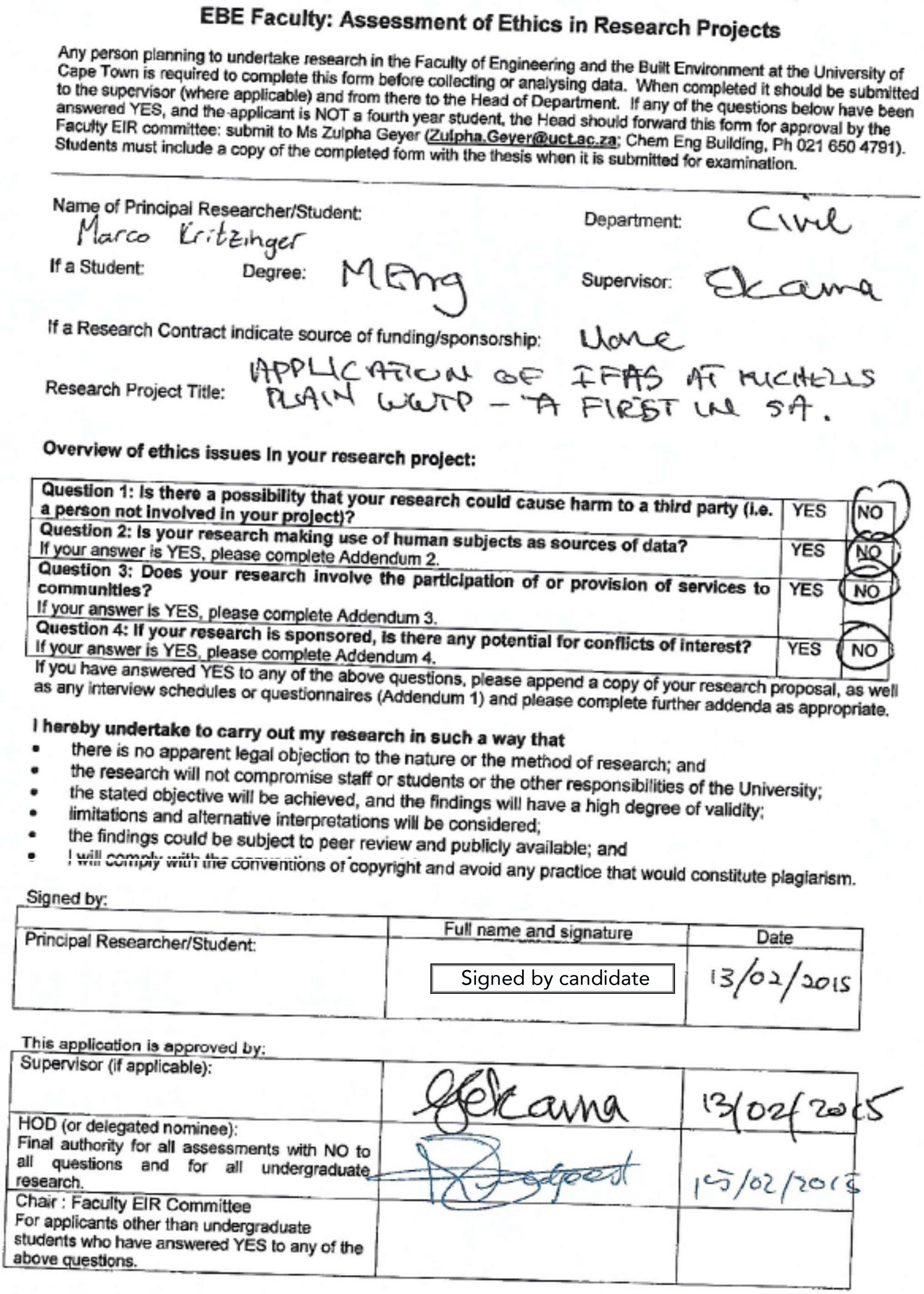
Unbiodegradable (Pu)
0.7 mgP/l

Unbiodeg Soluble (Pousi)	**0.00**	mgP/l

fpm,uso 0.0000 mgP/mg
mass 31.9 mg/l

Unbiodeg Partic (Poupi)	**0.74**	mgP/l
UPO VSS	29.6	mgVSS/l

fp,upo 0.025 mgP/mgVSS



EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791). Students must include a copy of the completed form with the thesis when it is submitted for examination.

Name of Principal Researcher/Student: Marco Kritzinger

Department: Civil

If a Student: Degree: MEng

Supervisor: Ekama

If a Research Contract indicate source of funding/sponsorship: None

Research Project Title: APPLICATION OF IFAS AT MICHELLS PLAIN WWTP – A FIRST IN SA.

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	[✓ NO]
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	[✓ NO]
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	[✓ NO]
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	[✓ NO]

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	Signed by candidate	13/02/2015

This application is approved by:

Supervisor (if applicable):	Ekama	13/02/2015
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.		15/02/2015
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		