DISSERTATION FOR THE DEGREE OF MASTER OF ENGINEERING (WATER QUALITY)

Comparing the Metcalf and Eddy and UCT steady state guidelines for sizing of biological nutrient removal activated sludge wastewater treatment plants

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Abstract

This dissertation aims to provide both a qualitative and quantitative comparison of two steady state activated sludge (AS) design guidelines - the University of Cape Town (UCT) guideline used in South Africa and the Metcalf and Eddy (M&E) guideline used in North America and other parts of the world. It looks at the key similarities and differences between the two steady state AS design guidelines and how, under dynamic conditions, a system that is sized using a particular guideline (i) compares to its steady state results and (ii) performs under these dynamic conditions.

In order to achieve the aims and objectives of this dissertation, an AS steady state model was created in a Microsoft Excel spreadsheet for the UCT guideline and M&E guideline respectively, and the models were analysed in terms of the key similarities and differences in the design guidelines in terms of inputs, equations, approaches and assumptions used. The results produced from each model were also analysed by setting the influent wastewater characteristics the same for each guideline and then analysing the results. The systems that were sized using the steady state AS models were then input into an AS system dynamic simulation software program, UCTOLD (which predicts virtually identical results as ASM1), together with a full set of diurnal influent data, to predict the behaviour of the system under steady state and dynamic conditions and compare the steady state predictions to those calculated in the steady state models and assess how the steady state model sized systems perform under dynamic loading conditions.

The results of the analyses found that the two guidelines are similar in terms of organic material removal, nitrification and the sizing of the secondary settling tank, but differ significantly in the sizing of the anoxic reactor to achieve a certain nitrate removal. The key findings are:

(1) Both UCT and M&E guidelines close the COD and N flux balances within 1%.

(2) For organics removal only, at the same SRT, sludge production and oxygen demand are about 5% higher and lower respectively for the M&E guideline than the UCT guideline. When a UCT and M&E sized fully aerobic system is simulated with ASM1, this difference is repeated. The UCT guideline results are closely correlated with the ASM1 results but the M&E results deviate from those of ASM1. These differences arise because the M&E guideline assigns different values to the kinetic, stoichiometric and temperature sensitivity constants. If these constants in the M&E guideline are assigned the same values as the UCT guideline, virtually identical results are obtained.

(3) For nitrification under fully aerobic conditions, the M&E guideline calculates a slightly shorter minimum aerobic SRT for nitrification than the UCT guideline. Again, the M&E guideline assigns different values to the nitrification kinetic (μ_{Am20}, b_{A20}), stoichiometric (Y_A, K_{n20}) and temperature sensitivity constants ($\theta_{\mu Am}$, θ_{bA}, θ_{Kn}) than the UCT guideline. The M&E guideline calculates the minimum sludge age for nitrification, R_{sm}, using a fixed maximum specific growth rate of nitrifiers at 20°C (μ_{Am20}) at 0.90 g/(g.d), and after

correcting for temperature, DO concentration in the aerobic reactor and assigning a safety factor (S_f = 1.5), the minimum sludge age for nitrification is slightly shorter than for the UCT guideline for a selected maximum specific growth rate of nitrifiers at 20^{o}C (μ_{Am20}) of 0.45 g/(g.d) and assigning S_f = 1.25. In the M&E guideline the mass of nitrifiers is added to the reactor MLSS concentration which increases the MLSS mass in the reactor by about 1-3%. This is not done in the UCT guideline to maintain the COD balance for organics removal. At the same SRT in a fully aerobic system (i.e. aerobic SRT = system SRT), the oxygen demand for nitrification is closely similar in the two guidelines. This is because the calculated concentrations of nitrate produced by nitrification (called nitrification capacity N_c in the UCT guideline) are closely similar – the difference in the sludge production of the two guideline make little difference to the N taken up for sludge production.

(4) If fully aerobic nitrifying reactors sized with the M&E and UCT guidelines are simulated with ASM1 at the same SRT, the same differences as with organic removal are observed. Hence the main difference in the sizing for nitrification in fully aerobic reactors in the two guidelines is the shorter aerobic SRT for nitrification in the M&E guideline (as a result of the different nitrification kinetics and safety factors) than in the UCT guideline.

(5) Significant differences between the two guidelines emerge when adding an anoxic reactor for denitrification, such as for the anoxic aerobic nitrification - denitrification (ND) Modified Ludzack-Ettinger (MLE) system. This is because (5.1) the nitrifiers are assumed to behave differently under anoxic conditions in the two guidelines and (5.2) the effective specific denitrification rates of the OHO biomass in the anoxic reactor are much higher in the M&E guideline than in the UCT guideline.

(6) With regard to difference (5.1), in the UCT guideline, the nitrifiers are assumed to grow only in the aerobic reactor but die in both the anoxic and aerobic reactors. In the M&E guideline, the nitrifiers are assumed to die (and grow) only in the aerobic reactor, i.e. they neither grow nor die in the anoxic reactor. Hence in the M&E guideline, the MLE system is sized based on an aerobic SRT, which excludes the mass of sludge in the anoxic reactor as in (3) above, but in the UCT guideline the MLE system is sized based on a system SRT, which includes the mass of sludge in the anoxic reactor.

(7) With regard to difference (5.2), the faster specific denitrification rate determined with the M&E guideline yield much smaller anoxic reactors by at least 50% to achieve the same nitrate removal.

(8) The consequence of these two differences is that the system SRT of the MLE system determined with the UCT guideline is considerably longer than that determined with the M&E guideline leading to larger anoxic, aerobic and system reactor volumes. This difference widens as the influent TKN/COD concentration ratio increases, i.e. as the concentration of nitrate to be denitrified increases.

(9) When simulating the UCT sized MLE systems (under steady state conditions) with ASM1, very similar reactor MLVSS and MLSS concentration, effluent ammonia and nitrate

concentrations and total oxygen demands are obtained with ASM1 and the UCT guideline. This indicates that the denitrification kinetics of the UCT guideline are well aligned with ASM1. This is not the case when simulating with ASM1 M&E guideline sized MLE systems under steady state conditions – while the effluent ammonia concentration compares well, the effluent nitrate concentration is far higher (increases from 6 mgNO_3-N/l to above 20 mgNO_3-N/l). This indicates that even though the denitrification kinetics of the M&E guideline were derived in part from ASM1 simulations, the denitrification kinetics of the M&E guideline are very poorly aligned with ASM1.

(10) When the $f_{manx,M\&E}$ of the denitrification MLE system in (9) is increased to $f_{manx,UCT}$ of 0.318 (but keeping the SRT = $SRT_{sys,M\&E}$) and simulated with ASM1, the effluent nitrate concentrations reduce from around 20 mgNO_3-N/ℓ to around 6 mgNO_3-N/ℓ, which is aligned with the UCT guideline ASM1 results.

(11) The enhanced biological phosphorus removal (EBPR) parts of the UCT and M&E guidelines were not compared. While the EBPR part of the UCT guideline is complete and accounts for the phosphorus accumulating organisms (PAO) and their polyphosphorus content in the VSS and TSS calculations, as well as the differences in the denitrification kinetics in NDEBPR system compared with ND systems, which aligns the UCT NDEBPR guideline with ASM2, this is not the case in the M&E guideline. Because there is insufficient information in the M&E guideline to execute a complete NDEBPR system design calculation, the EBPR parts of the guidelines could not be compared.

(12) The M&E overflow rates can be aligned with the UCT 1DFT to determine very similar SST surface areas. The lower resultant reactor MLSS of the M&E sized systems when simulated with ASM1 means that the SSTs will operate at a lower than designed for MLSS and thus under peak conditions (f_q is 2.5 or greater) the SST will operate at a higher than permissible overflow rate. This is because the M&E SST sizing procedure does not include a 1DFT flux rating of 0.80 (as the UCT guideline does), which has the effect of increasing the SST surface area estimated by the 1DFT by 25%.

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°C	degrees Celcius
μ_{AM20}	maximum specific growth rate of the nitrifiers at 20°C
μ_{AmT}	maximum specific growth rate of the nitrifiers corrected for temperature
1DFT	1-Dimensional Flux Theory
η_G	reduction factor
ADWF	average dry weather flow
ANO	ammonia nitrifying organisms
a_{opt}	optimum a-recycle ratio
a_{prac}	practical a-recycle ratio
a-recycle	mixed liquor recycle
AS	activated sludge
ASM	activated sludge models
ASM1	Activated Sludge Model No. 1
ASM2	Activated Sludge Model No. 2
ASM3	Activated Sludge Model No. 3
A_{ST}	surface area
b_{AT}	endogenous respiration rate for the ANOs
bCOD*	biodegradable COD
bCOD/BOD*	biodegradable COD to BOD ratio
b_{EH}	endogenous respiration rate
BEPR	biological excess phosphorus removal
BNR	biological nutrient removal activated sludge
BNRAS	biological nutrient removal activated sludge
BOD_5	biochemical oxygen demand
BPO	biodegradable particulate organics
COD	chemical oxygen demand
COD_T*	total COD
d	day
DO	dissolved oxygen
D_p	anoxic reactor denitrification potential
DSVI	diluted sludge volume index
EBPR	enhanced biological phosphorus removal
F	reduction factor
F/M	food to mass ratio
f_{cv}	COD/VSS ratio
f_H	endogenous residue fraction
f_{iOHO}	fraction of the OHO biomass that is inorganic.
f_{maer}	aerobic mass fraction
f_{manx}	anoxic mass fraction
$f_{n'a}$	influent FSA fraction
$f_{N'ous}$	fraction of unbiodegradable soluble organic nitrogen
FO_c	flux of oxygen utilised per day by the OHO’s for biodegradable organic material degradation
FO_d	flux of oxygen recovered by denitrification
FO_n	flux of oxygen required for nitrification
f_p	P fraction
f_q	peak flow factor
F-RBCOD	fermentable RBCOD

FSA	free and saline ammonia
$f_{sb's}$	RBSO fraction
$f_{s'up}$	fraction of UPO with respect to the total influent COD
$f_{s'us}$	fraction of USO with respect to the total influent COD
f_{x1}	anoxic mass fraction
f_{xm}	maximum unaerated sludge mass fraction
h	hour
HRT	hydraulic retention time
ISS	inorganic suspended solids
IWA	International Water Association
JHB	Johannesburg
K_1	K_1 denitrification rate
K_2	K_2 denitrification rate
K_{nT}	ANO half saturation coefficient
K_r	ammonification rate
ℓ	litre
M&E	Metcalf & Eddy
m^3/h	cubic metres per hour
mg/ℓ	milligrams per litre
Mℓ/d	megalitres per day
MLE	Modified-Ludzack-Ettinger
MLSS	mixed liquor suspended solids
MX_{BG}	active biomass of PAOs
MX_{BH}	active biomass of OHOs
MX_{EG}	endogenous residue from PAOs
MX_{EH}	endogenous residue from OHOs
MX_{Ev}	VSS of the OHO's endogenous residue
MX_{Ioi}	flux of influent ISS
MX_{Iv}	VSS of the unbiodegradable organics
MX_t	mass of total settleable solids in the reactor
n	hindered settling parameter
N	nitrogen
N_2	nitrogen gas
N_{ae}	effluent ammonia concentration
N_{ai}	influent ammonia nitrogen
nbCOD*	nonbiodegradable COD
nbpCOD*	nonbiodegradable particulate COD
nbsCOD*	nonbiodegradable soluble COD
N_c	concentration of nitrate generated by nitrification / nitrification capacity
ND	nitrification-denitrification
NDEBPR	nitrification, denitrification enhanced biological phosphorus removal
NH_3	free ammonia
NH_4^+	saline ammonia
N_{ne}	effluent nitrate concentration
NO_2^-	nitrite
NO_3^-	nitrate
NOO	nitrite oxidising organisms
NO_r*	nitrate load on anoxic reactor
N_{ti}	influent TKN concentration

O_a	dissolved oxygen concentration in a-recycle
OHO	ordinary heterotrophic organism
OP	orthophosphate
O_s	dissolved oxygen concentration in s-recycle
OUR_c	carbonaceous oxygen utilisation rate
OUR_t	total oxygen utilisation rate
P	elemental phosphorus
PAO	phosphate accumulating organisms
P_{te}	total effluent phosphorus
P_{ti}	influent total phosphorus
PWWF	peak wet weather flow
q_A	overflow rate
Q_i	influent flow rate
$Q_{i,adwf}$	influent ADWF flow
$Q_{i,pwwf}$	influent PWWF flow
Q_w	waste flow rate
RAS	return activated sludge
RBCOD	readily biodegradable COD
RBSO	readily biodegradable soluble organics
R_s	sludge age
R_{sm}	minimum sludge age to ensure nitrification
$R_{SMLEbal}$	balanced sludge age for the MLE system
$R_{Ssystem}$	system SRT
SBCOD	slowly biodegradable COD
S_{bi}	biodegradable COD
SDNR*	specific denitrification rate
$SDNR_{adj}$*	specific denitrification rate adjusted for internal recycle flow
$SDNR_b$*	specific denitrification rate for biomass
$SDNR_t$*	specific denitrification rate corrected for temperature (M&E)
S_f	factor of safety
$S_{f,i}$	fermentable SBCOD concentration
SLR	solids loading rate
s-recycle	sludge recycle
SRT	sludge age
$SRT_{aerobic}$	aerobic SRT
SST	secondary settling tank
SSVI	stirred specific volume index
S_{ti}	influent COD
S_{ui}	unbiodegradable COD
S_{upi}	unboidegradable particulate COD
S_{usi}	unbiodegradable soluble COD
$S_{VFA,i}$	volatile fatty acid concentration
SVI	sludge volume index
TKN	Total Kjeldahl Nitrogen
TKN/COD	TKN: COD ratio
T_{min}	minimum temperature
T_{max}	maximum temperature
TOD	total oxygen demand
TP	total phosphorus
TSS	total suspended solids
UBOD/BOD*	ultimate BOD to BOD ratio (oxygen consumed)

UCT	University of Cape Town
UPO	unbiodegradable particulate organics
V_0	initial settling velocity
V_{aer}	aerobic reactor volume
V_{anx}	anoxic reactor volume
VFA	volatile fatty acids
V_p	reactor volume
V_s	settling velocity
VSS	volatile suspended solids
WAS	waste activated sludge
WERF	Water Environment Research Foundation
WRC	Water Research Commission
WW	wastewater
WWTP	wastewater treatment plant
X_b*	OHO concentration in the aerobic reactor
X_t	reactor TSS concentration
X_{taer}	aerobic reactor TSS concentration
X_{tanx}	anoxic reactor TSS concentration
X_v	reactor VSS concentration
Y_{ANO}	ANO yield coefficient
Y_H	OHO yield coefficient

** terms marked with a (*) in the above list indicate terms/acronyms that are specific to the Metcalf & Eddy* (Metcalf & Eddy | AECOM, 2014) g*uideline*

1. Introduction

1.1 Background

The modelling of the activated sludge (AS) system has developed significantly over the last 40 years. The traditional models that were used prior to the 1980's had a 'black box' approach as they were based more on empirical relationships, experiences and rule of thumb, rather than actual biological and physical processes, which at that time were not yet fully understood (Van Loosdrecht, et al., 2008). Examples of these 'black box' approaches are the food to mass (F/M) ratio, biochemical oxygen demand (BOD_5) and Load Factor. Today, these approaches are not incorrect but are only appropriate depending on the purpose and requirements of the model.

More stringent environmental legislations lead to the need for more complexity in these AS models. Designs that were based simply on experience or empirical methods no longer resulted in optimal performance and thus design procedures based on more fundamental behaviour patterns were required. To meet this requirement, various research groups were developed and over decades these groups contributed to developing conceptual and mathematical steady state design and dynamic kinetic simulation models for the biological nutrient removal AS (BNRAS) system. These models have progressively included (i) aerobic organics (chemical oxygen demand, COD) removal and nitrification (Marais and Ekama, 1976; Dold et al. 1980), (ii) anoxic denitrification (van Haandel et al., 1981; WRC, 1984; Dold et al., 1991 [UCTOLD]; Henze et al., 1987 [ASM1]) and (iii) anaerobic/anoxic/aerobic biological excess phosphorus removal (BEPR) (Wentzel et al. 1990, 1992 [UCTPHO]; Henze et al., 1995 [ASM2]).

The models enable system design and operational parameters to be identified, provide guidance in selecting values for these parameters and quantify the expected behaviour of the system (Ekama, 2011). Steady state AS models in particular provide high-level answers efficiently using a low level of input information and explicit algebraic equations. They are extremely useful for determining the wastewater treatment plant (WWTP) size, capacity and operating parameters, which makes them powerful standalone tools and pre-processors to dynamic models as they can generate the overall WWTP scheme, main system defining parameters, and identify major sources of plant data error, all of which should be known before dynamic models are used (Ekama, 2009, 2011).

In consulting engineering, designers of biological wastewater treatment systems make use of design guidelines to create a steady state AS model of the WWTP to be designed. One such guideline used in South Africa, is the steady state model developed by the University of Cape Town (UCT), presented in Marais and Ekama (1976) and Water Research Commission (WRC, 1984) which has subsequently been revised in the International Water Association's (IWA) STR6 *"Secondary Settling Tanks: Theory, Modelling, Design and Operation"* (Ekama, et al., 1997), *Volume 4: Biological Nutrient Removal in Treatise on Water Science* (Ekama, 2011) and Chapters 4, 5, 7 and 12 of *Biological Wastewater Treatment: Principles Modelling and Design* by IWA publishing (Henze, et al., 2008). In North America, and other parts of the world, designers use the Metcalf & Eddy (M&E) textbook, which presents methods for activated sludge and secondary settling tank (SST) steady state design in Chapters 7 and 8 of *Wastewater Engineering: Treatment and Resource Recovery* (Metcalf & Eddy | AECOM, 2014).

Guidelines, such as the ones used in South Africa (the "UCT guideline") and North America (the "M&E guideline"), differ in terms of the inputs (i.e. wastewater characteristics, kinetic and stoichiometric constants), their approach to sizing of the biological reactor, and their assumptions regarding the behaviour of the nitrification organisms in the biological reactor. In the UCT guideline, for example, the behaviour of the nitrifiers is aligned with the Activated Sludge Model No. 1 (ASM1), while the M&E guideline is based on a different approach. Thus the results obtained when using these guidelines will differ, only slightly in some cases, and more significantly in others.

These guidelines are used as a first step in the AS design procedure to determine parameters such as sludge age (SRT), the size of the biological reactor and its anaerobic, anoxic or aerobic mass fractions, the recycle ratios and the size of the subsequent SST. Generally, these parameters are then input into a dynamic simulation program to refine the design and analyse the effect of the influent diurnal flows and loads on the WWTP, and, in some instances, the steady state AS model is used as a standalone design tool for the design of a WWTP. The parameters (i.e. SRT, reactor volume, mass fractions, recycle ratios and SST area), which are critical to the performance of a WWTP, are determined using the steady state AS design guidelines and thus it is important to understand which guidelines produce more accurate and realistic results, where accurate and realistic here means close match with ASM1 (or equivalent).

1.2 Aims and Objectives of this Dissertation

The aim of this dissertation is to provide both a qualitative and quantitative comparison of two steady state AS design guidelines, i.e. the UCT guideline and the M& E guideline, with specific reference to the dimensioning of the biological reactor of the AS system and the subsequent SST. The main objective of this dissertation is to provide the reader with an understanding of the key similarities and differences between the two steady state AS design guidelines and how, under dynamic conditions, a system that is sized using a particular guideline (i) compares to its steady state results and (ii) performs under these dynamic conditions.

1.3 Key Tasks

In order to achieve the aims and objectives (as described above) of this dissertation, the following key tasks were undertaken:

a) An AS steady state model was created in a Microsoft Excel spreadsheet for the UCT guideline and M&E guideline respectively. Each steady state model (i.e. the spreadsheet) was setup in five main sections; (i) for COD removal only, (ii) for COD removal and fully aerobic nitrification, (iii) for COD removal, nitrification and denitrification in the form of pre-anoxic denitrification using a Modified-Ludzack-Ettinger (MLE) configuration, (iv) for a nitrification, denitrification enhanced biological phosphorus removal (NDEBPR) system and (v) for the SST design.

The steady state models created in Microsoft Excel are shown in Appendix A. These models were used to undertake the quantitative assessment of the guidelines, described in (c) below.

b) For each of the five sections in (a) above, the models were analysed qualitatively, i.e. in terms of the key similarities and differences in the design guidelines in terms of inputs, equations, approaches and assumptions used.

The qualitative differences between the models is described in Chapter 3. The similarities and differences in the models are described in detail, section for section, and each section building on from the previous. The sections are described as follows; wastewater characteristics (Section 3.1), COD removal design (Section 3.2), nitrification design (Section 3.3), denitrification design (Section 3.4), enhanced biological phosphorus removal design (Section 3.5) and sizing of the secondary settling tank (Section 3.6).

c) For each of the five sections in (a) above, the models were analysed quantitatively by setting the influent wastewater characteristics the same for each guideline and then analysing the results. The effect of varying certain influent wastewater components were also analysed.

The quantitative differences between the guidelines is also described in Chapter 3, alongside the qualitative differences for each section. Chapter 3 has been structured in this manner in order for the reader to observe the key similarities and differences in the steady state models, not only from a generalised point of view, but also in terms of the data, which is the first main objective of this dissertation.

d) The systems that were sized (i.e. the SRT, reactor volume, mass fractions, recycle ratios and SST area) using the respective steady state AS models were then input into an AS system dynamic simulation software program, UCTOLD, together with the full set of diurnal influent data, to predict the behaviour of the system under these dynamic conditions. The results of these simulations were then used to compare the systems (that were sized using a particular guideline) in terms of the (i) dissolved effluent concentrations, (ii) reactor solids concentrations and (iii) the oxygen requirements, and to compare the 24-hour average for the dynamic simulation results with those calculated in the respective steady state guideline models.

The dynamic models are described in Chapter 4, and the full set of results of these models are shown in Appendix B. Chapter 4 discusses and describes the results of the dynamic model alongside the steady state model results, in order for the reader to observe the performance of systems sized by a particular guideline under dynamic conditions, which is the second main objective of this dissertation.

1.4 Structure of this Dissertation

This dissertation consists of 5 Chapters, References and Appendices. This introduction chapter, provides detail on the background, aims and objectives, key tasks and thesis structure.

Following this chapter, a review of literature, relevant to this study, is presented in Chapter 2.

Chapter 3 consists of the discussion and analyses of the steady state AS models created for each guideline and provides the results of the steady state design (to be used as inputs into the dynamic models in Chapter 4) in Section 3.7 of this chapter. Following this, Chapter 4 provides the analysis of the results of the dynamic simulations, of the systems sized using the steady state models, with UCTOLD.

Finally, Chapter 5 summarises the key findings of the study.

The various sources of literature used for the development of the steady state and dynamic models and this document are presented in the References. The Appendices, which follows after, contains supplementary information for the steady state and dynamic modelling chapters.

2. Literature Review

This literature review outlines the main topics which were researched in order to provide an understanding of the dissertation topic, *"Comparing the Metcalf and Eddy and UCT steady state guidelines for sizing of biological nutrient removal activated sludge wastewater treatment plants",* and how to address it.

The first section of this literature review provides an overview of the differences between steady state and dynamic models for AS systems.

The second section outlines the basis of steady state and dynamic AS models – the modelling of biological behaviour.

Following this, the various AS processes are reviewed. These processes include (i) organic material removal, (ii) nitrogen removal, (iii) enhanced biological phosphorus removal and (iv) sizing of the SST.

Finally, dynamic models are discussed in more detail, with specific reference to ASM1 and the dynamic model used for this dissertation – UCTOLD.

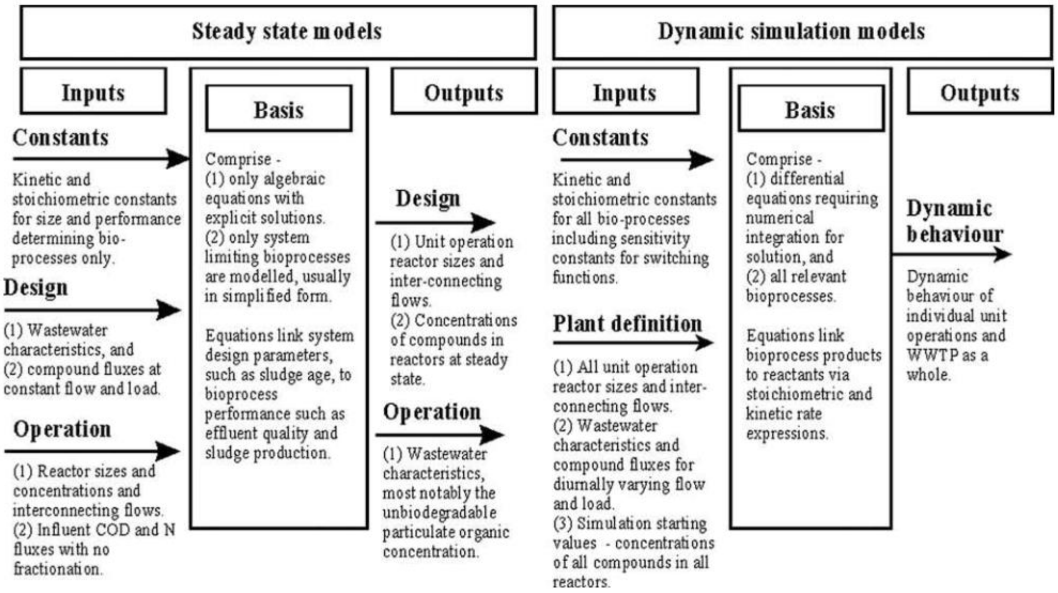
2.1 The Difference Between Steady State and Dynamic Models

There are two types of mathematical modelling of wastewater treatment AS systems – steady state and dynamic models. The steady state models are relatively simple, whilst dynamic models are far more complex. Although the two models are presented separately, they are in fact complementary. Ekama (2009) discusses how steady state models use the same bioprocesses as dynamic models, but in a simplified manner, and therefore can increase the reliability of dynamic models if they are incorporated as pre-processors to generate the required input information for dynamic models (Ekama, 2009).

In steady state models, many of the bioprocesses are assumed to reach completion, such as utilisation of influent biodegradable organics which then reduce the bioprocesses to ones of stoichiometry only. Other bioprocesses in the steady state model are assumed to not reach completion, these are either simplified (such as the ordinary heterotrophic organism (OHO) death regeneration to endogenous respiration) or retained as they govern the sizing of the system since they are the slowest, such as nitrification (Ekama, 2009). Because of this simplicity, steady state models can be used to easily estimate the initial system conditions such as sludge age, reactor volume, unaerated mass fractions, recycle ratios and oxygen demands. Another beneficial use of steady state models is to investigate the sensitivity to parameters that affect the system performance (Ekama, 2009) such as the unbiodegradable particulate organics (UPO) fraction, $f_{s'up}$, maximum specific growth rate of the nitrifiers, $\mu_{AM20,}$ the readily biodegradable soluble organics (BSO) fraction, $f_{sb's}$, as well as operational parameters such as sludge age.

Once the initial WWTP sizes are established using steady state models, dynamic models can be applied to refine the design sizes and evaluate the WWTPs performance under dynamic conditions. Similarly, a completely designed AS system is required in order to run a dynamic simulation, and dynamic AS models are therefore not suitable for application as a design tool (van Haandel & van der Lubbe, 2007). Figure 2-1 below, taken from Ekama (2009), provides a good summary of steady state and dynamic models, indicating that steady state models can conveniently and accurately generate the input for dynamic simulation software.

Figure 2-1: Inputs, basis and outputs of steady-state (left) and dynamic models (right). Source: (Ekama, 2009)



In practice AS systems never operate under steady state conditions and in reality there is daily variation in both flow and load. According to van Haandel & van der Lubbe (2007), for municipal wastewater, half of the organic load enters the AS system in only four hours (depending on the population, this occurs around 08:00 to 12:00), leaving twenty hours for the system to deal with the other half of organic load.

In contrast to steady state models, which assume that many of the bioprocesses reach completion and therefore the algebraic equations used provide explicit solutions, dynamic models comprise differential equations that require numerical integration to determine a solution (Ekama, 2009). The level of process knowledge required to undertake a design with a steady state model versus a dynamic model is very similar, however, the level of detail required by the two models are significantly different. Ekama (2009) emphasises that steady state models help keep the high-level decisions for a WWTP design in focus, and if the steady state model cannot be mastered, it is best to not use a dynamic model. Inexperienced users of dynamic models easily get distracted from the main problem when the prior knowledge of a steady state model is not there.

In summary, because of their ability to easily generate high-level information, steady state models are perfectly suited for system design or capacity estimation. The outputs from the steady state model (which comprise the system sludge age, reactor volume, unaerated mass fractions, recycle ratios and oxygen demands) can be used as inputs to the dynamic models for the evaluation of the dynamic response of the system. Steady state models should thus be used as pre-processors to the dynamic models. Steady state models complement the dynamic models as they generate the starting conditions required to initiate the dynamic simulation and because the steady state models are actually based on the dynamic models, the steady state models also provide a basis for cross-checking the results of the dynamic simulations (Ekama, 2009).

2.2 Modelling Biological Behaviour

To model the biological behaviour of organisms in a WWTP requires a conceptual model of their behaviour in the presence or absence of an external substrate (Ekama, 2011). Biological behaviour of organisms involves two bio-processes:

(1) Organism growth – utilisation of biodegradable organics for metabolism (i.e. anabolism and catabolism); and

(2) Organism decline – loss of organism mass due to maintenance energy requirements.

These principles of organism growth and decline are discussed below.

2.2.1 Organism Growth

2.2.1.1 Stoichiometry and kinetics

Transforming a conceptual biological model into a quantitative kinetic model requires both stoichiometry and kinetics (Ekama, 2011). The stoichiometry gives the quantitative relationships between the various compounds of the conceptual model and the kinetics consider the rate at which these biological processes take place. In the biological growth process organics and oxygen produce organisms, carbon dioxide and water. The electrons (i.e. COD) in the organics are conserved in organisms formed and water produced and because it is not possible to measure the water produced, the oxygen utilised is measured instead. AS mathematical models, such as ASM1, UCTOLD, ASM2 and UCTPHO are formulated on the principle of COD balance – over a defined period of time, the COD of the organisms formed plus the oxygen utilised must equal the COD utilised (Ekama, 2011).

2.2.1.2 Monod growth kinetics

Monod's equation is very useful in biological process modelling, as it is a self-controlling kinetic rate, meaning that when the substrate concentration is high, the rate is a maximum and when the substrate concentration is zero, the rate is zero. The Monod term is also a useful switching function for the progressive phasing-in and phasing-out of biological kinetic processes such as changing the conditions in the reactor from aerobic to anoxic (Ekama, 2011).

Monod kinetics is applied directly to model the utilisation of all soluble substrates, such as utilisation of RBSO by OHOs and free and saline ammonia (FSA) by ammonia nitrifying organisms (ANOs), and its form is also used to model the hydrolysis of biodegradable particulate organics (BPO), as well as switching functions for the progressive phasing-in and phasing-out of biological kinetic processes (as the environmental conditions in the reactor change from aerobic to anoxic conditions).

2.2.1.3 Active site surfaces kinetic for hydrolysis

The BPOs are enmeshed into the sludge mass and this process effectively removes most of the particulate organics from the wastewater liquid phase into the AS solids phase. Once enmeshed, some of the BPOs are adsorbed onto the active OHOs in the AS. Conceptually, the adsorption process is modelled as an active site surface kinetic reaction approach in which particulate organics are adsorbed onto the organism mass until their active sites are all occupied, at which point the organisms are saturated with particulate organics (Ekama, 2011).

2.2.2 Organism decline

It has been observed experimentally that, in the absence of an externally added substrate, over time there is still continuous oxygen utilisation and volatile suspended solids (VSS) reduction. There are two conceptual models to describe this organism decline – (i) death regeneration and (ii) endogenous respiration. Dynamic simulation models like ASM1 include (i) but (ii) is simpler and is therefore used in steady state AS models. Both (i) and (ii) produce similar results for the same condition. Ekama (2011) describes the two conceptual models as follows:

i) Death regeneration model

In this model the active organisms die and lyse all their organic material into the bulk liquid. The unbiodegradable part of this released organic material remains as endogenous residue. The biodegradable part is utilised by the remaining active organisms via the identical biological growth processes of anabolism and catabolism as influent organics to form new organism mass.

ii) Endogenous respiration model

In the absence of an externally available substrate, the organism utilises the organics of its own cell mass to generate energy via catabolism for essential cell functions. In this model, the utilisation of the organism organics in which the electrons of these organics are passed to oxygen accounts for the continued simultaneous decrease in VSS and utilisation of oxygen (Ekama, 2011).

2.2.3 System Modelling

The growth and endogenous respiration kinetic equations can be used to model the AS systems treating BSOs in batch, completely mixed or plug flow reactors. Provided that the kinetic constants are valid for BSOs, the predictions will match those for steady state and dynamic conditions.

The steady state AS model assumes that all biodegradable organics are completely utilised (i.e. that the growth process is complete). With the growth processes complete, its kinetics can be ignored and so in the steady state model only the stoichiometry of the growth processes need to be considered. The endogenous process transforms biomass biodegradable organics to (i) unbiodegradable endogenous residue, which accumulates in the reactor as VSS, and (ii) additional oxygen consumption. The endogenous process is very slow and does not reach completion, even at very long sludge ages. Its stoichiometry and kinetics therefore have to be retained, but because the endogenous respiration model is simple, the steady state model including it remains simple.

2.3 Activated Sludge Processes

2.3.1 Organic Material Removal

In order to describe the activated sludge behaviour, Marais and Ekama (1976) suggested a subdivision of the VSS into two basic theoretical fractions: (1) active sludge and (2) inactive sludge. The active biomass is composed of living bacterial organisms, which mediate metabolism of influent organic material. The inactive biomass originates from two distinct sources; the first being the influent unbiodegradable particulate organics, and the second being the continuous decay process of the active biomass. In the decay process (called endogenous respiration), a portion of the active biomass is oxidised. However, a portion of the biomass is unbiodegradable; thus, during the decay process, there is an accumulation of unbiodegradable particulates. This division proposed by Marais and Ekama (1976) is justified by the fact that it leads to a rational model of the activated sludge system, capable of predicting the measurable parameters under strongly varying operational conditions (van Haandel & van der Lubbe, 2007).

<u>Sludge Age</u>

From the basic steady state equations for COD balance, the mass of VSS and total suspended solids (TSS), oxygen demand and effluent COD are all functions of wastewater characteristics, wastewater COD load, system sludge age, OHO stoichiometric and kinetic constants. Since the stoichiometric and kinetic constants remain unchanged for different wastewaters, the above parameters are functions of wastewater characteristics, COD load and sludge age only. Thus wastewater (WW) characteristics and COD load must be well defined and system sludge age must be carefully selected.

It is noted that the longer the sludge age, the greater the mass of VSS (and TSS) in the reactor, but the lower the VSS (and TSS) mass wasted per day from the reactor. This is because the longer the sludge age, the longer the sludge stays in the reactor so the endogenous process occurs for longer, which causes the oxygen demand to increase, the biodegradable COD in VSS to decrease and the VSS (and TSS) mass wasted per day to decrease.

<u>Reactor volume and hydraulic retention time</u>

Once the mass of sludge in the reactor is known from the selected sludge age and influent COD flux, the reactor volume is determined by diluting the mass of sludge to a specified TSS concentration, called the reactor mixed liquor suspended solids (MLSS) concentration. With the volume known, the nominal hydraulic retention time is fixed by this volume and the influent flow rate. The hydraulic retention time is therefore immaterial in the design procedure, as it is a consequence of the mass of sludge in the reactor and a selected MLSS concentration, and thus design procedures that lay stress on the retention time as a basic design parameter should not be used as they can result in a miscalculation of the reactor volume requirements (Ekama, 2011).

Summary

Assumptions of the simplified models developed for steady state AS design are (i) the mass of the OH's seeded into the system with the influent is negligible in comparison with that which grows in the reactor, (ii) there is no loss of solids in the effluent from the SSTs, (iii) water mass is conserved, (iv) a 100% COD balance is achieved and (v) active OHO loss is modelled as endogenous respiration.

2.3.2 Nitrogen Removal

2.3.2.1 Nitrification

Nitrification process

Nitrification is the process of biological oxidation of free (NH_3) and saline (NH_4^+) ammonia (FSA) to nitrite (NO_2^-) and nitrate (NO_3^-) in two sequential steps by two groups of obligate aerobic autotrophic organisms. Ammonia oxidising organisms (ANOs) convert FSA to nitrite and nitrite oxidising organisms (NOOs) convert nitrite to nitrate. The nitrifiers utilise ammonia and nitrite primarily for catabolism but some ammonia is also used anabolically for synthesis of cell mass nitrogen requirements. The ammonia requirement for synthesis, however, is a negligible fraction of the total ammonia nitrified to nitrate by the nitrifiers and thus steady state models usually do not include this nitrogen requirement and only consider that the nitrifiers act as a biological catalyst in the nitrification process. This stoichiometric approach greatly simplifies the description of the kinetics of the process (Ekama, 2011) where it is assumed that the ANOs nitrify ammonia to nitrate directly and the kinetics of nitrification reduce to the kinetic behaviour of the ANOs only.

Nitrifier growth kinetics are based on Monod growth kinetics where (1) the ANO biomass generated is a fixed fraction of the FSA nitrified and (2) the specific growth rate, μ_{AT}, is related to the bulk liquid FSA concentration. The FSA utilisation rate, nitrate generation rate and nitrification oxygen rate are all linked to the ANO biomass growth rate. Like all organisms, the ANOs also undergo a biomass loss due to maintenance or endogenous energy requirements and therefore the endogenous respiration process for the ANOs is modelled in exactly the same way as that for the OHOs. The endogenous respiration rate of the OHOs is however much higher than for the ANOs.

Minimum sludge age for nitrification

For BNRAS systems, where nitrification and denitrification is used for the removal of nitrogen (N), the minimum SRT is primarily determined by the nitrifier specific growth rate (μ_{Am20}), -corrected for temperature (μ_{AmT}). The SRT must be sufficiently long so that nitrifiers are not washed out of the system. This minimum sludge age for nitrification, R_{sm}, is the most important design parameter for systems required to nitrify. μ_{AmT} is dependent on many factors, such as the wastewater composition, temperature, pH, reactor dissolved oxygen (DO) concentration and ANO population selection, and is therefore considered a wastewater characteristic rather than kinetic constant. Because nitrification is a prerequisite for N removal, μ_{AmT} is decreased by a factor of safety, S_f, to ensure nitrification. This S_f ensures that the selected sludge age is longer than the minimum for nitrification, it also covers the uncertainty in the μ_{AmT} value and ensures a low effluent FSA concentration and near-complete nitrification.

Unaerated zones

Unaerated zones can be implemented in nitrification design based on the assumptions that (1) ANOs grow only in the aerobic zone, (2) ANO endogenous respiration occurs in all zones at the same rate, and (3) the proportion of ANO's in the VSS is the same in all zones. This implies that the sludge mass fractions of different zones reflect the distribution of ANO's in the system. This sludge mass fraction approach is compatible with the nitrification kinetics in the AS kinetic models such as ASM1 and ASM2 (Henze et al., 1987, 1995) and UCTOLD and UCTPHO (Dold et al., 1991; Wentzel et al., 1992). In these models, the nitrifier growth only occurs in the aerobic zone but endogenous respiration takes place in all of the zones. This sludge mass fraction approach is not compatible with the aerobic sludge age approach, which is used in some nitrification-denitrification (ND) AS system design procedures. In these aerobic sludge age approaches, such as those in WEF (1998) and Metcalf and Eddy (1991), it is assumed that the growth and endogenous processes of the nitrifiers are active only in the aerobic zone, with neither of the processes active in the unaerated zones. According to Ekama (2011), this aerobic sludge age approach is not compatible with kinetic models and thus significantly different predictions can be expected for the nitrification behaviour from the aerobic sludge age-based design procedures and kinetic models versus those that undertake a sludge mass fraction approach.

Summary

AS simulation models such as ASM1 and ASM2 have described the complex interactions between the FSA and organic nitrogen in terms of the growth-death-regeneration approach. For steady state conditions a simple nitrification model can be developed from the nitrification kinetics and N requirements for sludge production. This is done by assuming that all the biodegradable organics are utilised in the reactor and that there is a Total Kjeldahl Nitrogen (TKN) mass balance over the AS system (Ekama, 2011). Dynamic system responses can be determined with the simulation models only once the AS system has been designed using a steady state model. The steady state model will determine the sludge age, zone and reactor volumes and recycle flows as well as the initial conditions of the system.

2.3.2.2 Denitrification

Nitrification is a prerequisite for denitrification – without it biological N removal is not possible. Once nitrification takes place, N removal by denitrification becomes possible and Ekama (2011) suggests that it should be included even when N removal is not required, by incorporating zones in the reactor that are intentionally unaerated as there are many benefits. These include a reduction in effluent nitrate concentrations, reduction of rising sludge in SSTs, reduction in oxygen demand, recovery of alkalinity, high reactor pH and reduced aggression to concrete.

Denitrification does, however, require longer sludge ages to ensure nitrification, as well as requires additional a-recycle pumps and is a slightly more complex system to operate.

Denitrification process

The process of denitrification is the biological reduction of NO_3^- and NO_2^- to nitrogen gas (N_2) by the OHOs. It is a consequence of bio-redox reactions to obtain energy for growth under anoxic conditions. Denitrification requires (1) the presence of nitrate (2) absence of DO (i.e. unaerated zone) (3) facultative heterotrophic organisms and (4) suitable electron donors.

Denitrification kinetics

There are three internal organics sources – two from the wastewater (RBSO and slowly biodegradable organics BPO), and the other is the slowly biodegradable organics generated by endogenous respiration. Denitrification in the primary anoxic reactor follows two phases – the first is an initial rapid phase where the rate is defined by the simultaneous utilisation of RBSO and BPO, and a second slower phase where the specific denitrification rate is defined by the utilisation of only BPO. If a secondary anoxic reactor is included in the system, only a single slow phase of denitrification will take place in this reactor, the specific rate being about two-thirds of the slow rate in the primary anoxic reactor (Ekama, 2011).

The influent RBSO is the preferred organic for denitrification, and the higher the influent RBSO concentration with respect to the total influent COD ($f_{s'bs}$) the greater the N removal.

System configurations for denitrification

The position of the anoxic zone in the biological reactor significantly affects the denitrification that can be achieved. In general, the type of biological nitrogen removal systems can be classified according to the position of the anoxic zone in the reactor, as either (1) post-denitrification in a secondary anoxic reactor or (2) pre-denitrification in a primary anoxic reactor. Different configurations for denitrification have been developed depending on the type of electron donor, i.e. Wuhrmann system is a self-generated electron donor, MLE is an internal electron donor and the 4-stage Bardenpho system is both internal and self-generated electron donor.

Denitrification potential

Calculation of the nitrate load and denitrification potential is central to the design for denitrification. The nitrate load is calculated from the nitrification capacity, which is the concentration of nitrate per litre influent flow generated by nitrification. The denitrification potential is calculated separately for the utilisation of the RBSO and BPO. The RBSO gives rise to a rapid denitrification rate so that it can be assumed that it is all utilized in the primary anoxic reactor and this is an objective in the design. (Ekama 2011).

Balanced MLE system

An MLE system with a sludge age (R_s) and influent TKN concentration (N_{ti}) such that the anoxic mass fraction, f_{x1}, is equal to the maximum unaerated sludge mass fraction, f_{xm}, allowed for the selected μ_{AM20} and minimum temperature, T_{min}, and optimum a-recycle ratio, $a_{opt,}$ equal to the practical a-recycle ratio, a_{prac}, so that this a_{prac} loads the anoxic reactor exactly to its denitrification potential, is called a balanced MLE system. This approach to design of the MLE system was proposed by van Haandel et al. (1982) and gives the most economical AS reactor design, that is, the lowest sludge age, and therefore the smallest reactor volume, and the highest denitrification with the a-recycle ratio fixed at some maximum practical limit (Ekama, 2011).

Summary

The most important decisions in the denitrification design are the R_s, anoxic mass fraction f_x, a-recycle ratio and the subdivision of the anoxic mass fraction into primary and secondary anoxic. A system that is designed for denitrification will have a longer sludge age, since nitrification is obligatory, and larger reactor volume. This system will see a reduction in oxygen demand over the fully aerobic system with nitrification, as well as an increased alkalinity and pH and reduced rising sludge problems in the SST.

The extent of denitrification depends on the influent TKN/COD ratio and the readily biodegradable COD (RBCOD) fraction of the wastewater (Ekama, 2011), these parameters need to be measured.

2.3.3 Enhanced Biological Phosphorus Removal

According to Henze et al. (2008), enhanced biological phosphorus removal (EBPR) is the biological uptake and removal by AS systems in excess of the amount that is removed by normal completely aerobic AS systems.

Principles of EBPR

To achieve EBPR in AS systems, the growth of organisms that accumulate phosphate accumulating organisms (PAOs) has to be stimulated. This is accomplished by (1) an anaerobic, then aerobic (or anoxic) sequence of reactors or zones; and (2) the addition or formation of volatile fatty acids (VFAs) in the anaerobic reactor or zone.

The EBPR Mixed Culture Steady State Model (Wentzel, et al., 1990) where the main principle is to divide the influent flux of COD between the following the two heterotrophic population groups: (1) OHOs – quantification of the OHOs is calculated in COD removal systems, however, must be modified to take account of the COD reduction due to uptake and storage by the PAOs; and (2) PAOs – which obtain the volatile fatty acids (VFA) and the greater part of the RBCOD in the influent.

With EBPR the reactor TSS mass includes the additional VSS terms for active biomass of PAOs (MX_{BG}) and endogenous residue from PAOs (MX_{EG}) to account for the PAO VSS masses. The other three parts of the VSS are the same as in ND systems, i.e. active biomass of OHOs (MX_{BH}), endogenous residue from OHOs (MX_{EH}) and the unbiodegradable particulate organics (UPO VSS) from the influent. The inorganic suspended solids (ISS) part of the reactor TSS also increases due to the stored polyphosphate in the PAO. The consequence is significantly larger system volumes than the equivalent ND only systems.

NDBEPR

For an NDBEPR model, the BEPR model is simply combined with the ND model. This is permissible because Wentzel et al. (1990) showed that analyses of the PAOs and non-PAOs can be separated as they act virtually independently of each other, the only link between the two groups is the interactions with VFA and fermentable RBCOD (F-RBCOD) in the anaerobic reactor. However, in terms of the sizing of the NDBEPR system, the ND process typically fixes the SRT of the system. The nitrifiers grow at a slower rate than the PAOs, thus the minimum SRT remains determined by the growth rate of the nitrifiers as in ND only systems.

NDBEPR system configurations

When selecting a system configuration for BEPR, it is necessary to establish whether complete denitrification can be achieved. There are a number of system configurations for BEPR all based on the principle of maximising BEPR, namely Phostrip, Phoredox, 5-stage Bardenpho, 3-stage Bardenpho, University of Cape Town (UCT), Modified-UCT, and Johannesburg (JHB).

Summary

In most designs of NDBEPR systems, the priority is to remove phosphate (P) and denitrification is a secondary design priority (Ekama, 2011). Because of this, the main principle to consider when designing these systems is to ensure that the anaerobic reactor is protected from recycling of nitrate, which causes a disproportionate decrease in the magnitude of P removal. This principle guides the selection of the system configuration and provides a starting point for sizing the anoxic reactors.

2.3.4 Sizing of the Secondary Settling Tank

The idealised 1-Dimensional Flux Theory (1DFT) is typically used for the steady-state design of SST. In the 1DFT model, a solids mass balance principle is applied with the assumption that all solids exit the SST via the underflow recycle; the effluent is thus void of solids.

The purpose of the 1DFT model is to determine the minimum required SST area for safe operation and as well as the operating and minimum recycle ratios for different flow conditions.

The overflow rate of the SST is determined by the SST area and influent flow rate. This maximum overflow rate at peak wet weather flow must be less than 0.8 times the settling velocity of the sludge at the SST feed TSS concentration. If this condition cannot be met then solids will exit via the effluent because the upwards velocity of the mixed liquor exceeds the downwards settling velocity at the feed point. The purpose of the 0.80, called the flux factor (Ekama and Marais, 1986, Ekama et al., 1997, Marais and Ekama, 2004), is to increase the SST area by 25% (1/0.80) to account for the different hydraulic conditions in real full-scale SSTs with significant horizontal flow) and the idealized SST (vertical flow of water and solids only).

The AS reactor particulates (TSS) concentration (X_t) is the feed concentration to the SST, which creates the link between the AS system volume and SST area.

2.4 Dynamic Activated Sludge Models

Knowledge and understanding of wastewater treatment has advanced extensively over the years, resulting in ‘first principle’ approaches that embrace chemistry, microbiology, physical and bioprocess engineering and mathematics (Van Loosdrecht, et al., 2015). Many of these advances have matured to such a level that they have been codified into mathematical models for simulation by computers.

Activated sludge models (ASMs) are developed to describe the oxygen uptake rate and sludge production as well as the N and P conversions at domestic WWTPs. The first dynamic ASM, Activated Sludge Model No. 1 (ASM1, Henze et al., 1987), was a result of an international task group put together by the IWA to accelerate the development of a common, unified mathematical model for the design and operation of biological wastewater treatment. ASM1 has been implemented in most commercial softwares for modelling and simulation of plants for N removal, in some cases with modifications.

ASM1 was developed based on a simplified and updated form of the Dold et al. (1980) and van Haandel et al. (1981) dynamic models, which were both based on the original steady state approach of Marais and Ekama (1976) and Ekama and Marais (1978). Simply put, ASM1 models the COD and N removal, oxygen consumption and sludge production. Wastewater is characterised in terms of the seven dissolved and six particulate components that are used to describe the two biomass groups, seven fractions of COD and four fractions of N. From the eight processes of the model, three are related to the growth of heterotrophic and autotrophic organisms, two describe the biomass decay and three are related to hydrolysis (Van Loosdrecht, et al., 2015). The model is presented in a matrix format known as the Petersen matrix or Guijer matrix, which contains stoichiometric coefficients and a kinetic vector.

EBPR was not included in ASM1, not because of a lack of knowledge of the EBPR processes, but because at the time most WWTPs did not include biologically, or chemically, enhanced phosphorus removal. The Activated Sludge Model No. 2 (ASM2) was later published and included the EBPR processes. ASM2 includes PAOs, growing only under aerobic conditions, with the associated anaerobic, anoxic and aerobic conditions. Later, ASM2 was expanded to include denitrifying PAOs and this version of the model was denoted ASM2d.

Activated Sludge Model No. 3 (ASM3) was developed by the IWA task group at the same time ASM2d was developed, and it was proposed to become the new standard for ASM-based modelling. It was introduced to correct the deficiencies of ASM1, but according to Van Loosdrecht et al. (2015) ASM3 is recommended to be used for simulating highly loaded nitrification-denitrification (ND) systems with short anoxic retention times and improving aeration demands for tapered systems, otherwise ASM1 should be equally successful in describing the activated sludge WWTP (Van Loosdrecht, et al., 2015).

For most engineering applications the ASMs are considered sufficiently developed.

2.4.1 Activated Sludge Model No. 1

The ASM1 is useful in the prediction of (i) degradation of organic material and denitrification, (ii) nitrification, (iii) the distribution of oxygen consumption along plug flow type reactor and in the course of diurnal variations, (iv) sludge productions and (v) variation in effluent quality under dynamic loading conditions (Gujer & Henze, 1991).

ASM1 may be characterised (Gujer & Henze, 1991) as follows:

- A total of 7 dissolved and 6 particulate components are used to characterise the wastewater and the activated sludge. In addition to DO and bicarbonate alkalinity (mol HCO_3) these include two forms of biomass, 7 fractions of COD (inert particular feed, particulate inert products, heterotrophic biomass, autotrophic biomass, slowly biodegradable substrate, inert soluble organics and soluble substrate) and 4 fractions of nitrogen (slowly biodegradable organic nitrogen, ammonium plus ammonia, nitrite plus nitrate and soluble organic nitrogen).
- Nine transformation processes are considered – three relate to growth of heterotrophic and autotrophic biomass, two represent decay of biomass and four describe ‘hydrolysis’ processes, in which complex organic material is made available for biodegradation in the form of simpler molecules.
- The process rate equations which rely on hyperbolic ‘Monod type’ switching functions to determine which processes are active under what environmental conditions. The switching functions are important in order to avoid negative concentrations of limiting components in the course of simulation. The stoichiometry for the nine transformation processes considers conservation principles for COD, nitrogen and electric charges. Not all nitrogen can be accounted for however, since ASM1 does not consider nitrogen gas as a component.

2.4.2 Dynamic Modelling Software

Steady state models comprise of explicit equations and procedures that can be done by hand calculations or using a calculation tool such as Microsoft Excel. Dynamic models require a more sophisticated method of calculation, and can include manually implemented code, general-purpose simulators or dedicated simulators

Examples of dedicated simulators include: *BioWin*, *EFOR*, *STOAT*, *WEST*, *SIMBA*, and *GPS-X* (Vanhooren et al., 2003; Gernaey et al., 2004).

UCTOLD is an activated sludge system diurnal simulation software programs written and compiled in TurboPascal 3.1 by the Water Research Group at the UCT in the late 1980s and early 1990s (Dold et al., 1991). UCTOLD is an earlier version of ASM1 and there is no material difference in the simulation results of UCTOLD and ASM1.

2.4.2.1 UCTOLD

The Water Research Group found that when the steady state model was applied to simulate single and in-series reactor systems under cyclic flows and loads gave predictions that deviated significantly from that observed experimentally. This problem was eventually resolved by the development of a dynamic model for the AS system based on a mechanistic conceptualisation of the kinetic behaviour of the organisms in such a system. The model developed by van Haandel, Ekama and Marais (1981) was the dynamic model that was incorporated into the UCTOLD program. Two features of this model are of particular importance, namely the bisubstrate and death-regeneration hypotheses.

The processes incorporated into the UCTOLD process model are described below:

Processes 1 and 2	Aerobic growth of heterotrophs on RBCOD	These two processes are responsible for removal of RBCOD under aerobic conditions. A fraction of the RBCOD is used for the production of heterotrophic biological organism mass and the balance is oxidised for energy giving rise to an associated synthesis oxygen demand. The growth is modelled using Monod kinetics.
Processes 3 and 4	Anoxic growth of heterotrophs on RBCOD	In the absence of oxygen, the heterotrophic organism population is capable of using nitrate, if available, as electron acceptor with RBCOD as substrate. In these two processes, a fraction of the RBCOD is used for production of heterotrophic biological organism mass and the balance is oxidised giving rise to reduction of nitrate to nitrogen gas. The anoxic growth is modelled using the same Monod kinetics used for aerobic growth.
Processes 5 and 6	Aerobic growth of heterotrophs on adsorbed SBCOD	In these two processes the SBCOD, which has been adsorbed on the organism (Process 10), is utilised under aerobic conditions. This utilisation consists of two steps, hydrolysis of the adsorbed SBCOD and direct utilisation of the hydrolysis products for the production of active organism mass and its associated oxygen demand. Since the rate limiting step is hydrolysis, only this step is modelled, using Levenspiel's surface reaction kinetics (Dold et al., 1980).
Processes 7 and 8	Anoxic growth of heterotrophs on adsorbed SBCOD	These processes are modelled in the same way as for the aerobic growth Processes 5 and 6 except that in the absence of oxygen, nitrate serves as an alternative electron acceptor and that the Levenspiel surface reaction for the hydrolysis/ utilisation kinetic rate expression is multiplied by the factor η_G. Again, either ammonia (Process 7) or nitrate (Process 8)

		can serve as nitrogen source for cell synthesis. Switching functions in both Processes 7 and 8 ensure that the anoxic growth rates decrease to zero at low nitrate concentrations.
Process 9	Death of heterotrophs	The process is modelled according to the death regeneration hypothesis. That is, the heterotrophic organism mass dies at a certain rate per unit organism mass; a portion of the material from the death is unbiodegradable particulate and adds to the unbiodegradable endogenous residue while the remainder adds to the pool of SBCOD.
Process 10	Adsorption of SBCOD	SBCOD is assumed to be enmeshed in the sludge mass immediately on contact with mixed liquor. The adsorption process transfers the enmeshed SBCOD to the adsorbed SBCOD.
Process 11	Hydrolysis of particulate organic nitrogen	BPO nitrogen is broken down to soluble organic nitrogen at a rate linked directly to the rate of hydrolysis/utilisation of adsorbed SBCOD under both aerobic (Processes 5 and 6) and anoxic (Processes 7 and 8) conditions. The product of breakdown adds to the pool of soluble organic nitrogen.
Process 12	Ammonification of soluble organic nitrogen	BSO nitrogen is converted to FSA, a process mediated by the heterotrophic biological active mass. Hydrogen ions consumed in the conversion process results in an alkalinity change.
Process 13	Aerobic growth of autotrophs	In this process ammonia is oxidized to nitrate via a single step resulting in production of autotrophic biological active mass and giving rise to an associated nitrification oxygen demand. The process requires the presence of oxygen; a switching function ensures that the process operates only if oxygen is present.
Process 14	Death of autotrophs	The process parallels that for heterotrophs (process 9)

3. Steady State Models

Designers of biological wastewater treatment systems make use of guidelines to create a steady state AS model of the wastewater treatment plant to be designed.

One such guideline used in South Africa, is the steady state model developed by UCT, presented in Marais and Ekama (1976) and Water Research Commission (WRC, 1984) which has subsequently been revised in IWA's STR6 "Secondary Settling Tanks: Theory, Modelling, Design and Operation" (Ekama, et al., 1997), Volume 4: Biological Nutrient Removal in Treatise on Water Science (Ekama, 2011) and Chapters 4, 5, 7 and 12 of Biological Wastewater Treatment: Principles Modelling and Design by IWA publishing (Henze, et al., 2008).

In North America, and other parts of the world, designers use the Metcalf & Eddy (M&E) textbook, which presents methods for activated sludge and SST steady state design in Chapters 7 and 8 of Wastewater Engineering: Treatment and Resource Recovery (Metcalf & Eddy | AECOM, 2014).

The sections that follow provide both a qualitative and quantitative comparison of the South African guidelines, i.e. the "UCT guideline", and the "M& E guideline" used in North America, with specific reference to the dimensioning of the biological reactor of the AS system and the subsequent SST.

3.1 Wastewater Characteristics

For all steady state and dynamic models, the common framework is the subdivision of the influent carbonaceous material, measured in COD (Wentzel, et al., 1990).

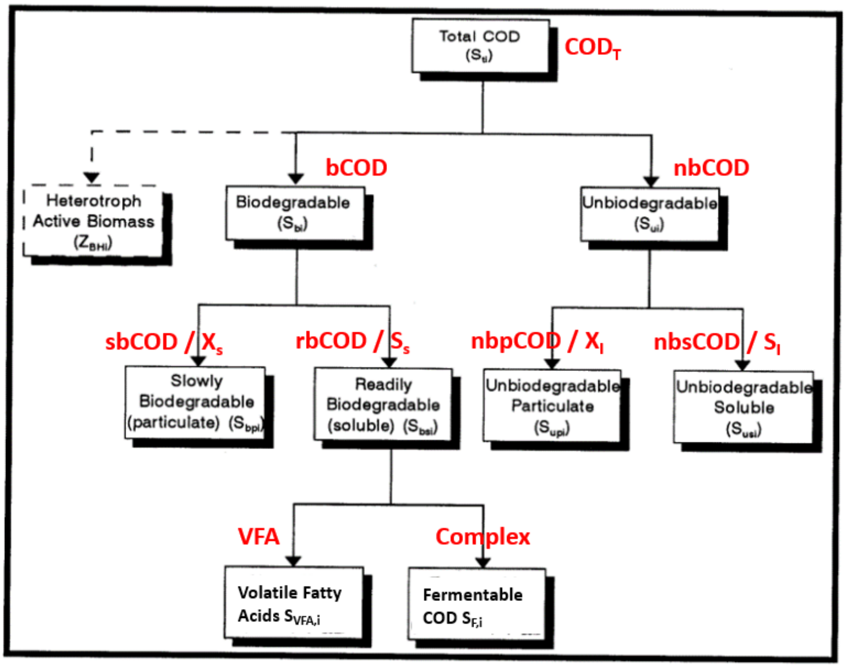
The COD fractionation used in the UCT guideline is given in Figure 3-1 below. The M&E approach to COD fractionation is similar to the UCT method, however, the nomenclature used in the textbook is taken from the IWA AS process simulation models and differs from the nomenclature used in the UCT guidelines. Where the terms or nomenclature differs from the UCT terms or nomenclature, it has been added in red text to Figure 3-1.

The first division of the influent COD (S_{ti}) is based on whether the COD fraction undergoes biological degradation or not. The UCT guideline refers to this as biodegradable COD (S_{bi}) and unbiodegradable COD (S_{ui}) respectively. The M&E guideline refers to unbiodegradable COD as nonbiodegradable COD (nbCOD) and uses the letters 's', 'p', 'nb' and 'b' as a prefix to '-COD' to indicate soluble, particulate, nonbiodegradable and biodegradable and combinations of these.

These 5 fractionations of the influent COD, i.e. S_{ti}, S_{bi}, S_{ui}, S_{upi} and S_{usi} (COD_T, bCOD, nbCOD, nbpCOD and nbsCOD in M&E), are sufficient to undertake a steady state design of a completely aerobic AS system. For systems that include EBPR, the RBCOD and SBCOD needs to be subdivided into VFAs, $S_{VFA,\,i}$, and fermentable COD, $S_{f,\,i}$, The $S_{VFA,i}$ is directly available to the PAOs for uptake and storage, while the $S_{f,i}$ is converted to VFAs in the anaerobic reactor by the

OHOs. The M&E guideline refers to the same two sub-fractions of the influent RBCOD, VFAs and complex soluble COD that can be fermented to VFAs.

Figure 3-1: COD fractionation. Source: (Henze, et al., 2008)



A notable difference between the M&E and UCT guidelines is that M&E still refers to and uses biochemical oxygen demand (BOD) analyses as a measure to obtain the total biodegradable COD (bCOD) by relating the bCOD and BOD as a ratio. The M&E guideline shows how the bCOD/BOD ratio can be estimated using an equation which is based on the fact that the bCOD consumed in the BOD tests equals the oxygen consumed (UBOD/BOD) plus the oxygen equivalent of the remaining cell debris after long-term incubation. For domestic wastewater with a UBOD/BOD ratio of 1.5, the bCOD/BOD ratio may be 1.6 to 1.7.

Chapter 1 of Henze et al. (2008) discusses that although the BOD_5 test has been used for more than a century, it is clearly lacking in many respects compared to the COD tests. The main reasons for this are that BOD mass balances over the biological reactor cannot be made and BOD does not measure the unbiodegradable particulate organics which accumulate in the reactor. Therefore BOD has not been used in models that have been developed in the past two decades. Henze et al. (2008) provide methods for the conversion of wastewater strength from BOD_5 to COD.

Despite this, the M&E guideline ultimately use the BOD and bCOD/BOD ratio to calculate the same five fractions as the UCT guideline, as listed above, for the fully aerobic steady state design. The reason for including the BOD_5 in the wastewater fractionation by M&E is that it allows an estimate to be made of the UPO concentration (nbpCOD in M&E) or fraction ($f_{S'up}$ in UCT) of the influent COD (Figure 3-1). This concentration/fraction cannot be easily measured on the wastewater itself and so in the UCT model is usually selected from a range of values found from past experience, such as 0.07 to 0.20 for unsettled (raw) wastewater and 0.00-0.10

for settled wastewater (WRC, 1984, Table 2-1) or 0.13 for raw wastewater and 0.08 for settled wastewater (Henze et al., 2008, Table 3.26).

In addition to the five COD fractions discussed above, both guidelines require the ISS, TSS and VSS, and the influent TKN, ammonia, orthophosphate (OP) and total phosphorus (TP) concentrations to be known in order to undertake the steady state design calculations for biological N removal and biological N and P removal systems.

In the sections that follow, the nomenclature used to describe the wastewater characteristics will follow the UCT standard unless otherwise noted in the text. For ease of reference, Table 3-1 below relates some terms and nomenclature used in M&E guideline to its UCT equivalent.

Table 3-1: Influent Wastewater Characteristics Nomenclature

Constituent Description	M&E Nomenclature	UCT Nomenclature (if different)
Biochemical Oxygen Demand	BOD	
Soluble Biochemical Oxygen Demand	sBOD	
Chemical Oxygen Demand	COD / COD_T	S_{ti}
Soluble COD	sCOD	
Biodegradable COD	bCOD	S_{bi}
Unbiodegradable (nonbiodegradable) COD	nbCOD	S_{ui}
Unbiodegradable (nonbiodegradable) particulate COD	nbpCOD / X_I	S_{upi}
Unbiodegradable (nonbiodegradable) soluble COD	nbsCOD / S_I	S_{usi}
Slowly biodegradable COD	sbCOD / X_s	S_{bpi}
Readily biodegradable COD	rbCOD / S_s	S_{bsi}
Total Kjeldahl Nitrogen	TKN	N_{ti}
Ammonia Nitrogen	NH4-N	N_{ai}
Total Phosphorus	TP	P_{ti}
Total Suspended Solids	TSS	TSS
Volatile Suspended Solids	VSS	VSS
Inert/Inorganic Suspended Solids	iTSS	ISS

In cases where the influent wastewater characteristics are unknown, the WRC (1984) guidelines provides values for approximate average municipal wastewater characteristics for raw and settled wastewaters in South Africa, which can be used. The M&E textbook also provides typical values for the composition of untreated domestic wastewater in Chapter 3 (Metcalf & Eddy | AECOM, 2014). The selection of these values play a vital role in the outcome of the design.

3.1.1 Steady State Design Values

It is important to note that there is inherently a difference in the conditions and wastewater characteristics in the areas which the different design guidelines are commonly used – i.e. South Africa and North America. However, for the purpose of this study, the well-known raw wastewater characteristics used in many papers that reference the UCT guideline, such as Volume 4: Biological Nutrient Removal In Treatise on Water Science (Ekama, 2011) and Chapters 4, 5, 7 and 12 of Biological Wastewater Treatment: Principles Modelling and Design by IWA publishing (Henze, et al., 2008) are used throughout this dissertation for ease of comparison. Table 3-2 below provides the typical wastewater characteristics found in South African (S.A) (WRC, 1984) and North American (N.A.) (Metcalf & Eddy | AECOM, 2014) domestic wastewaters, as well as the design values of the main raw wastewater characteristics used for this dissertation.

When these values are changed to analyse the effect of varying influent wastewater characteristics on specific results of the steady state design, then this shall be noted in the text.

Table 3-2: Influent Raw Wastewater Characteristics used for Steady State Design

Wastewater Characteristic	Symbol	Units	Typical S.A. Wastewater	Typical N.A. Wastewater	Design Value used in this dissertation
Influent flow rate	Q_i	m^3/d	-	-	15,000
Influent COD concentration	S_{ti}	mg COD/ℓ	500 - 800	339 - 1016	750
Influent TKN concentration	N_{ti}	mg N/ℓ	35 - 80	23 - 69	60
Influent phosphorus concentration	P_{ti}	mg P/ℓ	8 - 18	3.7 - 11	14
Influent TSS concentration	TSS	mg TSS/ℓ	270 - 450	130 - 389	416.3
Influent ISS concentration	ISS	mg ISS/ℓ	-	-	48
Minimum Temperature	T_{min}	°C	10 - 15	3 - 27	14
Maximum Temperature	T_{max}	°C	20 - 30		22
Fraction of unbiodegradable particulate COD in influent	$f_{s'up}$	-	0.07 – 0.20	0.06 – 0.18	0.15
Fraction of unbiodegradable soluble COD in influent	$f_{s'us}$	-	0.04 - 0.10	0.09 – 0.14	0.07
Influent readily biodegradable COD fraction	$f_{sb's}$	-	0.08 – 0.25	0.10 -0.40	0.25
Fraction of unbiodegradable soluble organic nitrogen	$f_{N'ous}$	-	0.00 – 0.04	*Information not available*	0.03
Influent FSA fraction	$f_{n'a}$	-	0.60 – 0.80	*Information not available*	0.723

3.2 COD Removal Design

3.2.1 Aerobic Reactor Volume Calculation

One of the main outputs of a design for COD removal only is the volume of the aerobic reactor for the fully aerobic AS system. In both design guidelines, the reactor volume is determined by simply dividing the mass of total settleable solids in the reactor, MX_t, by the reactor design value chosen for the MLSS concentration, X_t:

$$V_p = \frac{MX_t}{X_t} \ (m^3) \qquad (1)$$

The selection of the X_t value and the calculation of the MX_t value is provided in the guidelines as follows:

i) Selection of X_t:

Both guidelines indicate that the X_t value can be selected based on experience with similar wastewater treatment plants. The UCT guideline describes a procedure where X_t is determined from a construction cost minimisation analysis (Chapter 1, Ekama et al., 1997). In such an analysis, the construction cost of the reactor and the secondary settling tank are determined as functions of the reactor solids concentration, $X_{t,}$ and the X_t is selected is the one that minimised the construction cost of the reactor and SST.

ii) Calculation of MX_t:

The mass of TSS in the reactor consists of VSS and ISS. The UCT guideline uses the nomenclature MX_V and MX_{IO} for the VSS and ISS respectively.

In the UCT guideline, Henze et al. (2008) take the following into account when calculating the mass of the VSS and ISS in the reactor:

$$MX_V = MX_{BHv} + MX_{Ev} + MX_{Iv} \ (kg) \qquad (2)$$

$$MX_{Io} = MX_{Ioi}R_s + f_{iOHO}MX_{BHv} \ (kg) \qquad (3)$$

Where the total VSS consists of the VSS of the OHO biomass, MX_{BHv}, the VSS of the OHO's endogenous residue, MX_{Ev}, and the VSS of the unbiodegradable organics, MX_{Iv} and where the ISS consists of the flux of influent ISS, MX_{Ioi}, and a fraction, f_{iOHO}, given as 0.15, of the OHO biomass that is assumed to be inorganic.

The equations given in the UCT guideline for the various VSS components are given below:

$$MX_{BHv} = MS_{bi}\frac{Y_{Hv}R_s}{(1 + b_H R_s)} \quad (kg) \qquad (4)$$

$$MX_{Ev} = MS_{bi}\frac{Y_{Hv}R_s}{(1 + b_H R_s)} f_H b_H R_s \quad (kg) \qquad (5)$$

$$MX_{Iv} = \frac{MX_{Ii}}{f_{cv}} R_s \quad (kg) \qquad (6)$$

The M&E guideline calculates the sludge production, i.e. TSS, in the reactor in a similar manner to the UCT guideline. Both methods for calculation include the VSS terms for the heterotrophic biomass yield, heterotrophic endogenous residue (decay), unbiodegradable (inert) organics and the influent ISS which are notated in the UCT guideline as MX_{BHv}, MX_{Ev}, MX_{iv} and MX_{io} respectively.

Figure 3-2 below provides a graphical representation of the main similarities and difference in the approach of the calculation of the MX_t value in the two guidelines.

Figure 3-2: Graphical representation of the approach to the calculation of MX_t in the two guidelines

UCT Guideline			
MX_{BHV}	MX_{Ev}	MX_{Iv}	$MX_{Ioi} + 0.15MX_{BHV}$
MX_v			MX_{Io}
$MXt = MXv + MX_{Io}$			

Metcalf & Eddy Guideline		
P_{xbio}	P_{xnb}	*No calculation*
VSS		*No calculation*
$TSS = P_{xbio}/0.85^{*} + P_{xnb} + ISS_{influent}$		

**0.85 is a conversion factor to convert the P_{xbio} from VSS to TSS, thus taking the OHO ISS into account in this term (the $ISS_{influent}$ is added separately).*

In Figure 3-2 above, the M&E guideline calculates the sludge production (kgTSS/d), whereas the UCT guideline calculates the mass of sludge in the reactor (kgTSS). These two are of course related to each other via the sludge age, i.e. the M&E sludge production (kgTSS/d) can be converted to mass of sludge in the reactor by simply multiplying it by the sludge age, and vice versa, the UCT guideline mass of sludge in the reactor (kgTSS) can be converted to the sludge production (kgTSS/d) by dividing it by the sludge age.

The difference from the equations used in M&E for these terms in the UCT guideline (Equations 3, 4, 5 and 6) is the following:

- The calculation of the biodegradable COD:

  The M&E guideline uses the term (S_0-S) instead of the biodegradable COD (S_{bi}) concentration, where S_0 is the S_{bi} and 'S' is the biodegradable soluble COD in the effluent (S_{bse}), which is calculated as a function of the sludge age and kinetic coefficients of heterotrophic growth and decay. Calculations of the biodegradable soluble COD in this manner have shown that this number is relatively small for the kinetic coefficients for heterotrophic growth and decay given in the M&E guideline.

- The inclusion of the portion of the OHO biomass that is assumed to be inorganic:

  The UCT guideline stipulates that this f_{iOHO} value is 15 % of the OHO biomass, whilst the M&E guideline divides the total OHO's (biomass plus endogenous residue) by 0.85 when including it in the total TSS calculation, which results in 18 % ($^{1}/_{0.85}$) of the total OHO's being included as inorganic.

- The kinetic and stoichiometric constants used:

  Table 3-3 below shows the kinetic and stoichiometric constants provided in the M&E guideline and how they differ, if so, from the UCT guideline:

Table 3-3: Comparison of kinetic and stoichiometric constants and their temperature dependency (*source: Henze et al., 2008 and Metcalf & Eddy | AECOM, 2014)*

Constant (units)	M&E Guideline			UCT Guideline		
	Nomen-clature	$\theta^{\dagger}$	Standard value at 20°C	Nomen-clature	$\theta^{\dagger}$	Standard value at 20°C
Yield coefficient (mgVSS/mgCOD)	Y	1	0.45	Y_H	1	0.45
Endogenous respiration rate (/d)	b	1.04	0.12	b_{EH}	1.029	0.24
Endogenous residue fraction (-)	f_d	1	0.15	f_H	1	0.2
COD/VSS ratio (mgCOD/mgVSS)	VSS_{COD}	1	*	f_{cv}	1	1.48

† temperature sensitivity coefficient

* the COD/VSS ratio is calculated from measurements

From Table 3-3 above, the following is noted:

a) The yield coefficient is the same for both guidelines.
b) The specific endogenous respiration rate, b_{EH}, is the only kinetic constant in the steady state COD degradation model for fully aerobic systems that is affected by temperature. The standard value at 20°C given in the M&E guideline is half that given in the UCT guideline.
c) The endogenous residue fraction is 0.20 in the UCT guideline while it is 0.15 in the M&E guideline.
d) The UCT guideline provides a value of 1.48 mgCOD/mgVSS for the COD/VSS ratio, while the M&E guideline calculates this value directly from the wastewater characteristics using the influent BOD and VSS concentrations.

3.2.2 Selection of the Sludge Age

In general, the selection of the sludge age, also called solids retention time (SRT), will depend on the specific requirements of the wastewater treatment plant. For treatment of wastewater for COD removal only, the sludge age is not calculated and therefore must be selected by the designer. The UCT and M&E guidelines provide guidelines for the selection of the sludge age for COD removal only as follows:

- The UCT guideline classifies a short SRT as 1 to 5 days. Henze et al. (2008) state that for conventional wastewater treatment plants with the objective of COD removal only, SRT's of 1 to 3 days are sufficient. In these plants COD reductions range from 75 to 90 %. Henze et al. (2008) also discusses how biological P is possible at short SRT's of 3 to 5 days because of the PAO's are relatively fast growing heterotrophs. Hence the UCT guideline recommends a short SRT of 2 to 5 days for COD removal only, as seen in Table 3-4 below.

Table 3-4: Summary of sludge ages for various treatment objectives. Source: (Henze, et al., 2008)

Treatment Objective	Treatment Type	Sludge age (days)
COD removal only	**High rate step feed, aerated lagoons, contact stabilisation, pure oxygen**	**Short (2-5)**
COD removal, nitrification, biological N removal and/or biological P removal	Similar to high rate but with nitrification and sometimes denitrifications, BNR systems.	Intermediate (8-15)
COD removal, biological N removal and biological P removal	Extended aeration, orbal, carousel, BNR systems	Long (> 25)

- The M&E guideline refers to the sludge age as the SRT. M&E (2014) state that for BOD removal, the SRT generally ranges from 3 to 5 days, depending on the mixed-liquor temperature. Table 3-5 below provides the typical SRT's given in the M&E guideline.

Table 3-5: Typical minimum sludge age ranges for activated sludge treatment. Source: (Metcalf & Eddy | AECOM, 2014)

Treatment Objective	Sludge age range (days)
Removal of soluble BOD in domestic wastewater	1-2
Conversion of particulate organics in domestic wastewater	2-5
Develop flocculent biomass for treating domestic wastewater	2-3
Provide complete nitrification	3-18
Biological phosphorus removal	2-4
Aerobic digestion of waste activated sludge	20-40
Degradation of xenobiotic compounds	5-50

3.2.3 Carbonaceous Oxygen Demand calculation

Another main output of the COD removal design is the oxygen utilisation, in this case it is calculated as the flux of oxygen, FO_c, that is utilised per day by the OHO's for biodegradable organic material degradation; all of those from the influent via the growth process and some of those from the OHO biomass via the endogenous respiration process, given in the UCT guideline, as below:

$$FO_c = FS_{bi}\left[(1 - f_{cv}Y_H) + (1 - f_H)b_H \frac{Y_H f_{cv} R_s}{1 + b_H R_s}\right] \quad (kgO/d) \qquad (7)$$

In terms of the carbonaceous oxygen demand, the M&E guideline considers that the oxygen used in the biodegradation of carbonaceous material is the biodegradable COD concentration of the wastewater less the COD of the biomass wasted from the system per day. Here, for a given sludge age, a mass balance can be done on the system, where biodegradable COD removal equals the oxygen used plus the biomass remaining in terms of an oxygen equivalent. The biomass includes the active biomass and cell debris (endogenous residue) of the OHO's, as it does in the UCT guideline.

3.2.4 Main Considerations for COD Removal Design

Based on Sections 3.2.1, 3.2.2 and 3.2.3 above, there are a number of considerations when undertaking the steady state design of the biological reactor. The following main considerations with regard to the COD Removal design presented in both guidelines are analysed:

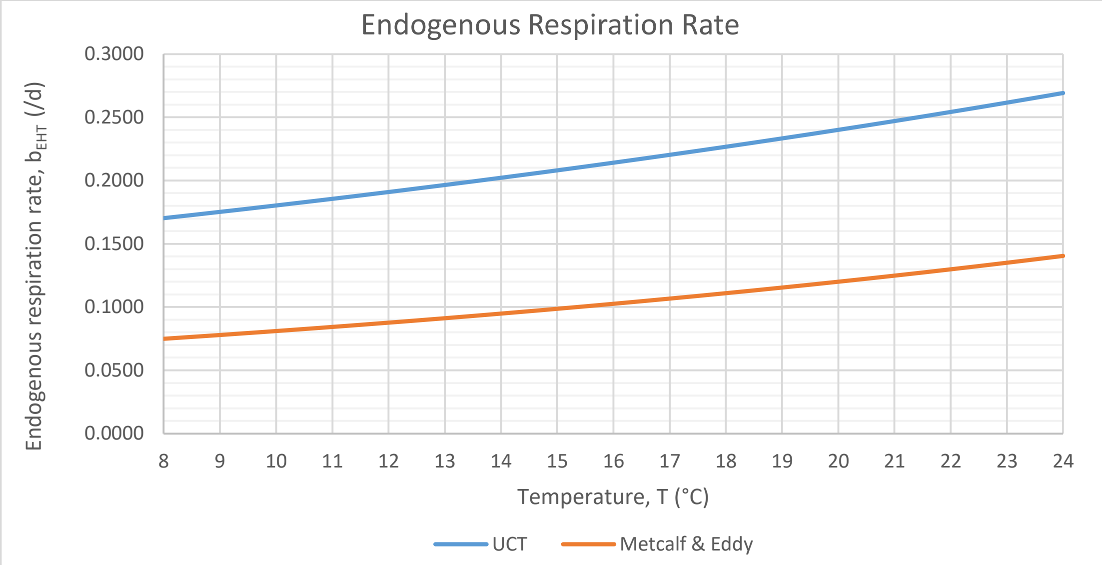
a) The kinetic and stoichiometric constants used

It was noted in Section 3.2.1 that the kinetic and stoichiometric constants provided in the guidelines differ.

While the endogenous respiration rate, b_{EHT}, is the only temperature dependent constant, the values provided for the standard value at 20°C for b_{EH20} in the M&E guideline is half that of the b_{EH20} given in the UCT guideline. Also, the temperature sensitivity coefficient of the b_{EHT} is higher in the M&E guideline (a 4 % increase per °C) than in the UCT guideline (2.9 % increase per °C) between 12°C and 24°C.

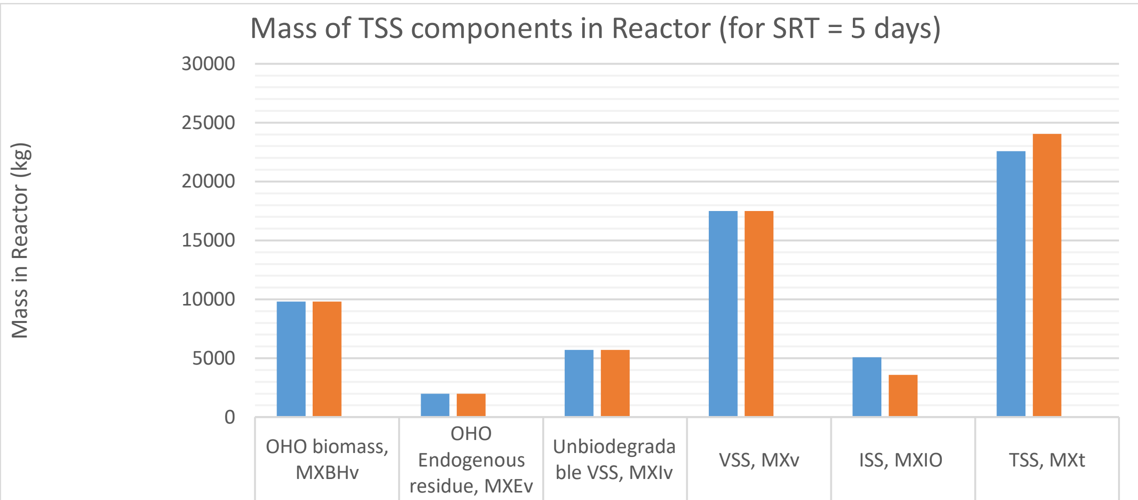
A comparison of the temperature dependency of the endogenous respiration rates for the two guidelines is given in Figure 3-3 below.

Figure 3-3 Endogenous Respiration Rate variation with Temperature



The effect of the difference in the kinetic and stoichiometric constants used was noted by setting the constants used in the M&E model equal to the constants provided in the UCT guideline. When comparing the results of the two steady state models for the same set of input parameters and an SRT of 5 days, it was found that the values of the VSS portion of the TSS only differ by only 0 to 0.15% in the two guidelines, while the ISS portion of the TSS differs by 34%, this is because the calculation of the ISS in the two guidelines is different (as discussed in Section 3.2.1). The overall effect on the TSS is that the M&E guideline's TSS is 6% higher than that of the UCT guideline, when the kinetic and stoichiometric constants are assigned the same values. This is shown in Figure 3-4 below.

Figure 3-4 Mass of TSS components in reactor when constants for both models are set the same



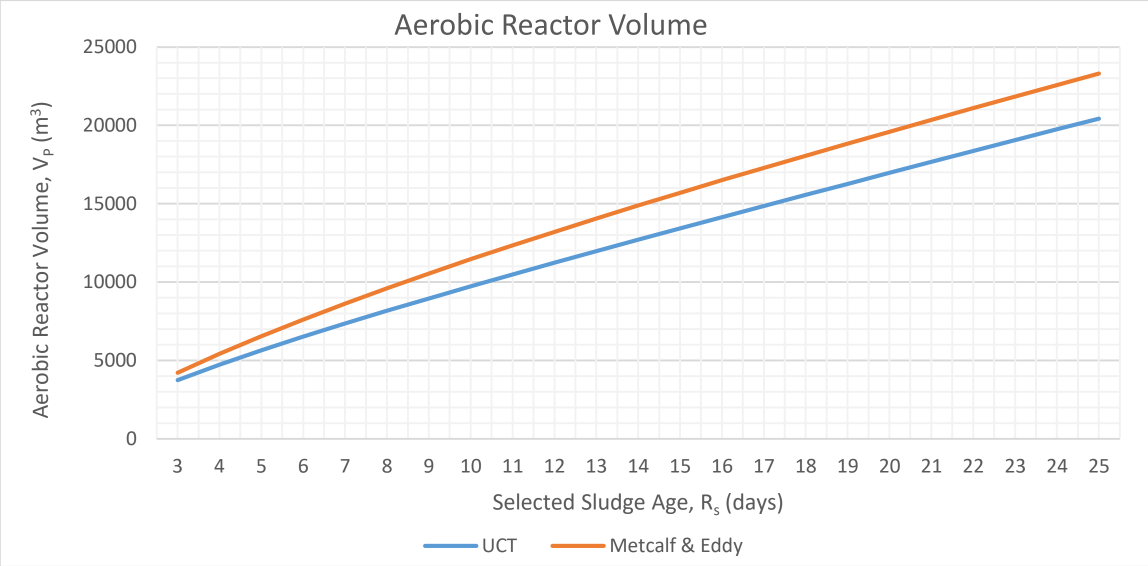
	OHO biomass, MXBHv	OHO Endogenous residue, MXEv	Unbiodegradable VSS, MXIv	VSS, MXv	ISS, MXIO	TSS, MXt
UCT	9819	1985	5701	17505	5073	22577
Metcalf & Eddy	9804	1982	5701	17487	3600	24033
Percentage difference	-0.15%	-0.15%	0.00%	-0.10%	-33.96%	6.25%

b) The selection of the SRT

The effect of the selection of the SRT on the aerobic reactor volume for the two guidelines is shown in Figure 3-5 below.

The M&E guideline results in an aerobic reactor volume that is 12.1 to 16.3 % larger than the aerobic reactor volume calculated using the UCT guideline, for the same influent wastewater characteristics (Table 3-3) and using the stoichiometric and kinetic constants as provided in the guidelines of each. As noted in (a) above, if the kinetic, stoichiometric and temperature sensitivity constants in the M&E guideline are assigned the same values as the UCT guideline, the M&E guideline reactor volumes will only be 6% larger than the UCT guideline volumes, due to the difference in calculation of the ISS component.

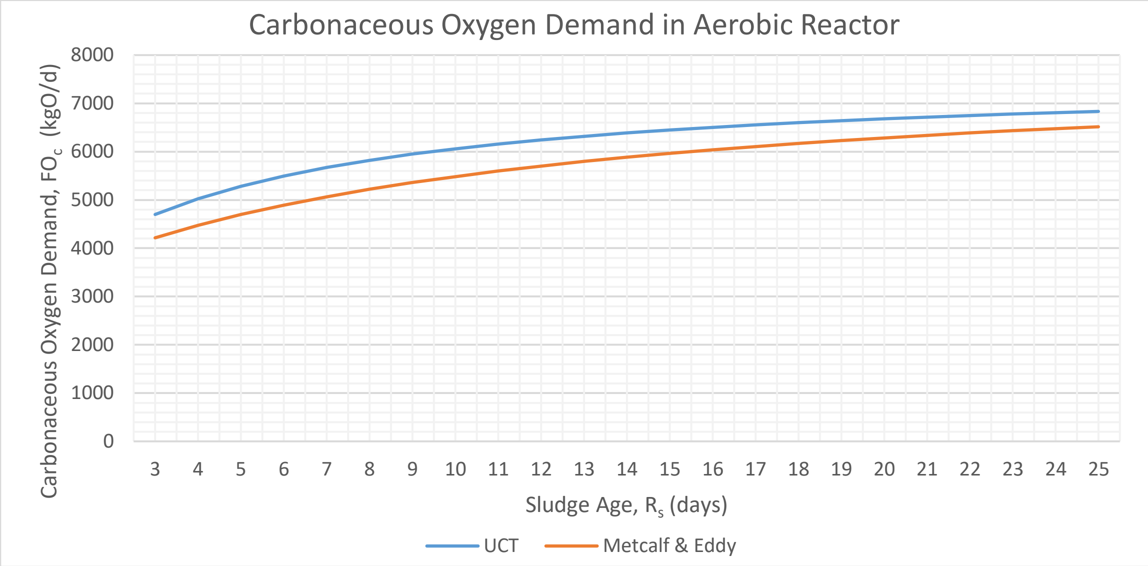
Figure 3-5: Aerobic reactor volume for selected sludge age



The effect of the selection of the sludge age on the carbonaceous oxygen demand for the two guidelines is shown in Figure 3-6 below.

Although the UCT guideline results in a smaller reactor than the M&E guideline for the same influent wastewater characteristics, it requires between 4.7 to 11.7 % more oxygen for carbonaceous material removal than the M&E guideline's reactor with the same SRT.

Figure 3-6 Carbonaceous Oxygen Demand in reactor for various selected sludge ages

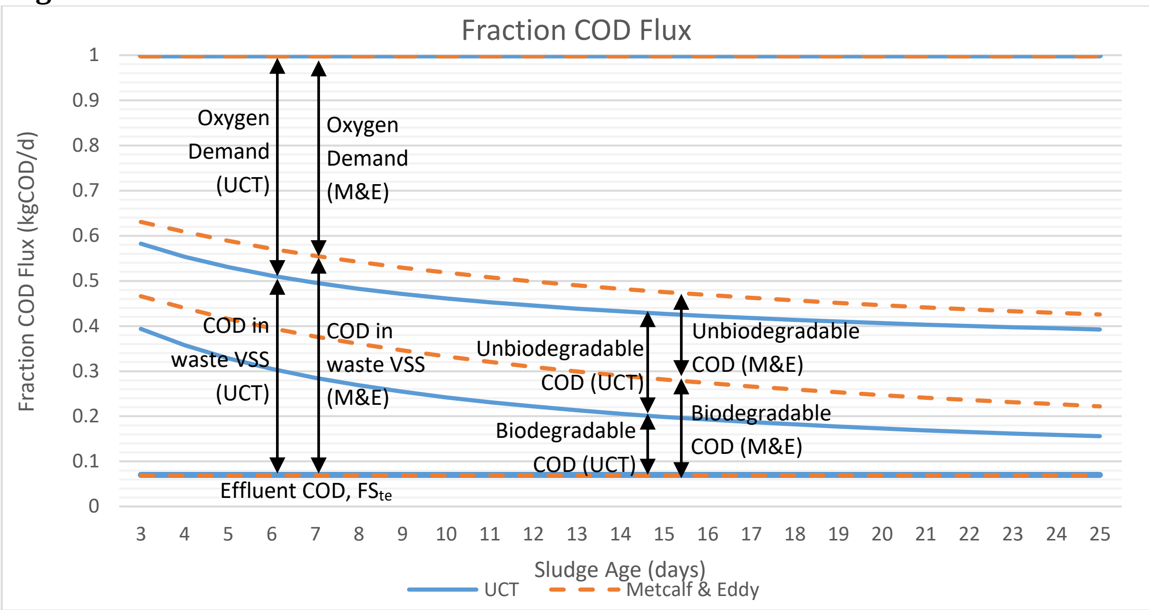


One of the assumptions of a steady state model for COD removal is that a 100% COD mass balance is achieved. The COD entering the system, i.e. the flux of influent COD, equals the COD exiting the system, whether it be via the effluent, COD in the waste VSS (biodegradable and unbiodegradable) or the carbonaceous oxygen demand.

Figure 3-7 below indicates the COD flux results of the mass balances undertaken for the UCT guideline design and the M&E guideline design. The fraction of COD flux is thus the proportion (out of one) of a specific type of COD exiting the system, with the value one being the flux of the influent COD.

It is seen in Figure 3-7 below that for both design guidelines, the higher the selected SRT value, the lower the flux of COD in the waste VSS (sludge production) and the higher the carbonaceous oxygen demand flux. For all selected SRT's the COD flux in the effluent remains the same because this is simply the fraction of unbiodegradable soluble COD, which does not change unless the influent wastewater characteristics change (which is not the case in the graph below).

Figure 3-7 Fraction of COD flux



The COD balances 100% in both the UCT and M&E guidelines, but because of the different kinetic, stoichiometric and temperature sensitivity constants, the influent organics is split differently between sludge production and oxygen demand in the two guidelines.

It is noted that, for a selected sludge age, the M&E guideline calculates a higher COD in waste VSS and specifically, a higher biodegradable COD in waste VSS. This has an effect on the waste activated sludge (WAS) sludge treatment design – the more wasted OHO biomass, the higher the calculated oxygen demand for aerobic digestion, and the higher the calculated methane production for anaerobic digestion. This would be the case if a plant wide design were undertaken using the M&E guideline as a basis and may lead to an error in the design of the WAS sludge treatment systems.

3.3 Nitrification Design for Fully Aerobic Systems

3.3.1 Calculation of the Minimum Sludge Age for Nitrification, R_{sm}

The SRT, or sludge age, R_s, is the most important design parameter for systems that are required to nitrify. For the nitrification part of a design, the first step is to calculate the minimum SRT to ensure nitrification, R_{sm}.

Both design guidelines provide equations to calculate the minimum SRT, or design SRT, as called in the M&E guideline, however, they are different SRT's. For the UCT guideline it is the system SRT, $R_{Ssystem}$, where the SRT is defined as the mass of sludge in both the anoxic and aerobic reactors divided by the mass per day (flux) of sludge wasted, i.e.:

$$R_{Ssystem} = \frac{MX_t}{X_t Q_{w,aer}} \frac{V_p X_{t,aer}}{Q_{w,aer} X_{t,aer}} = \frac{V_{p\,system}}{Q_{w,aer}} \quad (days) \quad (8)$$

where Q_w is the waste flow rate from the aerobic reactor at TSS concentration, X_{taer}, for hydraulic control of sludge age (Ekama, 2010).

For the M&E guideline approach, the SRT is the aerobic SRT defined as the mass of sludge in the aerobic reactor only, divided by the mass per day (flux) of sludge wasted. In the M&E guideline approach, sludge is usually wasted from the SST underflow, the concentration of TSS of which is X_R, i.e.:

$$SRT_{aerobic} = \frac{MX_{t\,aer}}{X_R Q_{w,SST}} \frac{V_{aer} X_{t,aer}}{Q_{w,SST} X_{t,aer}} \quad (days) \quad (9)$$

These two definitions of SRT are arrived at from two fundamentally different assumptions about the behaviour of the nitrifiers in N removal systems. In the UCT approach it is assumed that (1) nitrifiers grow only under aerobic conditions, (2) they die (endogenous respiration) in the entire reactor (anoxic and aerobic) and (3) they are uniformly distributed in the reactor, i.e. comprise the same proportion of the TSS in each reactor. The above approach is aligned with ASM1 which applies the assumptions listed above. In the M&E guideline approach, assumptions (1) and (3) above apply, but assumption (2) is different, where nitrifiers die (endogenous respiration) only in the aerobic reactor (they are moribund in the anoxic reactor, they neither grow nor die). This latter assumption allows the SRT to be defined in terms of the nitrifiers behaviour, i.e. aerobic SRT ($SRT_{aerobic}$). It is important to note that $SRT_{aerobic}$ is not the system SRT, unless the reactor is fully aerobic (it has no anoxic zones) which is the case in this Section. So in this section on nitrification in fully aerobic systems, the SRT of the UCT and M&E methods is the same.

The UCT guideline calculates the system minimum SRT based on the maximum specific growth rate, μ_{AMT}, and the endogenous respiration rate for the ANOs, b_{AT}:

$$R_{sm} = \frac{1}{\mu_{AMT} - b_{AT}} \quad (d) \quad (10)$$

Nitrification is a prerequisite for nitrogen removal and so a factor of safety, S_f, is applied to decrease the μ_{AMT} value. This safety factor ensures that the sludge age is longer than the minimum SRT required for nitrification. It covers the uncertainty in the μ_{AMT} value and ensures a low effluent ammonia, N_{ae}, concentration and near complete nitrification under dynamic loading conditions because the S_f value makes the system sludge age greater than the minimum for nitrification. The higher the system SRT above the minimum for nitrification, the greater the damping of the variation of the effluent ammonia concentration and the closer the average effluent ammonia concentration under dynamic flow and load conditions to the steady state ammonia concentration (Henze, et al., 2008). In the UCT guideline, the SRT, R_s, is thus the minimum SRT times the safety factor, as follows:

$$R_s = \frac{1}{\mu_{AMT}/S_f - b_{AT}} \quad (d) \qquad (11)$$

The M&E guideline calculates the minimum aerobic SRT for nitrification by first calculating a reduction factor (F) of the nitrifier maximum specific growth rate on the aerobic reactor by considering the aerobic reactor ammonia and DO concentrations, and then the minimum aerobic SRT is the inverse of the net nitrifier specific growth rate of the nitrifier maximum specific growth rate at the ammonia and DO concentrations in the aerobic reactor.

$$\mu_{AMT\ aerobic} = F\mu_{AMT} \quad (12)$$

where F consists of Monod switching functions for the DO an effluent ammonia concentrations, as follows:

$$F = \frac{DO}{K_{DO} + DO} \cdot \frac{N_{ae}}{K_N + N_{ae}} \quad (13)$$

Table 3-6 shows the similarities in the two equations. While the equations are similar in that the nitrifier specific growth rate is multiplied by $^1/_{Sf}$ in the UCT guideline and by F in M&E, they are actually fundamentally different because for the UCT system the SRT is the system SRT and for the M&E system it is the aerobic reactor SRT. For fully aerobic systems, the aerobic SRT and system SRT are equal and give similar results, as indicated in the COD Removal Design section (Section 3.2) alone. However, the UCT and M&E guidelines have different endogenous respiration rates for the nitrifiers (b_A) and different temperature coefficients for μ_{AM} and b_A as shown in Table 3-7.

Table 3-6: Equations for the Calculation of the Minimum Sludge Age

UCT guideline	M&E guideline
$R_{sm,system} = \frac{1}{\frac{\mu_{AMT}}{S_{f,UCT}} - b_{AT}}$ (14)	$R_{sm\ aerobic} = \frac{S_{f,ME}}{(\mu_{AMT} * F) - b_{AT}}$ (15) (Where F is a Monod switching function for the required N_{ae} value and dissolved oxygen concentration in MLSS)

The calculation of the minimum SRT for nitrification and the calculation of the design SRT in the two guidelines are dependent on the following two parameters:

i) The selection of the Safety Factor, S_f

The UCT guideline shows that a safety factor of 1.25 or greater, at the minimum wastewater temperature of 14°C, will ensure an effluent ammonia concentration, N_{ae}, under steady state conditions, of less than 2 mgFSA-N/ℓ:

$$N_{ae} = \frac{K_{nT}}{S_{f,UCT} - 1} \quad (d) \qquad (16)$$

The guideline indicates that in general, safety factors of 1.25 to 1.35 should be used for steady state designs that include nitrification.

The safety factor proposed in the M&E guideline, $S_{f,\ M\&E}$, is 1.5 and is based on the peak to average TKN load ratio.

The safety factors given in both guidelines serve similar purposes – they seek to dampen the effluent ammonia concentration under dynamic loading conditions by increasing the SRT above the minimum for nitrification.

ii) The nitrification specific growth kinetic constant values in the Monod Equation

In addition to the kinetic and stoichiometric constants used for COD removal (Table 3-3), additional nitrification kinetic values are given in both guidelines as follows:

Table 3-7: Comparison of ANO Kinetic and stoichiometric constants and their temperature dependency (*source: Henze et al., 2008 and Metcalf & Eddy | AECOM, 2014*)

Constant (units)	M&E Guideline			UCT Guideline		
	Nomen-clature	θ	Standard value at 20°C	Nomen-clature	θ	Standard value at 20°C
Maximum specific growth rate of ANO's (/d)	μ_{maxAOB}	1.072	0.9	μ_{AMT}	1.123	0.30-0.75
ANO half saturation coefficient (mg/ℓ)	K_{NH4}	1.000	0.50	K_{nT}	1.123	1.00
Endogenous respiration rate for ANO's (/d)	b_{AOB}	1.029	0.17	b_{AT}	1.029	0.04
ANO for oxygen half saturation coefficient (mg/ℓ)	K_{0AOB}	1.000	0.5			

As it can be seen in Table 3-7, the ANO coefficients provided in the M&E guidelines differ to those provided in the UCT guideline. The M&E guideline states that (1) values for these coefficients vary in the literature, and the values provided in the guideline are those used most commonly and (2) that these values also provide some degree of conservatism for the design. The nitrification kinetic values used in the M&E guideline are based, for the most part, on nitrification kinetics obtained in a Water Environment Research Foundation (WERF) study on parameters for AS modelling.

The maximum specific growth rate of the ANO's, μ_{AMT}, is the most important nitrification kinetic value to take into consideration in a COD removal and nitrification design, as the system SRT, for the UCT approach, and the aerobic SRT, for the M&E approach, as well as the reactor volume requirements are directly related to this value. The lower the μ_{AMT}, the longer the SRT and the larger the reactor volume.

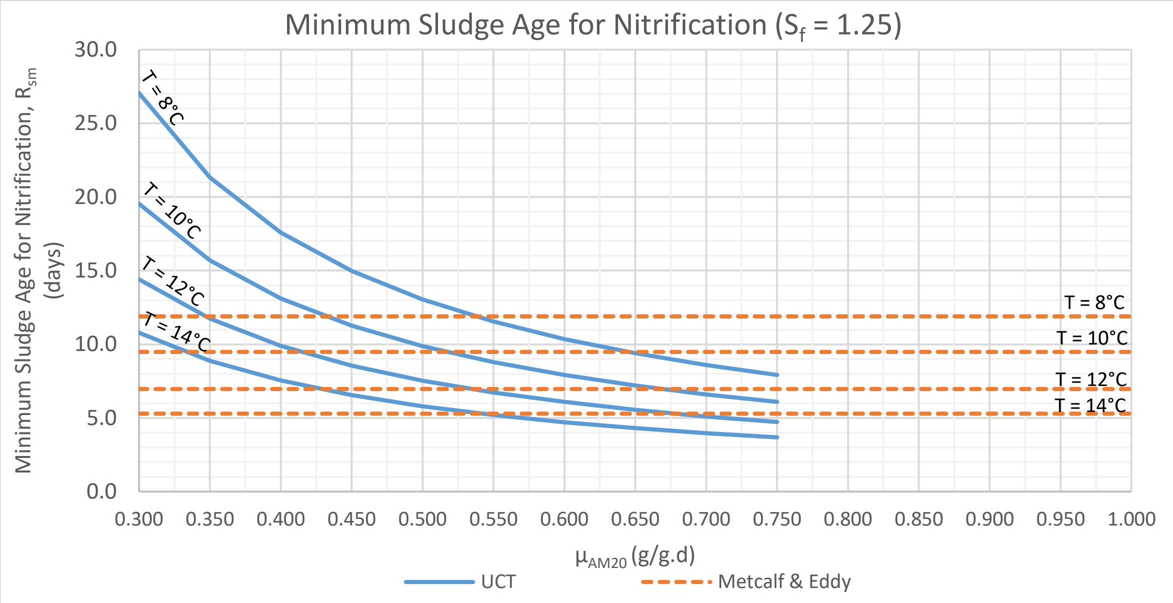
In the UCT guideline, the μ_{AM20} is a selected parameter that ranges between 0.30 and 0.75 g/g.d, the range has been reported for municipal wastewaters in South Africa. This large difference can mean that two systems at the opposite ends of the range may have minimum system sludge ages that differ by 250% (Henze, et al., 2008) and thus the μ_{AM20} should always be determined experimentally for an optimal design. Therefore, WRC (1984) and Henze et al. (2008) suggest that μ_{AM20} is considered a wastewater characteristic rather than a kinetic constant.

Noting the large impact that the selection of the μ_{AM20} has on the SRT and reactor volume, WERF sponsored a nation-wide research project to measure the μ_{AM20} values on municipal wastewaters (Melcer, et al., 2003) and (Jones, et al., 2005). This confirmed that the μ_{max} estimates for a number of plants in North America remained in the narrow range 0.85 to 1.05 g/g.d, provided the endogenous respiration rate was increased from 0.04 /d as first measured by (Downing & Hopwood, A. P., 1964) and adopted into the UCT guideline to 0.17 /d. Based on these findings, WERF (2007) adopted the value of 0.90 g/g.d for the μ_{AM20} and 0.17 /d for $b_{A20.}$ These WERF (2007) nitrification kinetic constants were in turn adopted into the M&E guideline.

Based on the above, the input parameter that affects the minimum SRT for nitrification the most is the maximum specific growth rate of the ANO's. In the UCT guideline specifically, where the μ_{AM20} value is given as a range of values, this input is selected by the designer. The resultant sludge ages calculated in the UCT model for a range of μ_{AM20} values (0.30-.075 g/g.d) versus the one sludge age calculated in the M&E for 0.90 g/g.d are shown in Figure 3-8 below.

The UCT guideline discusses how the effect of temperature on μ_{AMT} is particularly strong. For every 6°C drop in temperature, the μ_{AMT} value halves, which means that the minimum SRT doubles. Therefore the design of systems for nitrification should always be based on the minimum expected system temperature (Henze, et al., 2008) and Figure 3-8 below includes results for temperature ranges 8°C to 14°C.

Figure 3-8: Minimum Sludge Age for Nitrification for varying temperatures and μ_{AMT} values



Remember that for fully aerobic systems, the system SRT and aerobic SRT are the same (it is when anoxic zones are added that the two guidelines begin to diverge significantly). The following is noted for T = 14°C from Figure 3-8:

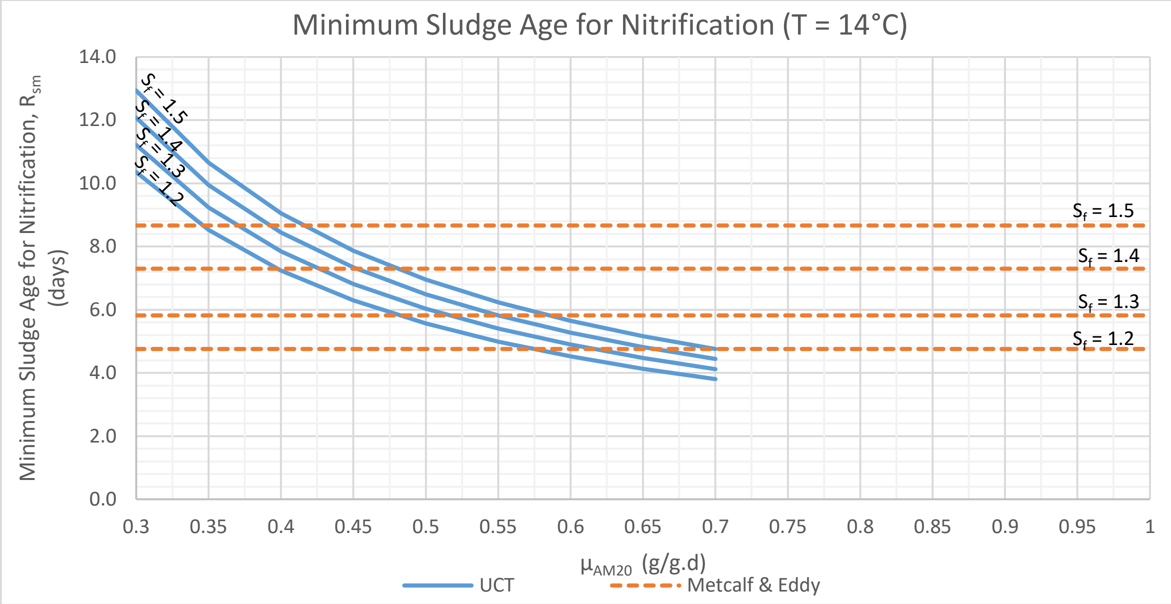
- The minimum SRT for nitrification calculated in the M&E model is 5.3 days for μ_{AM20} 0.90 g/g.d. For the same minimum SRT of 5.3 days, the UCT μ_{AM20} value is 0.544.
- The minimum SRT for UCT μ_{AM20} = 0.45 g/g.d, which is a value that is commonly used in South Africa, is 6.6 days, which is 19% longer than the 5.3 days calculated in the M&E model for its chosen μ_{AM20} of 0.90 g/g.d

The following is noted from Figure 3-8 for the temperature range 8°C to 14°C:

- For all temperatures, the minimum SRT of the UCT model that is equal to the minimum SRT calculated with the M&E model lies in the μ_{AM20} range 0.50 to 0.55.
- In the UCT model over the temperature range 8°C to 14°C, the lowest μ_{AM20} value of 0.30 g/g.d results in minimum SRT's that range from 10.8 to 27.1 days while the highest μ_{AM20} value of 0.75 g/g.d results in minimum SRT's that range from 3.7 to 7.9 days.
- For the UCT μ_{AM20} range (0.3 – 0.75 g/g.d), the lowest temperature results in a larger range (7.9 to 27.1 days for 8°C) of minimum SRT's than the highest temperature (3.7 to 10.8 days for 14°C).

The above comparison excludes the effect of the safety factor ($S_{f,\,UCT}$, $S_{f,\,M\&E}$) on the SRT. Figure 3-9 below includes results for the μ_{AM20} and minimum sludge age for safety factors ranging from 1.2 to 1.5 at 14°C, to include the entire S_f range as given in both the UCT and M&E guidelines (S_f 1.2 to 1.5).

Figure 3-9: Minimum Sludge Age for Nitrification for varying safety factors and μ_{AMT} values



Again, noting that for fully aerobic systems, system SRT and aerobic SRT are the same, the following is noted from Figure 3-9 for S_f values 1.2 to 1.5:

- For UCT μ_{AM20} = 0.45 g/g.d, which is a value that is commonly used in South Africa, the system SRT ranges from 6.3 to 7.9 days, compared with the 4.8 to 8.7 days SRT for the M&E chosen μ_{AM20} value of 0.90 g/g.d. This is not significantly different.

3.3.2 Calculation of Mass of TSS in Reactor and Fully Aerobic Reactor Volume

As already shown in Section 3.2 above, the UCT and M&E design guidelines yield similar sludge production, mass of TSS in reactor (MX_t) and carbonaceous oxygen demand for the same wastewater characteristics and system (fully aerobic) SRT. So with nitrification at the same SRT again the UCT and M&E guidelines will yield similar results for sludge production, mass of TSS in reactor and oxygen demand, because (1) the nitrifiers add negligibly little to the sludge production and (2) the oxygen demand is calculated similarly in both guidelines. It is when the SRT for fully aerobic systems (aerobic SRT = system SRT) differ that the two guidelines will yield different results. Once the mass of TSS in the reactor is known, from the determined SRT for nitrification and the COD Removal model, the total reactor volume is calculated by simply dividing the mass of total settleable solids, MX_t, by the design value chosen for the MLSS concentration, X_t.

The UCT guideline further divides the reactor into two zones, anoxic and aerobic. The anoxic volume is calculated as unaerated sludge mass fraction, f_{xt} times the total volume (Eq. 15), while the aerobic volume is simply the remaining volume (Eq. 16):

$$V_{anox} = f_{xt}\, V_p \qquad (17)$$

$$V_{aer} = (1 - f_{xt})\, V_p \qquad (18)$$

The selection of f_{xt} in the UCT guideline is based on the following assumptions:

- The ANOs grow only in the aerobic zone;
- The ANO endogenous respiration occurs in all zones at the same rate; and
- The proportion of ANO's in the VSS is the same in all zones (aerated or unaerated). This implies that the sludge mass fractions of different zones reflect the distribution of ANO's in the system.

From the above, the UCT guideline shows that the maximum unaerated sludge mass fraction, f_{xm}, allowed at a SRT of R_s to ensure nitrification with a safety factor of S_f is:

$$f_{xm} = 1 - \frac{S_f\,(b_{AT} + \frac{1}{R_s})}{\mu_{AMT}} \qquad (19)$$

The biggest difference between the M&E guideline and the UCT guideline, in terms of nitrification, is that the M&E guideline does not calculate an anoxic reactor volume for nitrification and the entire calculated reactor volume is aerobic.

The MX_t mass in the M&E guideline is calculated as before, however now the "P_{xbio}" term, i.e. the OHO biomass, now includes a term for sludge production of the ANO nitrifiers which is based on the amount of ammonia oxidised to nitrate. As a result, the MX_t mass is now slightly larger, and thus the aeration tank volume (which is the total reactor volume) for the M&E guideline design will be larger. This differs from the UCT guideline, where the MX_t mass used to calculate the total reactor volume usually takes into account only the carbonaceous material as calculated in the COD removal only system, and excludes the ANO mass because it is so small (less than 3% of the VSS). However, it is easy to include the ANO mass in the VSS (which is usually done in dynamic simulation models) by calculating it with an equation very similar to that given in the M&E guideline, i.e.

$$MX_{ANO} = \frac{Y_{ANO}\, Q_i N_c R_s}{1 + b_{AT} R_s} \quad (kg) \qquad (20)$$

Where R_s = SRT

N_c = Concentration of nitrate generated by nitrification (mg N/ℓ effluent)

Y_{ANO} = ANO yield coefficient = 0.10 mg VSS/(mgFSA nitrified)

$b_{AT} = 0.04(1.029)^{T-20}$ mgVSS/(mgVSS.d)

Based on the above, the main finding in the comparison of the two guidelines with respect to nitrification and COD removal are:

- The difference in the calculation of the minimum SRT for nitrification; and
- The small differences in calculation of the MX_t mass in the reactor, which results in a small difference in the total reactor volume.

Figure 3-10 and Figure 3-11 below shows the results for the total reactor volume for each guideline for a range of selected sludge ages, Figure 3-10 excluding nitrifiers and Figure 3-11 including nitrifiers.

Figure 3-10: Total reactor volume (excluding nitrifier mass) for selected sludge age

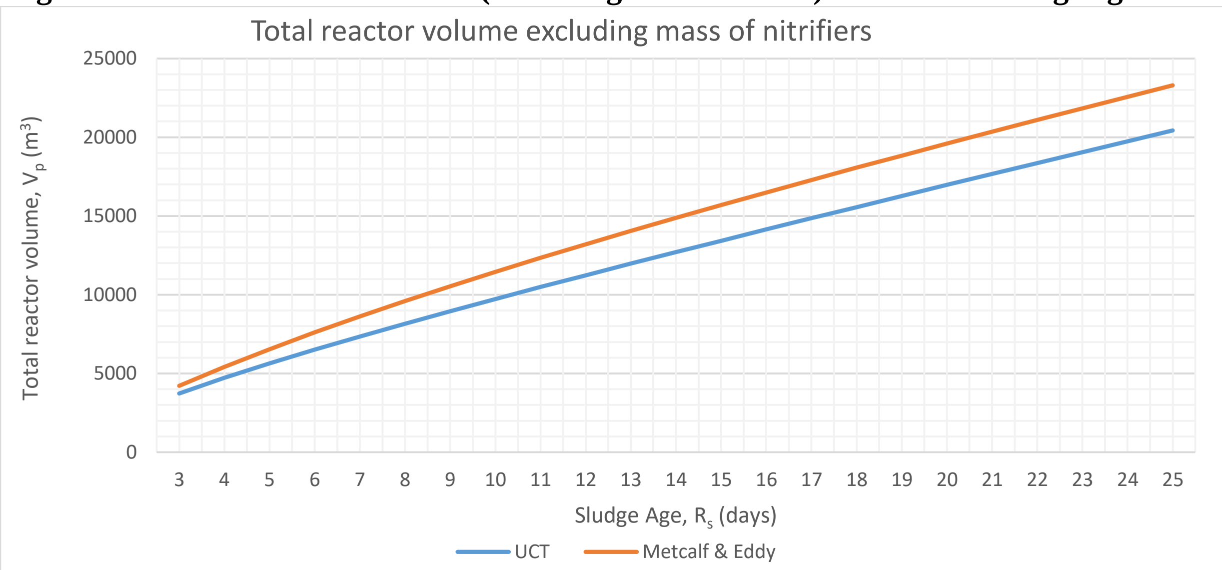
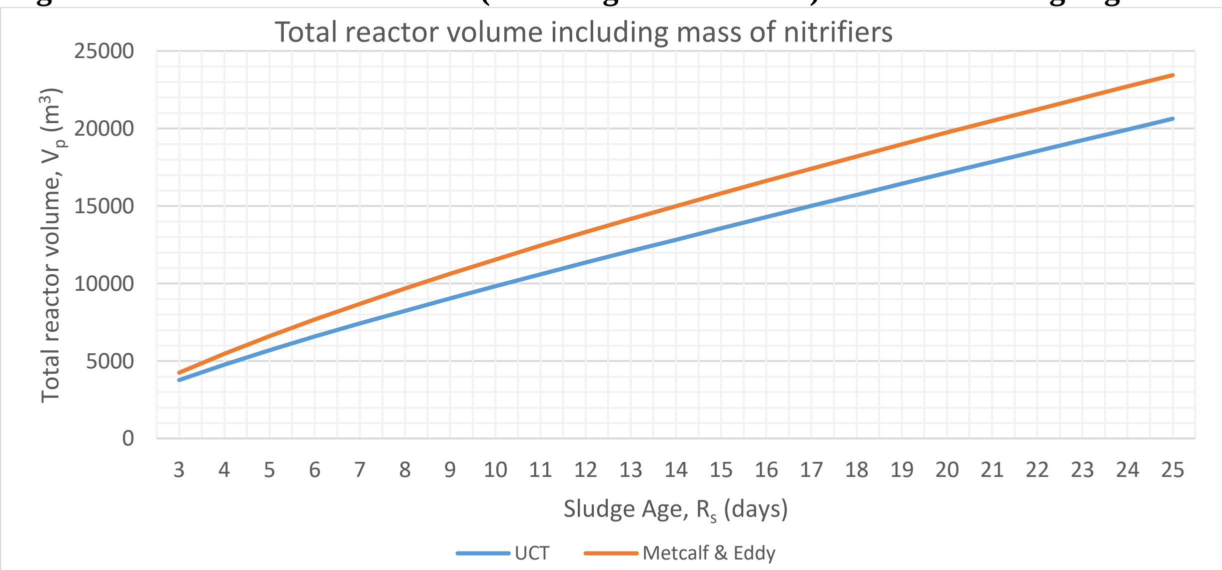


Figure 3-11: Total reactor volume (including nitrifier mass) for selected sludge age

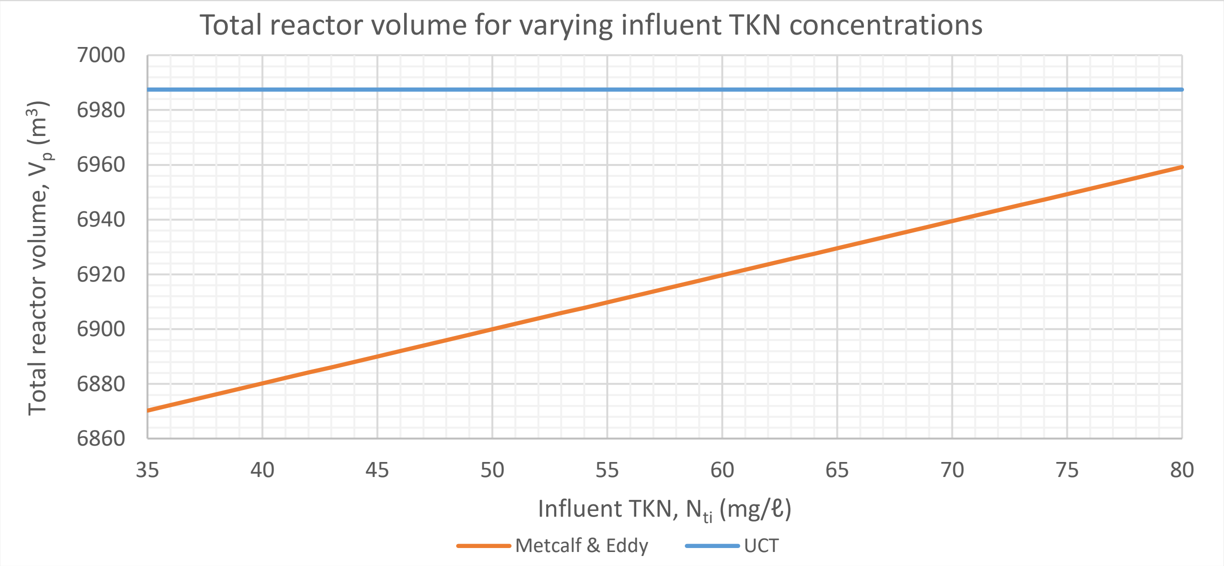


As seen in Section 3.2.4, the total reactor volume is larger when calculated using the M&E guideline for the same influent wastewater characteristics. The volume for the UCT guideline remains the same whether nitrification is included or not, but the volume using the M&E guideline differs when nitrification is added, because of the sludge production of the nitrifiers that is now included, as shown in Figure 3-11.

The inclusion of the ANO mass in the MX_t of the M&E guideline means that the fully aerobic reactor volume for the M&E guideline is affected by a variation in influent TKN concentration, while the UCT guideline is not because it does not include the mass of ANO's in the MX_t mass.

Figure 3-12 below shows the results of the total reactor volumes when varying the influent TKN concentration, within the typical municipal wastewater range of 35 to 80 mg/ℓ, for the minimum SRT's for nitrification calculated for each guideline (5.3 days for M&E and 6.6 days for UCT). It can be seen in Figure 3-12 that the M&E total reactor volume increases slightly, by 0.03% for every 1 mg/ℓ increase in influent TKN.

Figure 3-12: Total reactor volume for varying influent TKN

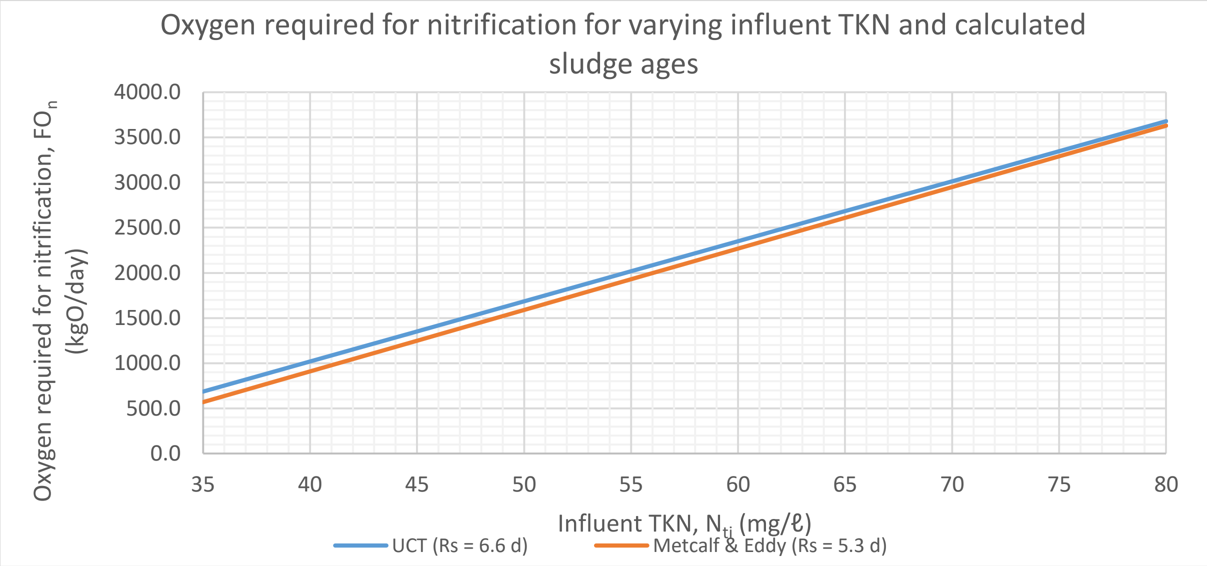


3.3.3 Oxygen required for nitrification

For both guidelines, the oxygen required for nitrification is simply 4.57 (the oxygen equivalent of nitrogen) times the mass of nitrate produced per day. Strictly this should be $[(4.57–f_{cv}Y_{ANO})/(1+b_{AT}R_s)]$ to maintain the total oxygen demand (TOD) balance, but the difference is small, increasing from 4.45 to 4.57 from 5 to 30 days SRT.

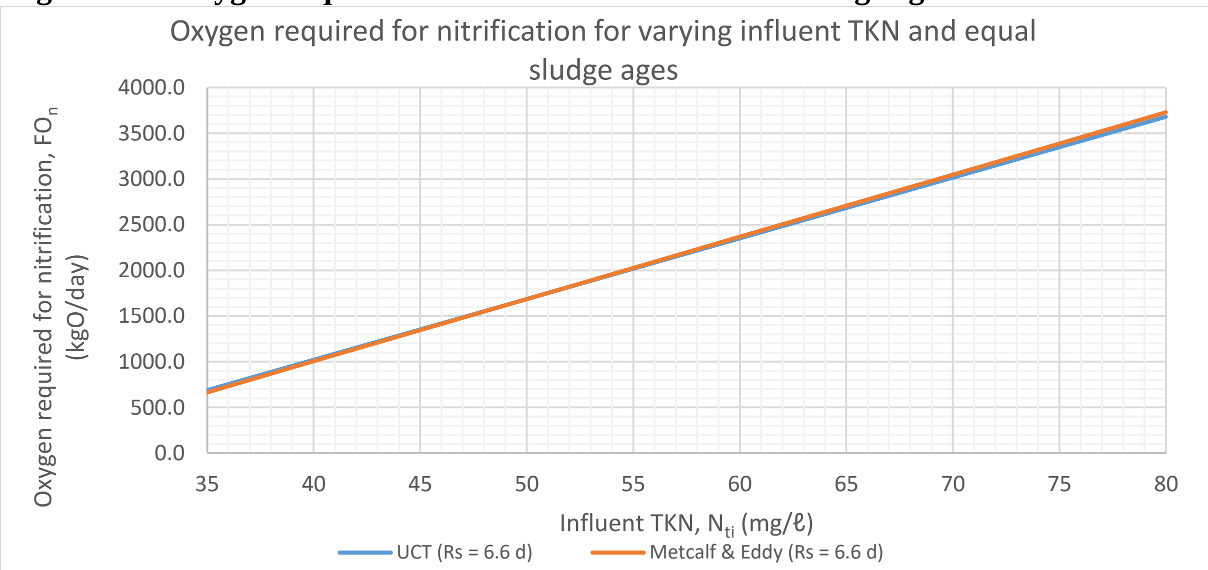
Figure 3-13 below shows the mass of oxygen required for a typical influent TKN concentration of 35 to 80 mg/ℓ. The results presented are based on the sludge ages calculated for each guideline which is 6.6 days and 5.3 days for the UCT and M&E guidelines respectively.

Figure 3-13 Oxygen required for nitrification for the calculated sludge ages for each guideline



It can be seen in Figure 3-13 that the oxygen required for nitrification of the UCT system is only 23% more than for the M&E system, although it is noted that the calculated sludge ages differ (UCT 6.6 days and M&E 5.5 days) – this higher oxygen demand is actually for COD removal at the longer SRT . Figure 3-14 shows the calculated FO_n flux almost the same when the sludge ages were set equal for the two guidelines.

Figure 3-14 Oxygen required for nitrification for selected sludge ages



3.4 Denitrification Design

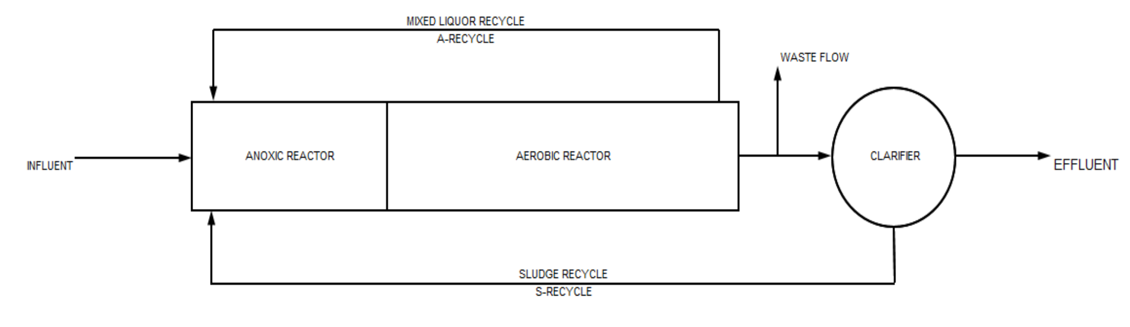
In general, the type of biological nitrogen removal systems can be classified according to the position of the anoxic zone in the reactor, as either (1) post-denitrification in a secondary anoxic reactor or (2) pre-denitrification in a primary anoxic reactor. Both design guidelines discuss these configurations, and the M&E guidelines adds a third type of nitrogen removal system, low DO and cyclic nitrification/denitrification, to the list.

Henze et al. (2008) discuss how post-denitrification utilises self-generated endogenous organics while pre-denitrification utilises the influent wastewater organics.

Post-denitrification systems have not been widely used in practice because of the low denitrification rate in the post denitrification reactor which requires that the subsequent anoxic reactor be large which does not allow the nitrification conditions to be satisfied.

An example of a pre-anoxic denitrification system, where the primary anoxic reactor is upfront of the aerobic reactor, is the MLE system as shown in Figure 3-15. Here, the underflow from the SST is recycled to the primary anoxic reactor (s-recycle) and there is a mixed-liquor recycle (a-recycle) from the aerobic to the primary anoxic reactor.

Figure 3-15: Configuration of the MLE pre-denitrification system



MODIFIED LUDZACK-ETTINGER (MLE) PROCESS for biological N removal

The 4-stage bardenpho system was developed to try and overcome the deficiency of the incomplete nitrate removal in the MLE system. The UCT guideline discusses how in practice however, the 4-stage bardenpho system cannot achieve complete removal of nitrate, i.e. zero nitrate in the underflow recycle, unless the influent TKN/COD ratio is low (< ~ 0.09 gN/gCOD at 14°C, Ekama et al., 1983; WRC, 1984), and for influent TKN/COD ratio above this at 14°C, it is better to remove the secondary anoxic reactor, enlarge the primary anoxic reactor to obtain an MLE and increase the a-recycle ratio. It is for this reason that only the MLE system for denitrification is discussed in the sections below.

3.4.1 Nitrate Mass Balance Principle

The principle of design for denitrification systems hinge around equalizing the nitrate load on the primary anoxic reactor with the denitrification potential of the anoxic reactor. While different words are used to express this principal, it is true for both guidelines. In the M&E guideline, the hydraulic retention time (HRT) is increased and in the UCT guideline, the anoxic mass fraction is increased until the nitrate load (via the a- and s-recycle) on the primary anoxic reactor matches its denitrification ability – which is called potential in the UCT guideline and the specific denitrification rate in the M&E guideline.

3.4.1.1 Calculation of the System Sludge Ages

UCT guideline

Following the publication of the UCT guideline (WRC, 1984), additional information has been added to Henze et al. (2008) which provides a calculation procedure for the balanced sludge age of a MLE system, $R_{sBalMLE}$ (see also Ekama, 2017). The UCT guideline finds the shortest SRT at which the effluent nitrate is lowest at a maximum practical a-recycle ratio (a_{prac}). Increasing the a-recycle ratio above 5 to 7:1 does not lead to a significant decrease in effluent nitrate concentration – the higher the a-recycle ratio, the smaller the decrease in effluent nitrate concentration for a further increase in a-recycle value. Hence 6:1 is set at the upper limit of the a-recycle because the small decrease in N_{ne} (< ~ 1 mgNO$_3$-N/ℓ) is not worth the additional energy cost. An a-recycle (and underflow s-recycle) returns a defined nitrate load on the primary anoxic reactor. In the UCT guideline, the size of the anoxic reactor is fixed by the maximum specific growth rate of the nitrifiers and the system SRT. As the system SRT get longer, so the anoxic reactor, specified as the anoxic mass fraction, gets larger. As the anoxic reactor gets larger so it is able to denitrify more nitrate, i.e. its denitrification potential, gets larger. At the SRT at which the nitrate load on the anoxic reactor at an a_{prac} = 6:1 (say) is equal to its denitrification potential (which is also the optimum a-recycle ratio, a_{opt}), is the MLE system's balanced SRT. Ekama (2017) derived an equation for the MLE system balanced SRT in terms of the influent wastewater characteristics temperature, maximum specific growth rate of nitrifiers and influent COD and TKN concentrations. Generally, the higher the influent TKN/COD concentration ratio, the longer the MLE balanced SRT.

This $R_{sBalMLE}$ is then used for sizing the entire system, in other words, it is used to calculate the total reactor volume and the anoxic and aerobic mass fractions, f_{manx} and f_{maer}, of the reactor.

M&E guideline

In contrast, the M&E guideline calculates a hydraulic retention time (HRT) for the anoxic reactor only, also based on equalizing the nitrate load and nitrate removal capacity of the primary anoxic reactor. This HRT is then converted into an anoxic volume and added to the aerobic reactor volume previously calculated in the aerobic SRT nitrification design to calculate the total reactor volume. This effectively adds an additional mass of TSS to the aerobic TSS mass calculated from the COD removal and nitrification equation at the aerobic SRT. This additional mass is the anoxic reactor's volume times the anoxic reactor TSS concentration, $X_{t,anx}$, which for the MLE system is the same as the aerobic reactor TSS concentration, $X_{t,aer}$ (Ekama et al., 2018). Because the waste flow cannot be increased to keep the aerobic sludge age at its calculated value, the system mass of TSS increases by the mass of TSS in the anoxic reactor and the system sludge age becomes longer than the aerobic sludge age, i.e.

$$R_{S,system} = \frac{R_{s,aer}}{1 - f_{manx}} \quad (d) \qquad (21)$$

Where f_{manx} is the anoxic mass fraction, i.e.

$$f_{manx} = \frac{V_{anx}X_{tanx}}{V_{anx}X_{tanx} + V_{aer}X_{taer}} \qquad (22)$$

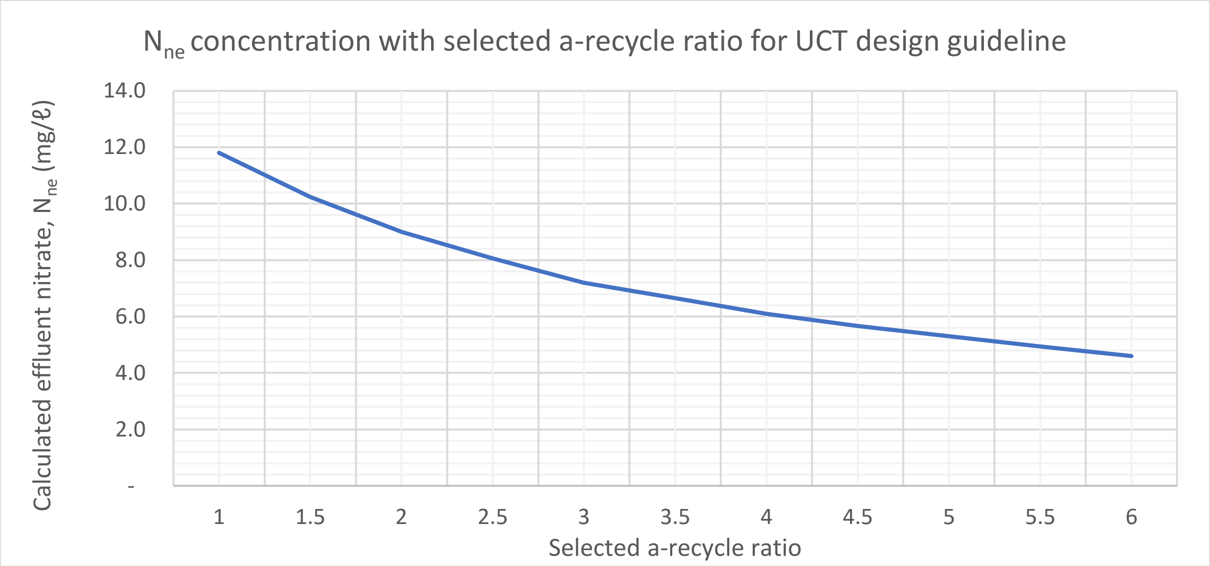
And because for the MLE system $X_{tanx} = X_{taer}$,

$$f_{manx} = \frac{V_{anx}}{V_{anx} + V_{aer}} \qquad (23)$$

Each of the nitrate balance procedures described above require system design inputs that are selected by the designer. The UCT guideline requires the designer to choose a practical a-recycle ratio, a_{prac}, whilst the M&E guideline requires that the designer input the required effluent nitrate concentration, N_{ne}. The a-recycle ratio in the M&E guideline is calculated from the selected N_{ne} concentration.

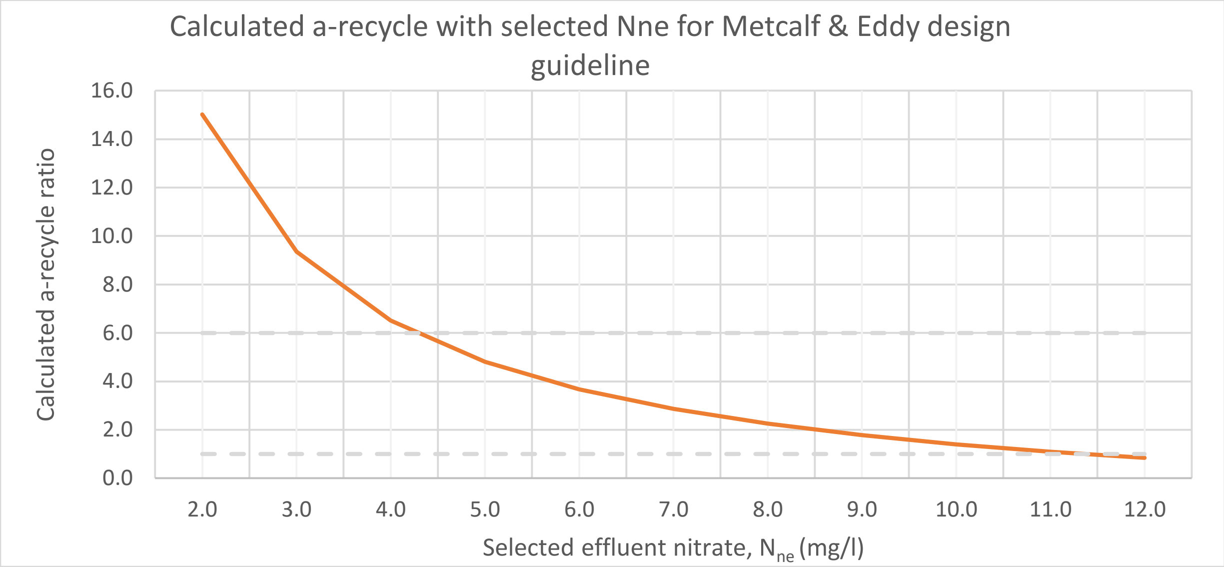
Figure 3-16 below shows how the higher the selected a-recycle ratio, a_{prac}, for the UCT guideline, the lower the resultant N_{ne} concentration. The same is true for the M&E guideline.

Figure 3-16 Results of N_{ne} concentrations for selected a-recycle ratios for the UCT design guideline



Similarly, Figure 3-17 below shows the lower the required N_{ne} concentration for the M&E guideline, the higher the calculated a-recycle ratio.

Figure 3-17 Calculated a-recycle ratios with selected N_{ne} concentrations for the Metcalf & Eddy design guidelines



It is noted from the two graphs above that whether the a-recycle is selected, as in the UCT guideline, or calculated, as in the M&E guideline, the N_{ne} concentrations are very similar for the two design guidelines (see Table 3-8 below). This is because for the same influent TKN concentration, nearly the same concentrations of nitrate produced by nitrification per litre influent (called nitrification capacity in the UCT guideline) are obtained. Provided the anoxic reactor can denitrify the nitrate recycled to it by the a- and s- recycles, the effluent nitrate concentration N_{ne} is given by:

$$N_{ne} = \frac{N_c}{a+s+1} \; (mg\, N/\ell) \qquad (24)$$

Table 3-8: Effluent nitrate concentrations for various a-recycle ratios

	a-recycle ratio	
	1	**6**
UCT design guideline	11.8	4.6
M&E design guideline	11.4	4.3

3.4.1.2 Calculation of the Nitrate Load on the Anoxic Reactor

If for the UCT guideline the MLE $R_{SMLEbal}$ is not directly calculated but instead a SRT is selected, then the nitrate load on the anoxic reactor for the MLE system is given by:

$$D_{p1} = \left[\frac{N_c}{(a+s+1)} + \frac{O_a}{2.86}\right] a + \left[\frac{N_c}{(a+s+1)} + \frac{O_s}{2.86}\right] s \quad (mgN/\ell) \qquad (25)$$

Where D_{p1} is the anoxic reactor denitrification potential (mgNO_3-N/ℓ influent) and N_c is the nitrification capacity (mgNO_3-N/ℓ) both calculated for known wastewater characteristics and selected SRT.

The recycle ratios, a and s, as well as the dissolved oxygen concentrations in these recycles, O_a and O_s, are values that are selected by the designer. Typically, s, the sludge recycle ratio from the SST underflow is selected as 1, and O_a and O_s are selected as 2 mgO/ℓ and 1 mgO/ℓ respectively. Because for a selected SRT D_{p1} and N_c are known, the above equation can be re-arranged to calculate the only unknown in it, i.e. the a recycle ratio. This is the optimum a-recycle ratio, a_{opt}, and will result in the lowest possible effluent nitrate concentration, N_{ne} at the selected SRT. An a-recycle ratio higher than a_{opt} will result in a higher effluent nitrate concentration N_{ne} – for $a < a_{opt}$ because the anoxic reactor is underloaded with nitrate (recycle limited denitrification) and for $a > a_{opt}$ because the anoxic now receives a high DO which decreases the reactor nitrate removal capacity (kinetics limited denitrification).

The M&E guideline calculates the nitrate load on the anoxic reactor, NO_r, for the MLE system as follows:

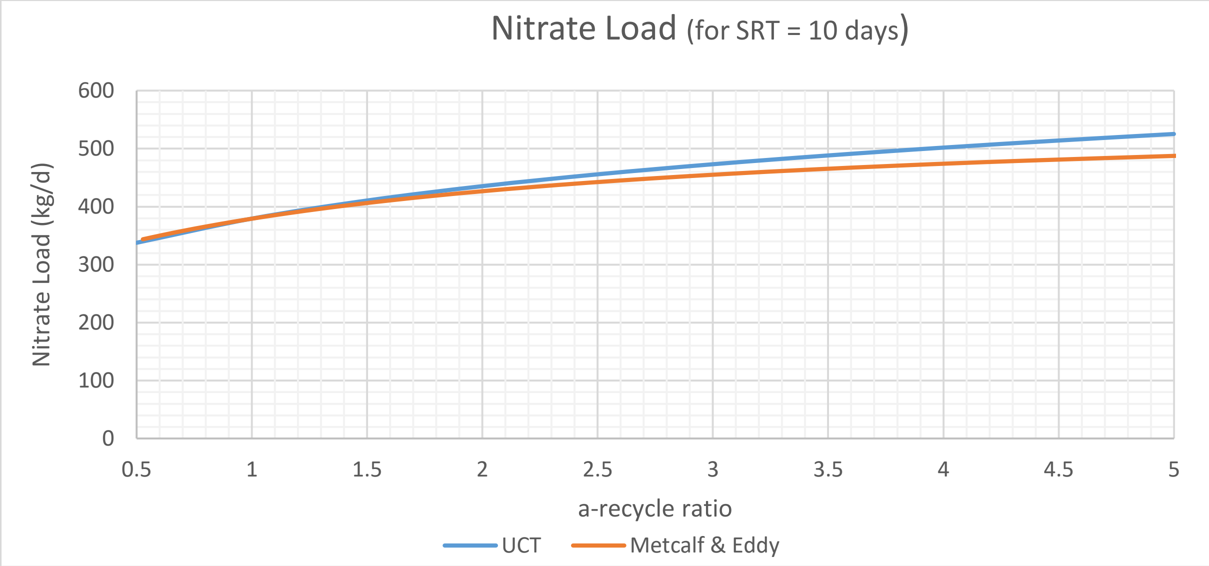
$$NO_r = (a+s)N_{ne}Q_i \quad (kg/d) \qquad (26)$$

Where the a-recycle is calculated (rather than selected as in the UCT guideline) from the ratio of the nitrate capacity (N_c) to the effluent nitrate concentration in (N_{ne}, or in the aerobic reactor), minus (1+s), i.e. a rearranged Eq. 24, viz $a=N_c/N_{ne} – (1+s)$.

Both guidelines take the a- and s-recycle ratios into account, while the UCT guideline also includes the addition of the dissolved oxygen concentrations, O_a and O_s, in these recycles. For the same *aerobic* SRT in the UCT and M&E guidelines, the nitrate load on the anoxic reactor at the same a and s recycle ratios are very similar, with the UCT guideline's nitrate load being slightly higher due to the inclusion of the dissolved oxygen in the recycles. This is because for the same aerobic SRT, closely similar nitrification capacities are calculated by the guidelines. This is seen in Figure 3-18 below. As expected, the higher the a-recycle ratio, the larger the difference between the UCT and M&E guideline nitrate loads because of the inclusion of the DO in the UCT guideline for calculating the nitrate load only. The M&E guideline incorporates the effect of the DO concentration in the calculation of the nitrate removal capacity by adjusting the specific denitrification rate (SDNR) to account for the internal recycle (IR) ratio. This is seen in Section 3.4.1.3 below.

As discussed previously, the UCT guideline requires the designer to choose a practical a-recycle ratio, a_{prac}, from which the effluent nitrate is calculated, whilst the M&E guideline requires that the designer input the required effluent nitrate concentration, N_{ne} and the a-recycle ratio is then calculated from this selected N_{ne} concentration. For the M&E results shown in Figure 3-18, the N_{ne} was selected so that the a-recycle ranges between 0.5 (for N_{ne} = 15 mgN/ℓ) and 5 (for N_{ne} = 5.4 mgN/ℓ).

Figure 3-18 Calculation of nitrate load on anoxic reactor for various a-recycle ratios for a selected SRT



3.4.1.3 Calculation of the nitrate removal capacity of the anoxic reactor

It is in the calculation of the nitrate removal capacity of the anoxic reactor that the two design guideline results differ. The UCT guideline defines the denitrification potential, D_p, as the concentration of nitrate, per litre influent flow, that an anoxic reactor can denitrify biologically (i.e. the nitrate removal capacity). It is called a potential because whether or not denitrification potential is achieved depends on the nitrate load on the anoxic reactor. The M&E design approach is based on a single specific denitrification rate (SDNR) to determine the nitrate removal rate from which an anoxic reactor HRT and volume are determined. These two approaches are elaborated further below:

<u>Denitrification rates in the UCT procedure:</u>

The specific denitrification K rates (mgNO_3-N/(mgOHOVSS.d) in the UCT guideline are based on the observed utilization rates of the readily biodegradable soluble organics (BSO or RBCOD) and the slowly biodegradable particulate organics (BPO or SBCOD) in the primary anoxic reactor (van Haandel et al., 1981, Henze et al., 2008). According to the UCT guideline, the K-rates are prescribed for these two phases of denitrification that occur in the anoxic reactor, as follows:

- Rapid initial phase where the rate is defined by the simultaneous utilisation (K_1 + K_2) of RBCOD (K_1) and SBCOD (K_2)
- Slower second phase where the specific denitrification rate (K_2) is defined by the utilisation of SBCOD only that originates from both the influent as well as that self-generated by the sludge through organism death and lysis (endogenous respiration).
- Other denitrification rates, K_3 and K_4 are defined for the specific denitrification rates in the secondary anoxic reactor and intermittent aerated anoxic aerobic digestion of

WAS respectively. However, these are not required for the pre-anoxic MLE system used for this dissertation.

The UCT K-rates for denitrification were measured in extensive laboratory investigations ((van Haandel, et al., 1981) and (Ekama & Wentzel , 1999)). Because both the UCTOLD (Dold et al., 1991) and ASM1 (Henze et al., 1987) simulation models were calibrated against this data set, the K rates also can be obtained by simplifying the kinetic equations that describe the utilisation of the RBCOD (Monod kinetics) and SBCOD (Saturation kinetics) from the influent or due to organism death and lysis with nitrate as electron acceptor in ASM1 (Henze, et al., 2008, pp. Chapter 5, Section 5.8.6) or UCTOLD (Dold et al., 1991). The comparison by Dold and Marais (1986) demonstrates that UCTOLD (which will be used later in this thesis) and ASM1 essentially give the same simulation results for most anoxic aerobic ND systems. The main difference between UCTOLD and ASM1 is that in UCTOLD, RBCOD is utilized via Monod kinetics simultaneously with SBCOD, which is utilized directly by the OHO via Saturation kinetics whereas in ASM1, SBCOD is first hydrolysed to RBCOD via the same Saturation kinetics, and then RBCOD is utilized via the same Monod kinetics. The only difference between the models is the slightly higher Monod maximum specific growth rate of OHO utilizing RBCOD in ASM1 to account for the utilization of the additional RBCOD generated by the hydrolysis of SBCOD.

The K_1 and K_2 denitrification rates are temperature dependent, as shown in Table 3-9 below.

Table 3-9: Denitrification rates for the UCT guideline (*source: Henze et al., 2008)*

Constant (units)	**UCT Guideline**		
	Nomencl ature	**θ**	**Standard value at 20°C**
K_1 denitrification rate (mgNO$_3$-N/ (mgOHOAVSS.d)	K_1	1.200	0.720
K_2 denitrification rate (mgNO$_3$-N/ (mgOHOAVSS.d)	K_2	1.080	0.101

For the standard minimum temperature of 14°C, the K_2 denitrification rate is 0.064 mgNO$_3$-N/(mgOHOAVSS.d).

The RBCOD fraction of the influent, $f_{Sb's}$, is an important influent wastewater characteristic to be accurately known as it has a substantial influence on the nitrate removal performance of a biological denitrification system.

The UCT guideline calculates the denitrification potential for the utilisation of the RBCOD and SBCOD separately. It assumes that the RBCOD is all utilised in the primary anoxic reactor because of its rapid denitrification rate. To ensure this, a minimum anoxic mass fraction (f_{x1min}) is calculated and the actual anoxic mass fraction (f_{x1}) must be larger than this minimum. This is usually the case because f_{x1min} is very low; <0.08 at 14˚C even at high influent RBCOD concentrations. Because the RBOD is completely utilized for denitrification, the $f_{Sb's}$ fraction has a direct effect on the denitrification potential of the anoxic reactor, as shown in the Equation 27 for the denitrification potential of the primary anoxic reactor of a MLE system:

$$D_{p1} = S_{bi}\left\{\frac{f_{Sb's}(1 - f_{cv}Y_{Hv})}{2.86} + K_{2T}f_{x1}Y_HR_s/(1 + b_{HT}R_s)\right\} \ (mgN/\ell) \qquad (27)$$

<u>Denitrification rate in the M&E procedure:</u>

The M&E design approach is based on using a single specific denitrification rate (SDNR) to determine the nitrate removal rate in an anoxic reactor volume. The SDNR is related to the amount of nitrate removed per unit time and the values provided in the guideline are based on observed denitrification rates in pilot and full-scale plants supplemented by ASM1 simulation results. The M&E guideline discusses that the SDNR value has been found to range from 0.04 to 0.42 gNO3-N/ (gMLVSS.d) for full scale pre-anoxic tanks.

The $SDNR_b$ is the specific denitrification rate based on OHO biomass concentration (instead of the VSS as above) at 20°C and is defined in terms of the food to OHO biomass ratio, F/M, for various percentages of influent RBCOD fraction ($f_{Sb's}$). Similar to the K-rates in the UCT guideline, the biokinetic coefficients used for the calculation of $SDNR_b$ are model parameter default values determined from ASM1 simulations, along with observed RBCOD kinetics under anoxic conditions from testing at various municipal wastewater treatment facilities (Stensel and Horne, 2000).

The $SDNR_b$ is then corrected to $SDNR_t$ for minimum temperature values, with a θ value of 1.026. Next, the $SDNR_t$ is adjusted to $SDNR_{adj}$ to account for the effect of the DO in the internal recycle (a-recycle) flow, and this $SDNR_{adj}$ value is used for the calculation of the nitrate removal capacity of the anoxic reactor (see Equation 28 below). Detailed equations for these calculations are not given to not infringe the copyright of the M&E (Metcalf & Eddy | AECOM, 2014) text book.

The M&E guideline calculates the nitrate removal capacity as follows:

$$N_{rem\ cap} = X_bSDNR_{adj}V_{anx} \ (kg/d) \qquad (28)$$

Where X_b is the OHO concentration in the aerobic reactor and V_{anx} is the anoxic reactor volume.

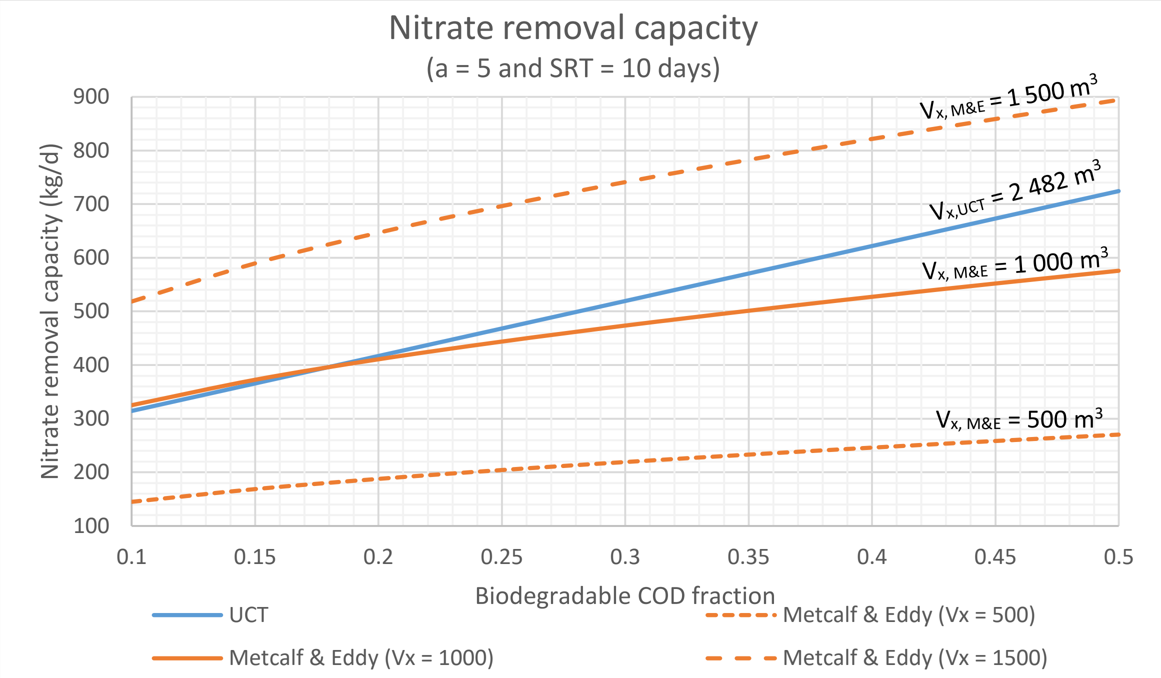
The nitrate removal capacity of the anoxic reactor (Eq. 28) is then set equal to the nitrate load on the anoxic reactor (Eq. 26). If Equations 26 and 28 are dividing through by Q_i, then the V_{anx} in Eq. 28 becomes the nominal HRT of the anoxic reactor ($HRT_{n,anx}$). This is done in the M&E guideline because it is easier to guess an $HRT_{n,anx}$ between 0.5 and say 6h to make Equations 26 and 28 equal than a V_{anx}. Then the anoxic reactor volume, $V_{anx\ is}$ calculated from the anoxic HRT.

In this V_{anx} calculation, it seems as if the influent RBCOD fraction does not affect the nitrate removal capacity of the primary anoxic reactor. However, it does, because it is indirectly included in the calculation of the $SDNR_{adj}$. The effect of the influent RBCOD fraction ($f_{Sb's}$) on the nitrate removal capacity via the $SDNR_{adj}$ is shown in Figure 3-19 below, together with the denitrification potential (D_{p1}) of the UCT guideline (called nitrate removal capacity in Figure 3-19).

In Figure 3-19, the nitrate removal capacity for the M&E guideline design are shown for three anoxic reactor volumes (500, 1000 and 1500 m^3) to indicate how the selection of the anoxic reactor volume (or $HRT_{n,anx}$) effects the nitrate removal capacity for different influent RBCOD fractions ($f_{sb's}$). The selected anoxic reactor volumes of 500, 1000 and 1500 m^3 yield 0.041, 0.079 and 0.115 respectively. The nitrate removal capacity (or denitrification potential for the UCT guideline is also shown for a fixed anoxic mass fraction (f_{x1}) of 0.255, which results in a fixed V_{anx} of 2,482 m^3. Note that the results shown in Figure 3-19 for both guidelines are for a selected SRT of 10 days, which in the UCT guideline is the system SRT, while in the M&E guideline it is the aerobic SRT, because this yield very closely similar nitrate concentrations produced by nitrification, i.e. nitrification capacities (N_c), for the UCT and M&E guidelines.

Although the purpose of Figure 3-19 is to show the effect of the influent RBCOD fraction on the nitrate removal capacity, what is immediately apparent in Figure 3-19 is the considerably smaller anoxic reactor result for the M&E guideline than from the UCT guideline. This aspect will be discussed in greater detail below.

Figure 3-19 Calculation of nitrate removal capacity for various biodegradable COD fractions for a selected SRT and a-recycle ratio



3.4.2 Approach to Reactor Volume Calculation

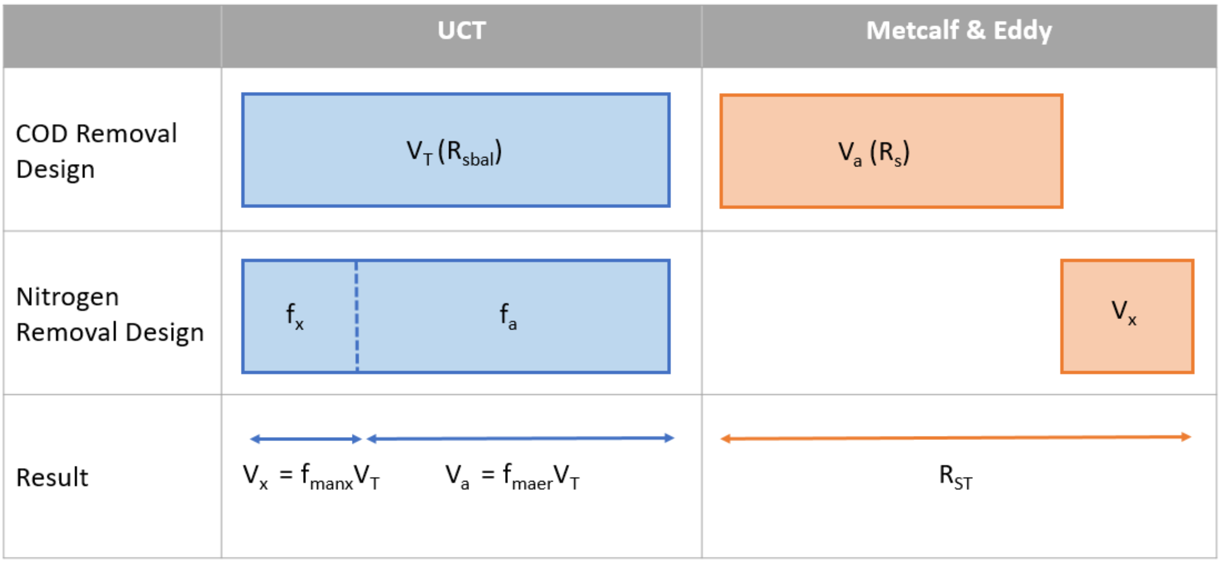
For both design guidelines, the denitrification design follows on the COD removal and nitrification design by incorporating the anoxic reactor design. However, the principle of how the denitrification design is incorporated is different in the two guidelines:

- The UCT guideline design for nitrogen removal is done entirely using sludge mass fractions and SRT and does not require the volume of the reactor to be known. The volume of reactor obtained from the SRT, the shortest possible for the MLE to ensure nitrification being the balanced sludge age, $R_{SBal,MLE}$, and the organic and ISS loads (FS_{ti} and FX_{IOi}) is subdivided into the anoxic and aerobic volumes from the calculated anoxic and aerobic mass fractions, f_{manx} and f_{maer}. The nitrogen removal design is thus grafted into the aerobic system design (for the same X_t and R_s) and both systems (anoxic-aerobic or fully aerobic) will have the same total reactor volume for the same SRT.

- The M&E guideline design for denitrification determines the volume (or HRT) required for the anoxic zone only. The required aerobic sludge age, calculated in the COD removal and nitrification design step is used to calculate the aerobic volume. This required aerobic SRT is the parallel shortest SRT to ensure nitrification in the M&E guideline to the balanced SRT in the UCT guideline. The anoxic reactor volume (or HRT) is then calculated separately with the nitrate mass balance procedure and added to the aerobic reactor volume at the same TSS concentration as the aerobic reactor. This implicitly adds the mass of TSS in the anoxic reactor to the mass of TSS in the aerobic reactor already calculated to give the mass of TSS in the system (whole reactor). This larger mass of TSS (i) divided into the anoxic TSS mass yields the anoxic mass fraction (f_{x1}) and (ii) divided by the waste flow rate to maintain the aerobic sludge yields the system SRT, which is longer than the aerobic SRT. This addition of the anoxic reactor TSS mass and calculation of the anoxic mass fraction and system SRT is not done in the M&E guideline, but is done here for comparative purposes with the UCT guideline, which works with anoxic mass fraction, system TSS mass and system SRT.

Figure 3-20 below illustrates the differences in incorporation of the volumes and sludge ages for the MLE system for the two guidelines.

Figure 3-20 Principle of incorporation of volumes and sludge ages for MLE system



3.4.2.1 Effect of Influent TKN/COD Ratio

The influent TKN/COD ratio has a large influence on the nitrification capacity, N_c, and thus the denitrification potential and N removal performance of a system that is designed for biological denitrification.

For domestic wastewater, the influent TKN/COD ratio is in the range of 0.07 to 0.13; 0.070 to 0.100 for raw wastewater and 0.100 to 0.130 for settled wastewater. In general, an increase in the TKN/COD ratio will result in an increase in nitrate produced by nitrification (N_c) per influent COD, and this decreases the possibility of obtaining complete denitrification.

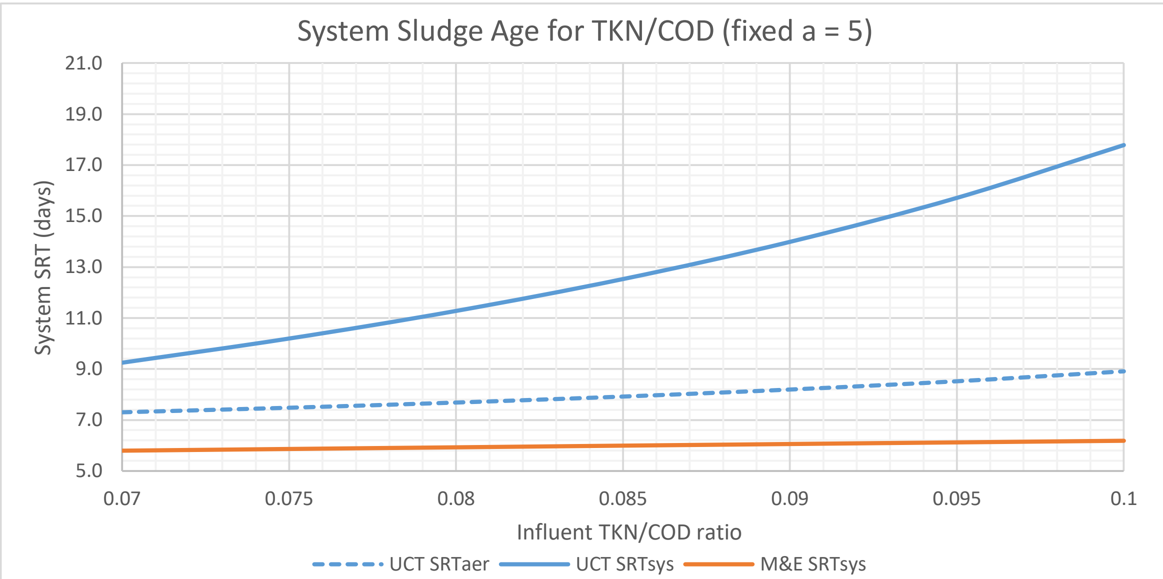
The effect of a varying influent TKN/COD ratios is described below:

i) Effect on System Sludge Age

The equation for the UCT guideline's MLE system balanced SRT, $R_{SbalMLE}$, was derived by Ekama (2017). It gives the $R_{SbalMLE}$ in terms of the influent wastewater characteristics like temperature, maximum specific growth rate of nitrifiers, influent COD and TKN concentrations and MLE system operating conditions like maximum practical a recycle ratio (a_{prac}). Generally, the higher the influent TKN/COD concentration ratio, the longer the MLE balanced SRT. This is because the higher influent TKN requires a larger anoxic reactor for denitrification of a higher nitrification capacity (N_c). This is seen clearly in Figure 3-21 below, where the balanced (system) SRT increases from 9.2 days to 17.8 days for TKN/COD ratios 0.070 to 0.100 respectively, for a fixed a-recycle (a_{prac}) of 5. Also shown is the increasing anoxic mass fraction (f_{x1}) and aerobic SRT [= (1-f_{manx}) x system SRT) with increasing influent TKN concentration. If the maximum a recycle ratio (a_{prac}) were 6:1, then the balanced (system) SRTs are slightly shorter.

The system SRT for the M&E guideline is the aerobic SRT (which is calculated in the nitrification design from the nitrification rate, μ_{AOB}, and safety factor, S_f) divided by (1-f_{manx}), where f_{manx} is the anoxic fraction of the total reactor volume (aerobic plus anoxic) (Figure 3-20). For a selected effluent ammonia concentration, the nitrification rate $\mu_{AOB,}$ and thus the aerobic SRT, will remain the same regardless of the influent TKN/COD ratio. As shown in Figure 3-21 below, the aerobic SRT is 5.3 days for a selected effluent ammonia concentration of 2.0 mg/ℓ and a selected a-recycle ratio of 5. In the M&E guideline, as the influent TKN/COD ratio increases, the f_{manx} increases slightly from 0.088 to 0.145 and hence for TKN/COD ratio of 0.070 to 0.100 the system SRT only slightly increases from 5.8 days to 6.2 days respectively. This is the major difference between the two design guidelines. The nitrate removal per m^3 anoxic volume in the M&E guideline is far greater than in the UCT guideline. This difference will be seen again when the M&E and UCT designed MLE system is simulated with ASM1 in Chapter 4.

Figure 3-21 System SRT for varying influent TKN/COD ratios



ii) Effect on Reactor Volumes and Mass Fractions

When applying the nitrate mass balance procedure for denitrification and calculating the system SRT for both guidelines as described above for varying influent TKN/COD ratios and a fixed a-recycle ratio of 5, the same trends of the guidelines as seen in the system SRT in Figure 3-21 are reflected in the reactor volumes in Figure 3-22, i.e. for the M&E guideline, as the system SRT increases slightly with TKN/COD ratio, so also does the total reactor volume increase slightly with TKN/COD ratio and for the UCT guideline, as the system SRT increases strongly with TKN/COD ratio, so also does the total reactor volume increase strongly with TKN/COD ratio.

Because for the UCT guideline design, the increasing TKN/COD ratio results in an increasing balanced sludge age (which is the system sludge age) and increasing f_{manx}, the same is seen for the total reactor volume, which increases as a result of the increasing sludge age, and the anoxic reactor volume, V_{anx}, therefore also increases as a result of the increase in both f_{manx} and total reactor volume. This is seen in Figure 3-22 and Figure 3-23 below.

For the M&E guideline, the aerobic SRT, and thus the aerobic reactor volume, remains the same for all TKN/COD ratios (because the aerobic SRT is calculated in the nitrification design from the nitrification rate, μ_{AOB}, and safety factor, S_f which do not change with varying TKN/COD ratios). The anoxic reactor volume, and the anoxic mass fraction, f_{manx}, and system SRT increase with the increasing TKN/COD ratio because a longer anoxic HRT is required to equalize the nitrate removal capacity equal and the nitrate load for the increasing N load as a result of the increasing TKN/COD ratio. This is seen in Figure 3-22, Figure 3-23 and Figure 3-24 below.

While the aerobic reactor volumes remain similar for all TKN/COD ratios, the higher the TKN/COD ratio, the greater the difference between the UCT guideline and M&E guideline anoxic reactor and total reactor volumes. This is seen in Figure 3-22 below.

Figure 3-22 Anoxic and aerobic reactor volumes for varying influent TKN/COD ratios

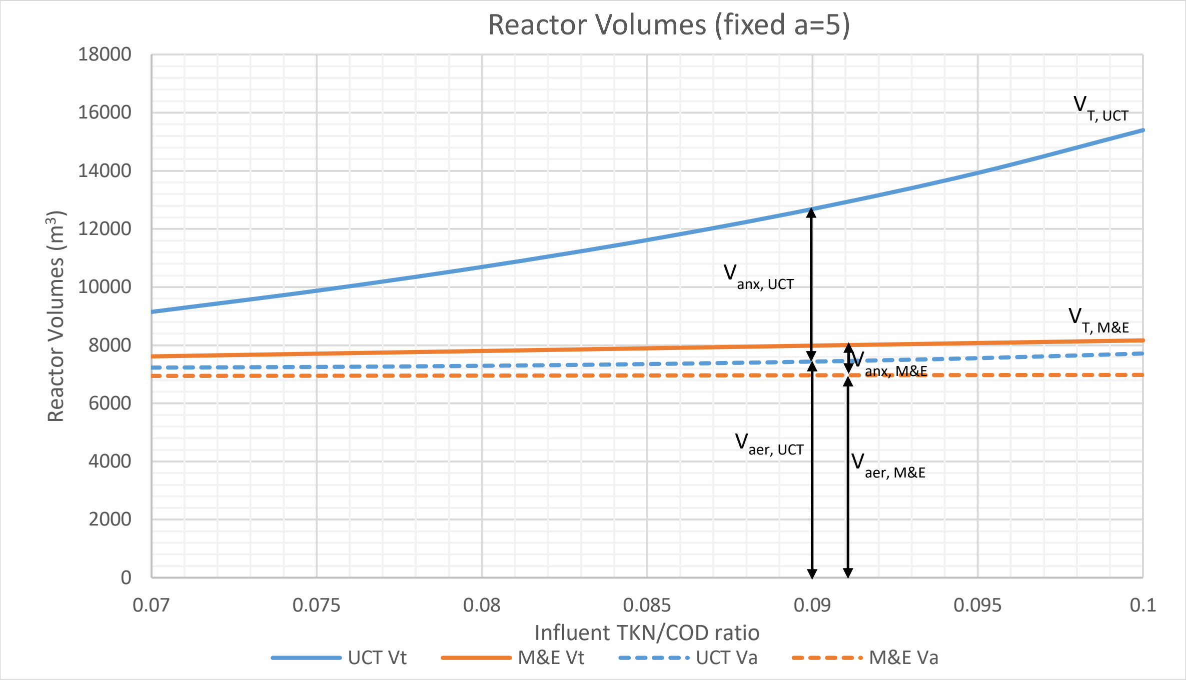


Figure 3-23 Anoxic and aerobic reactor mass fractions for varying influent TKN/COD ratios

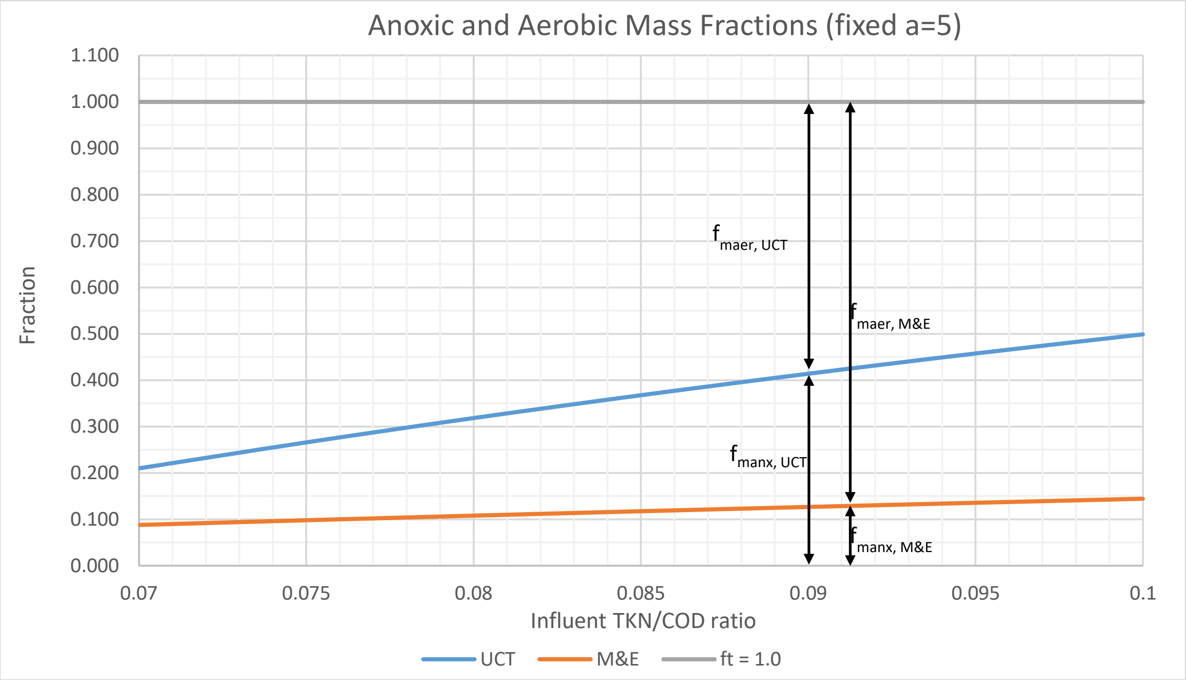
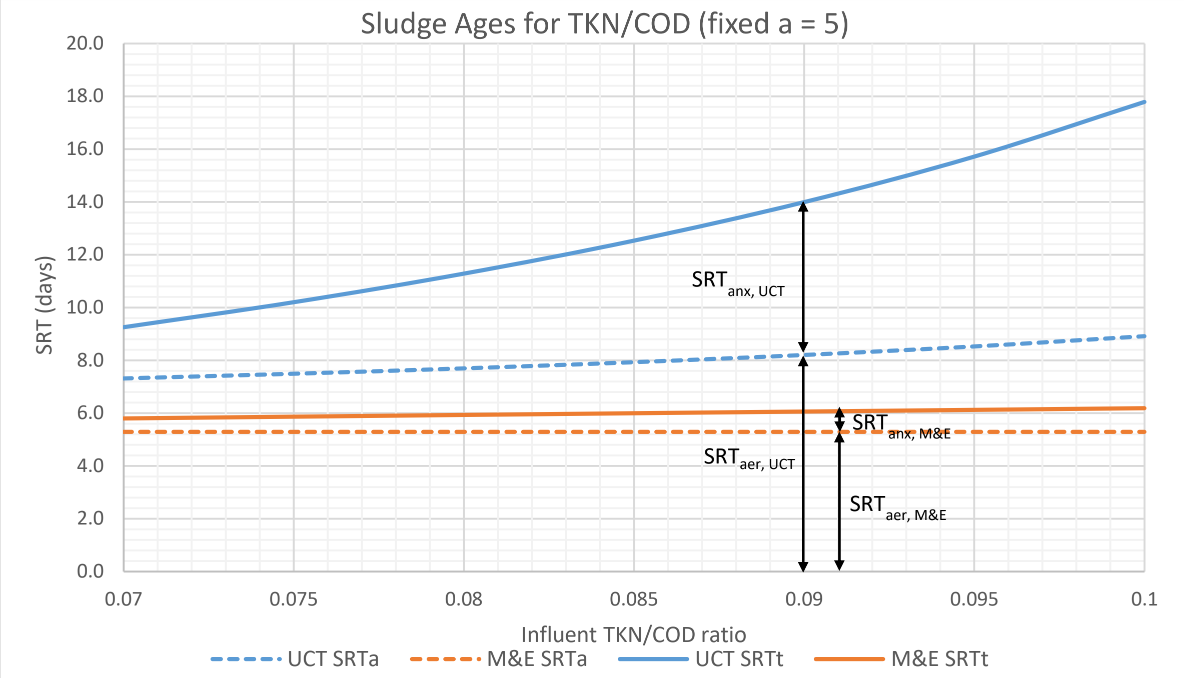


Figure 3-24 Anoxic and aerobic sludge ages for varying influent TKN/COD ratios



When denitrification is incorporated into the two guidelines by adding an anoxic reactor for denitrification, such as for the anoxic aerobic ND MLE system, the design hinges on the nitrate mass balance in the anoxic reactor, and this is where the two guidelines differ significantly. This is because (i) the nitrifiers are assumed to behave differently under anoxic conditions in the two guidelines and (ii) the effective specific denitrification rates of the OHO biomass in the anoxic reactor are much higher in the M&E guideline than in the UCT guideline.

i. With regard to difference (i), in the UCT guideline, the nitrifiers are assumed to grow only in the aerobic reactor but die in both the anoxic and aerobic reactors. In the M&E guideline, the nitrifiers are assumed to die (and grow) only in the aerobic reactor, i.e. they neither grow nor die in the anoxic reactor. Hence in the M&E guideline, the MLE system is sized based on an aerobic SRT, which excludes the mass of sludge in the anoxic reactor, but in the UCT guideline the MLE system is sized based on an system SRT, which includes the mass of sludge in the anoxic reactor.

ii. With regard to difference (ii), the faster specific denitrification rate determined with the M&E guideline yield much smaller anoxic reactors by at least 50% to achieve the same nitrate removal.

It is seen in this section on denitrification that, for the same influent wastewater characteristics and a-recycle ratio, the system SRT of the MLE system determined with the UCT guideline is considerably longer than that determined with M&E guideline, leading to larger anoxic, aerobic an system reactor volumes. This difference widens as the influent TKN/COD ratio increases, i.e. as the concentration of nitrate to be denitrified increases.

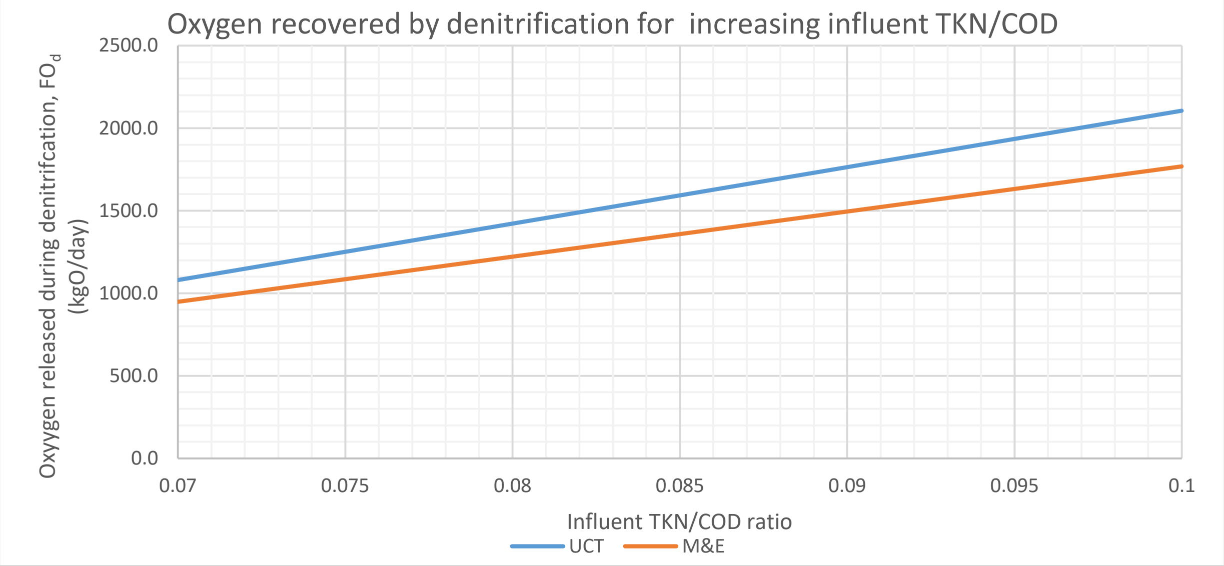
3.4.3 Oxygen Recovered During Denitrification

For both guidelines, the oxygen recovered by denitrification is simply 2.86 (the oxygen equivalent of nitrate) times the flux of nitrate denitrified per day.

Figure 3-25 below shows the flux of oxygen recovered for typical influent TKN/COD ratios for raw wastewater. The results presented are based on the balanced system sludge ages calculated for each guideline, which range from 9.2 to 17.8 days for the UCT guideline and 5.8 to 6.2 days for the M&E guideline (at a fixed a –recycle ratio of 5).

The oxygen recovered during denitrification for the UCT guideline system is more than for the M&E guideline system. This is because for a fixed a-recycle of 5, the UCT guideline system calculates a lower effluent nitrate concentration than the M&E guideline system, and thus more nitrate is denitrified in the UCT system.

Figure 3-25 Oxygen recovered by denitrification varying influent TKN concentrations



3.4.4 COD and N Mass Balances

Both the UCT and M&E guidelines close out the COD and N mass flux balances within 1%, but the different stoichiometric and kinetic constants for the two guidelines split the influent organics differently - between VSS sludge production and oxygen demand for COD flux and particulate N in sludge and soluble N in liquid or gas phase for TKN flux.

It is seen in Figure 3-26 below that for the COD flux over a range of influent TKN/COD ratios, the M&E guideline’s system results in higher sludge production and lower oxygen demand than the UCT guideline’s system. Similarly for the TKN flux over a range of influent TKN/COD ratios, it is seen in Figure 3-27 below that the M&E guideline’s system results in higher particulate N in sludge and lower N nitrified (transferred into liquid phase) and denitrified (transferred into gas phase) than the UCT guideline’s system.

Figure 3-26 Fractions COD flux

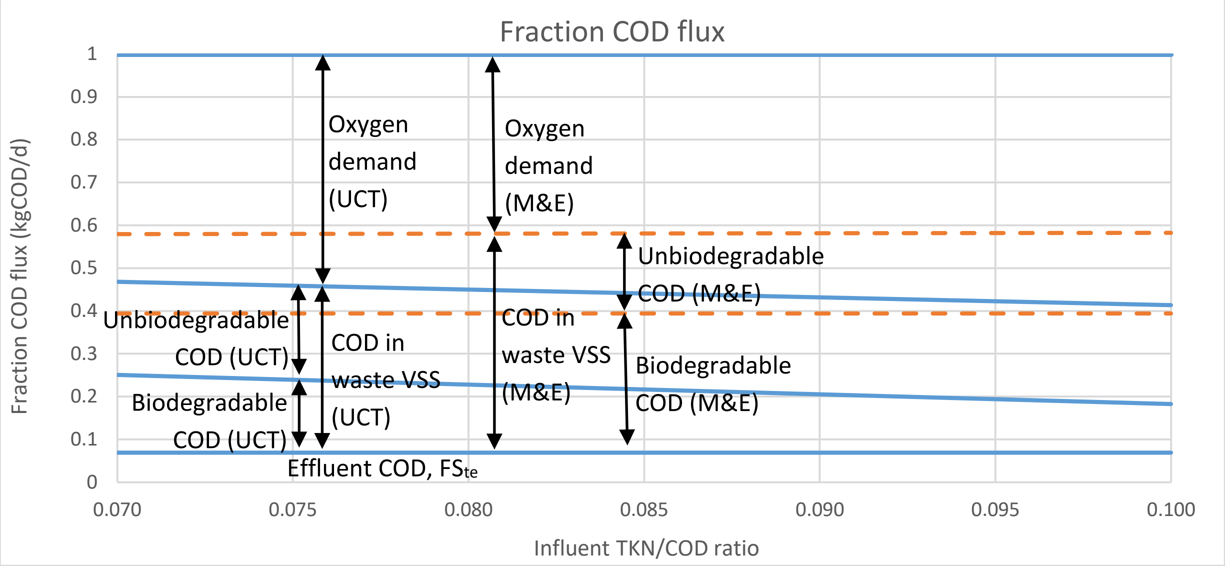
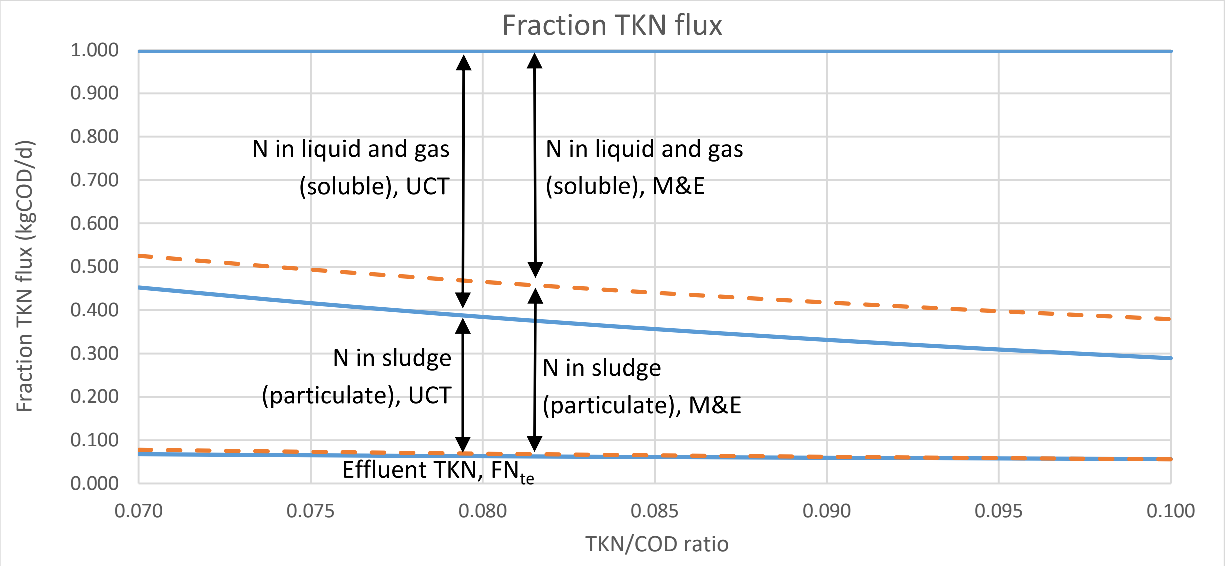


Figure 3-27 Fractions TKN flux



3.5 Enhanced Biological Phosphorus Removal Design

According to Henze et al. (2008), EBPR is the biological uptake and removal by AS systems in excess of the amount that is removed by normal completely aerobic AS systems. To achieve EBPR in AS systems, the growth of organisms that accumulate PAOs has to be stimulated. This is accomplished by:

- An anaerobic, then aerobic (or anoxic) sequence of rectors or zones; and
- The addition or formation of VFAs in the anaerobic reactor or zone.

The EBPR design processes presented in the UCT guideline are based on the Mixed Culture Steady State Model (Wentzel, et al., 1990) where the main principle is to divide the influent flux of COD between the following the two heterotrophic population groups:

i) OHOs – quantification of the OHOs is calculated in COD removal systems, however, must be modified to take account of the COD reduction due to uptake and storage by the PAOs.

ii) PAOs – which obtain the VFA and the greater part of the RBCOD in the influent.

With EBPR the reactor TSS mass includes the additional VSS terms for active biomass of PAOs (MX_{BG}) and endogenous residue from PAOs (MX_{EG}) to account for the PAO VSS masses. The other three parts of the VSS are the same as in ND systems, i.e. active biomass of OHOs (MX_{BH}), endogenous residue from OHOs (MX_{EH}) and the unbiodegradable particulate organics (UPO VSS) from the influent. ISS part of the reactor TSS also increases due to the stored polyphosphate in the PAO.

This means that the inclusion of the PAOs increases the TSS mass in the reactor per kgCOD load on the reactor and thus the total reactor volume calculated using the UCT guideline is significantly larger than an MLE system treating the same influent COD load. The UCT guideline provides in depth equations, explanations and examples when including EBPR in ND systems for a variety of system configurations such as the Johannesburg (JHB), UCT and 3 stage Bardenpho (3SB) systems.

The M&E guideline discusses that the amount of EBPR is directly related to the amount of acetate and propionate taken up by the PAOs in the anaerobic zone and converted to carbon storage products that provide energy and growth in the subsequent anoxic and aerobic zones. It further discusses how the VFA to P ratio is a good predictor of the amount of P that can be removed, and other wastewater characterisation parameters that correlate with the VFA utilisation in EBPR systems include RBCOD:P, BOD:P and COD:P ratios.

In contrast to the UCT guideline, the M&E guideline provides minimal insight into EBPR behaviour for design. It provides only very simplistic examples for calculation of the effluent soluble P concentration and the percentage of P content in the waste sludge.

The M&E guideline calculates the effluent soluble P concentration as follows:

$$P_{te} = P_{ti} - P_{EBPR} - P_{synthesis} \qquad (29)$$

Where P_{EBPR} is calculated simply as the influent RBCOD divided by the RBCOD/P ratio and $P_{synthesis}$, which is the P removal by OHO for synthesis, is calculated as 0.015 of P_{xbio} (i.e. the OHO biomass as calculated in the COD removal section of the M&E guideline). The calculation of the percentage of P content in the waste sludge is calculated in the M&E guideline as follows:

$$P\ in\ waste\ sludge, \% = \frac{(P_{ti} - P_{te}) \times Q_i}{P_{X,TSS}} \qquad (30)$$

Where $P_{x,TSS}$ is the total TSS sludge production, as calculated in the COD removal section of the M&E guideline (i.e. it ignores any differences the PAO make to the reactor TSS mass).

In comparison to the equations given in the M&E guideline for the effluent P and P in waste sludge, the UCT guideline provides the following equations for the effluent total P concentration. Using the same symbols as Chapter 7 in Henze et al. (2008), which are different to those in the equation for the organics and N removal used above.

$$P_{te} = P_{ti} - \Delta P_{SYS,ACT} + X_{P,e} \qquad (31)$$

Where $\Delta P_{SYS,ACT}$ is the potential P removal which consists of the following:

- ΔP_{PAO}, the P removal due to PAO's
- ΔP_{OHO}, the P removal due to OHO's
- ΔP_{XE}, the P removal due to endogenous mass, both for the PAO's and OHO's; and
- ΔP_{XI}, the P removal due to influent inert mass.

And $X_{P,e}$ is any suspended solids in the effluent that contributes to increasing the particulate phosphorus concentration in the effluent.

In the UCT guideline the average phosphorus content of the biomass is calculated by considering each mass contributing to the TSS, as follows:

$$f_{P,TSS} = \frac{\frac{f_{P,OHO} MX_{OHO}}{f_{VT}}}{MX_{TSS}} + \frac{\frac{f_{P,XE}(MX_{E,OHO} + MX_{E,PAO})}{f_{VT}}}{MX_{TSS}} + \frac{\frac{f_{P,XI} MX_{I,i}}{f_{VT}}}{MX_{TSS}} + \frac{\frac{f_{P,PAO} MX_{PAO}}{f_{VT,PAO}}}{MX_{TSS}} + \frac{\frac{f_{P,FSS,i} MX_{FSS}}{f_{VT,PAO}}}{MX_{TSS}} \qquad (32)$$

Where f_P denotes the P fraction of a particular VSS sludge mass, MX_{FSS} is the mass of fixed suspended solids in the system and f_{VT} is the sludge VSS to TSS ratio.

The above equations are an example of how the UCT guideline and M&E guideline differ markedly in the depth and complexity of the inclusion of P removal into a steady state design for EBPR and NDEBPR. The UCT guideline provides far more information, design calculations and considerations for EBPR and ND in EBPR systems than the M&E guideline. The UCT NDEBPR system design guideline is as detailed as the ND system guideline giving equations for calculating the (i) the proportion of the influent COD flux obtained by the OHO and PAO, (ii) masses of VSS and TSS in the reactor, (iii) anaerobic, anoxic and aerobic mass fractions, (iv) balanced SRT for the UCT, JHB and 3SB systems and (v) lowest effluent ammonia, nitrate and phosphate concentrations. The UCT NDEBPR steady state model takes into account the different K denitrification rates observed in the primary and secondary anoxic reactors of NDEBPR systems (Clayton, et al., 1992) (Ekama & Wentzel , 1999) and that aerobic uptake EBPR PAO do not contribute to denitrification. The UCT NDEBPR steady state guideline is well aligned with ASM2, the kinetic equations of which exhibit the same behaviour - the K denitrification rates can be calculated from the kinetics equations in ASM2. For this reason, the two design guidelines are not compared any further in terms of the EBPR design, as there is insufficient information in the M&E guideline for a designer to perform a complete EBPR design.

3.6 Secondary Settling Tank Design

SSTs form part of the AS system and their functions are to produce a concentrated stream of AS for return to the biological reactor (thickening) and a clarified effluent (clarification). In the MLE system, the return activated sludge (RAS) is returned to the start of the biological reactor via the s-recycle.

The SST is sized to determine the surface area, A_{ST}, required to achieve adequate thickening and clarification of the activated sludge. The UCT guideline uses the idealised 1DFT corrected by a flux factor to determine the surface area of the secondary settling tanks, A_{ST}. Henze et al (2008) state that the following parameters need to be specified for the SST design:

- The sludge settleability which is specified in terms of the flux V_0 and n values in the zone settling velocity V_s, versus solids concentration, X_t, relationship. Values for V_0 and n are not readily available, however, relationships between other sludge settleability parameters that allow the calculation of V_0 and n, like sludge volume index (SVI), stirred specific volume index (SSVI) and diluted sludge volume index (DSVI) have been proposed by various authors.
- The peak flow factor, f_q, which is simply the ratio of peak wet weather flow (PWWF) to average dry weather flow (ADWF).
- The flux factor, which is a reduction factor of the maximum permissible solids loading rate (SLR) on the SST predicted by the 1DFT to take account of the non-idealities in real large diameter/depth ratio SSTs, usually between 0.8 and 0.9 (Ekama et al., 1997; Marais and Ekama, 2003).

Taking the above into account, the SST surface area, $A_{ST,}$ for the UCT guideline can be calculated with the following equation:

$$A_{ST} = \frac{1000\, f_q Q_{i,adwf}/24}{0.8\, V_0 \exp(-nX_t)} \quad (m^2) \qquad (33)$$

Where 0.8 is the flux factor and the 1000 and 24 converts $Q_{i,adwf}$ in Mℓ/d to m^3/h.

In contrast, the M&E guideline does not use any sludge settleability data to calculate the area required for the SST, but rather uses the hydraulic application rate or overflow rate, $q_{A,}$ in $m^3/(m^2.d)$. The M&E guideline provides a table of typical design information for SSTs for the AS process where it states that q_A should be selected in the range of 16 to 28 $m^3/(m^2.d)$ for average conditions and 36 to 56 $m^3/(m^2.d)$ for peak conditions for settling that follows air activated sludge. The equation given in the M&E guideline for the SST A_{ST} is as follows:

$$A_{ST} = \frac{1000\, Q_{i,adwf}}{q_A} \quad (m^2) \quad (34)$$

From Equation 33 and 34 above, it can be seen that the equations for the SST surface area are similar, and that it would appear that the following is true:

$$q_A = f_q \times 24 \times 0.8\, V_0 \exp(-nX_t) \quad (m^3/m^2.d) \quad (35)$$

So if for a particular design using the UCT guideline, the DSVI, SVI or V_0 and n values are unknown, the overflow rate can be used to determine the required A_{ST}, where this overflow rate selection includes the flux rating reduction factor of 0.8.

Figure 3-28 below shows that for the overflow rate expressed using the sludge settleability method as per the UCT guideline, i.e. f_q x 24 x 0.8 x V_0 exp(-nX_t), where V_0 and n are calculated from an assumed DSVI of 150, the overflow rate range given in the M&E guideline for average conditions (16 to 28 $m^3/(m^2.d)$) is in the solids concentration range 3,224 to 4,512 mg/ℓ and for the peak conditions (36 to 56 $m^3/(m^2.d)$) is in the solids concentration range 3,736 to 4,753 mg/. For the design solids concentration of 4,000 mg/ℓ used throughout this dissertation, the corresponding q_A value is 20.0 $m^3/(m^2.d)$ for average flow (f_q=1.0) and 49.9. $m^3/(m^2.d)$ for peak flow (f_q=2.5).

It follows that both design guidelines will yield the same result for the required SST surface area, provided that the design q_A selected from the M&E guideline correlates to the same V_0 and n values used in the UCT guideline. The results of the required SST area for selected overflow rates are given in

Figure 3-29 below. It can be seen that for the q_A of 20 $m^3/(m^2.d)$ that is required for the 4,000 mg/ℓ design solids concentration at average flow (i.e. f_q = 1.0), a total SST surface area of 750 m^2 is required and for the q_A of 49.9 $m^3/(m^2.d)$ that is required at the same design solids concentration at peak flow (i.e. f_q = 2.5), a total SST surface area of 750 m^2 is also required. Thus the SST with surface area of 750 m^2 will operate between an overflow rate of 20 $m^3/(m^2.d)$ and 49.9 $m^3/(m^2.d)$ between average and peak flow periods.

Figure 3-28 Overflow rate and solids concentration

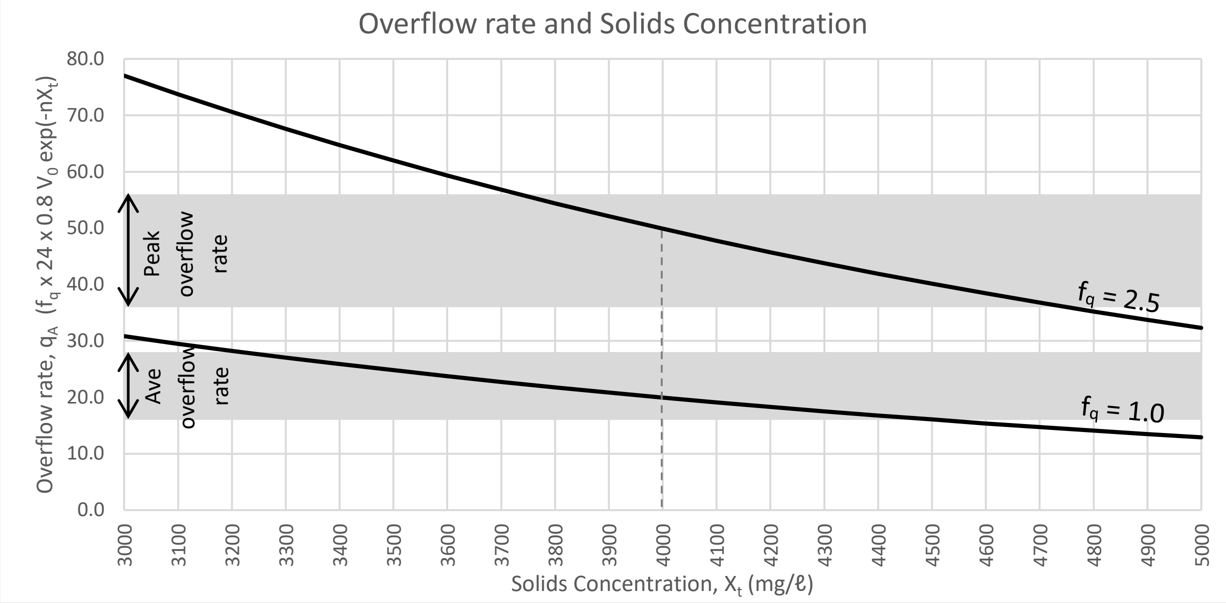
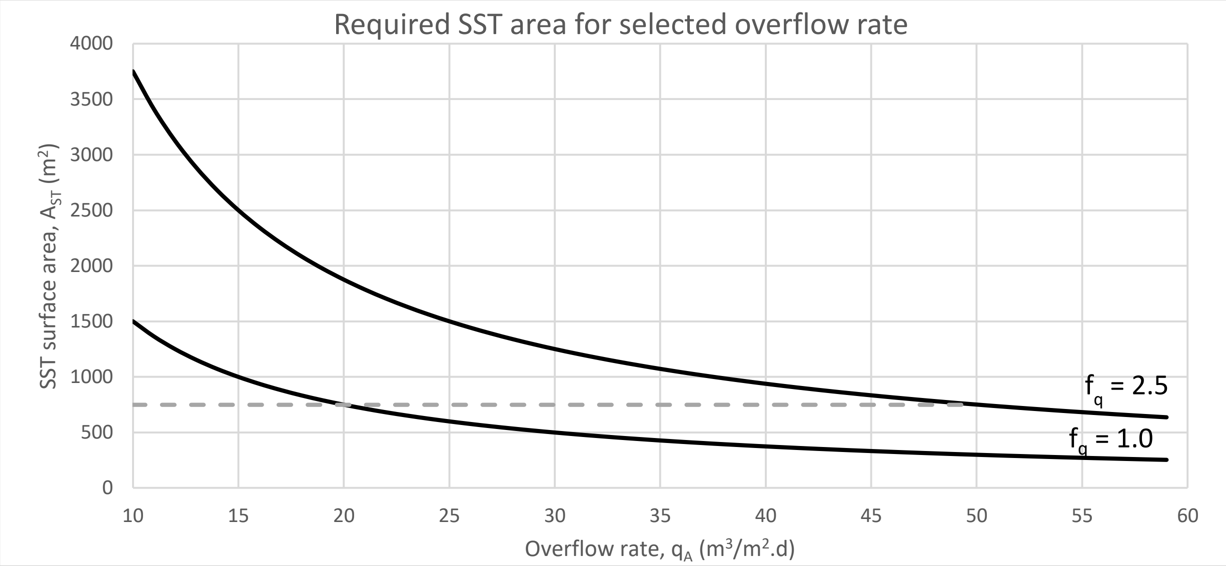


Figure 3-29 Required SST area for selected overflow rate



3.7 Results

In order to undertake a steady state design of a biological wastewater treatment works, a designer would create a steady state AS model in a software program such as Microsoft Excel using the equations and guidelines provided in the design guidelines. The tables below present results of steady state AS models set up in Microsoft Excel using both the UCT guideline and the M&E guideline.

The results given in Table 3-15, Table 3-16 and Table 3-17 show how the design of a wastewater treatment plant, with the same influent wastewater characteristics (as provided in Table 3-10 and Table 3-11), would differ if it were undertaken using either the UCT guideline steady state model or the M&E guideline steady state model, together with their specific input parameters. In the tables below, highlighted cells indicate direct inputs into the model whilst the un-highlighted cells indicate values that are calculated from the direct inputs. Where cells are left blank, that particular model does not require or calculate an equivalent parameter.

Table 3-10: Wastewater Characteristic Inputs

WASTEWATER CHARACTERISTICS	SYMBOL	UNITS	RAW WW		SETTLED WW	
			UCT	M&E	UCT	M&E
Influent flow rate	Q_i	ML/d	15	15	14.925	14.925
Influent COD concentration	S_{ti}	mgCOD/ℓ	750	750	450	450
Influent TKN concentration	N_{ti}	mgN/ℓ	60	60	51.1	51.1
Influent phosphorus concentration	P_{ti}	mgP/ℓ	14	14	11.04	11.04
Influent TSS	TSS	mg/ℓ	416.3	416.3	177.2	177.2
Influent ISS	ISS	mg/ℓ	48	48	9.6	9.6
Total Alkalinity	Alk	mg/ℓ as CaCO3	200	200	200	200
Minimum Temperature	T_{min}	degC	14	14	14	14
Maximum Temperature	T_{max}	degC	22	22	22	22

Table 3-11: Quantification of Wastewater Characteristic Inputs

QUANTIFICATION OF WASTEWATER CHARACTERISTICS	SYMBOL	UNITS	RAW WW		SETTLED WW	
			UCT	M&E	UCT	M&E
Fraction of unbiodegradable particulate COD in influent	$f_{s'up}$	-	0.1493	0.1493	0.04	0.04
Fraction of unbiodegradable soluble COD in influent	$f_{s'us}$	-	0.069	0.069	0.116	0.116
Influent readily biodegradable COD fraction	$f_{sb's}$	-	0.251	0.251	0.387	0.387
Fraction of unbiodegradable soluble organic nitrogen	$f_{N'ous}$	-	0.030		0.035	
Influent FSA fraction	$f_{n'a}$	-	0.723		0.850	
Influent TKN/COD ratio	f_{ns}	-	0.080	0.080	0.114	0.114
Unbiodegradable soluble COD concentration	S_{usi}	mgCOD/ℓ	51.8	51.8	51.8	51.8
Influent ammonia concentration	N_{ai}	mgN/ ℓ	43.4	43.4	43.4	43.4
Unbiodegradable soluble organic nitrogen	N_{ousi}	mgN/ℓ	1.8	1.8	1.8	1.8
Unbiodegradable particulate organic nitrogen	N_{oupi}	mgN/ℓ	7.6	7.6	1.2	1.2

Table 3-12: Steady State Model Input Parameters

STANDARD PARAMETERS	SYMBOL	UNITS	RAW WW		SETTLED WW	
			UCT	M&E	UCT	M&E
COD/VSS ratio of unbiodegradable particulate COD	f_{cv}	mgCOD/mgVSS	1.481	1.48	1.494	1.494
Endogenous residue fraction of volatile solids in influent	f_H	-	0.2	0.15	0.2	0.15
ISS content of OHO's	f_{iOHO}		0.15		0.15	
UPO VSS nitrogen content	f_n	mgN/mgVSS	0.1	0.12	0.1	0.12
VSS yield coefficient	Y_H	mgVSS/COD	0.45	0.45	0.45	0.45

TEMPERATURE SENSITIVE PARAMETERS	SYMBOL	UNITS	RAW WW		SETTLED WW	
			UCT	M&E	UCT	M&E
Endogenous respiration rate for biomass	b_{EH20}	/d	0.24	0.12	0.24	0.12
Theta for endogenous respiration rate for biomass	$b_{EH20}\ \theta$	-	1.029	1.04	1.029	1.04
Maximum specific growth rate of ANO's	μ_{AM20}	/d	0.45	0.9	0.45	0.9
Theta for maximum specific growth rate of ANO's	$\mu_{AM20}\ \theta$	-	1.123	1.072	1.123	1.072
ANO Half saturation coefficient	K_{n20}	/d	1	0.5	1	0.5
Theta for ANO Half saturation coefficient	$K_{n20}\ \theta$	-	1.123	1	1.123	1
Endogenous respiration rate for ANOs	b_{A20}	/d	0.04	0.17	0.04	0.17
Theta for endogenous respiration rate for ANOs	$b_{A20}\ \theta$	-	1.029	1.029	1.029	1.029
ANO yield coefficient	Y_A	/d	0.1	0.15	0.1	0.15
Theta for ANO yield coefficient	$Y_A\ \theta$	-	1	1	1	1
K_1 specific denitrification rate	K_{120}	/d	0.72		0.72	
Theta for K_1 specific denitrification rate	$K_{120}\ \theta$	-	1.2		1.2	
K_2 specific denitrification rate	K_{220}	/d	0.101		0.101	
Theta for K_2 specific denitrification rate	$K_{220}\ \theta$	-	1.08		1.08	
Half saturation for organic removal	K_s	/d		8		8
Theta for half saturation for organic removal	$K_s\ \theta$	-		1		1
maximum specific growth rate of OHOs	μ_{mT20}	/d		6		6
Theta for maximum specific growth rate of OHOs	$\mu_{mT20}\ \theta$	-		1.07		1.07
ANO for oxygen Half saturation coefficient	$K_{O,AOB20}$	/d		0.5		0.5
Theta for ANO for oxygen Half saturation coefficient	$K_{O,AOB20}\ \theta$	-		1		1

ADJUSTMENT OF TEMPERATURE SENSITIVE PARAMETERS	SYMBOL	UNITS	RAW WW		SETTLED WW	
			UCT	M&E	UCT	M&E
Temperature	T	degC	14	14	14	14
Endogenous respiration rate for biomass	b_{EHT}	/d	0.202	0.095	0.202	0.095
Maximum specific growth rate of ANO's	μ_{AMT}	/d	0.224	0.593	0.224	0.593
ANO Half saturation coefficient	K_{nT}	mgFSA/ℓ	0.499	0.500	0.499	0.500
Endogenous respiration rate for ANOs	b_{AT}	/d	0.034	0.143	0.034	0.143
ANO yield coefficient	Y_{AT}	mgVSS/mgFSA	0.100	0.150	0.100	0.150
K1 specific denitrification rate	K_{120}		0.241		0.241	
K2 specific denitrification rate	K_{220}		0.064		0.064	
Half saturation for organic removal	K_{sT}			8.000		8.000
Maximum specific growth rate of OHOs	μ_{mT}			3.998		3.998
ANO for oxygen Half saturation coefficient	$K_{O,AOBT}$			0.500		0.500

Table 3-13: Selection of Operational Parameters

SELECT OPERATIONAL PARAMETERS	SYMBOL	UNITS	RAW WW		SETTLED WW	
			UCT	M&E	UCT	M&E
Mixed Liquor Suspended Solids Concentration (MLSS)	X_t	mgTSS/ℓ	4000	4000	4000	4000
Dissolved oxygen concentration in MLSS	S_o	mg/ℓ		2.0		2.0

Table 3-14 below provides the results of the AS steady state models for the COD removal design only. The sludge age, R_s, was set to 5 days for both raw and settled wastewater for both design guideline models. The M&E guideline model results in aerobic reactor volumes that are larger than those for UCT guideline model – by 16% and 23% for the raw and settled wastewater respectively. Although the resultant reactor volumes are smaller for the UCT guideline, it calculates a higher oxygen utilisation rate, FO_c, for both the raw and settled wastewater.

Table 3-14: Steady State Model Results for COD Removal Only

COD REMOVAL DESIGN	SYMBOL	UNITS	RAW WW		SETTLED WW	
			UCT	M&E	UCT	M&E
Selected sludge age	R_s	days	5	5	5	5
Ordinary heterotrophic organisms VSS	MX_{BHv}	kgVSS	9 840	13 408	6 348	8 644
Endogenous residue VSS	MX_{Ev}	kgVSS	1 989	954	1 283	615
Unbiodegradable organics VSS	MX_{Iv}	kgVSS	5 674	-	899	-
Total Mass of VSS in the system	MX_V	kgVSS	17 504	20 036	8 530	10 158
Mass of inorganic settleable solids (ISS) in the system	MX_{IO}	kgISS	5 076	-	1 669	-
Mass of total settleable solids (TSS) in the system	MX_t	kgTSS	22 580	26 170	10 199	12 509
Aerobic reactor volume	V_a	m^3	5 645	6 542	2 550	3 127
Mass of (total) sludge produced/wasted per day	$M\Delta X_t$	kgTSS/d	4 516	5 233	2 040	2 501
Waste flow rate	Q_w	m^3/d	1 129	1 308	510	625
Carbonaceous oxygen demand	FO_c	$kg0_2/d$	5 293	4 706	3 393	3 034

Table 3-15 below provides the results of the AS steady state models for a fully aerobic nitrification design. The minimum sludge age for nitrification, R_{sm}, in both design guideline models is calculated from the safety factor, S_f, and the ANO growth rates. The S_f given in the UCT guideline is 1.25 and in the M&E guideline is 1.5. These values were used in the calculation below. The S_f and ANO growth rates are the same for both raw and settled wastewater, thus R_{sm} is the same for both the raw and settled wastewater for each guideline.

Table 3-15: Steady State Model Results for Nitrification Design Only

NITRIFICATION DESIGN	SYMBOL	UNITS	RAW WW		SETTLED WW	
			UCT	M&E	UCT	M&E
Safety Factor	S_f	-	1.25	1.5	1.25	1.5
Required effluent ammonia concentration	$N_{ae\ req}$	mg/ℓ	-	2.0	-	2.0
Nitrification rate	μ_{AOB}	g/g.d	-	0.236	-	0.236
Minimum sludge age for nitrification	R_{sm}	days	6.6	6.3	6.6	6.3
Ordinary heterotrophic organisms VSS	MX_{BHv}	kgVSS	11 133	15 665	7 196	10 098
Endogenous residue VSS	MX_{Ev}	kgVSS	2 951	1 414	1 908	912
VSS sludge production OHO nitrifiers	MX_n	kgVSS	-	258	-	248
Unbiodegradable organics VSS	MX_{Iv}	kgVSS	7 475	-	1 179	-
Total Mass of VSS in the system	MXv	kgVSS	21 559	24 282	10 282	12 151
Mass of inorganic settleable (ISS) solids in the system	MX_{IO}	kgISS	6 390	-	2 019	-
Mass of total settleable solids (TSS) in the system	MX_t	kgTSS	27 950	32 170	12 301	15 295
Aerobic reactor volume	V_a	m^3	6 987	8 043	3 075	3 824
Mass of (total) sludge produced/wasted per day	$M\Delta X_t$	kgTSS/d	4 263	3 826	1 876	1 915
Waste flow rate	Q_w	m^3/d	1 066	1 267	469	602
Carbonaceous oxygen demand	FO_c	$kg0_2/d$	5 596	4 965	3 597	3 201
Nitrification oxygen demand	FO_n	$kg0_2/d$	2 320	2 366	2 481	2 269
Total oxygen demand	FO_t	$kg0_2/d$	7 916	7 331	6 078	5 470
Nitrogen required for sludge production	N_s	mgN/ℓ	21.9	21.9	10.5	14.3
Effluent TKN concentration	N_{te}	mgN/ℓ	4.2	3.5	4.2	3.5
Effluent ammonia concentration	N_{ae}	mgN/ℓ	2.4	2.0	2.4	2.0
Effluent nitrate concentration	N_{ne}	mgN/ℓ	33.8	34.6	36.4	33.3

For this fully aerobic nitrification design, the M&E guideline model results in aerobic reactor volumes that are larger than those for UCT guideline model – by 15% and 24% for the raw and settled wastewater respectively. Although the resultant reactor volumes are smaller for the UCT guideline, it calculates a higher oxygen utilisation rate, FO_t, for both the raw and settled wastewater.

The effluent TKN and ammonia concentrations, N_{te} and N_{ae} are inputs into the M&E guideline design, while they are outputs of a UCT guideline design. The effluent nitrate concentrations, N_{ne}, are similar for both guidelines.

Results of a full nitrification-denitrification design of an AS steady state model are presented in Table 3-16 below.

Table 3-16: Steady State Model Results for Nitrification and Denitrification Design

NITIFICATION-DENITRIFICATION DESIGN	SYMBOL	UNITS	RAW WW		SETTLED WW	
			UCT	M&E	UCT	M&E
a-recycle ratio	a	-	5.0	4.87	5.0	4.61
s-recycle ratio	s	-	1.0	1.0	1.0	1.0
DO concentration in a-recycle	O_a	mgO/ℓ	2.0	-	2.0	-
DO concentration in s-recycle	O_s	mgO/ℓ	1.0	-	1.0	-
Required effluent nitrate concentration	$N_{ne\ req}$	mgN/ℓ	-	5	-	5
Denitrification potential / Nitrate load on anoxic reactor	D_{p1}	kg/d	532.7	440.4	565.5	418.5
Balanced Sludge Age for MLE system	$R_{SBalMLE}$	days	11.3	-	17.8	-
Minimum sludge age for nitrification	R_{sm}	days	-	6.3	-	6.3
Ordinary heterotrophic organisms VSS	MX_{BHv}	kgVSS	13 601	15 659	9 881	10 098
Endogenous residue VSS	MX_{Ev}	kgVSS	6 202	1 414	7 118	912
VSS sludge production OHO nitrifiers	MX_n	kgVSS	-	382	-	323
Unbiodegradable organics VSS	MX_{Iv}	kgVSS	12 789	-	3 203	-
Total Mass of VSS in the system	MXv	kgVSS	32 592	24 657	20 202	12 475
Mass of inorganic settleable solids (ISS) in the system	MX_{IO}	kgISS	10 160	-	4 035	-
Mass of total settleable solids (TSS) in the system	MX_t	kgTSS	42 752	32 307	24 237	15 384
Total biological reactor volume	V_P	m^3	10 688	8 971	6 059	4 371
Maximum anoxic sludge mass fraction available for denitrification	f_{xdm}	-	0.318	0.100	0.500	0.120
Aerobic mass fraction	f_a	-	0.682	0.900	0.500	0.880
Anoxic biological reactor volume	V_x	m^3	3 401	894	3 027	525
Aerobic biological reactor volume	V_a	m^3	7 287	8 077	3 033	3 846
Total system sludge age	R_{ST}	days	11.3	7.0	17.8	7.2
Nitrogen required for sludge production	N_s	mgN/ℓ	19.3	21.8	7.6	14.3
Effluent TKN concentration	N_{te}	mgN/ℓ	5.8	3.5	5.8	3.5
Effluent ammonia concentration	N_{ae}	mgNℓ	2.0	2.0	2.0	2.0
Effluent nitrate concentration	N_{ne}	mgN/ℓ	5.3	4.9	5.7	4.7
Carbonaceous oxygen demand	FO_c	$kg0_2/d$	6 190	4 963	4 246	3 201
Nitrification oxygen demand	FO_n	$kg0_2/d$	2 533	2 344	2 709	2 247
Oxygen recovered by denitrification	FO_d	$kg0_2/d$	1 422	1 263	1 534	1 209
Total oxygen demand	FO_t	$kg0_2/d$	7 300	6 044	5 422	4 239

The required effluent nitrate concentration is set as 5.0 mg/ℓ in the M&E guideline model, which results in an a-recycle ratio of 4.87 for the raw wastewater and 4.61 for the settled wastewater. The a-recycle for the UCT guideline model is set to 5.0 for both the raw and settled wastewater.

The UCT guideline model calculates a balanced sludge age for the MLE system, $R_{SBalMLE}$, as 11.3 days for the raw wastewater and 17.8 days for the settled wastewater. In comparison, the nitrate mass balance done on the anoxic reactor only in the M&E guideline model results in a total system sludge age of only 7.0 days for the raw wastewater and 7.2 for the settled wastewater. Here the total system sludge age is $(V_{anox}+V_{aer})/Q_W$.

Because of the longer sludge ages in the UCT guideline model, the total reactor volumes calculated in the UCT guideline model are larger than the total reactor volumes for the M&E guideline model. However, the aerobic volumes, V_a, are similar, with the M&E guideline V_a 10% larger for raw wastewater and 27% larger for settled wastewater.

The total oxygen demands for the UCT guideline models were higher than the M&E guideline models; 21% higher for the raw wastewater and 28% higher for the settled wastewater.

The results for the SST design are presented in Table 3-17 below. The required SST surface area is the same for both guidelines, as discussed in Section 3.6.

Table 3-17: Steady State Model Results for Secondary Settling Tank Design

SECONDARY SETTLING TANK DESIGN	SYMBOL	UNITS	UCT	M&E
Hydraulic application rate	q_A	$m^3/(m^2.d)$ (m/h)		20.0 (0.83)
Solids loading	Ls	$kgMLSS/(m^2.h)$		6.6
Diluted sludge volume index DSVI	DSVI	ml/g	150	
Stirred sludge volume index SSVI	SSVI	ml/g	100.5	
V_0/n	V_0/n	$kgTSS/(m^2.h)$	13.6	
n	n	$m^3/kgTSS$	0.435	
V_0	V_0	m/h	5.909	
PWWF factor	f_q	-	2.5	2.5
Surface area required	A	m^2	750	750
Number of clarifiers	N	no.	2	2
Diameter of each clarifier	D	m	21.9	21.9

4. Dynamic Modelling of Activated Sludge Processes

Once the initial wastewater treatment plant conditions are established using a steady state AS model, as discussed in Chapter 3, dynamic models can be applied to refine the design and evaluate the plant's performance under dynamic conditions.

In contrast to steady state models, which assume that many of the bioprocesses reach completion and therefore the algebraic equations used provide explicit solutions, dynamic models comprise differential equations that require numerical integration to determine a solution (Ekama, 2009). Because of this, dynamic models require a more sophisticated method of calculation that can include manually implemented code, general-purpose simulators or dedicated simulators.

UCTOLD and UCTPHO are two such activated sludge system diurnal simulation software programs written and compiled in TurboPascal 3.1 by the Water Research Group at the University of Cape Town in the late 1980s and early 1990s. UCTOLD is an earlier version of ASM1, where the product of the hydrolysis of the slowly biodegradable BPO is utilised directly by the OHO and so does not enter the bulk liquid, whereas in ASM1 this product enters the bulk liquid as BSO with the OHO utilising only BSO. The details of this difference is explained by Dold and Marais (1985). There is no material difference in the simulation results of UCTOLD and ASM1.

In the early 1990s, when the kinetics of PAOs were sufficiently well understood, EBPR was added to UCTOLD to create UCTPHO. The EBPR research that was codified into UCTPHO is detailed by Wentzel et al. (1991) and Clayton et al. (1991). Later, much of the Wentzel EBPR model was integrated into ASM1 to form ASM2 (Henze et al., 1995), thus UCTPHO and ASM2 differ in the same way as UCTOLD and ASM1 differ.

UCTOLD (and ASM1) is used only for biological N removal systems while UCTPHO (and ASM2) is used only for biological N and P removal systems, i.e. one cannot simulate a N and P removal system with UCTOLD and likewise, one cannot simulate a N removal system only with UCTPHO, because the kinetics of denitrification in UCTOLD (ASM1) and UCTPHO (ASM2) differ. The main reason for this is that the denitrification rates in UCTPHO for ND in NDEBPR systems are faster than in ND systems, which is expressed by the η_G reduction factor on the anoxic growth of heterotrophs with nitrate as electron acceptors and SBCOD as electron donor. In UCTPHO η_G is 0.60 and in UCTOLD it is 0.33. These differences are explained by Clayton et al. (1991).

The sections that follow describe the application of the UCTOLD software to the MLE system sized with the UCT and M&E steady state AS models (given in Section 3) and compare the simulation results with those estimated by the steady state models.

4.1 Description of UCTOLD

UCTOLD can be used to predict steady state and cyclic dynamic response behaviour for a range of system reactor configurations, operating conditions and waste flows and loads. The following must be noted with regard to the use and limitations of the UCTOLD computer program:

- The plant configuration input into the program is such that reactors must be single or in-series, completely mixed reactor systems, with or without inter-reactor recycles (i.e. RAS and a-recycles). The reactors may be aerated or unaerated, and the sludge age may vary from 2 to 30 days. Up to 12 reactors in series can be simulated.
- The program predicts the response of COD, VSS, nitrogen and alkalinity, and their various contributory components, and does not provide prediction for biological excess phosphorus removal.
- The default values used in the program are based on approximate averages observed when treating South African municipal wastewaters for temperatures in the range 14°C to 22°C. The default values can be changed by the user if required. In this study the default kinetic and stoichiometric values were used, except for the nitrification kinetics constants and their temperature sensitivity coefficients, for which the defined values in the UCT and M&E steady state models were used.

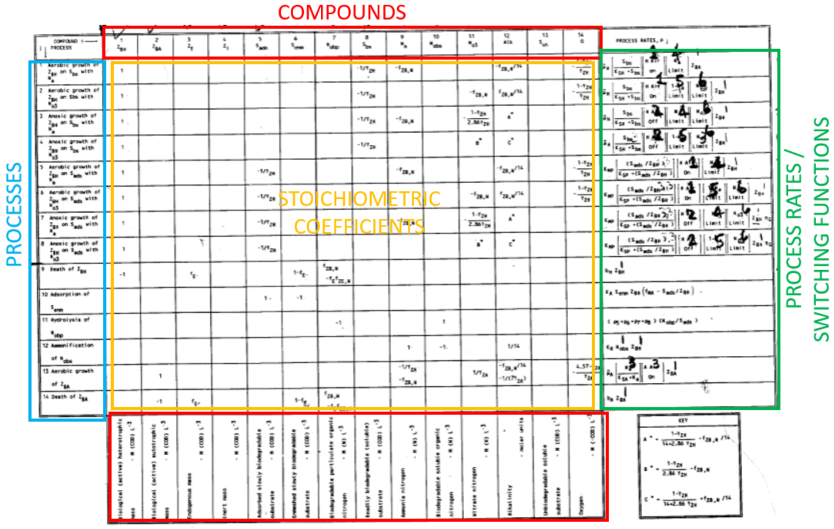
The system model that is used to obtain the response of the system under dynamic conditions consists of the process model together with the system configuration which describes the system type, hydraulic mixing regime and recycle flows.

UCTOLD process model

A process model describes the processes, their kinetics and the compounds on which they act and defines the behaviour at a single point in the system. Process models are presented in matrix format which provide a quantitative description of the inter-relationships between the processes and associated compounds.

Dold et al. (1991) provide the process model incorporated in the UCTOLD program, refer to the Gujer matrix in Figure 4-1 below. All fourteen compounds (*i*) in the model are listed by symbols across the top row of the matrix while their definitions are given across the bottom. All of the fundamental bioprocesses (*j*) which are important in single-sludge systems are listed down the extreme left column, while the rate expressions chosen to represent them are listed on the extreme right. There are fourteen processes in the UCTOLD model. The body of the matrix contains the stoichiometric coefficients, and if a particular process has no effect on a given compound the matrix cell formed by the intersection of the process row and compound column is blank (i.e. zero).

Figure 4-1 Matrix representation of UCT model (Source: Dold et al., 1991)



The process model Gujer matrix used in UCTOLD is not the same as the one used in ASM1, however, the two matrices (models) produce the same results.

UCTOLD system configuration

The system configuration describes the plant configuration and operating parameters. These parameters are determined beforehand in the steady state AS design and are input into dynamic models which are used to refine the design and evaluate the plant's performance under dynamic conditions.

In UCTOLD, the following system configuration information is required:

i) Number and volumes of reactors;

ii) Whether the reactors or aerated or unaerated, and if they are aerated, the DO concentration set point in the reactor;

iii) The recycle flows (RAS and a-recycle) configuration and flow rates;

iv) The operating system sludge age of the plant; and

v) The operating process temperature.

The sequence and number of reactors and their influent and recycle flows can be configured in UCTOLD to simulate a number of plant configurations such as MLE, 4-Stage Bardenpho, and many more.

For the purpose of this dissertation, items (i) to (v) above are determined using the steady state AS models produced from the UCT and M&E guidelines respectively.

The UCTOLD computer program then uses solution techniques and algorithms to solve the system model, i.e. the UCTOLD process matrix together with the wastewater flows, concentrations and characteristics, the system configuration, within the boundaries described above.

4.2 Influent Data

UCTOLD requires the influent wastewater characteristics, COD and TKN concentrations and the influent flowrate to be known. For analysing diurnal behaviour, the time-varying influent flow and concentration data must be input into the program. The program requires twelve sets of values, that is two-hourly values, for influent flow, COD and TKN. These are the average values for each of the twelve two-hour intervals, starting with the first interval at 00h00, and each time interval extends from the given time for the next 2 hours. This information produces the influent wastewater diurnal input pattern.

UCTOLD contains default values for both raw and settled wastewater characteristics, these default values are from standard South African municipal wastewaters, and changes can be made to these values where appropriate.

The diurnal influent data below was used to calculate the flow-weighted average values for the influent data used in the UCT and M&E guideline's steady state AS models described in Chapter 3. Now, instead of using a single average influent value for a particular wastewater constituent, the full set of diurnal influent data is input into the dynamic model to predict the behaviour of the system under these diurnal conditions.

The raw and settled diurnal influent data, as well as wastewater characteristics, used to assess the UCT and M&E guideline's steady state results (i.e. their system configurations) under dynamic conditions, are provided below.

4.2.1 Raw Wastewater

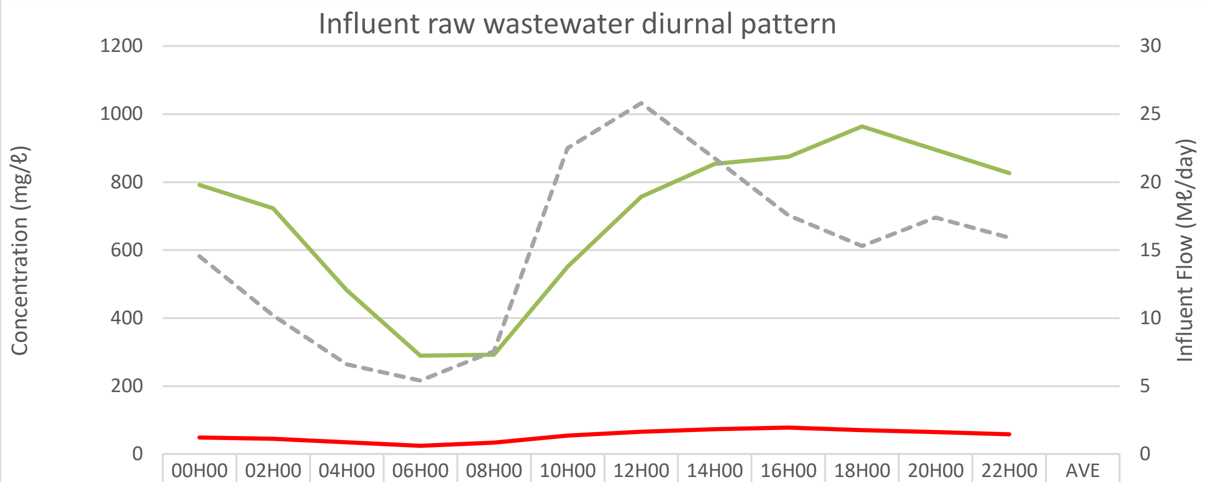
4.2.1.1 Influent Wastewater Diurnal Pattern

The influent raw wastewater diurnal data is presented in Figure 4-2 below. It can be seen that although the average influent flowrate, Q_i, which was used for the steady state AS design, is 15 Mℓ/day, the highest influent flowrate that the plant receives is 25.8 Mℓ/day (which is 72% more than the average) and the lowest influent flowrate that the plant receives is 5.4 Mℓ/day (which is only 36% of the average). Similarly, the influent COD concentrations range from 289.1 mg/ℓ to 963.7 mg/ℓ, and the flow-weighted average (used in the steady state AS design) is 750 mg/ℓ, and the influent TKN concentrations range from 24.4 mg/ℓ to 78.0 mg/ℓ, and the flow-weighted average (used in the steady state AS design) is 60 mg/ℓ.

This means that although the wastewater treatment plants designed using the steady state AS design guidelines are sized based on the average values for influent flowrate, COD and TKN and their components, the wastewater treatment plants should also be able to handle the minimum and maximum values, listed above, for these wastewater constituents.

Dynamic models allow one to analyse the effect of these varying influent flows and concentrations on a specific wastewater treatment plant configuration sized with a steady state model, in this comparison study the UCT and M&E models.

Figure 4-2 Influent raw wastewater diurnal pattern



	00H00	02H00	04H00	06H00	08H00	10H00	12H00	14H00	16H00	18H00	20H00	22H00	AVE
COD	791.6	722.8	481.9	289.1	292.6	550.7	757.2	853.6	874.2	963.7	894.9	826.1	750
TKN	48.8	45.3	34.5	24.4	33.6	54.4	66	73.6	78	70.2	64.8	58.6	60
Qi	14.550	10.200	6.600	5.400	7.575	22.500	25.800	21.750	17.550	15.300	17.400	15.900	15.000

4.2.1.2 Wastewater Characteristics

The wastewater characteristics for this specific raw wastewater are presented in Table 4-1 below. These characteristics differ from the default values given in UCTOLD for raw wastewater, and thus must be updated in the program.

Table 4-1: Raw Wastewater Characteristics

Parameter	Description	Units	Value
f_{sbs}	Readily Biodegradable COD in influent	mgCOD/mgCOD	0.251
$f_{s'us}$	Fraction of unbiodegradable soluble COD in influent	mgCOD/mgCOD	0.069
$f_{s'up}$	Fraction of unbiodegradable particulate COD in influent	mgCOD/mgCOD	0.149
$f_{n'a}$	Influent FSA fraction	mgN/mgN	0.723
$f_{nob'p}$	Fraction of particulate biodegradable organic nitrogen in influent	mgN/mgN	0.765
$f_{n'ous}$	Fraction of unbiodegradable soluble organic nitrogen in influent	mgN/mgN	0.030
$f_{s'zbh}$	Fraction of influent COD that is heterotrophs	mgCOD/mgCOD	0.000
VSS/TSS	VSS/TSS ratio	mgVSS/mgTSS	0.885
Inf Alk	Influent alkalinity	mol/m^3	10

4.2.2 Settled Wastewater

4.2.2.1 Influent Wastewater Diurnal Pattern

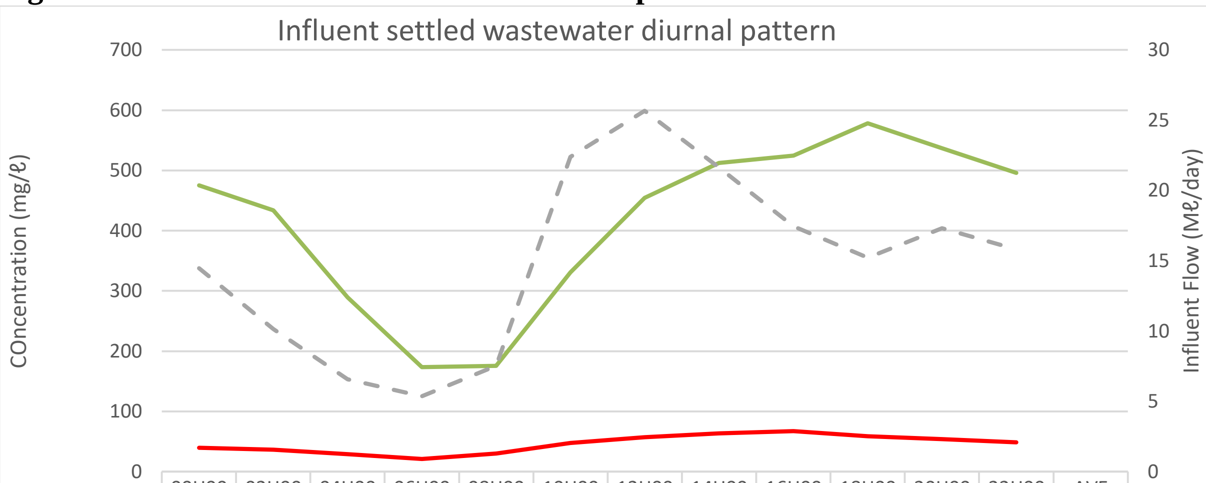
The influent settled wastewater diurnal data is presented in Figure 4-3 below. Because primary settling achieves a percentage removal of the raw wastewater constituents, the diurnal pattern for the settled wastewater is similar to the pattern of the raw wastewater, only with lower values.

Setting the primary sludge flow to 0.5% of the average influent flow, the average influent flowrate is 14.925 Mℓ/day, and as noted in the raw wastewater section, the plant receives both a maximum of 72 % more (i.e. 25.7 Mℓ/day) than the average flowrate and a minimum of 36% of the average flowrate (i.e. 5.4 Mℓ/day).

Similarly, the influent COD concentrations range from 173.5 mg/ℓ to 578.4 mg/ℓ, and the flow-weighted average (used in the steady state AS design) is 450.1 mg/ℓ, and the influent TKN concentrations range from 20.9 mg/ℓ to 67.5 mg/ℓ, and the flow-weighted average (used in the steady state AS design) is 51.1 mg/ℓ.

The UCTOLD dynamic model allows one to analyse the effect of these varying influent flows and concentrations on a specific wastewater treatment plant configuration.

Figure 4-3 Influent settled wastewater diurnal pattern



	00H00	02H00	04H00	06H00	08H00	10H00	12H00	14H00	16H00	18H00	20H00	22H00	AVE
COD	475.1	433.8	289.2	173.5	175.6	330.5	454.5	512.3	524.7	578.4	537.1	495.8	450.1
TKN	39.4	36.7	28.8	20.9	30.1	47.8	57	63.4	67.5	58.7	54.1	48.7	51.1
Qi	14.477	10.149	6.567	5.373	7.537	22.388	25.671	21.641	17.462	15.224	17.313	15.821	14.925

4.2.2.2 Wastewater Characteristics

The wastewater characteristics for this specific settled wastewater are presented in Table 4-2 below. As for the raw wastewater, these characteristics differ from the default values given in UCTOLD for settled wastewater, and thus must be updated in the program.

Table 4-2: Settled Wastewater Characteristics

Parameter	Description	Units	Value
f_{sbs}	Readily Biodegradable COD in influent	mgCOD/mgCOD	0.387
$f_{s'us}$	Fraction of unbiodegradable soluble COD in influent	mgCOD/mgCOD	0.116
$f_{s'up}$	Fraction of unbiodegradable particulate COD in influent	mgCOD/mgCOD	0.040
$f_{n'a}$	Influent FSA fraction	mgN/mgN	0.850
$f_{nob'p}$	Fraction of particulate biodegradable organic nitrogen in influent	mgN/mgN	0.633
$f_{n'ous}$	Fraction of unbiodegradable soluble organic nitrogen in influent	mgN/mgN	0.035
$f_{s'zbh}$	Fraction of influent COD that is heterotrophs	mgCOD/mgCOD	0.000
VSS/TSS	VSS/TSS ratio	mgVSS/mgTSS	0.946
Inf Alk	Influent alkalinity	mol/m^3	10

4.2.3 Kinetic Constants

UCTOLD contains default values for the kinetic constants (heterotrophs and autotrophs) and their temperature dependency constants. These default values are averages that have been obtained in simulation of the observed response of a range of system configurations over a range of operating conditions. Where necessary, changes can be made to any of these values.

Figure 4-4, Figure 4-5 and Figure 4-6 below show the default kinetic constants given in UCTOLD for a temperature of 20°C.

Figure 4-4 UCTOLD heterotroph kinetic (at 20°) constants

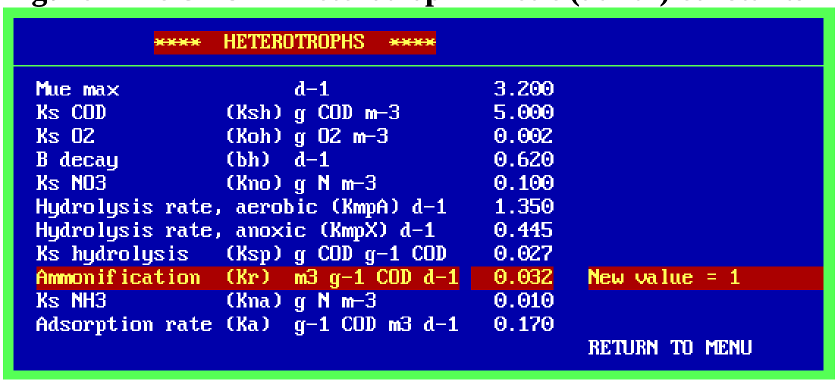


Figure 4-5 UCTOLD autotroph kinetic (at 20°) constants

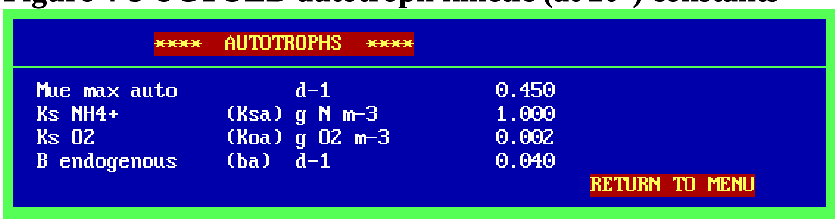
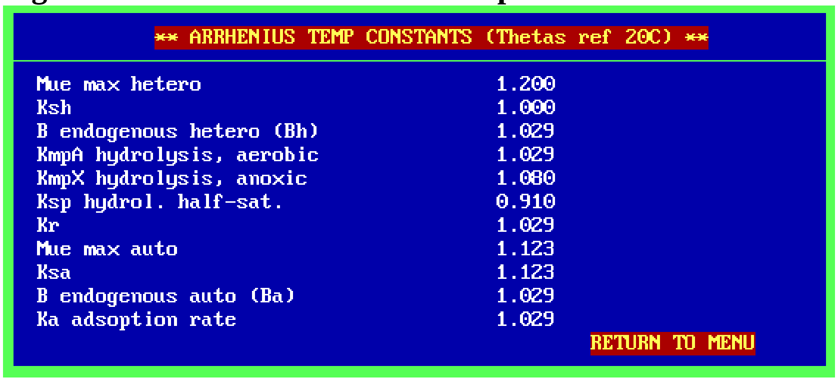


Figure 4-6 UCTOLD Arrhenius temperature constants



For the purpose of the simulations in the sections that follow, the default kinetic constant values provided in the program were not changed, with the exception of the ammonification rate, K_r and the nitrification kinetics constants and their temperature sensitivity coefficients, as follows:

- The ammonification rate, K_r, was changed from the default 0.032 to 1.0 in the dynamic simulations with UCTOLD. This is because in the original UCTOLD (and ASM1) models, organic nitrogen was thought of as a component of its own, when in fact it is not, it is a part of the biodegradable COD - as the biodegradable COD is consumed, so the nitrogen part of it gets released to the liquid as ammonia. So in the process model used in UCTOLD, the utilisation rate of the biodegradable COD and the conversion (or utilisation) of organic nitrogen is ‘disconnected’. Because this “independent” conversion of organic nitrogen to ammonia is (i) unrealistic, (ii) tends to obscure the effluent ammonia concentration dynamics, and (iii) the most important dynamics of a WWTP is the dynamics of the effluent ammonia concentration (as nitrification is the slowest process that is used to size the system, i.e. determine the SRT), this K_r value was increased to 1.0 in the dynamic simulations with UCTOLD so that the ammonification rate happens faster and more ‘connected’ to the utilisation of slowly biodegradable (SB)COD. The magnitude of the K_r rate increases the number of cycles that are undertaken in the UCTOLD dynamic simulation in order to achieve a dynamic steady state so the simulation takes a little longer.

- The nitrification kinetic constants and their temperature sensitivity coefficients were changed in UCTOLD from the default values to the defined values used in the UCT and M&E guideline steady state models (as described in Chapter 3), when simulating the UCT-sized and M&E-sized systems respectively. Figure 4-3 below provides a summary of the nitrification constants. It can be seen that the values used for the UCT guideline steady state model align with the UCTOLD default values, thus the nitrification kinetic constants were only changed in UCTOLD when simulating the M&E-sized systems.

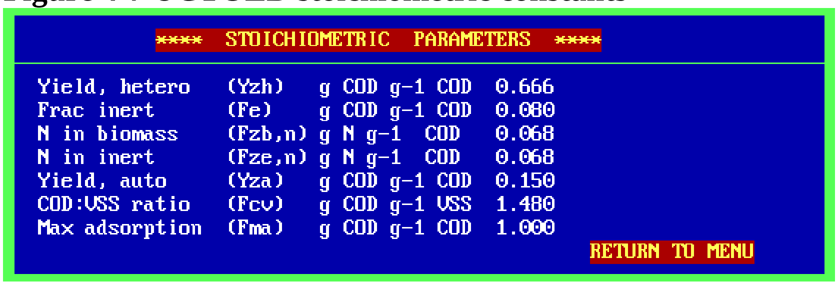
Table 4-3: Nitrification constants and temperature dependent coefficients

Nitrification constant (units)	M&E guideline		UCT guideline		UCTOLD Default Values	
	θ	Standard value at 20°C	θ	Standard value at 20°C	θ	Standard value at 20°C
Maximum specific growth rate of ANO's (/d)	1.072	0.9	1.123	0.45	1.123	0.45
ANO half saturation coefficient (mg/ℓ)	1.000	0.50	1.123	1.00	1.123	1.00
Endogenous respiration rate for ANO's (/d)	1.029	0.17	1.029	0.04	1.029	0.04
ANO for oxygen half saturation coefficient (mg/ℓ)	1.000	0.5				

4.2.4 Stoichiometric Constants

As is the case with kinetic constants, default values for the stoichiometric constants are provided in the program and are averages that have been obtained in simulation of the observed response of a range of system configurations over a range of operating conditions. Where necessary, changes can be made to any of these values. Figure 4-7 below shows the default stoichiometric constants given in UCTOLD.

Figure 4-7 UCTOLD stoichiometric constants



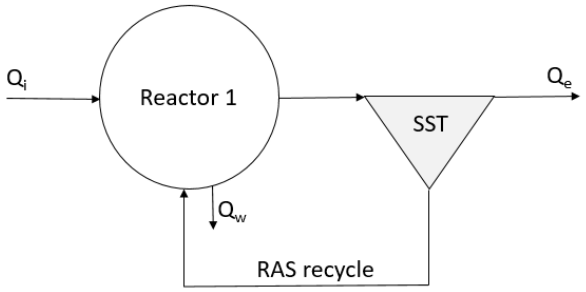
For the purpose of the simulations in the sections that follow, the default values for stoichiometric constants provided in the program were not changed.

4.3 COD Removal with UCTOLD

4.3.1 System Configuration Inputs into UCTOLD

For AS systems with COD removal only, the system is configured with a single completely mixed aerobic reactor (Reactor 1) with a downstream SST and a RAS recycle from the SST underflow to the start of aerobic reactor, as indicated in Figure 4-8 below.

Figure 4-8 System configuration with aerobic reactor only



This system configuration is input into UCTOLD using the results of the steady state design for COD removal (provided in Table 4-4 below), for the UCT and M&E guidelines respectively, for an AS system at 14°C, treating raw and settled wastewaters. These sizes were generated in Chapter 3, Section 3.7, Table 3-14:

Table 4-4: COD removal only system configurations at 14°C

Input Parameter (units)	**Raw WW**		**Settled WW**	
	UCT	**M&E**	**UCT**	**M&E**
System sludge age (days)	5	5	5	5
Aerobic reactor (*Reactor 1*) volume (Mℓ)	5.645	6.542	2.550	3.127
Influent flow rate, Q_i (Mℓ/day)	15	15	14.925	14.925
RAS recycle flow rate (Mℓ/day)	15	15	14.925	14.925

The UCT-sized and M&E-sized systems, as described above, were input into UCTOLD together with the diurnal influent data in Section 4.2, the results of the dynamic simulations for this COD removal only system are discussed below.

4.3.2 Results

The steady state AS design of a plant that has the objective of COD removal only determines the sludge age and reactor volume of the plant. A dynamic simulation will assess the effect of the diurnal influent flows and loads on the performance of the plant based on the selected sludge age and reactor volume.

Table 4-5 below provides a summary of the 24-hour-average values of the dynamic (D) results obtained in UCTOLD when simulating the respective UCT-sized and M&E-sized systems with the diurnal influent data, and compares these results with those calculated in the respective steady state (SS) guideline models in Chapter 3.

Table 4-5: 24-hour-average dynamic (D) results from UCTOLD and steady state (SS) design results for COD removal

Dynamic simulation 24-hour average (D) Steady state design (SS)	Raw WW		Settled WW	
	UCT D (SS)	M&E D (SS)	UCT D (SS)	M&E D (SS)
Effluent COD, S_{te} (mg/ℓ)	52.5 (52.5)	52.4 (52.5)	52.7 (52.0)	52.9 (52.0)
Reactor solids concentration, X_t (mg/ℓ)	4 064 (4 000)	3 552 (4 000)	4 066 (4 000)	3 416 (4 000)
Carbonaceous Oxygen Demand, FO_c (kgO_2/d)	5 150 (5 293)	4 444 (4 706)	3 327 (3 393)	2 713 (3 034)

The performance of these UCT-sized and M&E-sized systems can be assessed in more detail by further considering the dynamic results for (i) the effluent COD concentrations, (ii) the reactor VSS and TSS concentrations and (iii) the carbonaceous oxygen utilisation rates. The following is noted from the results of the dynamic simulation with UCTOLD for these output parameters:

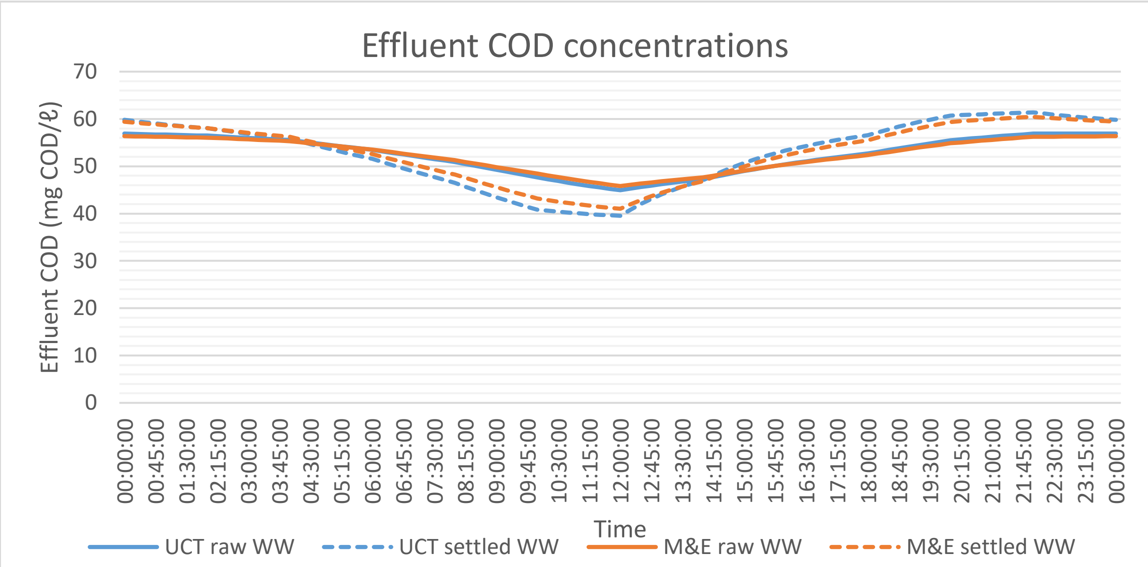
i) Effluent COD

Under normal operating conditions for AS systems, and where the sludge age is sufficient to achieve biological nutrient removal (i.e. in excess of 5 days), the nature of the influent organics in municipal wastewaters is such that the COD concentration in the effluent is inconsequential in the system design. This is because the soluble readily biodegradable organics are completely utilised in a very short period of time (i.e. less than 2 hours) and, if operating correctly, the particulate organics are enmeshed in the sludge mass and settle out in the SST's. Thus the effluent COD that exits via the effluent stream of a wastewater treatment plant comprises virtually wholly the soluble unbiodegradable COD from the influent plus the COD of the sludge particles which escape with the effluent due to defective operation of the SST. Assuming perfect operation of the SST (as is the case with UCTOLD) the effluent COD is simply:

$$S_{te} = f_{s'us} S_{ti} \ (mg/\ell) \qquad (36)$$

Figure 4-9 below shows the diurnal effluent COD concentrations as output from UCTOLD, i.e. the unbiodegradable soluble COD concentration, S_{us}, that exits the aerobic reactor. It can be seen that the effluent COD concentrations are very similar for the UCT and M&E-sized systems for raw and settled wastewater respectively, even though the reactor volumes provided for the UCT guideline system differs to the reactor volumes provided for the M&E guideline systems (i.e. the UCT volumes are smaller). This is because, as noted above, the effluent COD concentration has a negligible influence on biological reactor design parameters, such as the reactor volume.

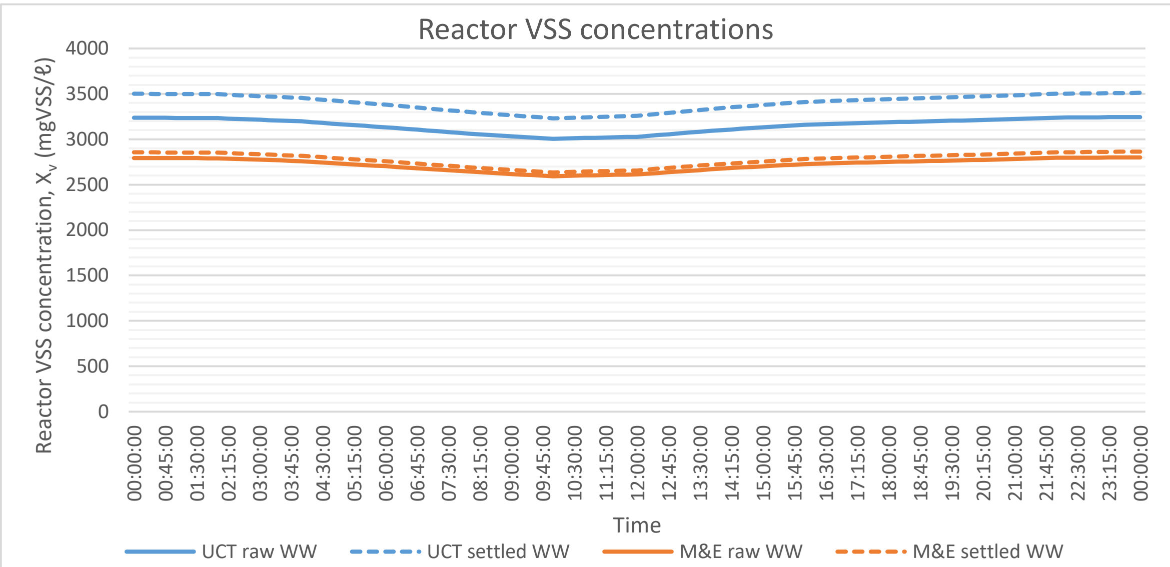
Figure 4-9 Diurnal effluent COD concentration



ii) Reactor VSS and TSS Concentrations

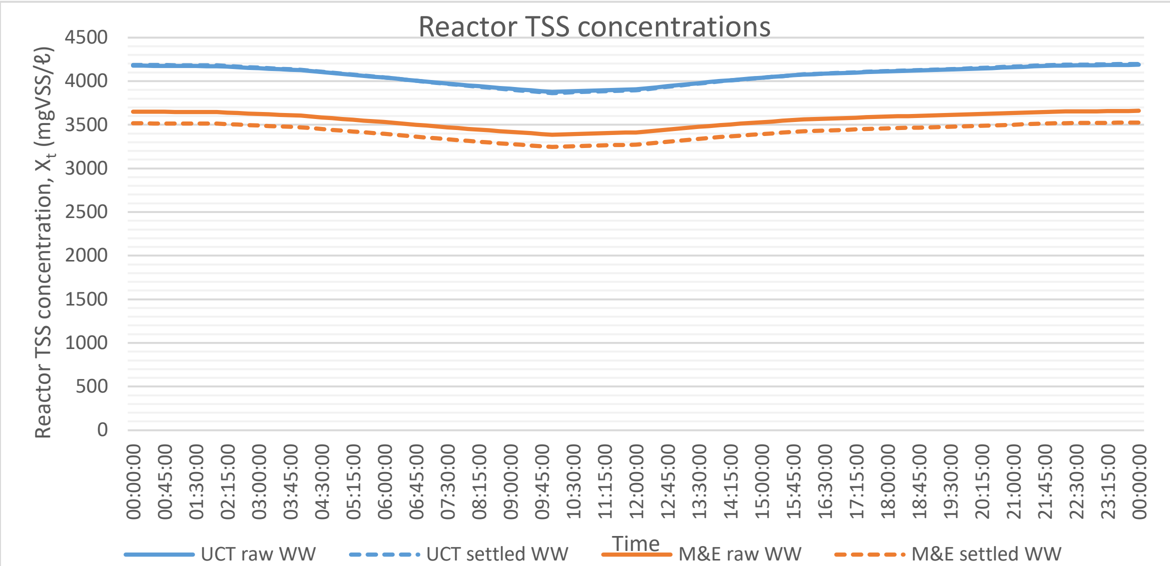
One of the output parameters of a dynamic simulation with UCTOLD is the diurnal reactor VSS concentration, X_v. The VSS mass in the reactor consists of OHO VSS, endogenous residue VSS, unbiodegradable organics VSS and volatile settleable solids VSS. The diurnal reactor VSS concentrations, as output from UCTOLD, are given in Figure 4-10 below.

Figure 4-10 Reactor VSS Concentrations



The reactor TSS concentration (or MLSS concentration) X_t, is an operational parameter selected by the designer in the steady state design, it is the MLSS concentration at which the reactor is designed to operate at and is used to determine the volume of reactor required. The X_t concentrations given in Figure 4-11 below are calculated from the VSS concentrations as output from UCTOLD (Figure 4-10) and the VSS/TSS ratios as calculated in the respective steady state designs, from the VSS and TSS masses in the reactor, i.e. MX_v/MX_t, as UCTOLD does not calculate the ISS itself.

Figure 4-11 Reactor TSS Concentrations (calculated from VSS)



A design reactor MLSS concentration of 4,000 mg/ℓ and sludge age of 5 days were selected for the steady state designs used to size both the UCT guideline and M&E guideline steady state systems. From the dynamic simulations on the UCT-sized systems and the M&E-sized systems for raw and settled wastewater, it is seen in Table 4-6 below that the 24-hour average X_t concentrations for the UCT-sized systems are close to the design reactor MLSS of 4,000 mg/ℓ while the average X_t concentrations for the M&E-sized systems are significantly lower.

Table 4-6: Reactor TSS concentrations comparison

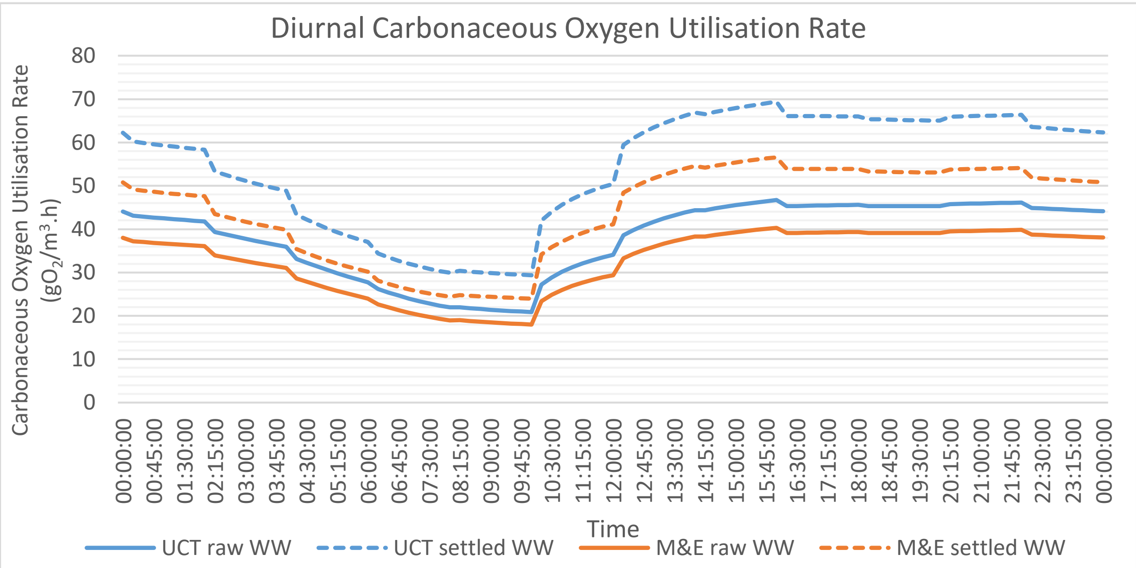
Parameter (units)	Raw WW		Settled WW	
	UCT	M&E	UCT	M&E
Selected steady state design MLSS concentration (mgTSS/ℓ)	4 000	4 000	4 000	4 000
Selected steady state design sludge age (days)	5	5	5	5
Steady state design aerobic reactor volume (Mℓ)	5.645	6.542	2.550	3.127
Dynamic simulation average TSS concentration, X_t (mgTSS/ℓ)	4 064	3 552	4 066	3 416

UCTOLD assumes hydraulic control of the sludge age which means that irrespective of the flow through the plant, a fixed fraction ($^1/_{R_S}$) of the volume of the reactor is wasted every day and thus the sludge age is fixed (Ekama, 2010). If the COD mass load increases, the sludge concentration will increase automatically to maintain the same sludge age. Because of this hydraulic control of sludge age, for the same influent wastewater, sludge age and design reactor MLSS, the 24-hour average dynamic X_t concentrations for the UCT-sized and M&E-sized systems should be the same, and in the range of the design reactor MLSS concentration of 4,000 mg/ℓ. The lower 24-hour average X_t concentrations for the dynamic simulations with UCTOLD for the M&E-sized systems is because the M&E guideline calculates larger reactor volumes than the UCT guideline. As discussed in Section 3.2.4, this is mostly because of the different kinetic, stoichiometric and temperature sensitivity constants assigned in the M&E guideline. When the kinetic, stoichiometric and temperature sensitivity constants in the M&E guideline are assigned the same values as the UCT guideline, virtually identical results will be obtained because virtually identical aerobic reactor volumes will be calculated.

iii) Carbonaceous Oxygen Demand

The diurnal carbonaceous oxygen utilisation rate (OUR_c), i.e. the amount of oxygen utilised by the OHO's for biodegradable organic material degradation in the aerobic reactor, was simulated in UCTOLD. Figure 4-12 below shows the results for the 24 hour period at 15 minute intervals.

Figure 4-12 Diurnal oxygen utilisation rate



It can be seen that the M&E guideline systems (for both raw and settled wastewater) have lower OUR_c's than the UCT guideline systems.

The results shown in the above figure are presented as output from UCTOLD - as a rate that is measured in $gO_2/m^3.h$, i.e. the amount of oxygen utilised per hour, per m^3 of volume of reactor. Table 4-7 below shows the results for the flux of oxygen utilised (per day) as calculated in the respective steady state AS (UCT and M&E guideline) models for both raw and settled wastewater, versus the average, minimum and maximum diurnal fluxes, calculated from the dynamic oxygen utilisation rates in Figure 4-12 above and the respective aerobic reactor volumes.

Table 4-7: Flux of oxygen per day system results for COD removal

FO_c (kgO_2/day)	Raw WW				Settled WW			
	UCT		M&E		UCT		M&E	
Steady state results:	5 293		4 696		3 393		3 034	
Dynamic results:	24-hr ave. FO_t	% of steady state	24-hr ave. FO_t	% of steady state	24-hr ave. FO_t	% of steady state	24-hr ave. FO_t	% of steady state
Minimum diurnal	2 826	*53.4%*	2 439	*46.2%*	1 799	*53.0%*	1 467	*43.0%*
Maximum diurnal	6 331	*119.6%*	5 461	*103.4%*	4 251	*125.3%*	3 466	*101.5%*
Average diurnal	5 150	*97.3%*	4 444	*84.2%*	3 327	*98.1%*	2 713	*79.5%*

The 24-hour average FO_c values from the dynamic simulation for the UCT-sized systems are close (97.5% for both raw and settled wastewater) to their respective calculated steady state FO_c values. The 24-hour average FO_c values from the dynamic simulation for the M&E-sized systems, however, are significantly less than the respective calculated steady state FO_c values (84.2% for raw and 79.5% for settled wastewater).

The 24-hour maximum FO_c from the dynamic simulation can be used to size the aeration equipment (so that it can handle the peak OUR_c) that will be required for the respective systems. The 24-hour maximum FO_c values from the UCT-sized systems require an aeration equipment peak factor on the steady state FO_c of 19.6% and 25.3% for raw and settled wastewater respectively, while the M&E-sized systems only require an aeration equipment peak factor 3.4% and 1.5% for raw and settled wastewater respectively. Generally, a peak factor of 20% is applied to the steady state FO_c value to account for the maximum aeration requirements under dynamic conditions.

From the above it would appear that the FO_c values calculated in the UCT guideline steady state design are closer to those seen under dynamic conditions and that the FO_c values calculated in the M&E guideline steady state design are too high and aeration equipment sized using the peak of 20% on these steady state values would be over-sized.

It is apparent from the summaries above that under dynamic conditions the UCT-sized systems perform as expected by their steady state designs - at virtually the same design reactor MLSS and with the same carbonaceous oxygen requirements – and this means that the UCT guideline is closely correlated with ASM1. The results of the M&E-sized systems deviate from those of ASM1 - the 24-hour average dynamic reactor X_t concentration is below the design reactor MLSS concentration used in the steady state design and the steady state FO_c is higher than the FO_c simulated under dynamic conditions.

The effect of the lower X_t concentrations for the M&E-sized systems on the SST operation is discussed in Section 4.6.

4.4 Nitrification for Fully Aerobic Systems with UCTOLD

4.4.1 System Configuration inputs into UCTOLD

As discussed in Section 3.3.1, the UCT guideline and M&E guideline define the minimum SRT for nitrification differently – the UCT guideline defines the system SRT based on the mass of sludge in both the anoxic and aerobic reactors, while the M&E guideline defines an aerobic SRT only because of the assumption that nitrifiers die only in the aerobic reactor (as opposed to the UCT guideline which assumes that they die in the entire reactor, i.e. anoxic and aerobic). The UCT guideline approach is more aligned with ASM1.

UCTOLD assumes hydraulic control of system sludge age (Ekama, 2010) and the wasteflow rate (Q_w) from the aerobic reactor is calculated from the entered system SRT as $Q_w = (V_{anx}+V_{aer})/SRT$. If there is no anoxic reactor for fully aerobic conditions, as is the case in this simulation, then $V_{anx} = 0$. Because the UCT guideline is based on a system SRT, this SRT is simply entered into UCTOLD. The M&E guideline is different because it only takes into account the aerobic SRT and thus only has an aerobic reactor (Reactor 1) with a downstream SST and a RAS recycle from the SST underflow to the start of aerobic reactor, as indicated in Figure 4-8 in the COD Removal section. Because for fully aerobic conditions $SRT_{sys} = SRT_{aer}$, the aerobic SRT is entered into UCTOLD.

This system configuration data, provided in Table 4-8 below, is based on the steady state designs for COD removal and nitrification for fully aerobic systems, for both the UCT and M&E guidelines, for an AS system at 14°C, treating both raw and settled wastewaters. These sizes were generated in the steady state design in Chapter 3, Section 3.7, Table 3-15.

Table 4-8: Nitrification system configurations at 14°C

Input Parameter (units)	Raw WW		Settled WW	
	UCT	M&E	UCT	M&E
System sludge age* (days)	6.6	6.3	6.6	6.3
Aerobic reactor volume (Mℓ)	6.987	8.043	3.075	3.824
Influent flow rate (Mℓ/day)	15	15	14.925	14.925
RAS recycle flow rate (Mℓ/day)	15	15	14.925	14.925

** for this simulation (i.e. fully aerobic system), the system sludge age input into UCTOLD is the aerobic sludge age (SRT_{aer})*

The UCT-sized and M&E-sized systems, as described above, were input into UCTOLD together with the diurnal influent data in Section 4.2, the results of the dynamic simulations for this COD removal and aerobic nitrification system are discussed below.

4.4.2 Results

The steady state AS design of a plant that undergoes nitrification involves the determination of the minimum sludge age for nitrification and the associated reactor volumes. A dynamic simulation will assess the effect of the diurnal influent flows and loads on the performance of the plant based on the selected sludge age and reactor volumes (which for this case is only the aerobic reactor).

The dynamic simulation with UCTOLD can be assessed by comparing the 24-hour average for the dynamic (D) results for the dissolved effluent concentrations and reactor solids concentrations with those calculated in the respective steady state (SS) guideline models in Chapter 3. Table 4-9 below provides a comparison of these values.

Table 4-9: 24-hour-average dynamic (D) results from UCTOLD and steady state (SS) design results for fully aerobic nitrification

Dynamic simulation 24-hour average (D) Steady state design (SS)	**Raw WW**		**Settled WW**	
	UCT **D (SS)**	**M&E** **D (SS)**	**UCT** **D (SS)**	**M&E** **D (SS)**
Effluent TKN, N_{te} (mg/ℓ)	6.9 (4.2)	2.5 (3.5)	10.2 (4.2)	2.6 (3.5)
Effluent Ammonia, N_{ae} (mg/ℓ)	5.2 (2.4)	0.9 (2.0)	8.5 (2.4)	1.0 (2.0)
Effluent Nitrate, N_{ne} (mg/ℓ)	29.8 (33.8)	33.8 (34.6)	28.7 (36.4)	36.1 (33.3)
Reactor solids concentration, X_t (mg/ℓ)	4 153 (4 000)	3 535 (4 000)	4 222 (4 000)	3 427 (4 000)
Carbonaceous Oxygen Demand, FO_c (kgO_2/d)	5 518(5 596)	5 453 (4 965)	3 565 (3 597)	3 521 (3 201)
Nitrification Oxygen Demand, FO_c (kgO_2/d)	1 964 (2 320)	2 340 (2 366)	1 841 (2 481)	2 469 (2 269)

It is seen in the above table that for the UCT-sized systems, the nitrification efficiency of the AS system is decreased under dynamic conditions, compared with that under steady state conditions. This is due to Monod kinetics which is applied to the nitrifier growth behaviour under dynamic conditions - during the high flow (and load) periods, even though the nitrifiers are operating at their maximum rate, it is not possible to oxidize all of the ammonia available, and an increased ammonia concentration is discharged in the effluent (Henze, et al., 2008).

When looking at the 24-hour average results of the dynamic simulation for the dissolved effluent concentrations (N_{te}, N_{ae}, N_{ne}) it would appear that the M&E-sized systems perform better than the UCT-sized systems. Because the M&E guideline uses a faster μ_{AM20} (0.9 g/g.d versus 0.45 g/g.d for the UCT guideline), in dynamic simulations nitrification is "complete" at a shorter SRT. The M&E guideline also uses a safety factor of 1.5, and thus the system SRT is 50% longer than the minimum SRT for nitrification, this explains the lower effluent ammonia values for the M&E-sized systems. However, it is a concern that the reactor solids concentrations (X_t)

of the M&E-sized systems are much lower than the design reactor MLSS concentration of 4000 mg/ℓ.

The performance of these UCT-sized and M&E-sized systems can be assessed in more detail by further considering the dynamic results for (i) the nitrogen removal capabilities of the plant, (ii) the reactor VSS and TSS concentrations and (iii) the oxygen utilisation, which now includes an additional oxygen requirement for nitrification. The following is noted from the results of the dynamic simulation with UCTOLD for these output parameters:

i) Nitrogen Removal

From the input diurnal influent data it is noted that the plant receives the minimum influent TKN, N_{ti}, (24.4 mg/ℓ raw and 20.9 mg/ℓ settled) at time 06:00 and the maximum N_{ti} (78 mg/ℓ raw and 67.5 mg/ℓ settled) at time 16:00. This is apparent in Figure 4-13 and Figure 4-14 below, where, in general, the effluent TKN (N_{te}) and ammonia (N_{ae}) values are lowest in the period after 06:00 and highest in the period after 16:00:

Figure 4-13 Diurnal effluent TKN concentrations

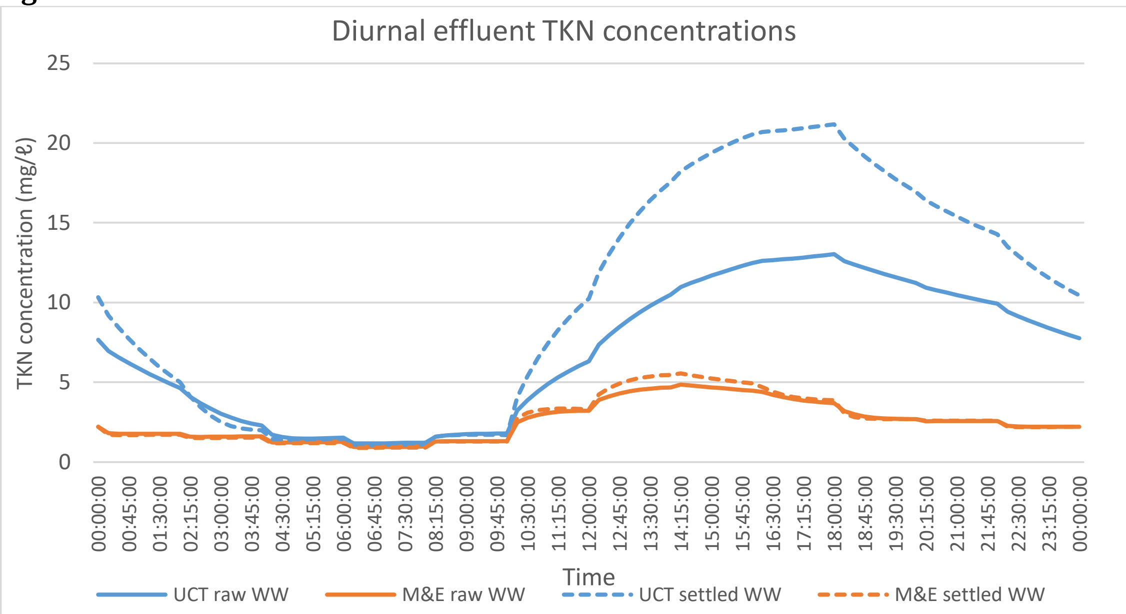
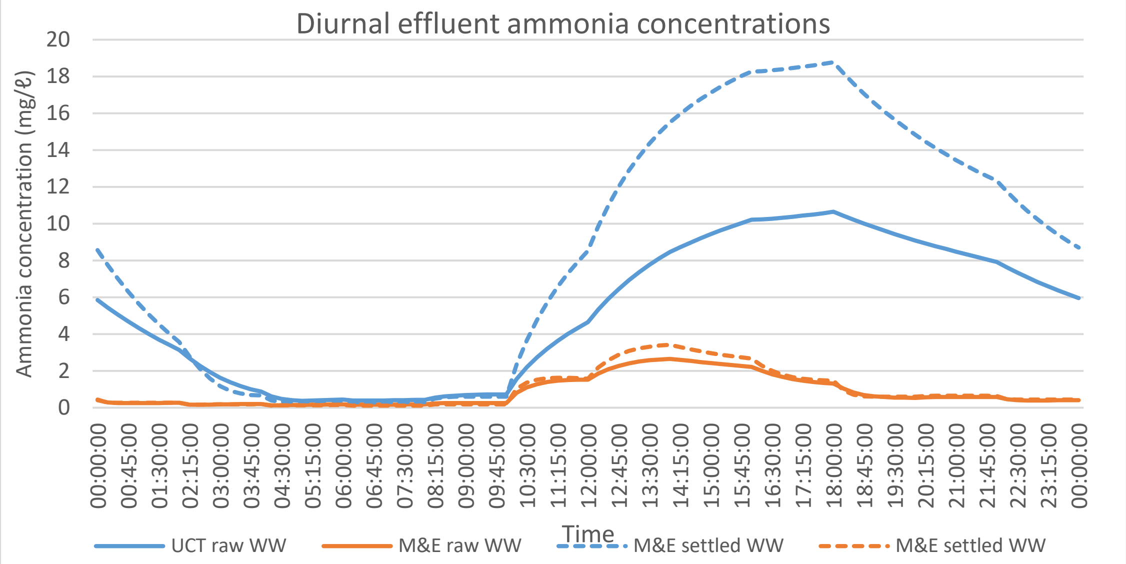


Figure 4-14 Diurnal effluent ammonia concentrations



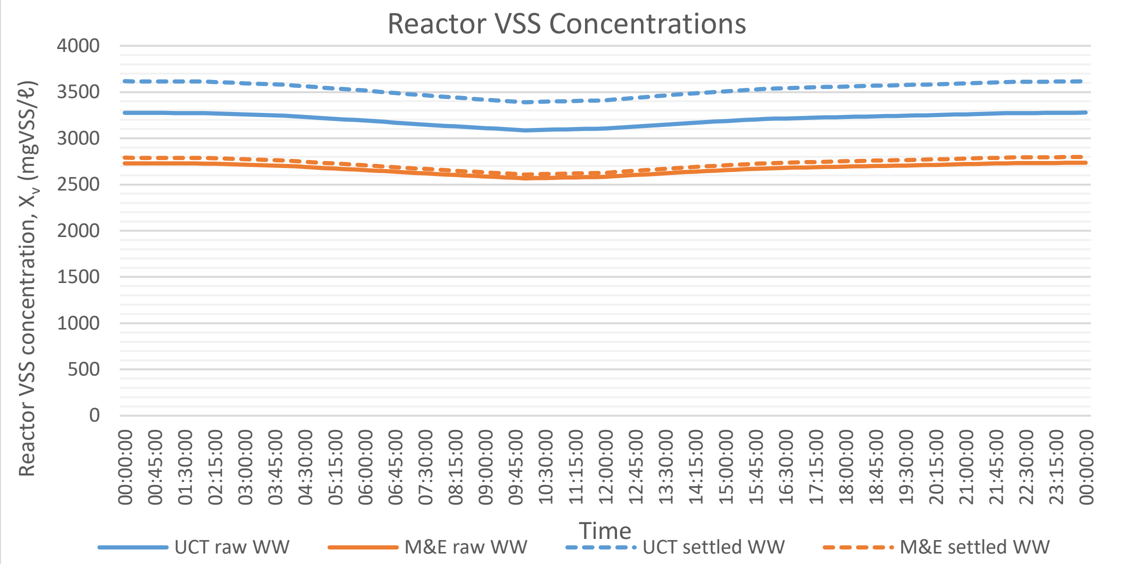
For the period around 06:00, when the plant receives the lowest influent TKN load, the N_{te} and N_{ae} values are very similar for the UCT-sized and M&E-sized systems, for both raw and settled wastewater. However, after this period when the influent TKN load is increasing, there is a noticeable difference between the N_{te} and N_{ae} concentrations for the two guideline's systems for both the raw and settled wastewater. The UCT-sized systems' maximum dynamic N_{te} concentrations are 13.0 mg/ℓ and 21.2 mg/ℓ for the raw and settled wastewater, and the M&E-sized systems' maximum dynamic N_{te} concentrations are 4.8 mg/ℓ and 5.5 mg/ℓ for the raw and settled wastewater. The UCT-sized systems' maximum dynamic N_{ae} concentrations are 10.6 mg/ℓ and 18.8 mg/ℓ for the raw and settled wastewater, and the M&E-sized systems' maximum dynamic N_{ae} concentrations are 2.6 mg/ℓ and 3.4 mg/ℓ for the raw and settled wastewater.

As discussed previously, although it appears from Figure 4-13 and Figure 4-14 that the M&E-sized systems perform better than the UCT-sized systems, this is not the case. The M&E guideline has higher nitrification kinetic values and a higher nitrification safety factor, which makes nitrification "complete" faster than the UCT-sized systems, but also makes the sludge age longer and thus the aerobic reactor volume larger. The effect of this on the reactor is seen in (ii) below where the M&E-sized systems reactors have significantly lower X_t values compared to the design reactor MLSS concentration.

ii) Reactor VSS and TSS Concentrations

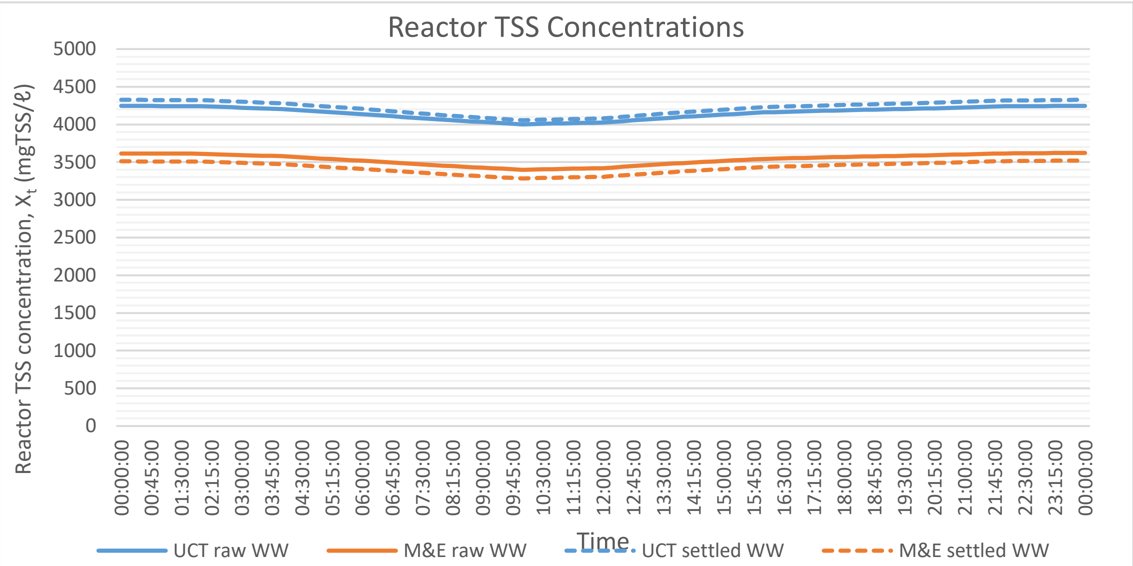
One of the output parameters of a dynamic simulation with UCTOLD is the diurnal reactor VSS concentration, X_v, and the VSS mass in the reactor consists of OHO VSS, endogenous residue VSS, unbiodegradable organics VSS and volatile settleable solids VSS. The diurnal reactor VSS concentrations, as output from UCTOLD, are given in Figure 4-15 below.

Figure 4-15 Reactor VSS concentrations



The reactor TSS concentration (or MLSS concentration) X_t, is an operational parameter selected by the designer in the steady state design, it is the MLSS concentration at which the reactor is designed to operate at and in both guidelines it is used to determine the volume of reactor required. The X_t concentrations given in Figure 4-16 below are calculated from the VSS concentrations as output from UCTOLD (Figure 4-15) and the VSS/TSS ratios as calculated in the respective steady state designs, from the VSS and TSS masses in the reactor, i.e. MX_v/MX_t, as UCTOLD does not calculate the ISS itself.

Figure 4-16 Reactor TSS Concentrations (calculated from VSS)



A design MLSS concentration of 4,000 mg/ℓ was selected for the steady state design to size the UCT and M&E guideline systems. The minimum sludge age for nitrification was calculated as stipulated for each guideline (as in Section 3.3.1). From the dynamic simulations on the UCT-sized systems and the M&E-sized systems for raw and settled wastewater, it is seen in Table 4-10 below that the 24-hour average X_t concentrations for the UCT-sized systems are close to the design reactor MLSS of 4,000 mg/ℓ while the 24-hour average X_t concentrations for the M&E-sized systems are significantly lower.

Table 4-10: Fully aerobic nitrification: Reactor TSS concentrations comparison

Parameter (units)	Raw WW		Settled WW	
	UCT	**M&E**	**UCT**	**M&E**
Selected steady state design MLSS concentration (mgTSS/ℓ)	4 000	4 000	4 000	4 000
Selected steady state design sludge age (days)	6.6	6.3	6.6	6.3
Steady state design aerobic reactor volume (Mℓ)	6.987	8.043	3.075	3.824
Dynamic simulation average TSS concentration, X_t (mgTSS/ℓ)	4 153	3 535	4 221	3 427

Again, because UCTOLD uses hydraulic control of sludge age (which is particularly important for nitrification) for the same influent wastewater, sludge age and design reactor MLSS, the 24-hour average dynamic X_t concentrations for the UCT-sized and M&E-sized systems should be the same, and in the range of the design reactor MLSS concentration of 4,000 mg/ℓ. The lower 24-hour average X_t concentrations for the dynamic simulations with UCTOLD for the M&E-sized systems thus indicates that their aerobic reactor volumes are over-sized.

iii) Oxygen Utilisation Rate

For a nitrification design, the total OUR_t, measured in $gO_2/m^3.h$, includes the carbonaceous OUR, OUR_c, as well as the nitrification OUR, OUR_n. Figure 4-17 and Figure 4-18 below presents the UCTOLD results for OUR for the 24 hour period at 15 minute intervals for the influent raw and settled wastewater data respectively.

Figure 4-17 Diurnal oxygen utilisation rate for raw wastewater

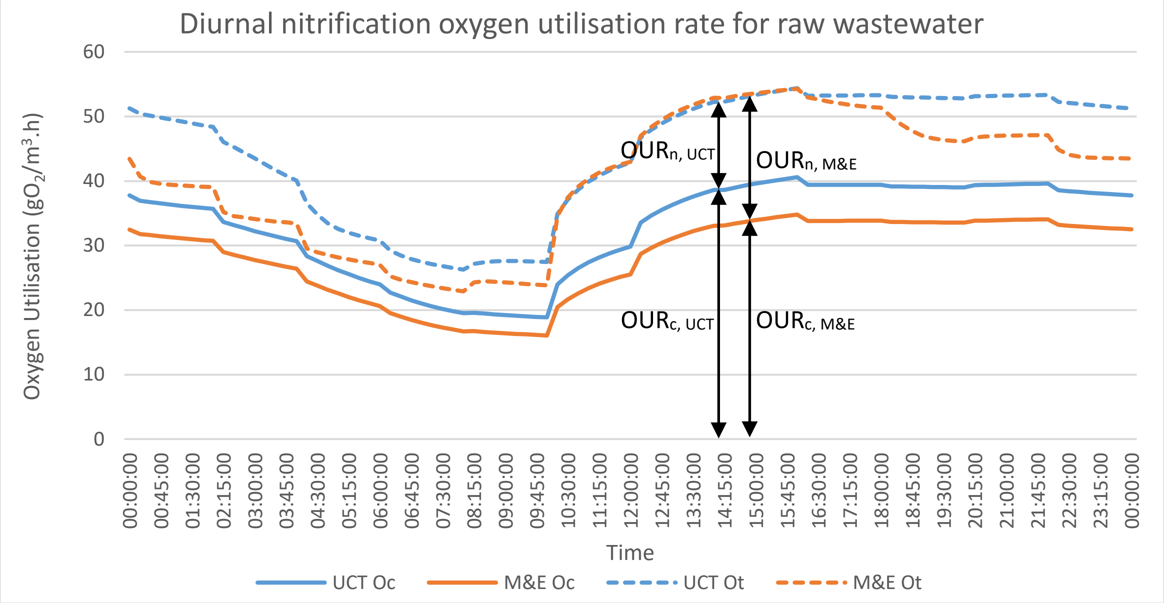
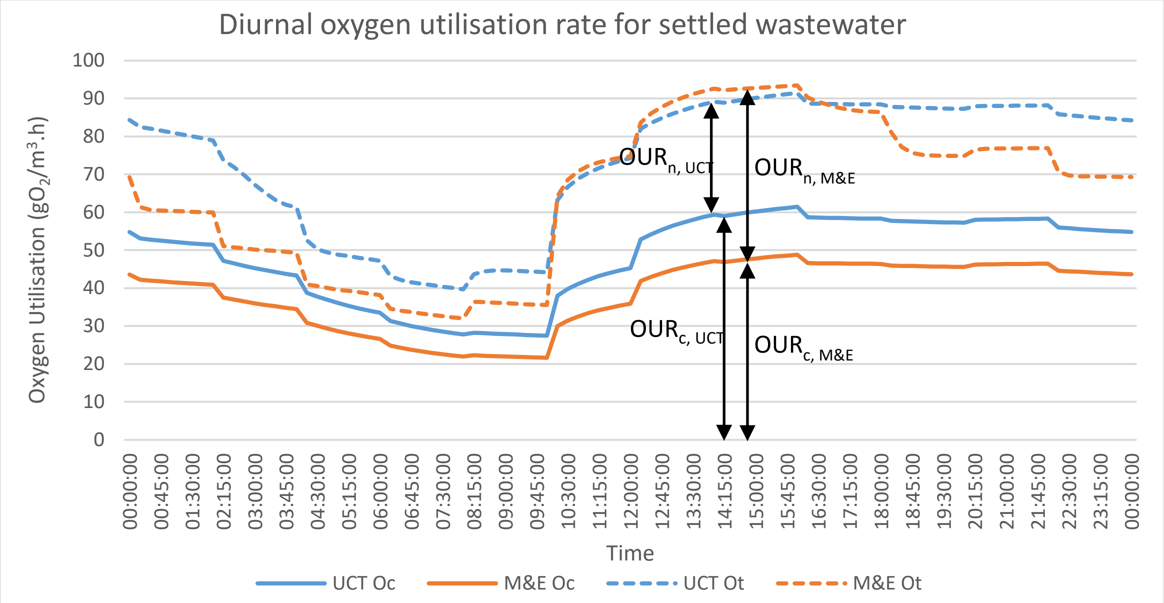


Figure 4-18 Diurnal oxygen utilisation rate for settled wastewater



The results shown in the above figures are presented as output from UCTOLD - as a rate that is measured in $gO_2/m^3.h$, i.e. the amount of oxygen utilised per hour, per m^3 of volume of reactor. Table 4-11 below shows the results for the total flux of oxygen utilised (per day), FO_t, as calculated in the respective steady state AS (UCT and M&E guideline) models for both raw and settled wastewater, versus the average, minimum and maximum diurnal fluxes, calculated from the dynamic total oxygen utilisation rates (OUR_c plus OUR_n) in Figure 4-17 and Figure 4-18 above and the respective aerobic reactor volumes.

Table 4-11: Flux of oxygen per day system results nitrification

FO_t (kgO_2/day)	Raw WW				Settled WW			
	UCT		M&E		UCT		M&E	
Steady state results	7 916		7 331		6 078		5 470	
Dynamic results:	24-hr ave. FO_t	% of steady state	24-hr ave. FO_t	% of steady state	24-hr ave. FO_t	% of steady state	24-hr ave. FO_t	% of steady state
Minimum diurnal	4 406	*55.7%*	4 416	*60.2%*	2 929	*48.2%*	2 937	*53.7%*
Maximum diurnal	9 122	*115.2%*	10 479	*142.9%*	6 748	*111.0%*	8 577	*156.8%*
Average diurnal	7 482	*94.5%*	7 793	*106.3%*	5 406	*88.9%*	5 990	*109.5%*

From the table above it is noted that the average diurnal FO_t values from the dynamic simulation for the UCT-sized systems are close (94.5% for raw and 88.9% for settled wastewater) to their respective calculated steady state FO_t values. The average diurnal FO_t values from the dynamic simulation for the M&E-sized system configurations, however, are significantly more than the respective calculated steady state FO_t values (106.3% for raw and 116.3% for settled wastewater).

The maximum diurnal FO_t value from the dynamic simulation can be used to size the aeration equipment (so that it can handle the peak OUR_t) that will be required for the respective systems. The maximum diurnal FO_t values from the UCT-sized systems require an aeration equipment peak factor of 15.2% and 11% for raw and settled wastewater respectively, while the M&E-sized systems require an aeration equipment peak factor 42.9% and 56.8% for raw and settled wastewater respectively. Generally, a peak factor of 20% is applied to the steady state FO_t value to account for the maximum aeration requirements under dynamic conditions.

The FO_t values calculated in the UCT guideline are more aligned with those seen under dynamic conditions. The FO_t values calculated in the M&E guideline steady state design are lower than those seen under dynamic conditions and thus aeration equipment sized using the M&E guideline steady state results would be under-sized.

The dynamic simulations of the fully aerobic nitrifying reactors sized with the M&E and UCT guidelines with ASM1 show the same differences as observed with the organics removal simulations – that the UCT guideline results are closely correlated with the ASM1 results but the M&E results deviate from those of ASM1. The main difference for fully aerobic nitrifications between the two guidelines is this the sizing of the fully aerobic reactors, where the minimum aerobic SRT for nitrification is shorter in the M&E guideline than in the UCT guideline. The consequence of this shorter SRT (as a result of the M&E guideline nitrification rate and safety factor), but larger aerobic reactor volumes (as a result of the M&E guideline kinetic constants) in the M&E guideline is that although the nitrogen removal is good, the reactor 24-hour average X_t concentrations are significantly lower than the design reactor MLSS.

The effect of the lower X_t concentrations for the M&E-sized systems on the SST operation is discussed in Section 4.6.

4.5 Denitrification with UCTOLD

4.5.1 System Configuration inputs into UCTOLD

The design of AS systems that achieve N-removal by denitrification follows on the COD removal and nitrification design by incorporating the aerobic system design. As discussed in Section 3.4.1.1, the UCT guideline calculates a balanced sludge age to size the entire system (i.e. system SRT), in other words, to calculate the total reactor volume and the anoxic and aerobic mass fractions of the reactor. In contrast, the M&E guideline calculates a hydraulic retention time for the anoxic reactor only, which is converted to an anoxic volume and added to the aerobic volume previously calculated in the nitrification design.

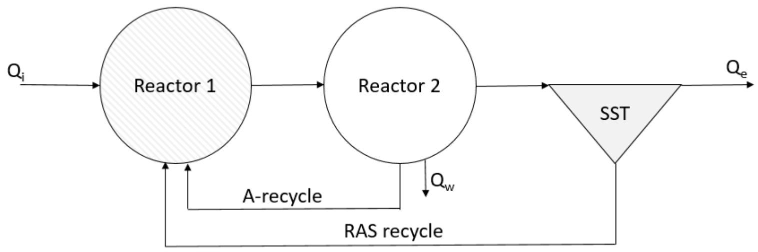
Because the UCT guideline is based on a system SRT, this is simply entered into UCTOLD. The M&E guideline differs, and the SRT entered into UCTOLD is

$$SRT_{sys} = \frac{V_{aer} + V_{anox}}{Q_w} \qquad (37)$$

Where V_{anox} is calculated from the anoxic reactor hydraulic retention time in the denitrification design, V_{aer} is calculated in the nitrification design (using the minimum sludge age for nitrification), and $Q_w = V_{aer}/SRT_{aer}$ in the nitrification design.

The MLE pre-denitrification system configuration, assessed in the dynamic simulation, is given in Figure 4-19 below. This system is a two in-series reactor anoxic/aerobic system, where the underflow from the SST is recycled to the primary anoxic reactor (Reactor 1) via the RAS-recycle and there is a mixed-liquor recycle (a-recycle) from the aerobic (Reactor 2) to the primary anoxic reactor and only Reactor 2 is aerated.

Figure 4-19 MLE system configuration for Nitrification-Denitrification



This system configuration data, provided in Table 4-12 below, is based on the steady state designs for nitrification-denitrification, for both the UCT and M&E guidelines, for an AS system at 14°C, treating both raw and settled wastewaters. These sizes were generated in Chapter 3, Section 3.7, Table 3-16.

Table 4-12: Denitrification system configurations at 14°C

Input Parameter (units)	Raw WW		Settled WW	
	UCT	M&E	UCT	M&E
System sludge age* (days)	11.3	7.0	17.8	7.2
Anoxic reactor volume (Mℓ)	3.401	0.894	3.027	0.525
Aerobic reactor volume (Mℓ)	7.287	8.077	3.033	3.846
Influent flow rate (Mℓ/day)	15	15	14.925	14.925
RAS recycle flow rate (Mℓ/day)	15	15	14.925	14.925
A-Recycle ratio†	5.0	4.87	5.0	4.61
A-recycle flow rate (Mℓ/day)	75.0	73.0	74.6	68.8

** the system sludge age input into UCTOLD is the SRT_{sys}, as described above, for each guideline*

† the a-recycle ratio is an input in the UCT guideline steady state design, while it is calculated in the M&E guideline steady state design (refer to Section 3.4.1.1 in Chapter 3)

The UCT-sized and M&E-sized systems, as described above, were input into UCTOLD together with the diurnal influent data in Section 4.2, the results of the dynamic simulations for this denitrification system are discussed below.

4.5.2 Results

The steady state AS design of a plant that undergoes denitrification hinges around equalizing the nitrate load on the primary anoxic reactor with the denitrification potential of the primary anoxic reactor. This nitrate balance will determine the a-recycle flowrate, total system sludge age as well as the total reactor volume, which for an MLE system consists of an anoxic and aerobic reactor.

A dynamic simulation will assess the effect of the diurnal influent flows and loads on the performance of the plant based on the selected a-recycle flowrate, total system sludge age and reactor volumes.

The dynamic simulation with UCTOLD can be assessed by comparing the 24-hour average for the dynamic (D) results for the dissolved effluent concentrations and reactor solids concentrations with those calculated in the respective steady state (SS) guideline models in Chapter 3. Table 4-13 below provides a comparison of these values.

Table 4-13: 24-hour-average dynamic (D) results from UCTOLD and steady state (SS) design results for denitrification

Dynamic simulation 24-hour average (D) Steady state design (SS)	Raw WW		Settled WW	
	UCT D (SS)	M&E D (SS)	UCT D (SS)	M&E D (SS)
Effluent TKN, N_{te} (mg/ℓ)	5.4 (5.8)	2.7 (3.5)	6.9 (5.8)	2.9 (3.5)
Effluent Ammonia, N_{ae} (mg/ℓ)	3.7 (2.0)	1.0 (2.0)	5.2 (2.0)	1.2 (2.0)
Effluent Nitrate, N_{ne} (mg/ℓ)	6.0 (5.3)	20.1 (4.9)	5.5 (5.7)	24.5 (4.7)
Reactor solids concentration, X_t (mg/ℓ)	4 210 (4 000)	3 439 (4 000)	4 274 (4 000)	3 429 (4 000)
Total Oxygen Demand, FO_t (kgO_2/d)	7 125 (7 300)	7 318 (6 044)	5 252 (5 422)	5 592 (4 239)

As seen with the comparison of dynamic and steady state results for the fully aerobic nitrification system in 4.4.2, because of Monod kinetics the nitrification efficiency of the AS system is decreased under dynamic conditions, compared with that under steady state conditions. The 24-hour average results of the dynamic simulation for the N_{te} and N_{ae} concentrations show better results for the M&E-sized systems in comparison to the UCT-sized systems, however, there is a notable difference in the 24-hour average dynamic N_{ne} concentrations for the M&E-sized system. The high N_{ne} concentrations indicate a deficiency in the M&E guideline denitrification design. As in the nitrification results, it is also a concern here that the reactor solids concentrations (X_t) of the M&E-sized systems are much lower than the design reactor MLSS of 4000 mg/ℓ.

The performance of these UCT-sized and M&E-sized systems can be assessed in more detail by further considering the dynamic results for (i) the nitrogen removal capabilities of the plant. (ii) the reactor VSS and TSS concentrations and (iii) the oxygen utilisation, which now includes the additional oxygen requirement for nitrification as well as the oxygen recovered by denitrification.

The results presented below are taken from the dynamic outputs from UCTOLD for the aerobic reactor, i.e. Reactor 2. The following is noted from the results of the dynamic simulations with UCTOLD for these output parameters:

i) Nitrogen Removal

The effluent TKN (N_{te}) and ammonia (N_{ae}) results observed in the dynamic simulation for the denitrification system are similar to the N_{te} and N_{ae} results observed in the dynamic simulation for the nitrification system in Section 4.4.2 – that is, in general, the N_{te} and N_{ae} values are lowest in the period after 06:00 (when N_{ti} is lowest) and highest in the period after 16:00 (when N_{ti} is highest). This is apparent in Figure 4-20 and Figure 4-21 below.

Figure 4-20 Diurnal effluent TKN concentrations

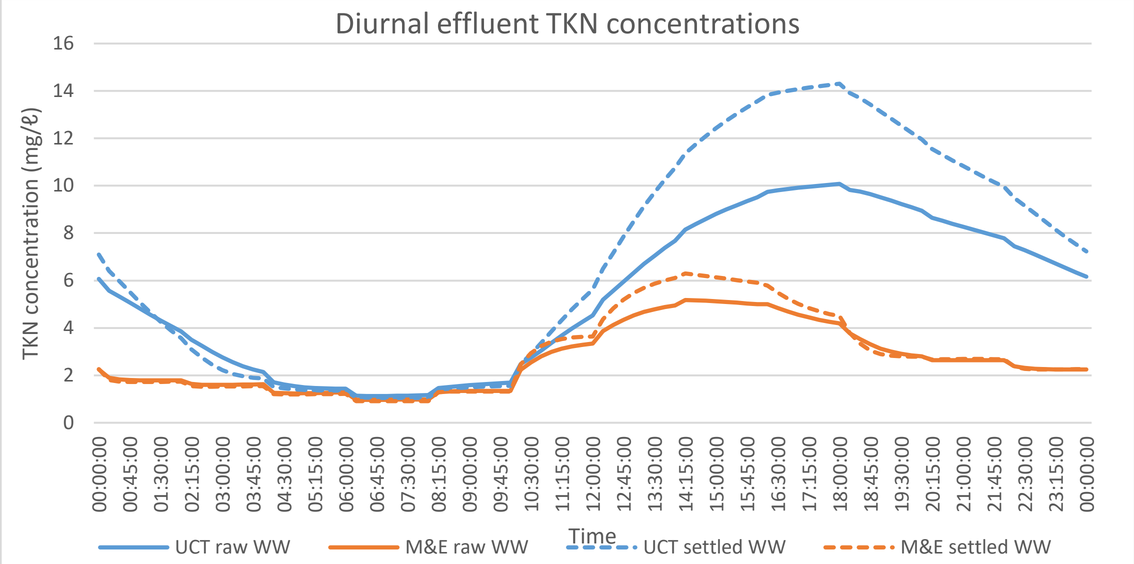
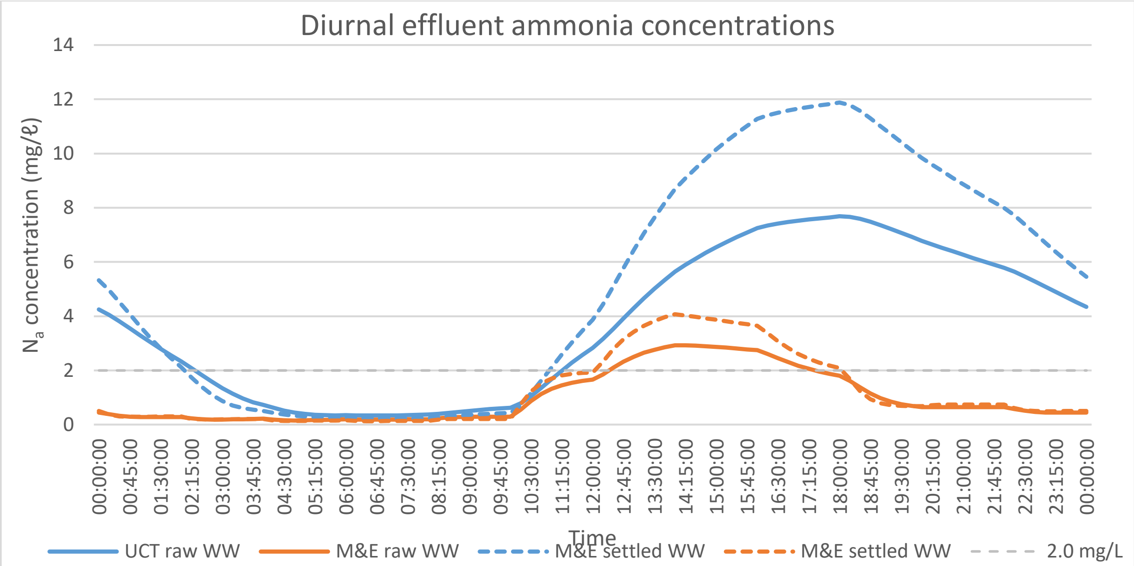


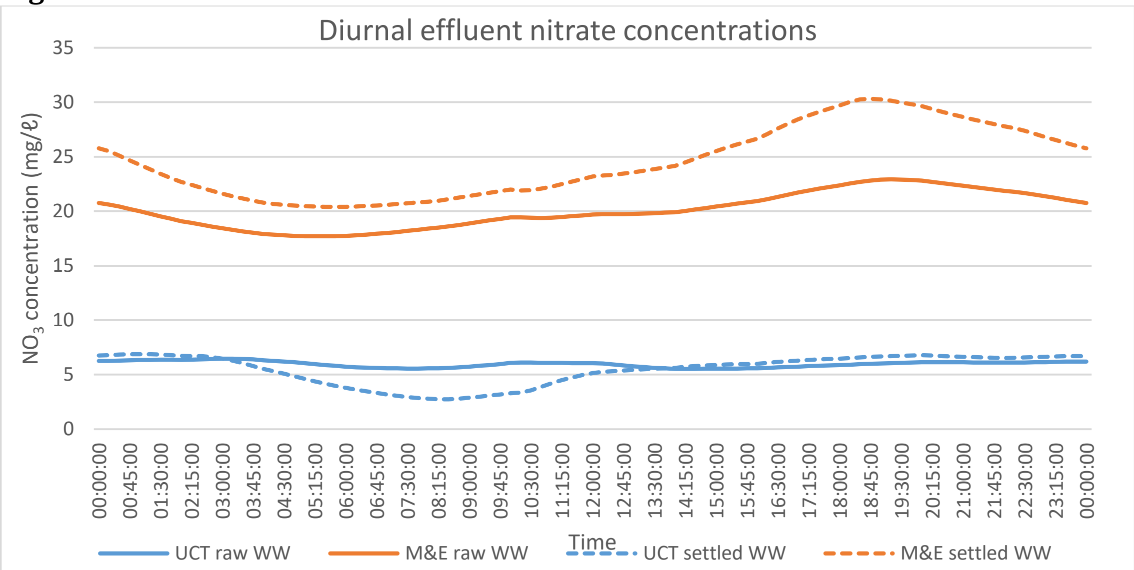
Figure 4-21 Diurnal effluent ammonia concentrations



For the period around 06:00, when the plant receives the lowest influent TKN load, the N_{te} and N_{ae} values are very similar for the UCT-sized and M&E-sized systems, for both raw and settled wastewater. However, after this period when the influent TKN load is increasing, there is a noticeable difference between the N_{te} and N_{ae} concentrations for the two guideline's systems for both the raw and settled wastewater. The UCT-sized systems' maximum dynamic N_{te} concentrations are 10.1 mg/ℓ and 14.3 mg/ℓ for the raw and settled wastewater, and the M&E-sized systems' maximum dynamic N_{te} concentrations are 2.6 mg/ℓ and 3.4 mg/ℓ for the raw and settled wastewater. The UCT-sized systems' maximum dynamic N_{ae} concentrations are 3.7 mg/ℓ and 5.2 mg/ℓ for the raw and settled wastewater, and the M&E-sized systems' maximum dynamic N_{ae} concentrations are 1.0 mg/ℓ and 1.2 mg/ℓ for the raw and settled wastewater.

As discussed previously, although it appears from Figure 4-20 and Figure 4-21 that the M&E-sized systems perform better than the UCT-sized systems, this is not the case (because the M&E guideline has higher nitrification kinetic values and a higher nitrification safety factor, which makes nitrification "complete" faster than the UCT-sized systems). As seen in Figure 4-22 below, when considering the effluent nitrate concentrations, it is apparent that there is a deficiency in denitrification in the M&E guideline design.

Figure 4-22 Diurnal effluent nitrate concentrations



In the steady state AS design, the effluent nitrate concentration, N_{ne}, is a value that is calculated in the UCT guideline based on the selected a-recycle ratio but it is selected in the M&E guideline and the a-recycle ratio is calculated from this selected value. In the steady state AS design for the UCT-sized system the N_{ne} concentration was calculated as 5.3 mg/ℓ for the raw wastewater and 5.7 mg/ℓ for the settled wastewater, and both of these values were based on a selected a-recycle ratio of 5. In the steady state design for the M&E-sized system the N_{ne} concentration was set as 5 mg/ℓ for both the raw and settled wastewaters, which resulted in calculated a-recycle ratios of 4.87 and 4.61 for the raw and settled wastewater respectively.

Even though the steady state N_{ne} concentrations and a-recycle values (as described above) for the UCT-sized and M&E-sized systems are very similar, when input into the UCTOLD dynamic simulation, the results show that the UCT-sized systems result in better nitrate removal in comparison to that of the M&E-sized systems. This is apparent in Figure 4-22, where the N_{ne} concentration of the UCT-sized systems remain stable at around 6 mg/ℓ for the raw wastewater and 3 to 6 mg/ℓ for the settled wastewater, whilst N_{ne} concentration of the M&E-sized systems results in significantly higher N_{ne} concentrations and higher fluctuations in the N_{ne} concentrations of 18 to 23 mg/ℓ for the raw wastewater and 20 to 30 mg/ℓ for the settled wastewater.

It was noted in Chapter 3 (Section 3.4.2) that one of the major differences between the two guidelines was that the M&E guideline determined a faster effective specific denitrification rate of the OHO biomass in the anoxic reactor than the UCT guideline and thus yielded much smaller anoxic reactors (by at least 50%) to achieve the same nitrate removal as the equivalent UCT guideline system. The high effluent nitrate concentrations seen when simulating the M&E sized systems with ASM1 indicates that even though the denitrification kinetics of the M&E guideline were derived in part from ASM1 simulations, the denitrification kinetics of the M&E guideline are very poorly aligned with ASM1.

ii) Reactor VSS and TSS Concentrations

The X_t concentrations in the anoxic reactor are given in Figure 4-23 and aerobic reactor in Figure 4-24 below. These values are calculated from the VSS concentrations as output from UCTOLD and the VSS/TSS ratios as calculated in the respective steady state designs, from the VSS and TSS masses in the reactor, i.e. MX_v/MX_t, as UCTOLD does not calculate the ISS itself.

Figure 4-23 Reactor 1 (anoxic reactor) TSS concentrations (calculated from VSS)

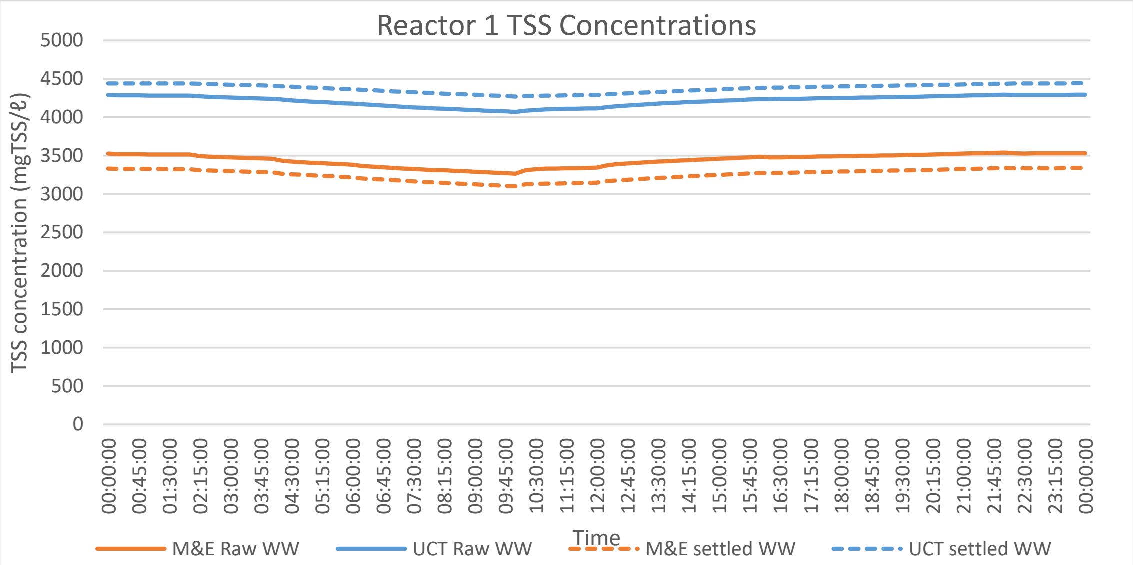
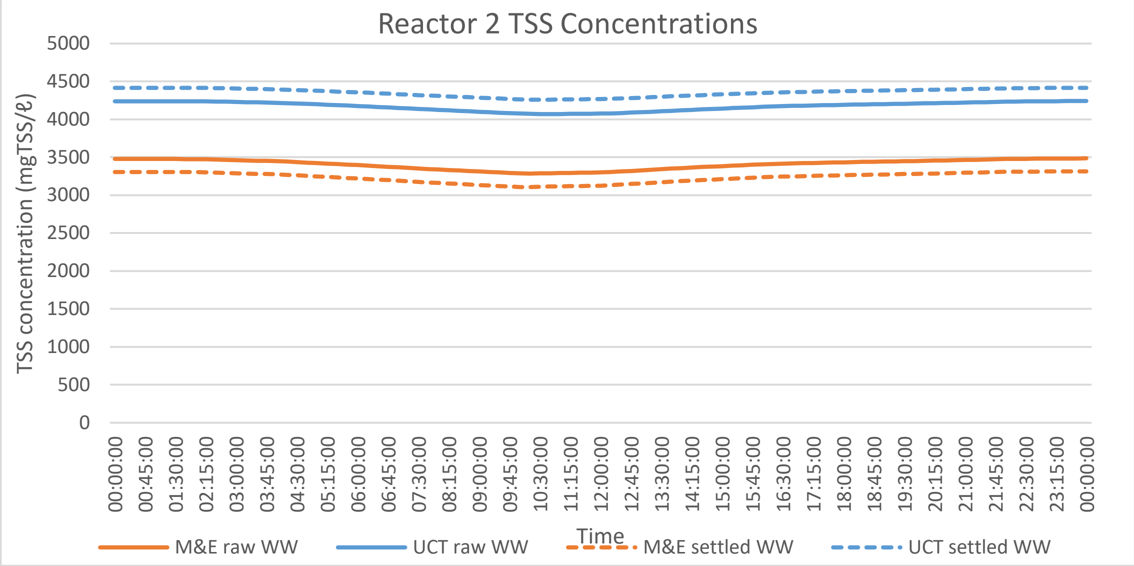


Figure 4-24 Reactor 2 (aerobic reactor) TSS concentrations (calculated from VSS)



A design reactor MLSS concentration of 4,000 mg/ℓ was selected for the steady state design to size the UCT and M&E guideline systems and the system sludge age was calculated as stipulated for each guideline. From the dynamic simulations on the UCT-sized systems and the M&E-sized systems for raw and settled wastewater, it is seen in Table 4-14 below that the 24-hour average X_t concentrations for the UCT-sized systems are close to the design reactor MLSS of 4,000 mg/ℓ while the 24-hour average X_t concentrations for the M&E-sized systems are significantly lower.

Table 4-14: Denitrification: Reactor TSS concentrations comparison

Parameter (units)	**Raw WW**		**Settled WW**	
	UCT	**M&E**	**UCT**	**M&E**
Selected steady state design MLSS concentration (mgTSS/ℓ)	4 000	4 000	4 000	4 000
Selected steady state design sludge age (days)	11.3	7.0	17.8	7.2
Steady state design anoxic reactor volume (Mℓ)	3.401	0.894	3.027	0.525
Dynamic simulation anoxic reactor 24-hour average TSS concentration (mgTSS/ℓ)	4 210	3 439	4 274	3 429
Steady state design aerobic reactor volume (Mℓ)	7.287	8.077	3.033	3.846
Dynamic simulation aerobic reactor 24-hour average TSS concentration (mgTSS/ℓ)	4 172	3 405	4 254	3 232

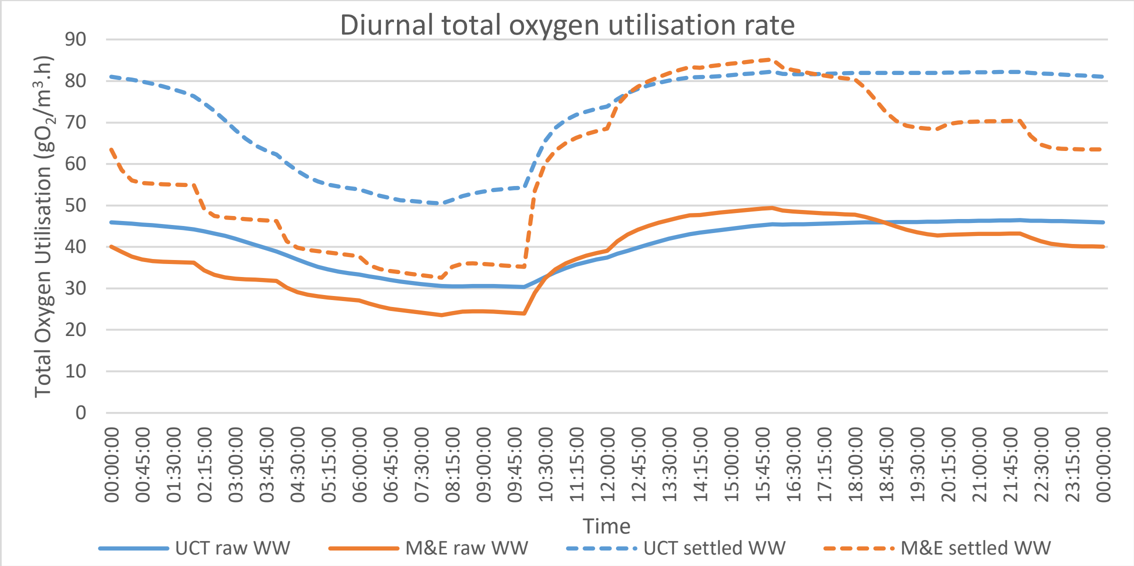
Again, because UCTOLD uses hydraulic control of sludge age (which is particularly important for nitrification) for the same influent wastewater, sludge age and design reactor MLSS, the 24-hour average dynamic X_t concentrations for the UCT-sized and M&E-sized

systems should be the same, and in the range of the design reactor MLSS concentration of 4,000 mg/ℓ. The lower 24-hour average X_t concentrations for the dynamic simulations with UCTOLD for the UCT-sized and M&E-sized systems thus indicates that their aerobic reactor volumes are over-sized.

iii) Oxygen Utilisation Rate

The total OUR_t as output by UCTOLD (measured in $gO_2/m^3.h$) takes into account the oxygen recovered by denitrification via the stoichiometry of the bioprocesses. So the OUR_t (i.e. O_t) of UCTOLD is in effect $OUR_c + OUR_n - OUR_d$. Figure 4-25 below presents the UCTOLD results for OUR_t for the 24 hour period at 15 minute intervals for the influent raw and settled wastewater data respectively.

Figure 4-25 Diurnal total oxygen utilisation rate



It can be seen that the M&E guideline systems (for both raw and settled wastewater) have lower OUR's than the UCT guideline systems.

The average diurnal FOt values from the dynamic simulation for the UCT-sized systems are very close (97.6% and 96.9% for raw and settled wastewater respectively) to their respective calculated steady state FOt values. The average diurnal FOt values from the dynamic simulation for the M&E guideline's system configurations, however, are significantly higher than the their respective calculated steady state FOt values (121.1% for raw and 131.9% for settled wastewater).

Table 4-15 below shows the results for the total flux of oxygen utilised (per day), FO_t, as calculated in the respective steady state AS (UCT and M&E guideline) models for both raw and settled wastewater, versus the average, minimum and maximum diurnal fluxes, calculated from the dynamic total oxygen utilisation rates in Figure 4-25 above and the respective aerobic reactor volumes.

The average diurnal FO_t values from the dynamic simulation for the UCT-sized systems are very close (97.6% and 96.9% for raw and settled wastewater respectively) to their respective calculated steady state FO_t values. The average diurnal FO_t values from the dynamic simulation for the M&E guideline's system configurations, however, are significantly higher than the their respective calculated steady state FO_t values (121.1% for raw and 131.9% for settled wastewater).

Table 4-15: Flux of oxygen per day system results

FO_t (kgO_2/day)	**Raw WW**				**Settled WW**			
	UCT		**M&E**		**UCT**		**M&E**	
Steady state results:	7 300		6 044		5 422		4 239	
Dynamic results:	24-hr ave. FO_t	% of steady state	24-hr ave. FO_t	% of steady state	24-hr ave. FO_t	% of steady state	24-hr ave. FO_t	% of steady state
Minimum diurnal	5 304	*72.7%*	4 572	*75.6%*	3 674	*67.8%*	3 004	*70.9%*
Maximum diurnal	8 123	*111.3%*	9 582	*158.5%*	5 986	*110.4%*	7 863	*185.5%*
Average diurnal	7 125	*97.6%*	7 318	*121.1%*	5 252	*96.9%*	5 592	*131.9%*

The maximum diurnal FO_t value from the dynamic simulation can be used to size the aeration equipment (so that it can handle the peak OUR_t) that will be required for the respective systems. The maximum diurnal FO_t values from the UCT-sized systems require an aeration equipment peak factor of 11.3% and 10.4% for raw and settled wastewater respectively, while the M&E-sized systems require an aeration equipment peak factor 58.5% and 85.5% for raw and settled wastewater respectively. Generally a peak factor of 20% is applied to the steady state FO_c value to account for the maximum aeration requirements under dynamic conditions.

From the above it would appear that the FO_t values calculated in the UCT guideline steady state design are closer to dynamic conditions and that the FO_t values calculated in the M&E guideline steady state design are too low and aeration equipment sized using these values would thus be under-sized.

As with the dynamic simulations of the fully aerobic nitrifying reactors sized with the M&E and UCT guidelines with ASM1, the denitrification systems show the same differences as observed with the organics removal simulations – that the UCT guideline results are closely correlated with the ASM1 results but the M&E results deviate from those of ASM1. This indicates that the denitrification kinetics of the UCT guideline are well aligned with ASM1. This is not the case when simulating the M&E sized systems with ASM1 – while the effluent ammonia compares well, the high effluent nitrate concentration is a result of the much smaller anoxic reactors calculated in the M&E guideline. This is discussed further in Section 4.5.3 below.

4.5.3 Effect of increasing $f_{manx,M\&E}$ on nitrate removal performance

It is apparent from the high N_{ne} results in the dynamic simulation of the M&E-sized MLE system in Section 4.5.2, that the anoxic reactor volume calculated in the M&E guideline steady state design is too small to achieve sufficient nitrate removal. This M&E-sized MLE system was calculated with an $f_{manx,M\&E}$ of 0.100 and an $SRT_{sys,M\&E}$ of 7.0 days for the raw wastewater and an $f_{manx,M\&E}$ of 0.120 and an $SRT_{sys,M\&E}$ of 7.2 days for the settled wastewater. When the $f_{manx,M\&E}$ is increased in the dynamic simulations for the M&E-sized systems (using the M&E nitrification constants) to equal $f_{manx,UCT}$ (the anoxic mass fraction calculated in the steady state design for the same system using the UCT guideline), i.e. increased from 0.100 to 0.318 for the raw wastewater and 0.120 to 0.500 for the settled wastewater, and the $SRT_{sys,M\&E}$ remains the same, i.e. 7.0 days and 7.2 days for the raw and settled wastewater respectively, the dynamic 24-hour average N_{ne} reduces significantly from 20.08 mg/ℓ to 5.68 mg/ℓ for the raw wastewater and from 24.5 mg/ℓ to 3.7 mg/ℓ for the settled wastewater. This indicates that the increase in f_{manx} improves the nitrate removal ability of the M&E-sized systems and also that the $S_{f,M\&E}$ of 1.5 can absorb this increase in f_{manx}. These results, as well as the dynamic simulation 24-hour average results for N_{te} and N_{ae}, are provided in Table 4-16 below.

As seen in Table 4-16, the N_{te}, N_{ae} and N_{ne} values for the raw wastewater M&E-sized systems, with $f_{manx,M\&E}$ increased to $f_{manx,UCT}$, but keeping the SRT = $SRT_{sys,M\&E}$, are very similar to the UCT-sized N_{te}, N_{ae} and N_{ne} values. For the settled wastewater, however, the results of the M&E-sized systems for N_{te}, N_{ae} and N_{ne} are very similar when the $f_{manx,M\&E}$ is increased to $f_{manx,UCT}$ together with an increase in $SRT_{sys,M\&E}$ = $SRT_{sys,UCT}$.

Table 4-16: Effect of increasing f_{manx} and SRT_{sys} of M&E-sized systems on nitrate removal performance

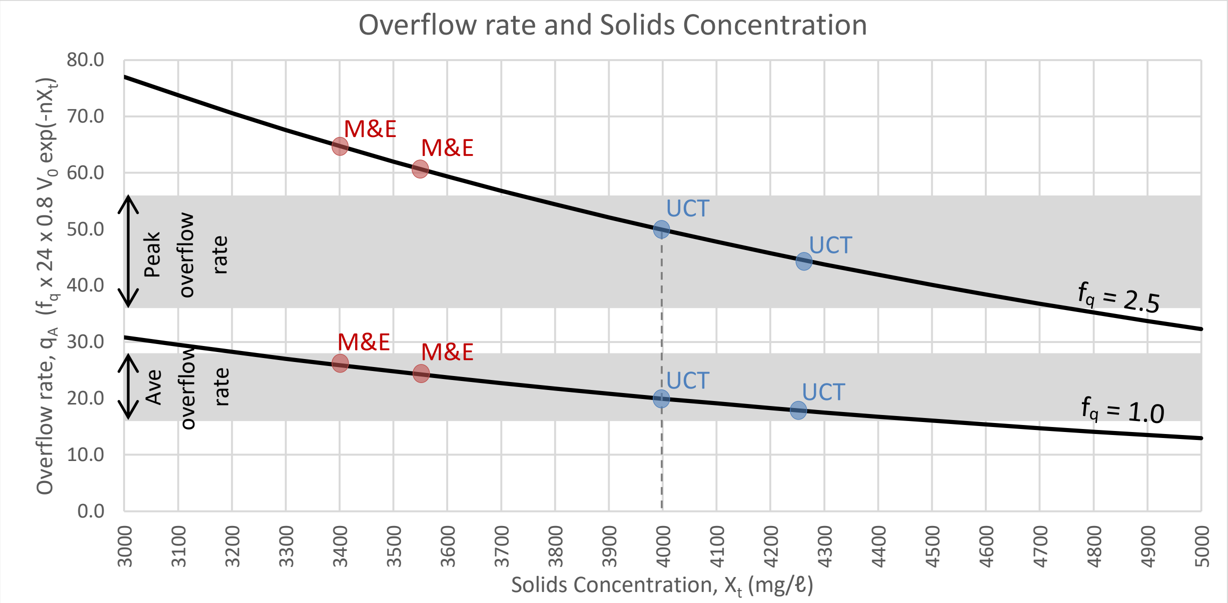
Dynamic simulation 24-hour average	Raw WW				Settled WW			
	M&E as per guide-line	M&E increase f_{manx} only	M&E increase f_{manx} and SRT	UCT as per guide-line	M&E as per guide-line	M&E increase f_{manx} only	M&E increase f_{manx} and SRT	UCT as per guide-line
Anoxic mass fraction, f_{x1}	0.100	0.318	0.318	0.318	0.120	0.500	0.500	0.500
System SRT	7.0	7.0	11.3	11.3	7.2	7.2	17.8	17.8
Effluent TKN, N_{te} (mg/ℓ)	2.68	4.74	2.90	5.41	2.9	16.3	4.8	6.9
Effluent Ammonia, N_{ae} (mg/ℓ)	1.00	3.05	1.21	3.73	1.2	14.6	3.1	5.2
Effluent Nitrate, N_{ne} (mg/ℓ)	20.08	5.68	6.85	5.97	24.5	3.7	6.5	5.5

4.6 Secondary Settling Tank Considerations

As discussed in the results above (Sections, 4.3.2, 4.4.2 and 4.5.2) for the reactor VSS and TSS concentrations, the M&E-sized systems results in 24-hour average dynamic reactor X_t concentrations that are well below the design reactor MLSS of 4,000 mg/ℓ (and are on average between 3,400 mg/ℓ and 3,550 mg/ℓ). The UCT-sized systems result in 24-hour average dynamic reactor X_t concentrations of around 4,000 mg/ℓ to 4,250 mg/ℓ.

As seen in Chapter 3, Section 3.6, the SST overflow rate, q_A, can be calculated in terms of X_t (Equation 35) and Figure 4-26 below (taken from Section 3.6) provides the range of permissible overflow rates for both average and peak conditions for varying X_t concentrations. The M&E-sized and UCT-sized systems minimum and maximum X_t concentrations, as described above, are marked on the figure below.

Figure 4-26 Overflow rate and solids concentration



It can be seen that the UCT-sized systems X_t concentrations still fall within the permissible overflow rates for both average and peak conditions. The M&E –sized systems X_t concentrations fall within the permissible overflow rates for average conditions, however, for peak conditions these low X_t concentrations will result in higher overflow rates. This means that under peak conditions (f_q is 2.5 or greater), the M&E-sized systems SST's will fail. This is because the M&E SST sizing procedure does not include a 1DFT flux rating of 0.80 (Ekama and Marias, 1986, 2004), which has the effect of increasing the SST surface area estimated by the 1DFT by 25%.

5. Summary of Key Findings

The aim of this dissertation is to provide both a qualitative and quantitative comparison of two steady state AS design guidelines, i.e. the UCT guideline and the M& E guideline, with specific reference to the dimensioning of the biological reactor of the AS system and the connected SST. The main objective of this dissertation is to provide the reader with an understanding of the key similarities and differences between the two steady state AS design guidelines and how, under dynamic conditions, a system that is sized with a particular guideline (i) compares to its steady state results and (ii) performs under these dynamic conditions.

A summary of the key findings of this dissertation are listed below.

5.1 COD Removal Design

(1) The M&E sized aerobic reactor volumes are larger (12.1% to 16.3%) than the UCT sized aerobic reactor volumes for the same SRT and influent wastewater characteristics. This is mainly because the kinetic and stoichiometric constants provided in the guidelines differ – the endogenous residue fraction (f_H) is 0.20 in the UCT guideline while it is 0.15 in the M&E guideline and the specific endogenous respiration rate standard value at 20°C for b_{EH20} in the M&E guideline is half that (0.12) of the b_{EH20} given in the UCT guideline (0.24). Also, the temperature sensitivity coefficient of the b_{EHT} is higher in the M&E guideline (a 4 % increase per °C) than in the UCT guideline (2.9 % increase per °C) between 12°C and 24°C. If the kinetic, stoichiometric and temperature sensitivity constants in the M&E guideline are assigned the same values as the UCT guideline, virtually identical results are obtained.

(2) At the same SRT, and if the kinetic, stoichiometric and temperature sensitivity constants in the M&E guideline are assigned the same values as the UCT guideline, the VSS portion of the TSS differs by only 0 to 0.15% in the two guidelines, while the ISS portion of the TSS differs by 34%, this is because the calculation of the ISS in the two guidelines is different. The UCT guideline stipulates that the ISS content of OHO (f_{iOHO}) making the OHO ISS 15 % of the OHO biomass. In the M&E guideline the OHO biomass and their endogenous residue are divided by 0.85 when including it in the total TSS calculation, which results in 18 % ($^1/_{0.85}$) of the OHO (X_{OHO}) plus endogenous residue ($X_{E,OHO}$) being included as inorganic ISS. The mass of ISS in the reactor accumulating from the influent is calculated in the same way i.e. flux of ISS into reactor times SRT.

(3) The COD balances 100% in both the UCT and M&E guidelines, but because of the different kinetic, stoichiometric and temperature sensitivity constants, the influent organics is split differently between sludge production and oxygen demand in the two guidelines. The M&E guideline results in higher sludge production and lower oxygen demands relative to the UCT steady state guideline and the ASM1 model. At the same SRT, sludge production and oxygen demand are about 5% lower and higher respectively for the M&E guideline than the UCT guideline. When a UCT and M&E sized fully

aerobic system is simulated with ASM1, this difference is repeated. The UCT guideline results are closely correlated with the ASM1 results but the M&E results deviate from those of ASM1. If the kinetic, stoichiometric and temperature sensitivity constants in the M&E guideline are assigned the same values as the UCT guideline, virtually identical results are obtained.

(4) At the same SRT, the M&E guideline calculates a higher residual biodegradable COD in waste VSS due to a higher OHO biomass active fraction. Again, this difference arises because the M&E guideline assigns different values to the kinetic, stoichiometric and temperature sensitivity constants. This will have an effect on the WAS sludge treatment design – the higher wasted OHO biomass, the higher the calculated oxygen demand for aerobic digestion and the higher the calculated methane production in anaerobic digestion. This would be the case if a design were undertaken using the M&E guideline and may lead to error (relative to plant wide models based on ASM1) in the design of the WAS sludge treatment systems.

5.2 Nitrification Design for Fully Aerobic Systems

(1) Only nitrification under fully aerobic conditions is considered. When considering the minimum sludge age for nitrification to occur, both design guidelines provide equations to calculate the SRT, however, they are different SRT's. For the UCT guideline it is the system SRT, $R_{Ssystem}$, where the SRT is defined as the mass of sludge in both the anoxic and aerobic reactors divided by the mass per day (flux) of sludge wasted. For the M&E guideline approach, the SRT is the aerobic SRT defined as the mass of sludge in the aerobic reactor only, divided by the mass per day (flux) of sludge wasted. In the M&E guideline approach, sludge is usually wasted from the secondary settling tank underflow. These two definitions of SRT are arrived at from two fundamentally different assumptions about the behaviour of the nitrifiers in N removal systems. In the UCT approach it is assumed that (i) nitrifiers grow only under aerobic conditions, (ii) they die (endogenous respiration) in the entire reactor (anoxic and aerobic) and (iii) they are uniformly distributed in the reactor, i.e. comprise the same proportion of the TSS in each reactor. The above approach is aligned with ASM1 which applies the assumptions listed above. In the M&E guideline approach, assumptions (i) and (iii) above apply, but assumption (ii) is different, where nitrifiers die (endogenous respiration) only in the aerobic reactor (they are moribund in the anoxic reactor, they neither grow nor die). This latter assumption allows the SRT to be defined in terms of the nitrifier's behaviour, i.e. aerobic SRT ($SRT_{aerobic}$). It is important to note that $SRT_{aerobic}$ is not the system SRT, unless the reactor is fully aerobic (it has no anoxic zones) which is the case here, so for nitrification in fully aerobic systems, the SRT of the UCT and M&E methods is the same.

(2) The maximum specific growth rate of the ANO's, μ_{AMT}, is the most important nitrification kinetic value to take into consideration in a COD removal and nitrification design, as the

system SRT, for the UCT approach, and the aerobic SRT, for the M&E approach, as well as the reactor volume requirements are directly related to this value. The lower the $\mu_{AMT,}$ the longer the SRT and the larger the reactor volume. Again, the M&E guideline assigns different values to the nitrification kinetic (μ_{Am20}, b_{A20}), stoichiometric (Y_A, K_{n20}) and temperature sensitivity constants ($\theta_{\mu Am}$, θ_{bA}, θ_{Kn}) than the UCT guideline. The M&E guideline calculates the minimum sludge age for nitrification, R_{sm}, using a fixed maximum specific growth rate of nitrifiers at 20^{o}C (μ_{Am20}) at 0.90 g/(g.d), and after correcting for temperature, DO concentration in the aerobic reactor and assigning a safety factor (S_f = 1.5), the minimum sludge age for nitrification is slightly shorter than for the UCT guideline for a selected maximum specific growth rate of nitrifiers at 20^{o}C (μ_{Am20}) of 0.45 g/(g.d) and assigning S_f = 1.25.

(3) In the M&E guideline the mass of nitrifiers is added to the reactor MLSS concentration which increases the MLSS mass in the reactor by about 2-4% and thus the aeration tank volume (which is the total reactor volume) for the M&E guideline design will be slightly larger. This is not done in the UCT guideline to maintain the COD balance for organics removal. The inclusion of the ANO mass in the MX_t of the M&E guideline means that the fully aerobic reactor volume for the M&E guideline is affected by a variation in influent TKN concentration, while the UCT guideline is not because it does not include the mass of ANO's in the MX_t mass. However, the overall effect of this difference is very small.

(4) At the same SRT in a fully aerobic system (i.e. $SRT_{aerobic} = SRT_{system}$), the oxygen demand for nitrification is closely similar – the difference in sludge production of the two guidelines make little difference to the N taken up for sludge production.

(5) The M&E guideline's faster μ_{Am20} (0.90 g/(g.d) versus 0.45 g/(g.d) in UCT guideline) means that when simulated using ASM1, nitrification is complete at a shorter SRT, while the higher S_f (1.5 versus 1.25 in UCT guideline) means that the system SRT is 50% longer than the minimum SRT for nitrification and when simulated using ASM1 the M&E sized systems result in lower effluent ammonia concentrations compared to the UCT sized systems.

(6) If fully aerobic nitrifying reactors sized with the M&E and UCT guidelines are simulated with ASM1 at the same SRT, the same differences as with organics removal are observed, i.e. the M&E aerobic reactor volumes are larger than the UCT aerobic reactor volumes (because of the different kinetic and stoichiometric constants in the two guidelines) and hence the UCT guideline results are closely correlated with the ASM1 results but the M&E results deviate from those of ASM1).

(7) The consequence of (5) and (6) above is that although when simulated with ASM1 the nitrogen removal for the M&E system is good, the simulated average reactor MLSS concentrations are significantly lower than the design reactor MLSS.

5.3 Denitrification Design

(1) Significant differences between the two guidelines emerge when adding an anoxic reactor for denitrification, such as for the anoxic aerobic nitrification - denitrification (ND) Modified Ludzack-Ettinger (MLE) system. This is because (i) the nitrifiers are assumed to behave differently under anoxic conditions in the two guidelines and (ii) the effective specific denitrification rates of the OHO biomass in the anoxic reactor are much higher in the M&E guideline than in the UCT guideline.

i. With regard to difference (i), in the UCT guideline, the nitrifiers are assumed to grow only in the aerobic reactor but die in both the anoxic and aerobic reactors. In the M&E guideline, the nitrifiers are assumed to die (and grow) only in the aerobic reactor, i.e. they neither grow nor die in the anoxic reactor. Hence in the M&E guideline, the MLE system is sized based on an aerobic SRT, which excludes the mass of sludge in the anoxic reactor as in Section 5.2 (1) above, but in the UCT guideline the MLE system is sized based on a system SRT, which includes the mass of sludge in the anoxic reactor.

ii. With regard to difference (ii), the faster specific denitrification rate determined with the M&E guideline yield much smaller anoxic reactors by at least 50% to achieve the same nitrate removal.

The consequence of these two differences is that the system SRT of the MLE system determined with the UCT guideline is considerably longer than that determined with the M&E guideline leading to larger anoxic, aerobic and system reactor volumes. This difference widens as the influent TKN/COD concentration ratio increases, i.e. as the concentration of nitrate to be denitrified increases.

(2) When simulating the UCT sized MLE systems (under steady state conditions) with ASM1, very similar reactor MLVSS and MLSS concentration, effluent ammonia and nitrate concentrations and total oxygen demands are obtained with ASM1 and the UCT guideline. This indicates that the denitrification kinetics of the UCT guideline are well aligned with ASM1. This is not the case when simulating the M&E sized MLE systems (under steady state conditions) with ASM1 – while the effluent ammonia concentration compares well, the effluent nitrate concentration is far higher (increases from 6 mgNO_3-N/ℓ to above 20 mgNO_3-N/ℓ). This indicates that even though the denitrification kinetics of the M&E guideline were derived in part from ASM1 simulations, the denitrification kinetics of the M&E guideline are very poorly aligned with ASM1.

(3) The high effluent nitrate concentration when simulating the M&E sized system with ASM1 is a result of the much smaller anoxic reactors calculated in the M&E guideline. When the f_{manx} of the M&E-sized system is increased from 0.100 to the $f_{manx,UCT}$ of 0.318 (but keeping SRT = $SRT_{sys,M\&E}$) and simulated with ASM1, the effluent nitrate concentrations reduce from around 20 mgNO_3-N/ℓ to around 6 mgNO_3-N/ℓ, which is aligned with the UCT guideline ASM1 results.

5.4 Enhanced Biological Phosphorus Removal

In contrast to the UCT guideline, the M&E guideline provides minimal insight into EBPR design. It provides only very simplistic examples for calculation of the effluent soluble P concentration and the percentage of P content in the waste sludge. In comparison, the UCT guideline provides far more information, design calculations and considerations for EBPR and ND in EBPR systems than the M&E guideline. The UCT NDEBPR system design guideline is as detailed as the ND system guideline giving equations for calculating the (i) the proportion of the influent COD flux obtained by the OHO and PAO, (ii) masses of VSS and TSS in the reactor, (iii) anaerobic, anoxic and aerobic mass fractions, (iv) balanced SRT for the UCT, JHB and 3SB systems and (v) lowest effluent ammonia, nitrate and phosphate concentrations. The UCT NDEBPR steady state model takes into account the different K denitrification rates observed in the primary and secondary anoxic reactors of NDEBPR systems (Clayton, et al., 1992) (Ekama & Wentzel , 1999) and that aerobic uptake EBPR PAO do not contribute to denitrification. The UCT NDEBPR steady state guideline is well aligned with ASM2, the kinetic equations of which exhibit the same behaviour - the K denitrification rates can be calculated from the kinetics equations in ASM2.

For this reason, the two design guidelines were not compared any further in terms of the EBPR design, as there is insufficient information in the M&E guideline for a designer to perform a complete EBPR design.

5.5 Secondary Settling Tank Design

The UCT guideline uses the idealised one-dimensional flux theory (1DFT) corrected by a flux factor to determine the surface area of the secondary settling tanks, A_{ST}. In contrast, the M&E guideline does not use any sludge settleability data to calculate the area required for the SST, but rather uses the hydraulic application rate or overflow rate, q_{A}, in $m^3/(m^2.d)$. The M&E guideline provides a table of typical design information for SSTs. The M&E overflow rates can be aligned with the UCT 1DFT to determine very similar SST surface areas.

The M&E guideline provides a table of typical design information for SSTs for the AS process where it states that q_A should be selected in the range of 16 to 28 $m^3/(m^2.d)$ for average conditions and 36 to 56 $m^3/(m^2.d)$ for peak conditions for settling that follows air activated sludge. It was seen in the steady state design that for the q_A of 20 $m^3/(m^2.d)$ that is required for the 4,000 mg/ℓ design solids concentration at average flow (i.e. $f_q = 1.0$), a total SST surface area of 750 m^2 is required and for the q_A of 49.9 $m^3/(m^2.d)$ that is required at the same design solids concentration at peak flow (i.e. $f_q = 2.5$), a total SST surface area of 750 m^2 is also required. Thus the SST with surface area of 750 m^2 will operate between an overflow rate of 20 $m^3/(m^2.d)$ and 49.9 $m^3/(m^2.d)$ between average and peak flow periods.

The lower resultant reactor MLSS of the M&E sized systems when simulated with ASM1 means that the SSTs will operate at a lower than designed for MLSS and thus under peak conditions (f_q is 2.5 or greater) the SST will operate at a higher than permissible overflow rate. This is because the M&E SST sizing procedure does not include a 1DFT flux rating of 0.80 (as the UCT guideline does), which has the effect of increasing the SST surface area estimated by the 1DFT by 25%.

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A. Steady State Models in Microsoft Excel

Screenshots of the steady state models setup in Microsoft Excel for the UCT guideline and M&E guideline respectively (Chapter 3) are provided in this section, as follows:

Section	**UCT guideline**	**M&E guideline**
COD removal only	Figure A-1	Figure A-2
COD removal and nitrification	Figure A-3	Figure A-4 Figure A-5
COD removal, nitrification and denitrification	Figure A-6 Figure A-7	Figure A-8 Figure A-9
SST sizing	Figure A-10	Figure A-11

Figure A-1 UCT guideline steady state model for COD removal only

1	COD REMOVAL ONLY							INPUT CELL
2	(Biological Wastewater Treatment: Principles, Modelling and Design Henze et al. 2008)							CALCULATED CELL
3	**WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
4	Influent flow rate	Qi	15	15	14.925	14.925	m^3/d	*Input value*
5	Influent COD concentration	Sti	750	750	450.1	450.1	mgCOD/l	*Input value*
6	Influent TKN concentration	Nti	60	60	51.07	51.07	mgN/l	*Input value*
7	Influent phosphorus concentration	Pti	14	14	11.04	11.04	mgP/l	*Input value*
8	Influent TSS	TSS	416.3	416.3	177.2	177.2		
9	Influent ISS	ISS	48	48	9.6	9.6		
10	Total Alkalinity	Alk	200	200	200	200	mg/l as $CaCO_3$	*Input value*
11	Minimum Temp	Tmin	14	14	14	14	degC	*Input value*
12	Maximum Temperature	Tmax	22	22	22	22	degC	*Input value*
13	**QUANTIFICATION OF WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
14	Fraction of unbiodegradable particulate COD in influent	fs'up	0.1493	0.1493	0.04	0.04		*Input value*
15	Fraction of unbiodegradable soluble COD in influent	fs'us	0.069	0.069	0.1155	0.1155		*Input value*
16	Unbiodegradable soluble COD concentration (=Ste)	Susi	51.8	51.8	52.0	52.0	mgCOD/l	
17	**STANDARD PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
18	COD/VSS ratio of unbiodegradable particulate COD	fcv	1.480	1.480	1.494	1.494	mgCOD/mgVSS	*Table 4.1*
19	Endogenous residue fraction of volatile solids in influent	f_H	0.200	0.200	0.200	0.200	-	*Table 4.1*
20	VSS/TSS of activated sludge	f_i	0.750	0.750	0.750	0.750	mgVSS/mgTSS	*Table 4.1*
21	ISS content of OHO's	f_{iOHO}	0.150	0.150	0.150	0.150		
22	VSS yield coefficient	Y_H	0.450	0.450	0.450	0.450	mgVSS/COD	*Table 4.1*
23	**TEMPERATURE SENSITIVE PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
24	Endogenous respiration rate for biomass	b_{EH20}	0.24	0.24	0.24	0.24	/d	*Table 4.1*
25	Theta for endogenous respiration rate for biomass	$b_{EH20}\theta$	1.029	1.029	1.029	1.029	-	*Table 4.1*
26	**ADJUSTMENT OF TEMPERATURE SENSITIVE PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
27	Temperature	T	**14**	**22**	**14**	**22**	degC	
28	Endogenous respiration rate for biomass	b_{EHT}	0.202	0.254	0.202	0.254	/d	
29	**SELECT OPERATIONAL PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
30	Sludge Age	Rs	5	5	5	5	days	*Select Sludge Age*
31	Mixed Liquor Suspended Solids Concentration (MLSS)	Xt	4000	4000	4000	4000	mgTSS/l	*Select MLSS concentration*
32	**PROCESS VOLUME AND CARBONACEOUS MATERIAL REMOVAL**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
33	Mass of COD treated per day	MSti	11250	11250	6718	6718	kgCOD/d	Qi*Sti
34	Mass of biodegradable COD treated per day	MSbi	8794	8794	5673	5673	kgCOD/d	Qi*Sbi
35	Daily mass flow of ISS	MX_{IOi}	720	720	143	143	kgISS/d	
36	Flux of unbiodegradable particulate (UPO) volatile solids in influent	MX_{Ivi}	1135	1135	180	180	kgVSS/d	Qi*(fs'up*Stii/fcv)
37	**OHO VSS**	MX_{BHv}	**9840**	**8714**	**6348**	**5622**		
38	**Endogenous residue VSS**	MX_{Ev}	**1989**	**2214**	**1283**	**1429**		
39	**Unbiodegradable organics VSS**	MX_{Iv}	**5674**	**5674**	**899**	**899**		
40	**Total Mass of volatile settleable solids in the system**	**MXv**	**17504**	**16603**	**8530**	**7950**	kgVSS	
41	**Mass of inorganic settleable solids in the system**	MX_{IO}	**5076**	**4907**	**1669**	**1560**	kgISS	
42	**Mass of total settleable solids in the system**	**MXt**	**22580**	**21510**	**10199**	**9509**	kgTSS	MXv/fi
43	**Total biological reactor volume**	V_P	**5645**	**5378**	**2550**	**2377**	m^3	MXt/(Xt/1000)
44	**Average Daily carbenaceous oxygen demand**	**FOc**	**5293**	**5559**	**3393**	**3567**	kgO/d	
45	Active sludge mass fraction w.r.t volatile solids	fav	0.562	0.772	0.836	0.836		
46	Active sludge mass fraction w.r.t total suspended solids	fat	0.422	0.579	0.627	0.627		
47	**Mass of (total) sludge produced/wasted per day**	**M∆Xt**	**4516**	**4302**	**2040**	**1902**	kgTSS/d	
48	Mass of VSS sludge produced/wasted per day	M∆Xv	3387	3227	1530	1426	kgVSS/d	fi*M∆Xt
49	Waste flow rate	Qw	1129	1076	510	475	m3/d	
50	MLVSS		2249	3087	3346	3344	mg/l	
51	**COD MASS BALANCE:**		**Raw WW**		**Settled WW**			
52	COD MASS IN: Mass COD entering system		11250.0	11250.0	6717.7	6717.7	kgCOD/d	
53	*Soluble COD in effluent and waste flows*		*776.3*	*776.3*	*775.9*	*775.9*	*kgCOD/d*	
54	*Particulate COD in waste flow*		*5181.1*	*4914.5*	*2548.9*	*2375.3*	*kgCOD/d*	
55	*Carbonaceous oxygen utilised*		*5292.6*	*5559.2*	*3392.9*	*3566.5*	*kgCOD/d*	
56	COD MASS OUT:		11250.0	11250.0	6717.7	6717.7	kgCOD/d	
57	% COD Mass balance		100.0%	100.0%	100.0%	100.0%		

Figure A-2 M&E guideline steady state model for COD removal only

1	COD REMOVAL ONLY							INPUT CELL
2	*Wastewater Engineering: Treatment and Resource Recovery, Metcalf & Eddy / AECOM, 5th Ed. 2014*							CALCULATED CELL
3	**WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
4	Influent flow rate	Qi	15	15	14.925	14.925	m^3/d	*Input value*
5	Influent COD concentration	Sti	750	750	450.1	450.1	mgCOD/l	*Input value*
6	Influent TKN concentration	Nti	60	60	51.07	51.07	mgN/l	*Input value*
7	Influent phosphorus concentration	Pti	14	14	11.04	11.04	mgP/l	*Input value*
8		TSS	416.3	416.3	177.2	177.2		
9		ISS	48	48	9.6	9.6		
10	Total Alkalinity	Alk	200	200	200	200	mg/l as $CaCO_3$	*Input value*
11	Minimum Temp	Tmin	14	14	14	14	degC	*Input value*
12	Maximum Temperature	Tmax	22	22	22	22	degC	*Input value*
13	**QUANTIFICATION OF WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
14	Fraction of unbiodegradable particulate COD in influent	fs'up	0.1493	0.1493	0.04	0.04		*Input value*
15	Fraction of unbiodegradable soluble COD in influent	fs'us	0.069	0.069	0.1155	0.1155		*Input value*
16	Unbiodegradable soluble COD concentration (=Ste)	Susi	51.8	51.8	52.0	52.0	mgCOD/l	
17	**STANDARD PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
18	COD/VSS ratio of unbiodegradable particulate COD	fcv	1.480	1.480	1.494	1.494	mgCOD/mgVSS	*Table 8.14*
19	Endogenous residue fraction of volatile solids in influent	f_H	0.150	0.150	0.150	0.150	-	*Table 8.14 (same as fH in UCT)*
20	VSS/TSS of activated sludge	f_i	0.750	0.750	0.750	0.750	mgVSS/mgTSS	
21	VSS yield coefficient	Y_H	0.450	0.450	0.450	0.450	mgVSS/COD	*Table 8.14*
22	**TEMPERATURE SENSITIVE PARAMETERS (at 20˚C)**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
23	Half saturation for organic removal	Ks	8	8	8	8	mg/L	*Table 8.16*
24	Theta for half saturation for organic removal	Ks θ	1	1	1	1		*Table 8.16*
25	maximum specific growth rate of OHOs	μ_{mT20}	6	6	6	6		
26	Theta for maximum specific growth rate of OHOs	μ_{mT20} θ	1.07	1.07	1.07	1.07		
27	Endogenous respiration rate for biomass	b_{EH20}	0.12	0.12	0.12	0.12	/d	*Table 4.1*
28	Theta for endogenous respiration rate for biomass	b_{EH20} θ	1.04	1.04	1.04	1.04	-	*Table 4.1*
29	**ADJUSTMENT OF TEMPERATURE SENSITIVE PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
30	Temperature	T	**14**	**22**	**14**	**22**	degC	
31	Half saturation for organic removal	K_{sT}	8.000	8.000	8.000	8.000		
32	maximum specific growth rate of OHOs	μ_{mT}	3.998	6.869	3.998	6.869		
33	Endogenous respiration rate for biomass	b_{EHT}	0.095	0.130	0.095	0.130	/d	
34	**SELECT OPERATIONAL PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
35	Sludge Age	Rs	5	5	5	5	days	*Select Sludge Age*
36	Mixed Liquor Suspended Solids Concentration (MLSS)	Xt	4000	4000	4000	4000	mgTSS/l	*Select MLSS concentration*
37	**PROCESS VOLUME AND CARBONACEOUS MATERIAL REMOVAL**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
38	Effluent biodegradable soluble COD	S	0.64	0.40	0.64	0.40	mg/l	
39	VSS sludge production OHO active biomass	$P_{xbio\ (active\ biomass)}$	2681.5	2398.3	1728.8	1546.6	kgVSS/d	*Xbh*
40	VSS sludge production OHO endogenous residue	$P_{xbio\ (endog.\ res)}$	190.7	233.5	123.0	150.5	kgVSS/d	*Xe*
41	VSS sludge production OHO's	P_{xbio}	2872.2	2631.7	1851.8	1697.1	kgVSS/d	
42	VSS sludge production UPO	P_{xnb}	1134.9	1134.9	179.9	179.9	kgVSS/d	*Xi*
43	Total VSS sludge production	$P_{x,VSS}$	4007.1	3766.6	2031.7	1877.0	kgVSS/d	*Xv*
44	Total ISS production	P_{ISS}	720.0	720.0	143.3	143.3		*Xio*
45	Total TSS sludge production	$P_{x,TSS}$	5234.0	4951.0	2501.7	2319.7	kgTSS/d	*Xt*
46								
47	**Mass of MLVSS in aerobic reactor (VSS)**	**MXv**	**20035.6**	**18833.0**	**10158.3**	**9384.8**	kgVSS	
48	**Mass of MLSS in aerobic reactor (TSS)**	**MXt**	**26170.0**	**24755.1**	**12508.7**	**11598.6**	kgTSS	
49	MLVSS/MLSS ratio	*fav*	0.669	0.761	0.812	0.809		
50	Mixed Liquor VSS Concentration (MLVSS)	Xv	2677	3043	3248	3237	mgVSS/l	
51	**Aeration tank volume**	V_P	**6542.5**	**6188.8**	**3127.2**	**2899.7**	m^3	
52	Hydraulic retention time of aerobic reactor	Rhn	10.5	9.9	5.0	4.7	hrs	
53	**Daily carbonaceous oxygen demand**	**MOc**	**4706.0**	**5051.0**	**3034.1**	**3257.2**	kgO_2/d	
54	**Mass of (total) sludge produced/wasted per day**	**MΔXt**	**5234.0**	**4951.0**	**2501.7**	**2319.7**		
55	Waste flow rate	Qw	**1308.5**	**1237.8**	**625.4**	**579.9**		
56	**COD MASS BALANCE:**		**Raw WW**		**Settled WW**			
57	COD MASS IN: Mass COD entering system		11250.0	11250.0	6717.7	6717.7	kgCOD/d	
58	*Soluble COD in effluent and waste flows*		776.3	776.3	775.9	775.9	kgCOD/d	
59	*Particulate COD in waste flow*		5930.5	5574.6	3035.3	2804.2	kgCOD/d	
60	*Carbonaceous oxygen utilised*		4706.0	5051.0	3034.1	3257.2	kg02/d	
61	COD MASS OUT:		11252.8	11241.9	6715.3	6677.3	kgCOD/d	
62	% COD Mass balance		100.0%	100.1%	100.0%	100.6%		

Figure A-3 UCT guideline steady state model for COD removal and nitrification

1	COD REMOVAL AND NITRIFICATION							INPUT CELL
2	(Biological Wastewater Treatment: Principles, Modelling and Design Henze et al. 2008)							CALCULATED CELL
3	**WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
4	Influent flow rate	Qi	15	15	14.925	14.925	m^3/d	*Input value*
5	Influent COD concentration	Sti	750	750	450	450	mgCOD/l	*Input value*
6	Influent TKN concentration	Nti	60	60	51.1	51.1	mgN/l	*Input value*
7	Influent phosphorus concentration	Pti	14	14	11.04	11.04	mgP/l	*Input value*
8	Influent TSS	TSS	416.3	416.3	177.2	177.2		
9	Influent ISS	ISS	48	48	9.6	9.6		
10	Total Alkalinity	Alk	200	200	200	200	mg/l as $CaCO_3$	*Input value*
11	Minimum Temp	Tmin	14	14	14	14	degC	*Input value*
12	Maximum Temperature	Tmax	22	22	22	22	degC	*Input value*
13	**QUANTIFICATION OF WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
14	Fraction of unbiodegradable particulate COD in influent	fs'up	0.15	0.15	0.04	0.04		*Input value*
15	Fraction of unbiodegradable soluble COD in influent	fs'us	0.07	0.07	0.1155	0.1155		*Input value*
16	Fraction of unbiodegradable soluble organic nitrogen	fN'ous	0.03	0.03	0.035	0.035		*Input value*
17	Influent FSA fraction	fns	0.723	0.723	0.85	0.85		*Input value*
18	Influent COD/TKN ratio	fN'a	0.08	0.08	0.113556	0.1135556		
19	Unbiodegradable soluble COD concentration (=Ste)	Susi	52.5	52.5	52.0	52.0	mgCOD/l	
20	Influent ammonia concentration	Nai	43.4	43.4	43.4	43.4	mgN/l	
21	Unbiodegradable soluble organic nitrogen (=Nouse)	Nousi	1.8	1.8	1.8	1.8	mgN/l	
22	Unbiodegradable particulate organic nitrogen	Noupi	7.6	7.6	1.2	1.2	mgN/l	
23	**STANDARD PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
24	COD/VSS ratio of unbiodegradable particulate COD	fcv	1.480	1.480	1.494	1.494	mgCOD/mgVSS	*Table 4.1*
25	Endogenous residue fraction of volatile solids in influent	f_H	0.200	0.200	0.200	0.200	-	*Table 4.1*
26	VSS/TSS of activated sludge	f_i	0.750	0.750	0.750	0.750	mgVSS/mgTSS	*Table 4.1*
27	UPO VSS nitrogen content	f_n	0.100	0.100	0.100	0.100	mgN/mgVSS	
28	ISS content of OHO's	f_{iOHO}	0.150	0.150	0.150	0.150		
29	VSS yield coefficient	Y_H	0.450	0.450	0.450	0.450	mgVSS/COD	*Table 4.1*
30	**TEMPERATURE SENSITIVE PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
31	Endogenous respiration rate for biomass	b_{EH20}	0.24	0.24	0.24	0.24	/d	*Table 4.1*
32	Theta for endogenous respiration rate for biomass	$b_{EH20}\,\theta$	1.029	1.029	1.029	1.029	-	*Table 4.1*
33	Maximum specific growth rate of ANO's	μ_{AH20}	0.45	0.45	0.45	0.45		*Table 5.3*
34	Theta for maximum specific growth rate of ANO's	$\mu_{AH20}\,\theta$	1.123	1.123	1.123	1.123		*Table 5.3*
35	ANO Half saturation coeffiecient	K_{n20}	1	1	1	1		*Table 5.3*
36	Theta for ANO Half saturation coeffiecient	$K_{n20}\,\theta$	1.123	1.123	1.123	1.123		*Table 5.3*
37	Endogenous respiration rate for ANOs	b_{A20}	0.04	0.04	0.04	0.04		*Table 5.3*
38	Theta for endogenous respiration rate for ANOs	$b_{A20}\,\theta$	1.029	1.029	1.029	1.029		*Table 5.3*
39	ANO yield coefficient	Y_A	0.1	0.1	0.1	0.1		*Table 5.1*
40	Theta for ANO yield coefficient	$Y_A\,\theta$	1	1	1	1		*Table 5.1*
41	**ADJUSTMENT OF TEMPERATURE SENSITIVE PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
42	Temperature	T	14.000	22.000	14.000	22.000	degC	
43	Endogenous respiration rate for biomass	b_{EHT}	0.202	0.254	0.202	0.254	/d	
44	Maximum specific growth rate of ANO's	μ_{AHT}	0.224	0.568	0.224	0.568	/d	
45	ANO Half saturation coeffiecient	K_{nT}	0.499	1.261	0.499	1.261	mgFSA/l	
46	Endogenous respiration rate for ANOs	b_{AT}	0.034	0.042	0.034	0.042	/d	
47	ANO yield coefficient	Y_{AT}	0.100	0.100	0.100	0.100	mgVSS/mgFSA	
48	**SELECT OPERATIONAL PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
49	Sludge Age	Rs	6.6	2.4	6.6	2.4	days	*Sludge Age selected in "Nitrification"*
50	Mixed Liquor Suspended Solids Concentration (MLSS)	Xt	4000	4000	4000	4000	mgTSS/l	*Select MLSS concentration*

51	**PROCESS VOLUME AND CARBONACEOUS MATERIAL REMOVAL**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
52	Mass of COD treated per day	MSti	11250	11250	6716	6716	kgCOD/d	Qi*Sti
53	Mass of biodegradable COD treated per day	MSbi	8775	8775	5672	5672	kgCOD/d	Qi*Sbi
54	Daily mass flow of ISS	MX_{IOi}	720	720	143	143	kgISS/d	
55	Flux of unbiodegradable particulate (UPO) volatile solids in influent	MX_{Ivi}	1140	1140	180	180	kgVSS/d	Qi*(fs'up*Sti/fcv)
56	**OHO VSS**	$\mathbf{MX_{BHv}}$	**11133**	**5857**	**7196**	**3785**		
57	**Endogenous residue VSS**	$\mathbf{MX_{Ev}}$	**2951**	**708**	**1908**	**458**		
58	**Unbiodegradable organics VSS**	$\mathbf{MX_{Iv}}$	**7475**	**2714**	**1179**	**428**		
59	**Total Mass of volatile settleable solids in the system**	**MXv**	**21559**	**9279**	**10282**	**4671**	kgVSS	
60	**Mass of inorganic settleable solids in the system**	$\mathbf{MX_{IO}}$	**6390**	**2592**	**2019**	**909**		
62	**Mass of total settleable solids in the system**	**MXt**	**27950**	**11871**	**12301**	**5580**	kgTSS	
63	**Total biological reactor volume**	$\mathbf{V_P}$	**6987**	**2968**	**3075**	**1395**	m^3	
64	**Average Daily carbenaceous oxygen demand**	**FOc**	**5596**	**4693**	**3597**	**3008**	kgO/d	
65	Active sludge mass fraction w.r.t volatile solids	fav	0.516	0.631	0.700	0.810		
66	Active sludge mass fraction w.r.t total suspended solids	fat	0.387	0.473	0.525	0.608		
67	**Mass of (total) sludge produced/wasted per day**	**MΔXt**	**4263**	**4987**	**1876**	**2344**		
68	Mass of VSS sludge produced/wasted per day	MΔXv	3197	3741	1407	1758		
69	Waste flow rate	Qw	1066	1247	469	586		
70	**COD MASS BALANCE:**		**Raw WW**		**Settled WW**			
71	COD MASS IN: Mass COD entering system		11250.0	11250.0	6716.3	6716.3	kgCOD/d	
72	*Soluble COD in effluent and waste flows*		*787.5*	*787.5*	*775.7*	*775.7*	*kgCOD/d*	
73	*Particulate COD in waste flow*		*4866.8*	*5769.5*	*2343.1*	*2332.1*	*kgCOD/d*	
74	*Carbonaceous oxygen utilised*		*5595.7*	*4693.0*	*3597.4*	*3008.4*	*kgCOD/d*	
75	COD MASS OUT:		11250.0	11250.0	6716.3	6716.3	kgCOD/d	
76	% COD Mass balance		100.0%	100.0%	100.0%	100.0%		
77	**NITRIFICATION**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
78	Safety Factor	Sf	1.25	1.25	1.25	1.25		
79	Minimum sludge age for nitrification	Rsm	6.6	2.4	6.6	2.4	days	
80	**Choose sludge age (Rs>Rsm to ensure nitrification)**	**Rs**	**6.6**	**2.4**	**6.6**	**2.4**	**days**	
81	Maximum design unaerated sludge mass fraction	fxm	-0.038	-0.019	-0.038	-0.019		
82	Design unaerated sludge mass fraction	fxt	0	0	0	0		Set = 0 for fully aerobic
83	Nitrogen required for sludge production	Ns	21.9	26.0	10.5	13.1	mg/l	
84	Effluent ammonia concentration	Nae	2.4	5.6	2.4	5.6	mg/l	
85	Effluent TKN concentration	Nte	4.2	7.4	4.2	7.3	mg/l	
86	Nitrification capacity	Nc	33.8	26.7	36.4	30.6	mg/l	
87	Nitrifier organism mass	MX_A	273	86	291	99	kgVSS	
88	**Oxygen demand for nitrification**	**FOn**	**2320**	**1827**	**2481**	**2088**	**kgO/d**	
89	**Total oxygen demand**	**FOt**	**7916**	**6520**	**6078**	**5096**	**kgO/d**	
90	**Anoxic biological reactor volume**	**Vx**	**0**	**0**	**0**	**0**	$\mathbf{m^3}$	
91	**Aerobic biological reactor volume**	**Va**	**6987**	**2968**	**3075**	**1395**	$\mathbf{m^3}$	
92	**NITROGEN MASS BALANCE:**		**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
93	TKN MASS IN: Mass TKN entering system		900.0	900.0	762.7	762.7	kgN/d	
94	*Soluble TKN in effluent and waste flows*		*571.2*	*510.2*	*605.8*	*566.4*	*kgN/d*	
95	*Particulate TKN in waste flow*		*328.8*	*389.8*	*156.8*	*196.3*	*kgN/d*	
96	TKN MASS OUT:		900.0	900.0	762.7	762.7	kgN/d	
97	% TKN Mass balance		100.0%	100.0%	100.0%	100.0%		

Figure A-4 M&E guideline steady state model for COD removal and nitrification

1	COD REMOVAL AND NITRIFICATION							INPUT CELL
2	Wastewater Engineering: Treatment and Resource Recovery, Metcalf & Eddy / AECOM. 5th Ed. 2014							CALCULATED CELL
3	**WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
4	Influent flow rate	Qi	15	15	14.925	14.925	m^3/d	*Input value*
5	Influent COD concentration	Sti	750	750	450	450	mgCOD/l	*Input value*
6	Influent TKN concentration	Nti	60	60	51.1	51.1	mgN/l	*Input value*
7	Influent phosphorus concentration	Pti	14	14	11.04	11.04	mgP/l	*Input value*
8	Total Settleable Solids	TSS	416.3	416.3	177.2	177.2	mgTSS/l	
9		ISS	48	48	9.6	9.6		
10	Total Alkalinity	Alk	250	250	200	200	mg/l as $CaCO_3$	*Input value*
11	Minimum Temp	Tmin	14	14	14	14	degC	*Input value*
12	Maximum Temperature	Tmax	20	20	22	22	degC	*Input value*
13	**QUANTIFICATION OF WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
14	Fraction of unbiodegradable particulate COD in influent	fs'up	0.15	0.1493	0.04	0.04		*Input value*
15	Fraction of unbiodegradable soluble COD in influent	fs'us	0.07	0.069	0.1155	0.1155		*Input value*
16	Unbiodegradable soluble COD concentration (=Ste)	Susi	51.8	51.8	52.0	52.0	mgCOD/l	
17	**STANDARD PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
18	COD/VSS ratio of unbiodegradable particulate COD	fcv	1.480	1.480	1.494	1.494	mgCOD/mgVSS	*Table 8.14*
19	Endogenous residue fraction of volatile solids in influent	f_H	0.150	0.150	0.150	0.150	-	*Table 8.14 (same as fH in UCT)*
20	VSS/TSS of activated sludge	f_i	0.750	0.750	0.750	0.750	mgVSS/mgTSS	
21	VSS yield coefficient	Y_H	0.450	0.450	0.450	0.450	mgVSS/COD	*Table 8.14*
22	N content of OHO and UPO	f_n	0.120	0.120	0.120	0.120		
23	**TEMPERATURE SENSITIVE PARAMETERS (at 20°C)**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
24	Half saturation for organic removal	Ks	8	8	8	8	mg/L	*Table 8.16*
25	Theta for half saturation for organic removal	Ks θ	1	1	1	1		*Table 8.16*
26	maximum specific growth rate of OHOs	μ_{mT20}	6	6	6	6		
27	Theta for maximum specific growth rate of OHOs	μ_{mT20} θ	1.07	1.07	1.07	1.07		
28	Endogenous respiration rate for biomass	b_{EH20}	0.12	0.12	0.12	0.12	/d	*Table 4.1*
29	Theta for endogenous respiration rate for biomass	b_{EH20} θ	1.04	1.04	1.04	1.04	-	*Table 4.1*
30	Maximum specific growth rate of ANO's	μ_{AH20}	0.9	0.9	0.9	0.9		*Table 8.14*
31	Theta for maximum specific growth rate of ANO's	μ_{AH20} θ	1.072	1.072	1.072	1.072		*Table 8.14*
32	ANO Half saturation coeffiecient	K_{n20}	0.5	0.5	0.5	0.5		*Table 8.14*
33	Theta for ANO Half saturation coeffiecient	K_{n20} θ	1	1	1	1		*Table 8.14*
34	Endogenous respiration rate for ANOs	b_{A20}	0.17	0.17	0.17	0.17		*Table 8.14*
35	Theta for endogenous respiration rate for ANOs	b_{A20} θ	1.029	1.029	1.029	1.029		*Table 8.14*
36	ANO for oxygen Half saturation coeffiecient	$K_{O,AOB20}$	0.5	0.5	0.5	0.5		*Table 8.14*
37	Theta for ANO for oxygen Half saturation coeffiecient	$K_{O,AOB20}$ θ	1	1	1	1		*Table 8.14*
38	ANO yield coefficient	Y_N	0.15	0.15	0.15	0.15		*Table 8.14*
39	Theta for ANO yield coefficient	Y_N θ	1	1	1	1		*Table 8.14*
40	**ADJUSTMENT OF TEMPERATURE SENSITIVE PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
41	Temperature	T	**14**	**20**	**14**	**20**	degC	
42	Half saturation for organic removal	K_{sT}	8.000	8.000	8.000	8.000		
43	maximum specific growth rate of OHOs	μ_{mT}	3.998	6.000	3.998	6.000		
44	Endogenous respiration rate for biomass	b_{EHT}	0.095	0.120	0.095	0.120	/d	
45	Maximum specific growth rate of ANO's	μ_{AHT}	0.593	0.900	0.593	0.900		
46	ANO Half saturation coeffiecient	K_{nT}	0.500	0.500	0.500	0.500		
47	Endogenous respiration rate for ANOs	b_{AT}	0.143	0.170	0.143	0.170		
48	ANO for oxygen Half saturation coeffiecient	$K_{O,AOBT}$	0.500	0.500	0.500	0.500		
49	ANO yield coefficient	Y_N	0.150	0.150	0.150	0.150		
50	**NITRIFICATION (first to determine sludge age)**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
51	Effluent TKN	Nte	3.5	3.8	3.5	3.8	mg/L	
52	Effluent Ammonia	Nae	**2**	**2**	**2**	**2**		
53	Nitrification rate	μ_{AOB}	0.236	0.406	0.236	0.406	g/g.d	
54	Theoretical SRT	SRTt	4.2	2.5	4.2	2.5	days	
55	Safety Factor (peak to average TKN load)	SF	1.5	1.5	1.5	1.5		
56	Calculated SRT	SRT	6.347	3.695	6.347	3.695	days	
57	**Choose Design SRT**	**SRT**	**6.3**	**3.7**	**6.3**	**3.7**	**days**	
58	First estimation of NOx (%)		0.812	0.812	0.812	0.812		
59	Pxbio VSS including assumed NOx		2748.4	2988.7	1783.3	1940.2		
60	Calculate NOx (ammonia oxidised)	NOx	34.5	32.3	33.3	31.7		
61	Recalculate Pxbio - including nitrifiers	P_{xbio}	2731.6	2966.0	1773.7	1926.8		
62	*Nitrogen removed by sludge production (from UCT)*	*Ns*	*21.9*	*23.7*	*14.3*	*15.5*	mg/l	
63	*Nitrate concentration produced (from UCT = NOx)*	*Nc*	*34.6*	*32.5*	*33.3*	*31.8*	mg/l	
64	**SELECT OPERATIONAL PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
65	Sludge Age	Rs	6.3	3.7	6.3	3.7	days	*Select Sludge Age from nitrification calc*
66	Mixed Liquor Suspended Solids Concentration (MLSS)	Xt	**4000**	**4000**	**4000**	**4000**	mgTSS/l	*Select MLSS concentration*
67	Dissolved oxygen concentration in MLSS	So	2	2	2	2	mg/l	*Select DO concentration*
68	**CARBONACEOUS MATERIAL REMOVAL AND PROCESS VOLUM**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
69	Effluent biodegradable soluble COD	S	0.54	0.56	0.54	0.56	mg/l	
70	VSS sludge production OHO active biomass	$P_{xbio\ (active\ biomass)}$	2468.1	2739.2	1591.0	1765.8	kgVSS/d	
71	VSS sludge production OHO endogenous residue	$P_{xbio\ (endog.\ res)}$	222.8	182.2	143.7	117.4	kgVSS/d	
72	VSS sludge production OHO's (excl nitrifiers)	P_{xbio}	2690.9	2921.3	1734.7	1883.2	kgVSS/d	
73	VSS sludge production UPO	P_{xnb}	1134.9	1134.9	179.8	179.8	kgVSS/d	
74	VSS sludge production OHO nitrifiers	P_{xN}	40.7	44.6	39.0	43.6	kgVSS/d	
75	Total VSS sludge production	$P_{x,VSS}$	3866.5	4100.8	1953.5	2106.6	kgVSS/d	
76	Total ISS production	P_{ISS}	720.0	720.0	143.3	143.3		
77	Total TSS sludge production for OHO & UPO	$P_{x,TSS}$	5068.5	5344.3	2409.8	2589.9	kgTSS/d	
78	Mass of MLVSS in aerobic reactor (VSS)	MXv	24282	14986	12151	7622	kgVSS	
79	**Mass of MLSS in aerobic reactor (TSS)**	**MXt**	**32170**	**19745**	**15295**	**9569**	kgTSS	
80	MLVSS/MLSS ratio		1	1	1	1		
81	Mixed Liquor VSS Concentration (MLVSS)	Xv	3019	3036	3178	3186	mgVSS/l	
82	**Volume of aerobic reactor**	$\mathbf{V_P}$	**8043**	**4936**	**3824**	**2392**	m^3	
83	Hydraulic retention time of aerobic reactor	Rhn	13	8	6	4	hrs	
84	**Daily carbonaceous oxygen demand**	**FOc**	**4965**	**4637**	**3201**	**2989**	kgO_2/d	
85	**Nitrification oxygen demand**	**FOn**	**2366**	**2214**	**2269**	**2162**	kgO_2/d	
86	**Total oxygen demand for nitrification**	**FOt**	**7331**	**6851**	**5469**	**5152**	kgO_2/d	

Figure A-5 M&E guideline steady state model for COD removal and nitrification (cont.)

87	**COD MASS BALANCE:**	**Raw WW**		**Settled WW**			
88	COD MASS IN: Mass COD entering system	11250.0	11250.0	6716.3	6716.3	kgCOD/d	
89	*Soluble COD in effluent and waste flows*	776.3	776.3	775.7	775.7	kgCOD/d	
90	*Particulate COD in waste flow*	5662.2	6003.2	2860.3	3082.1	kgCOD/d	
91	*Carbonaceous oxygen utilised*	4964.9	4637.5	3200.6	2989.4	kg02/d	
92	COD MASS OUT:	11253.4	11251.9	6716.6	6717.3	kgCOD/d	
93	% COD Mass balance	100.0%	100.0%	100.0%	100.0%		
94	**NITROGEN MASS BALANCE:**	**Raw WW**		**Settled WW**			
95	TKN MASS IN: Mass TKN entering system	900.0	900.0	762.7	762.7	kgN/d	
96	*Soluble TKN in effluent and waste flows*	*572.2*	*544.1*	*549.8*	*531.5*	*kgN/d*	
97	*Particulate TKN in waste flow*	*327.8*	*355.9*	*212.8*	*231.2*	*kgN/d*	
98	TKN MASS OUT:	900.0	900.0	762.7	762.7	kgN/d	
99	% COD Mass balance	100.0%	100.0%	100.0%	100.0%		

Figure A-6 UCT guideline steady state model for COD removal, nitrification and denitrification of MLE system

1	COD REMOVAL, NITRIFICATION AND DENITRIFICATION							INPUT CELL
2	(Biological Wastewater Treatment: Principles, Modelling and Design Henze et al. 2008)							CALCULATED CELL
3	**WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
4	Influent flow rate	Qi	15	15	14.925	14.925	m^3/d	*Input value*
5	Influent COD concentration	Sti	750	750	450	450	mgCOD/l	*Input value*
6	Influent TKN concentration	Nti	60	60	51.1	51.1	mgN/l	*Input value*
7	Influent phosphorus concentration	Pti	14.00	14	11.04	11.04	mgP/l	*Input value*
8	Influent TSS	TSS	416.3	416.3	177.2	177.2		
9	Influent ISS	ISS	48	48	9.6	9.6		
10	Total Alkalinity	Alk	200	200	200	200	mg/l as $CaCO_3$	*Input value*
11	Minimum Temp	Tmin	14	14	14	14	degC	*Input value*
12	Maximum Temperature	Tmax	22	22	22	22	degC	*Input value*
13	**QUANTIFICATION OF WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
14	Fraction of unbiodegradable particulate COD in influent	fs'up	0.1493	0.1493	0.04	0.04		*Input value*
15	Fraction of unbiodegradable soluble COD in influent	fs'us	0.0693	0.0693	0.116	0.1155		*Input value*
16	Influent readily biodegradable COD fraction	fsb's	0.2509	0.2509	0.387	0.3867		
17	Fraction of unbiodegradable soluble organic nitrogen	fN'ous	0.0299	0.0299	0.035	0.0351		*Input value*
18	Influent FSA fraction	fn'a	0.723	0.723	0.850	0.8498		*Input value*
19	Influent COD/TKN ratio	fns	0.08	0.08	0.114	0.114		
20	Unbiodegradable soluble COD concentration (=Ste)	Susi	52.0	51.975	52.0	52.0	mgCOD/l	
21	Influent ammonia concentration	Nai	43.4	43.4	43.4	43.4	mgN/l	
22	Unbiodegradable soluble organic nitrogen (=Nouse)	Nousi	1.8	1.794	1.8	1.8	mgN/l	
23	Unbiodegradable particulate organic nitrogen	Noupi	7.6	7.6	1.2	1.2	mgN/l	
24	**STANDARD PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
25	COD/VSS ratio of unbiodegradable particulate COD	fcv	1.481	1.481	1.494	1.494	mgCOD/mgVSS	*Table 4.1*
26	Endogenous residue fraction of volatile solids in influent	f_H	0.200	0.200	0.200	0.200	-	*Table 4.1*
27	VSS/TSS of activated sludge	f_i	0.750	0.750	0.750	0.750	mgVSS/mgTSS	*Table 4.1*
28	ISS content of OHO's	f_{iOHO}	0.150	0.150	0.150	0.150		
29	UPO VSS nitrogen content	f_n	0.100	0.100	0.100	0.100	mgN/mgVSS	
30	VSS yield coefficient	Y_H	0.450	0.450	0.450	0.450	mgVSS/COD	*Table 4.1*
31	**TEMPERATURE SENSITIVE PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
32	Endogenous respiration rate for biomass	b_{EH20}	0.24	0.24	0.24	0.24	/d	*Table 4.1*
33	Theta for endogenous respiration rate for biomass	$b_{EH20}\theta$	1.029	1.029	1.029	1.029	-	*Table 4.1*
34	Maximum specific growth rate of ANO's	μ_{AH20}	0.45	0.45	0.45	0.45		*Table 5.3*
35	Theta for maximum specific growth rate of ANO's	$\mu_{AH20}\theta$	1.123	1.123	1.123	1.123		*Table 5.3*
36	ANO Half saturation coeffiecient	K_{n20}	1	1	1	1		*Table 5.3*
37	Theta for ANO Half saturation coeffiecient	$K_{n20}\theta$	1.123	1.123	1.123	1.123		*Table 5.3*
38	Endogenous respiration rate for ANOs	b_{A20}	0.04	0.04	0.04	0.04		*Table 5.3*
39	Theta for endogenous respiration rate for ANOs	$b_{A20}\theta$	1.029	1.029	1.029	1.029		*Table 5.3*
40	ANO yield coefficient	Y_A	0.1	0.1	0.1	0.1		*Table 5.1*
41	Theta for ANO yield coefficient	$Y_A\theta$	1	1	1	1		*Table 5.1*
42	K1 specific denitrification rate	K_{120}	0.72	0.72	0.72	0.72		
43	Theta for K1 specific denitrification rate	$K_{120}\theta$	1.2	1.2	1.2	1.2		
44	K2 specific denitrification rate	K_{220}	0.101	0.101	0.101	0.101		
45	Theta for K2 specific denitrification rate	$K_{220}\theta$	1.08	1.08	1.08	1.08		
46	**ADJUSTMENT OF TEMPERATURE SENSITIVE PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
47	Temperature	T	14.000	22.000	14.000	22.000	degC	
48	Endogenous respiration rate for biomass	b_{EHT}	0.202	0.254	0.202	0.254	/d	
49	Maximum specific growth rate of ANO's	μ_{AHT}	0.224	0.568	0.224	0.568	/d	
50	ANO Half saturation coeffiecient	K_{nT}	0.499	1.261	0.499	1.261	mgFSA/l	
51	Endogenous respiration rate for ANOs	b_{AT}	0.034	0.042	0.034	0.042	/d	
52	ANO yield coefficient	Y_{AT}	0.100	0.100	0.100	0.100	mgVSS/mgFSA	
53	K1 specific denitrification rate	K_{120}	0.241	1.037	0.241	1.037		
54	K2 specific denitrification rate	K_{220}	0.064	0.118	0.064	0.118		
55	**SELECT OPERATIONAL PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
56	Sludge Age	Rs	11.3	3.1	17.8	4.1	days	*Sludge Age selected in "Balanced Sludge Age"*
57	Mixed Liquor Suspended Solids Concentration (MLSS)	Xt	**4000**	**4000**	**4000**	**4000**	mgTSS/l	*Select MLSS concentration*
58	**PROCESS VOLUME AND CARBONACEOUS MATERIAL REMOVA**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
59	Mass of COD treated per day	MSti	11250	11250	6716	6716	kgCOD/d	Qi*Sti
60	Mass of biodegradable COD treated per day	MSbi	8791	8791	5672	5672	kgCOD/d	Qi*Sbi
61	Daily mass flow of ISS	MX_{IOi}	720	720	143	143		
62	Flux of unbiodegradable particulate (UPO) volatile solids in influent	MX_{Ivi}	1134	1134	180	180	kgVSS/d	Qi*(fs'up*Sti/fcv)
63	**OHO VSS**	MX_{BHv}	**13601**	**6915**	**9881**	**5153**		
64	**Endogenous residue VSS**	MX_{Ev}	**6202**	**1105**	**7118**	**1086**		
65	**Unbiodegradable organics VSS**	MX_{Iv}	**12789**	**3567**	**3203**	**746**		
66	**Total Mass of volatile settleable solids in the system**	**MXv**	**32592**	**11588**	**20202**	**6985**	kgVSS	
67	**Mass of inorganic settleable solids in the system**	MX_{IO}	**10160**	**3302**	**4035**	**1367**	kgISS	
68	**Mass of total settleable solids in the system**	**MXt**	**42752**	**14890**	**24237**	**8352**	kgTSS	
69	**Total biological reactor volume**	V_P	**10688**	**3723**	**6059**	**2088**	m^3	
70	**Average Daily carbenaceous oxygen demand**	**FOc**	**6190**	**5014**	**4246**	**3424**	kgO/d	
71	Active sludge mass fraction w.r.t volatile solids	fav	0.417	0.597	0.489	0.738		
72	Active sludge mass fraction w.r.t total suspended solids	fat						
73	**Mass of (total) sludge produced/wasted per day**	**MΔXt**	**3791**	**4734**	**1360**	**2014**	kgTSS/d	
74	Mass of VSS sludge produced/wasted per day	MΔXv	2843	3550	1020	1511	kgVSS/d	
75	Waste flow rate	Qw	948	1183	340	504	m3/d	
76	**COD MASS BALANCE:**		**Raw WW**		**Settled WW**			
77	COD MASS IN: Mass COD entering system		11250.0	11250.0	6716.3	6716.3	kgCOD/d	
78	*Soluble COD in effluent and waste flows*		*779.6*	*779.6*	*775.7*	*775.7*	*kgCOD/d*	
79	*Particulate COD in waste flow*		*4280.3*	*5456.1*	*1694.2*	*2516.7*	*kgCOD/d*	
80	*Carbonaceous oxygen utilised*		*6190.0*	*5014.2*	*4246.3*	*3423.8*	*kgCOD/d*	
81	COD MASS OUT:		11250.0	11250.0	6716.3	6716.3	kgCOD/d	
82	% COD Mass balance		**100.0%**	**100.0%**	**100.0%**	**100.0%**		
83	**NITRIFICATION**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
84	Safety Factor	Sf	1.25	1.25	1.25	1.25		
85	Minimum sludge age for nitrification	Rsm	6.6	2.4	6.6	2.4	days	
86	**Choose sludge age (Rs>Rsm to ensure nitrification)**	**Rs**	**11.28**	**3.15**	**17.81**	**4.15**	**days**	**Set = SRTbal**
87	Maximum design unaerated sludge mass fraction	fxm	0.318	0.206	0.500	0.375		
88	Design unaerated sludge mass fraction	fxt	0.318	0.206	0.500	0.375		Should not be more than 0.6
89	Nitrogen required for sludge production	Ns	19.3	24.6	7.6	11.3	mg/l	
90	Effluent ammonia concentration	Nae	2.0	5.0	2.0	5.0	mg/l	
91	Effluent TKN concentration	Nte	3.8	6.8	3.8	6.8	mg/l	
92	Nitrification capacity	Nc	36.9	28.6	39.7	33.0	mg/l	
93	Nitrifier organism mass	MX_A	453	119	660	174	kgVSS	
94	Oxygen demand for nitrification	FOn	2533	1961	2709	2249	kgO/d	
95	Total oxygen demand	FOt	8723	6975	6955	5673	kgO/d	
96	**Anoxic biological reactor volume**	**Vx**	**3401**	**769**	**3027**	**784**	m^3	
97	**Aerobic biological reactor volume**	**Va**	**7287**	**2954**	**3033**	**1304**	m^3	

Figure A-7 UCT guideline steady state model for COD removal, nitrification and denitrification of MLE system (cont.)

98	**NITROGEN MASS BALANCE:**		**Raw WW**		**Settled WW**			
99	TKN MASS IN: Mass TKN entering system		900.0	900.0	762.7	762.7	kgN/d	
100	*Soluble TKN in effluent and waste flows*		*611.0*	*531.6*	*649.3*	*594.2*	*kgN/d*	
101	*Particulate TKN in waste flow*		*289.0*	*368.4*	*113.4*	*168.5*	*kgN/d*	
102	TKN MASS OUT:		900.0	900.0	762.7	762.7	kgN/d	
103	% COD Mass balance		100.0%	100.0%	100.0%	100.0%		
104	**DENITRIFICATION**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
105	Maximum anoxic sludge mass fraction available for denitrification	fxdm	0.318	0.206	0.500	0.375		
106	Aerobic mass fraction	fa	0.682	0.794	0.500	0.625		
107	Denitrification potential of primary anoxic reactor	Dp1	35.512	28.361	37.887	32.111	mg/l	
108			532.684	425.417	565.459	479.250	kg/d	
109		rbCOD	17.149	17.149	16.838	16.838	mg/l	
110			257.230	257.230	251.311	251.311	kg/d	
111		sbCOD	18.364	11.212	21.048	15.272	mg/l	
112			275.454	168.187	314.148	227.939	kg/d	
113	DO concentration in a-recycle	Oa	2.00	2.00	2.00	2.00		
114	DO concentration in s-recycle	Os	1.00	1.00	1.00	1.00		
115	s-recycle ratio	s	1.00	1.00	1.00	1.00		
116	A	A	0.70	0.70	0.70	0.70		
117	B	B	3.2	2.0	3.6	2.6		
118	C	C	33.4	27.4	35.3	30.5		
119	Optimum a-recycle	aopt	5.0	5.0	5.0	5.0		
120	Select a-recycle ratio (if aopt> aprac, set a to aprac (=6))	aprac	5.00	5.00	5.00	5.00		
121	Effluent nitrate concentration at aprac	Nne	5.3	4.1	5.7	4.7	mg/l	
122	Effluent TKN concentration	Nte	5.8	11.9	5.8	11.9	mg/l	
123	**Total effluent N**	**N**	**11.1**	**16.0**	**11.5**	**16.6**	mg/l	
124	**Percentage of nitrogen removal**	**%**	**82%**	**73%**	**78%**	**68%**		
125	**Oxygen recovered by denitrification**	**FOd**	**1422**	**934**	**1534**	**1116**	kgO/d	
126	**Total oxygen demand**	**FOt**	**7300**	**6041**	**5422**	**4557**	kgO/d	
127								
128	**Check nitrate load on anoxic, with selected recycles**	**Nnlp**	**532.65**	**425.39**	**565.43**	**479.22**	kg/d	
130	**CALCULATE BALANCED SRT:**	SRTbal	**11.28**	**3.15**	**17.81**	**4.15**	days	**Use Goal Seek to set 'Nti calc - Nti' = 0 by changing 'SRTbal'**
131		fxm	0.318	0.206	0.500	0.375		
132		fx1min	0.078	0.036	0.105	0.047		
133		fx1=fxm	0.318	0.206	0.500	0.375		
134		fx1	0.318	0.206	0.500	0.375		
135		Dp1	35.5	28.4	37.9	32.1		
136		aprac	5.0	5.0	5.0	5.0		
137		s	1.0	1.0	1.0	1.0		
138		Oa	2.0	2.0	2.0	2.0		
139		Os	1.0	1.0	1.0	1.0		
140		Nc	36.9	28.6	39.7	33.0	mg/l	
141		L MLE,VSS	2.9	1.0	3.0	1.0		
142		Ns	19.3	24.6	7.6	11.3	mg/l	
143		Nae	2.0	5.0	2.0	5.0	mg/l	
144		Nte	3.8	6.8	3.8	6.8	mg/l	
145		Nti calc	**60.00**	**60.00**	**51.10**	**51.10**	mg/l	
146		Nti	**60.00**	**60.00**	**51.10**	**51.10**	mg/l	
147		Nti calc- Nti	0.0	0.0	0.0	0.0		

Figure A-8 M&E guideline steady state model for COD removal, nitrification and denitrification of MLE system

1	COD REMOVAL, NITRIFICATION AND DENITRIFICATION							INPUT CELL
2	Wastewater Engineering: Treatment and Resource Recovery, Metcalf & Eddy / AECOM. 5th Ed. 2014							CALCULATED CELL
3	**WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
4	Influent flow rate	Qi	15	15	14.925	14.925	m^3/d	*Input value*
5	Influent COD concentration	Sti	750	750	450	450	mgCOD/l	*Input value*
6	Influent TKN concentration	Nti	60	60	51.1	51.1	mgN/l	*Input value*
7	Influent phosphorus concentration	Pti	14.00	14	11.04	11.04	mgP/l	*Input value*
8	Total Settleable Solids	TSS	416.3	416.3	177.2	177.2	mgTSS/l	
9		ISS	48	48	9.6	9.6		
10	Total Alkalinity	Alk	200	200	200	200	mg/l as $CaCO_3$	*Input value*
11	Minimum Temp	Tmin	14	14	14	14	degC	*Input value*
12	Maximum Temperature	Tmax	22	22	22	22	degC	*Input value*
13	**QUANTIFICATION OF WASTEWATER CHARACTERISTICS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
14	Fraction of unbiodegradable particulate COD in influent	fs'up	0.1493	0.1493	0.04	0.04		*Input value*
15	Fraction of unbiodegradable soluble COD in influent	fs'us	0.0693	0.0693	0.1155	0.1155		*Input value*
16	Influent readily biodegradable COD fraction	fsb's	0.2509	0.2509	0.3867	0.3867		
17	Unbiodegradable soluble COD concentration (=Ste)	Susi	52.0	51.975	52.0	52.0	mgCOD/l	
18	**STANDARD PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
19	COD/VSS ratio of unbiodegradable particulate COD	fcv	1.480	1.480	1.494	1.494	mgCOD/mgVSS	*Table 8.14*
20	Endogenous residue fraction of volatile solids in influent	f_H	0.150	0.150	0.150	0.150	-	*Table 8.14 (same as fH in UCT)*
21	VSS/TSS of activated sludge	f_i	0.750	0.750	0.750	0.750	mgVSS/mgTSS	
22	VSS yield coefficient	Y_H	0.450	0.450	0.450	0.450	mgVSS/COD	*Table 8.14*
23	N content of OHO and UPO	f_n	0.120	0.120	0.120	0.120		
24	**TEMPERATURE SENSITIVE PARAMETERS (at 20˚C)**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
25	Half saturation for organic removal	Ks	8	8	8	8	mg/L	*Table 8.16*
26	Theta for half saturation for organic removal	Ks θ	1	1	1	1		*Table 8.16*
27	maximum specific growth rate of OHOs	μ_{mT20}	6	6	6	6		
28	Theta for maximum specific growth rate of OHOs	μ_{mT20} θ	1.07	1.07	1.07	1.07		
29	Endogenous respiration rate for biomass	b_{EH20}	0.12	0.12	0.12	0.12	/d	*Table 4.1*
30	Theta for endogenous respiration rate for biomass	b_{EH20} θ	1.04	1.04	1.04	1.04	-	*Table 4.1*
31	Maximum specific growth rate of ANO's	μ_{AH20}	0.9	0.9	0.9	0.9		*Table 8.14*
32	Theta for maximum specific growth rate of ANO's	μ_{AH20} θ	1.072	1.072	1.072	1.072		*Table 8.14*
33	ANO Half saturation coeffiecient	K_{n20}	0.5	0.5	0.5	0.5		*Table 8.14*
34	Theta for ANO Half saturation coeffiecient	K_{n20} θ	1	1	1	1		*Table 8.14*
35	Endogenous respiration rate for ANOs	b_{A20}	0.17	0.17	0.17	0.17		*Table 8.14*
36	Theta for endogenous respiration rate for ANOs	b_{A20} θ	1.029	1.029	1.029	1.029		*Table 8.14*
37	ANO for oxygen Half saturation coeffiecient	$K_{O,AOB20}$	0.5	0.5	0.5	0.5		*Table 8.14*
38	Theta for ANO for oxygen Half saturation coeffiecient	$K_{O,AOB20}$ θ	1	1	1	1		*Table 8.14*
39	ANO yield coefficient	Y_N	0.15	0.15	0.15	0.15		*Table 8.14*
40	Theta for ANO yield coefficient	Y_N θ	1	1	1	1		*Table 8.14*
41	**ADJUSTMENT OF TEMPERATURE SENSITIVE PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
42	Temperature	T	14.000	22.000	14.000	22.000	degC	
43	Half saturation for organic removal	K_{sT}	8.000	8.000	8.000	8.000		
44	maximum specific growth rate of OHOs	μ_{mT}	3.998	6.869	3.998	6.869		
45	Endogenous respiration rate for biomass	b_{EHT}	0.095	0.130	0.095	0.130	/d	
46	Maximum specific growth rate of ANO's	μ_{AHT}	0.593	1.034	0.593	1.034		
47	ANO Half saturation coeffiecient	K_{nT}	0.500	0.500	0.500	0.500		
48	Endogenous respiration rate for ANOs	b_{AT}	0.143	0.180	0.143	0.180		
49	ANO for oxygen Half saturation coeffiecient	$K_{O,AOBT}$	0.500	0.500	0.500	0.500		
50	ANO yield coefficient	Y_N	0.150	0.150	0.150	0.150		
51	**NITRIFICATION (first to determine aerobic sludge age)**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
52	Effluent TKN	Nte	3.8	3.8	3.8	3.8	mg/L	
53	Effluent Ammonia	Nae	**2**	**2**	**2**	**2**		
54	Nitrification rate	μ_{AOB}	0.236	0.482	0.236	0.482	g/g.d	
55	Theoretical SRT	SRTt	4.2	2.1	4.2	2.1	days	
56	Safety Factor (peak to average TKN load)	SF	1.5	1.5	1.5	1.5		
57	Calculated SRT	SRT	6.347	3.113	6.347	3.113	days	
58	**Choose Design SRT**	**SRT**	**6.3**	**3.1**	**6.3**	**3.1**	**days**	
59	First estimation of NOx (%)		0.850	0.850	0.850	0.850		
60	Pxbio VSS including assumed NOx		2750.0	3059.0	1785.6	1987.6		
61	Calculate NOx (ammonia oxidised)	NOx	34.2	31.7	32.9	31.3		
62	Recalculate Pxbio - including nitrifiers	P_{xbio}	2730.2	3031.2	1773.3	1970.2		
63	*Nitrogen removed by sludge production (from UCT)*	*Ns*	*21.8*	*24.2*	*14.3*	*15.8*		
64	*Nitrate concentration produced (from UCT = NOx)*	*Nc*	*34.4*	*32.0*	*33.0*	*31.5*		
65	**SELECT OPERATIONAL PARAMETERS**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
66	Sludge Age	Rs	6.3	3.1	6.3	3.1	days	*Select Sludge Age from nitrification calc*
67	Mixed Liquor Suspended Solids Concentration (MLSS)	Xt	**4000**	**4000**	**4000**	**4000**	mgTSS/l	*Select MLSS concentration*
68	Dissolved oxygen concentration in MLSS	So	2	2	2	2	mg/l	*Select DO concentration*
69	**CARBONACEOUS MATERIAL REMOVAL AND PROCESS VOLUME**	**SYMBOL**	**Raw WW**		**Settled WW**		**UNITS**	**NOTE**
70	Effluent biodegradable soluble COD	S	0.54	0.56	0.54	0.56	mg/l	
71	**VSS sludge production OHO active biomass**	$P_{xbio\ (active\ biomass)}$	**2467.1**	**2814.9**	**1591.0**	**1815.2**	kgVSS/d	
72	**VSS sludge production OHO endogenous residue**	$P_{xbio\ (endog.\ res)}$	**222.8**	**170.6**	**143.7**	**110.0**	kgVSS/d	
73	**VSS sludge production OHO's (excl nitrifiers)**	P_{xbio}	**2689.9**	**2985.5**	**1734.7**	**1925.2**	kgVSS/d	
74	**VSS sludge production UPO**	P_{xnb}	**1134.9**	**1134.9**	**179.8**	**179.8**	kgVSS/d	
75	**VSS sludge production OHO nitrifiers**	P_{xN}	**60.1**	**73.5**	**50.9**	**62.3**	kgVSS/d	
76	**VSS sludge production for OHO & UPO**	$P_{x,VSS}$	**3884.9**	**4193.9**	**1965.4**	**2167.4**	kgVSS/d	
77	**Total ISS production**	P_{ISS}	**720.0**	**720.0**	**143.3**	**143.3**		
78	**Total TSS sludge production for OHO & UPO**	$P_{x,TSS}$	**5090.2**	**5453.7**	**2423.8**	**2661.4**	kgTSS/d	
79	Mass of MLVSS in aerobic reactor (VSS)	MXv	24657	13053	12475	6746	kgVSS	
80	**Mass of MLSS in aerobic reactor (TSS)**	**MXt**	**32307**	**16975**	**15384**	**8284**	kgTSS	
81	MLVSS/MLSS ratio		0.763	0.769	0.811	0.814		
82	Mixed Liquor VSS Concentration (MLVSS)	Xv	3053	3076	3244	3257	mgVSS/l	
83	**Volume of aerobic reactor**	V_a	**8077**	**4244**	**3846**	**2071**	m^3	
84	Hydraulic retention time of aerobic reactor	Rhn	12.9	6.8	6.2	3.3	hrs	
85	**Daily carbonaceous oxygen demand**	**FOc**	**4963**	**4543**	**3201**	**2930**	kgO_2/d	
86	**Nitrification oxygen demand**	**FOn**	**2344**	**2175**	**2247**	**2136**	kgO_2/d	
87	**Total oxygen demand**	**FOt**	**7307**	**6718**	**5448**	**5066**	kgO_2/d	

Figure A-9 M&E guideline steady state model for COD removal, nitrification and denitrification of MLE system (cont.)

88	DENITRIFICATION (PRE-DENITRIFICATION)	SYMBOL	Raw WW		Settled WW		UNITS	NOTE
89	Required effluent nitrate concentration	Nne req	5.0	5.0	5.0	5.0	mg/l	
90	s recycle ratio (= return sludge ratio in SST sizing)	s	1.0	1.0	1.0	1.0		
91	a recycle ratio	a	4.87	4.39	4.61	4.29		
94	**nitrate load on anoxic reactor**		**440.4**	**404.3**	**418.5**	**394.9**	kg/d	
95	OHO concentration	Xb	1938.7	2064.6	2625.6	2728.2	mg OHOVSS/l	
96	Assume anoxic reactor nominal retention time	HRTanox	**1.431**	**0.999**	**0.844**	**0.622**	hrs	**Use Goal Seek to set 'nitrate load - nitrate removal capacity' to zero by changing HRT**
97	**Anoxic reactor volume**	**Vx**	**894.4**	**624.3**	**525.0**	**387.0**	m3	
98	BOD		366.3	366.3	237.5	237.5	mg/l	
99	Anoxic reactor F/M ration (OHO biomass)	F/M	3.169	4.262	2.571	3.358	90000	
100	Fraction rbCOD/bCOD		25.09	25.09	38.67	38.67	450000	g/d Nox feed
101		b0	0.2210	0.2210	0.2491	0.2491	440374.29	
102		b1	0.1282	0.1282	0.1509	0.1509		
103	Specific denitrification rate	SDNRb	0.3493	0.3493	0.4001	0.4001		
104	Temperature adjusted specific denitrification rate	SDNRt	0.2994	0.3677	0.3430	0.4212		
105	Specific denitrification rate adjusted for a-recycle	SDNRadj	0.2540	0.3136	0.3036	0.3740		
106	Specific denitrification rate adjusted for MLVSS	SDNR MLVSS	0.1613	0.2105	0.2458	0.3133		
107	Nitrate removal capacity of anoxic		440.4	404.3	418.5	394.9	kg/d	
108	*Nitrate load / nitrate removal capacity ratio (adjust HRT until ratio = 1)*		*1.0000*	*1.0000*	*1.0000*	*1.0000*		
109	Nitrate concentratiion denitrified		29.4	27.4	28.3	27.0	mg/l	
110		Nne	4.9	4.6	4.7	4.5		
111	**Oxygen recovered by denitrification**	**FOd**	**1263.4**	**1174.9**	**1208.9**	**1151.0**	kgO_2/d	
112	**Total oxygen demand for denitrification**	**FOt**	**6044.0**	**5543.1**	**4238.6**	**3914.8**	kgO_2/d	
113		**% N rem**	**94%**	**94%**	**93%**	**93%**		
114	**Total system volume (aerobic+anoxic)**	**V**	**8971.2**	**4868.0**	**4371.1**	**2457.9**	m3	
115	**Anoxic mass fraction**	**fx**	**0.100**	**0.128**	**0.120**	**0.157**		
116	**Waste flow rate from aerobic reactor**	**Qw**	**1272.5**	**1363.4**	**606.0**	**665.4**	m3/d	
117	**System SRT**	**SRTt**	**7.050**	**3.6**	**7.2**	**3.7**	days	
118	nitrate load - nitrate removal capacity		*0.0*	*0.0*	*0.0*	*0.0*		
119	**COD MASS BALANCE:**		**Raw WW**		**Settled WW**			
120	COD MASS IN: Mass COD entering system		11250.0	11250.0	6716.3	6716.3	kgCOD/d	
121	*Soluble COD in effluent and waste flows*		779.6	779.6	775.7	775.7	kgCOD/d	
122	*Particulate COD in waste flow*		5749.6	6207.0	2936.4	3238.1	kgCOD/d	
123	*Carbonaceous oxygen utilised*		4963.0	4543.0	3200.6	2929.6	kg02/d	
124	COD MASS OUT:		11252.3	11250.5	6716.7	6716.4	kgCOD/d	
125	% COD Mass balance		100.0%	100.0%	100.0%	100.0%		
126	**NITROGEN MASS BALANCE:**		**Raw WW**		**Settled WW**			
127	TKN MASS IN: Mass TKN entering system		900.0	900.0	762.7	762.7	kgN/d	
128	*Soluble TKN in effluent and waste flows*		*572.4*	*536.3*	*549.9*	*526.2*	*kgN/d*	
129	*Particulate TKN in waste flow*		*327.6*	*363.7*	*212.8*	*236.4*	*kgN/d*	
130	TKN MASS OUT:		900.0	900.0	762.7	762.7	kgN/d	
131	% COD Mass balance		100.0%	100.0%	100.0%	100.0%		

Figure A-10 UCT guideline steady state model for SST sizing

172	SST SIZING	SYMBOL	Raw WW		Settled WW		UNITS	NOTE
173	Diluted sludge volume index DSVI	DSVI	150	150	150	150		
174	Stirred sludge volume index SSVI	SSVI	101	101	101	101		
175	V_0/n	V_0/n	13.600	13.600	13.600	13.600		
176	n	n	0.435	0.435	0.435	0.435		
177	V_0	V_0	5.909	5.909	5.909	5.909		
178	PWWF factor	f_q	2	2	2	2		
179	Surface area required	A	751.8	751.8	748.0	748.0	m^2	
180	Number of clarifiers	N	3	3	3	3		
181	Diameter of each clarifier	D	17.9	17.9	17.8	17.8	m	

Figure A-11 M&E guideline steady state model for SST sizing

132	SST SIZING	SYMBOL	Raw WW		Settled WW			NOTE
133	Return sludge mass concentration	X_R	8000	8000	8000	8000	mg/l	
134	Return sludge recycle ratio	R	1.0	1.0	1.0	1.0		
135	Hydraulic application rate	q_A	20	20	20	20	m2/m2.d	
136	Area required	A	750.0	750.0	746.3	746.3	m2	
137	Number of clarifiers	N	3	3	3	3		
138	Diameter of each clarifier	D	17.8	17.8	17.8	17.8	m	
139	Solids loading	Ls	6.7	6.7	6.7	6.7	kgMLSS/m2.h	

B. Dynamic Simulation with UCTOLD

Screenshots of the UCTOLD dynamic simulations of the MLE systems of the UCT-sized and M&E-sized plants are given below:

Figure B-1 UCTOLD program

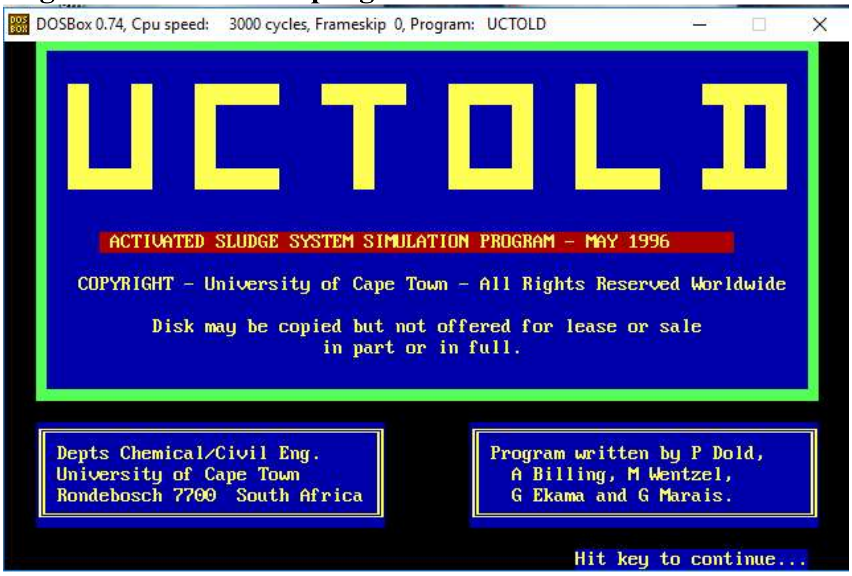


Figure B-2 UCTOLD flowrate and volume unit selection

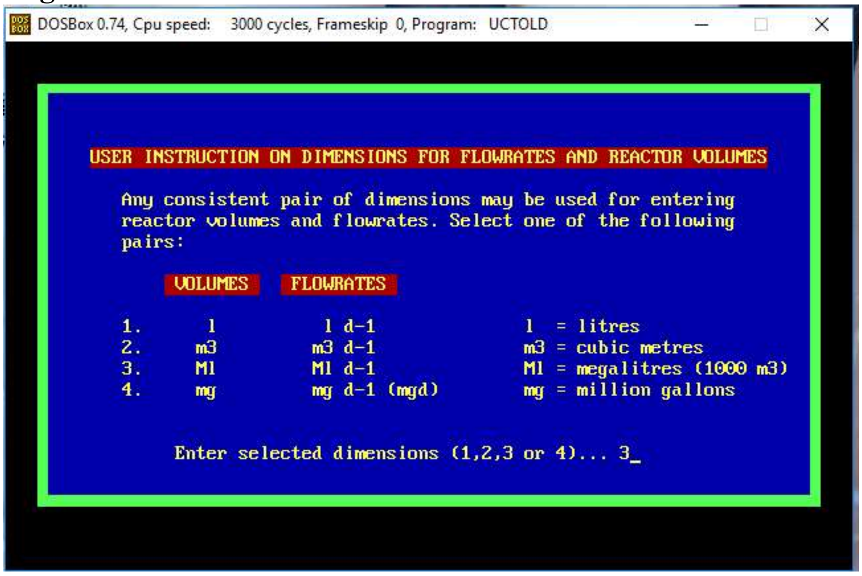
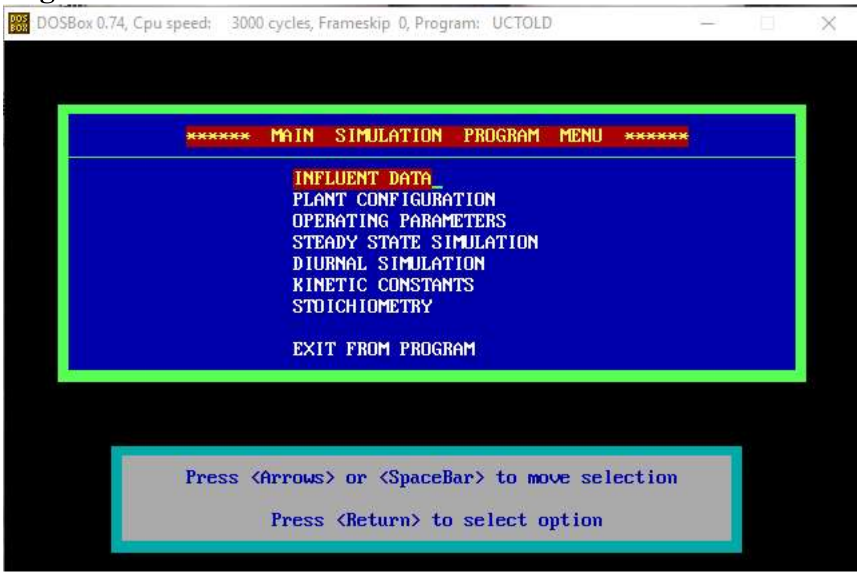


Figure B-3 UCTOLD main menu



B.1 Influent Data

Figure B-4 Inputting diurnal influent data

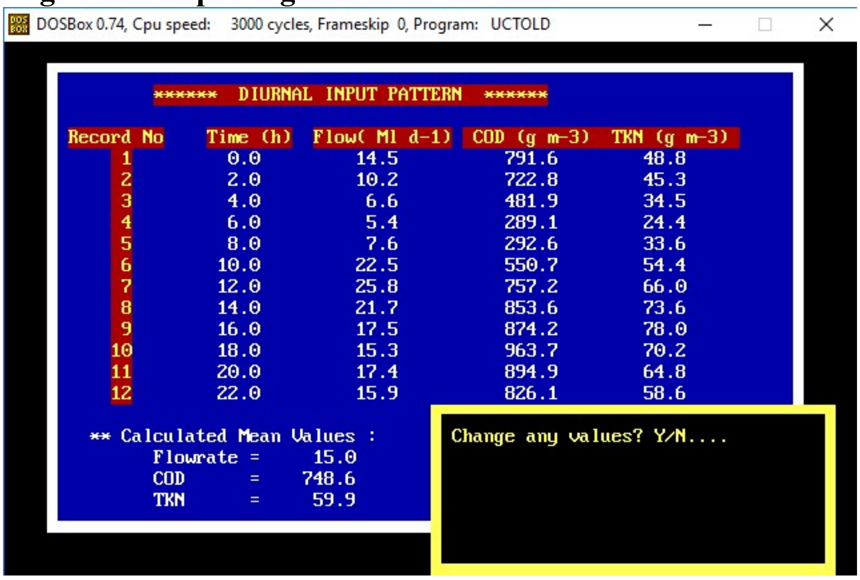
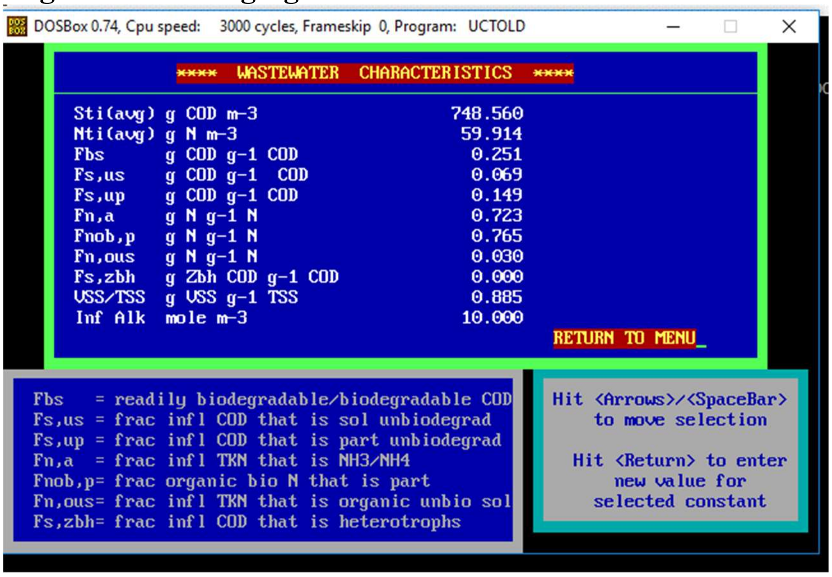


Figure B-5 Changing default wastewater characteristics



B.2 Plant configuration

Figure B-6 UCT-sized plant configuration inputs

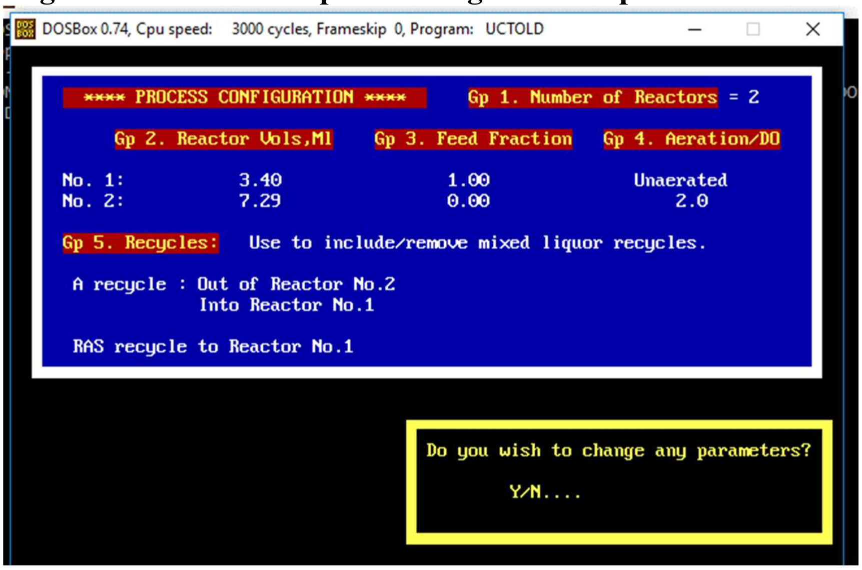
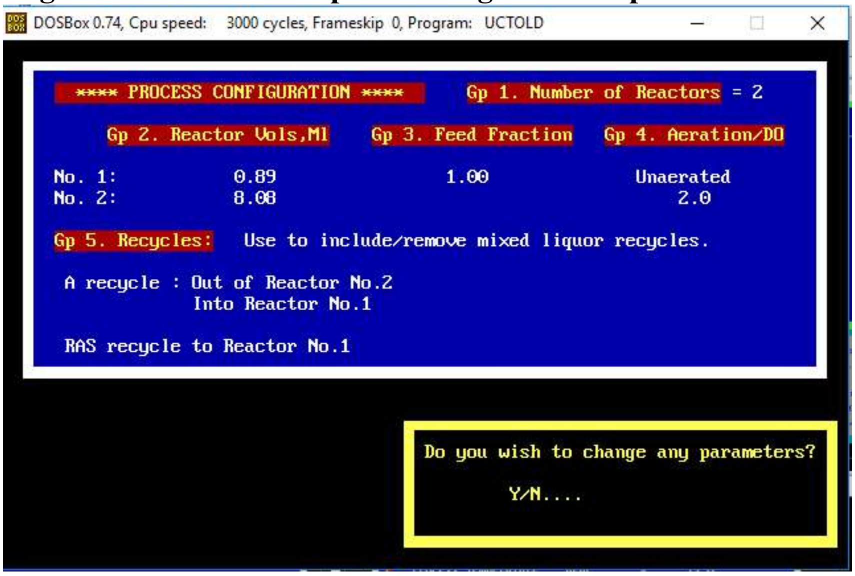


Figure B-7 M&E-sized plant configuration inputs



B.3 Plant operating parameters

Figure B-8 UCT-sized plant operating parameter inputs

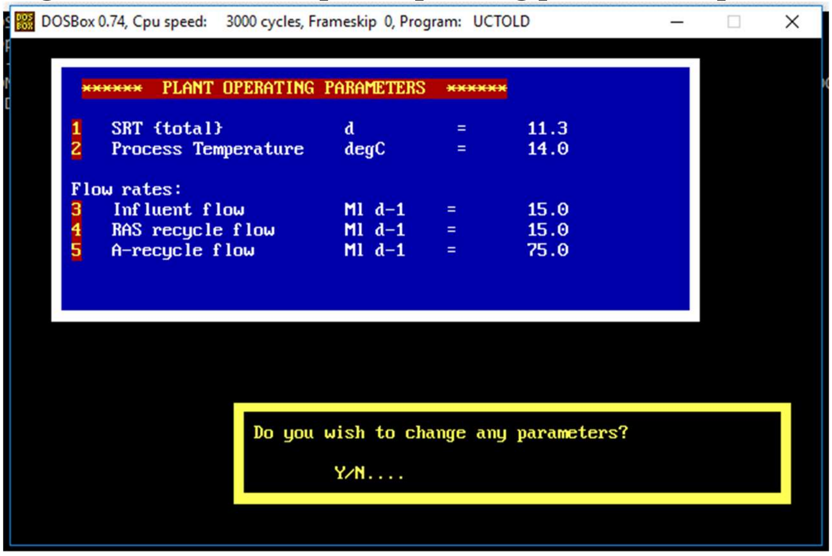
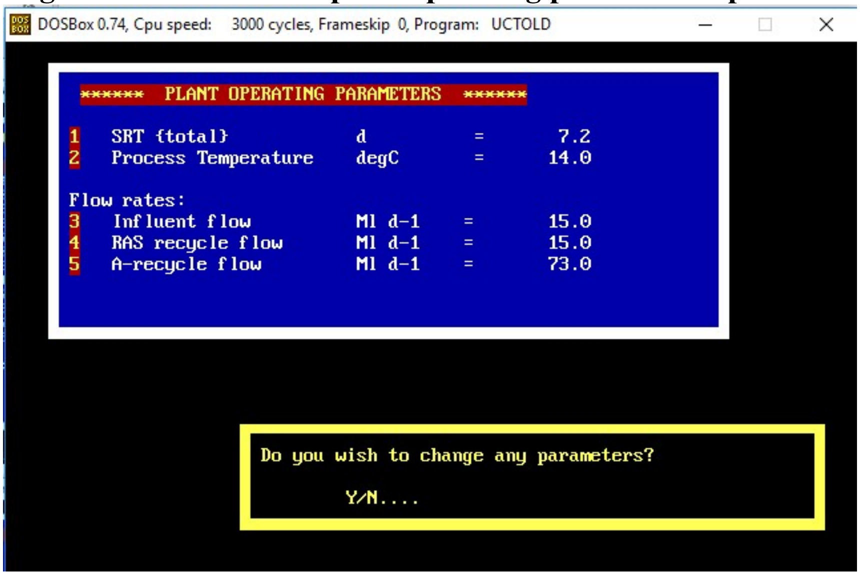


Figure B-9 M&E-sized plant operating parameter inputs



B.4 Kinetic constants

Figure B-10 Kinetic constants menu

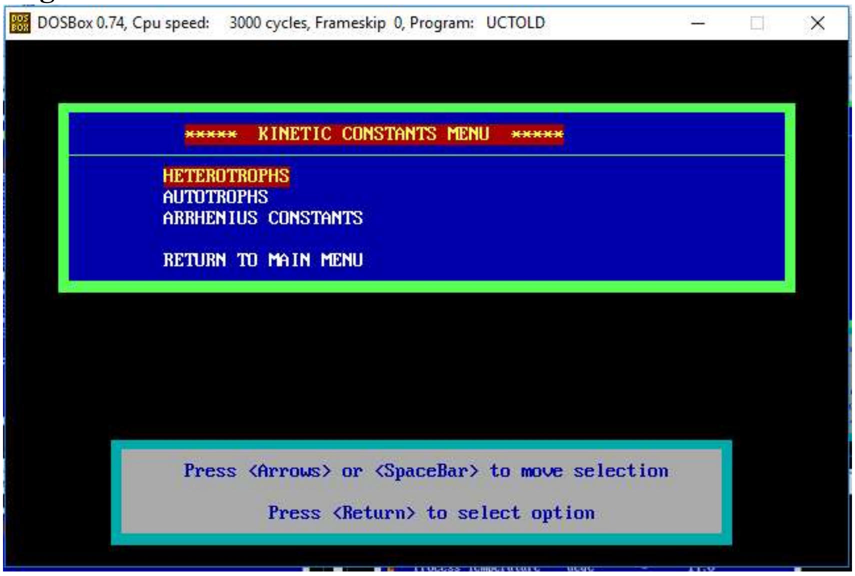


Figure B-11 UCT guideline heterotrophic kinetic constants

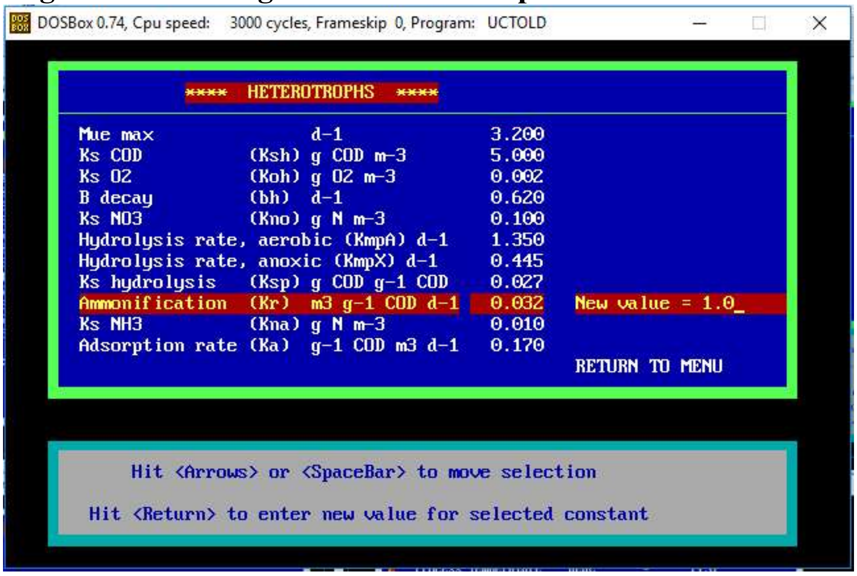


Figure B-12 UCT guideline autotrophic kinetic constants

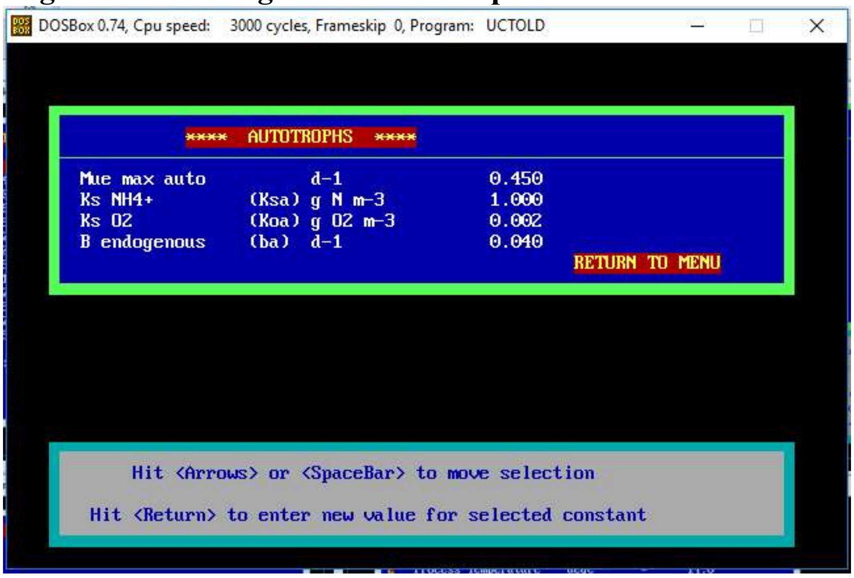


Figure B-13 UCT guideline temperature dependent kinetic constants

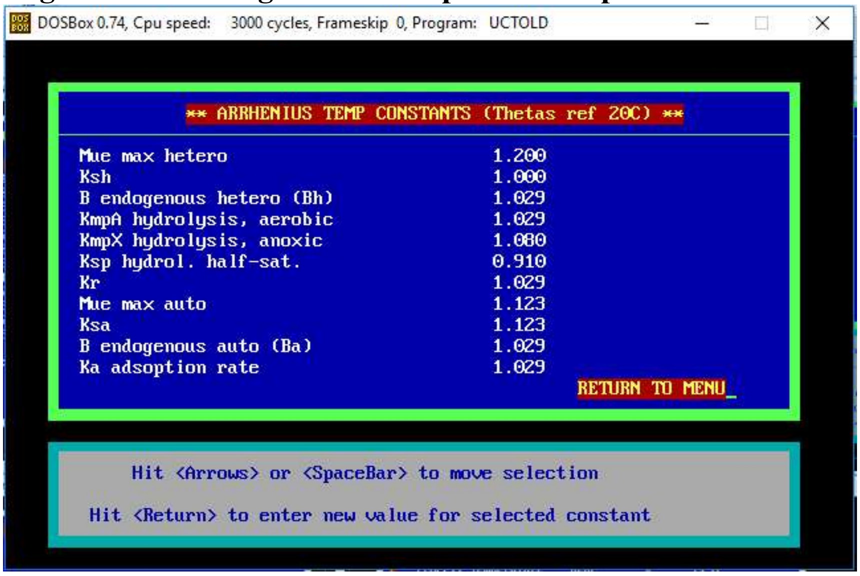


Figure B-14 M&E guideline heterotrophic kinetic constants

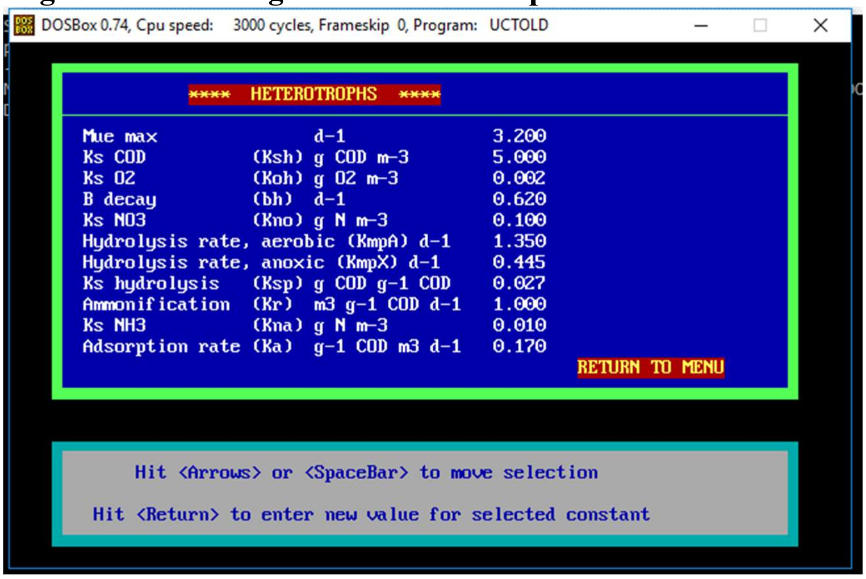


Figure B-15 M&E guideline autotrophic kinetic constants

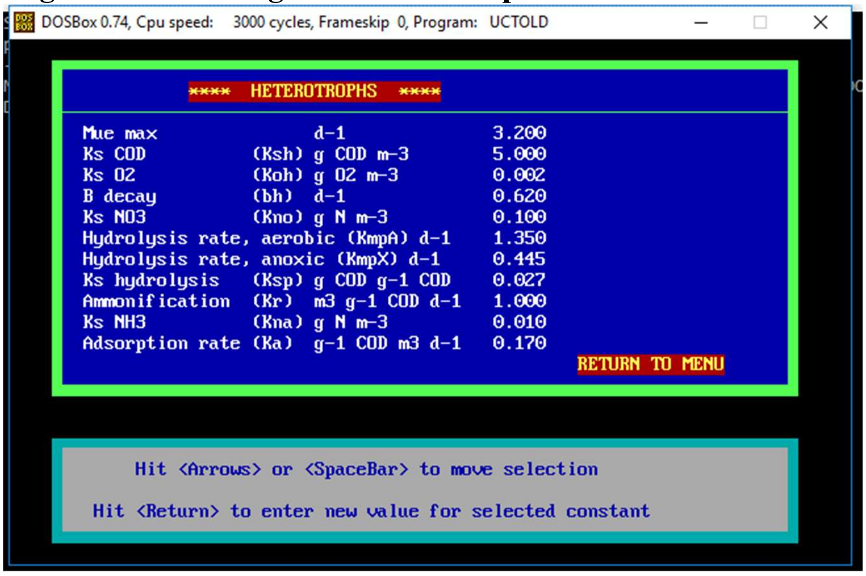
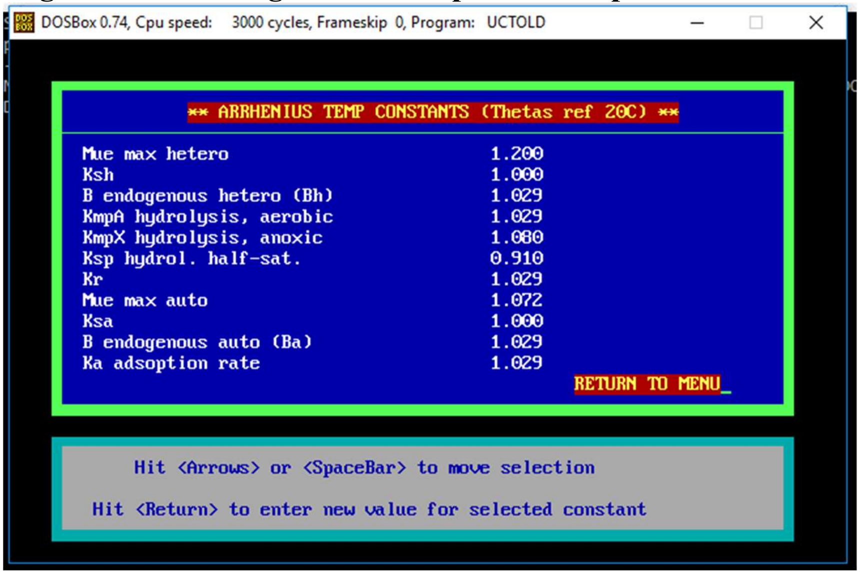
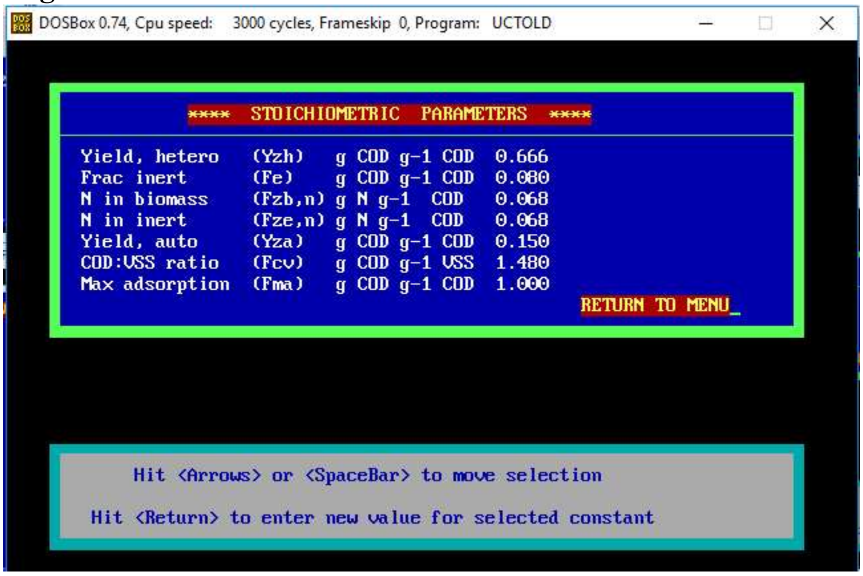


Figure B-16 M&E guideline temperature dependent kinetic constants



B.5 Stoichiometric constants

Figure B-17 UCTOLD default stoichiometric constants



B.6 Steady state simulation

Figure B-18 UCT-sized system steady state results

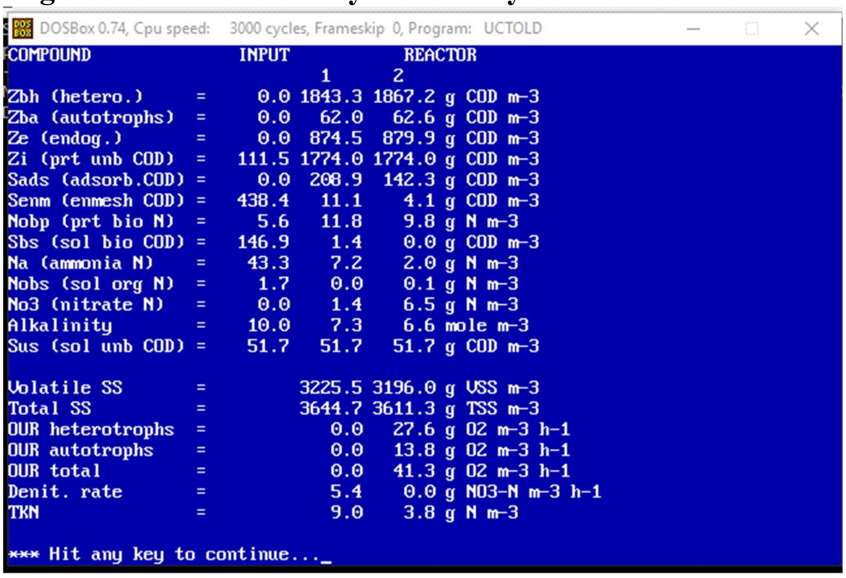
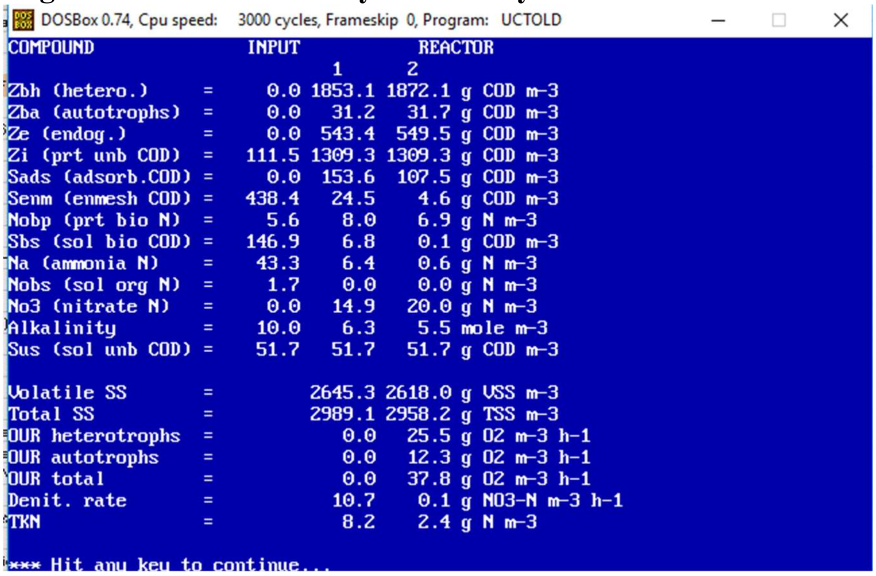


Figure B-19 M&E-sized system steady state results



COMPOUND		INPUT	REACTOR 1	REACTOR 2	
Zbh (hetero.)	=	0.0	1853.1	1872.1	g COD m-3
Zba (autotrophs)	=	0.0	31.2	31.7	g COD m-3
Ze (endog.)	=	0.0	543.4	549.5	g COD m-3
Zi (prt unb COD)	=	111.5	1309.3	1309.3	g COD m-3
Sads (adsorb.COD)	=	0.0	153.6	107.5	g COD m-3
Senm (enmesh COD)	=	438.4	24.5	4.6	g COD m-3
Nobp (prt bio N)	=	5.6	8.0	6.9	g N m-3
Sbs (sol bio COD)	=	146.9	6.8	0.1	g COD m-3
Na (ammonia N)	=	43.3	6.4	0.6	g N m-3
Nobs (sol org N)	=	1.7	0.0	0.0	g N m-3
No3 (nitrate N)	=	0.0	14.9	20.0	g N m-3
Alkalinity	=	10.0	6.3	5.5	mole m-3
Sus (sol unb COD)	=	51.7	51.7	51.7	g COD m-3
Volatile SS	=		2645.3	2618.0	g VSS m-3
Total SS	=		2989.1	2958.2	g TSS m-3
OUR heterotrophs	=		0.0	25.5	g O2 m-3 h-1
OUR autotrophs	=		0.0	12.3	g O2 m-3 h-1
OUR total	=		0.0	37.8	g O2 m-3 h-1
Denit. rate	=		10.7	0.1	g NO3-N m-3 h-1
TKN	=		8.2	2.4	g N m-3

*** Hit any key to continue...

B.7 Dynamic simulation

Figure B-20 UCTOLD dynamic simulation menu

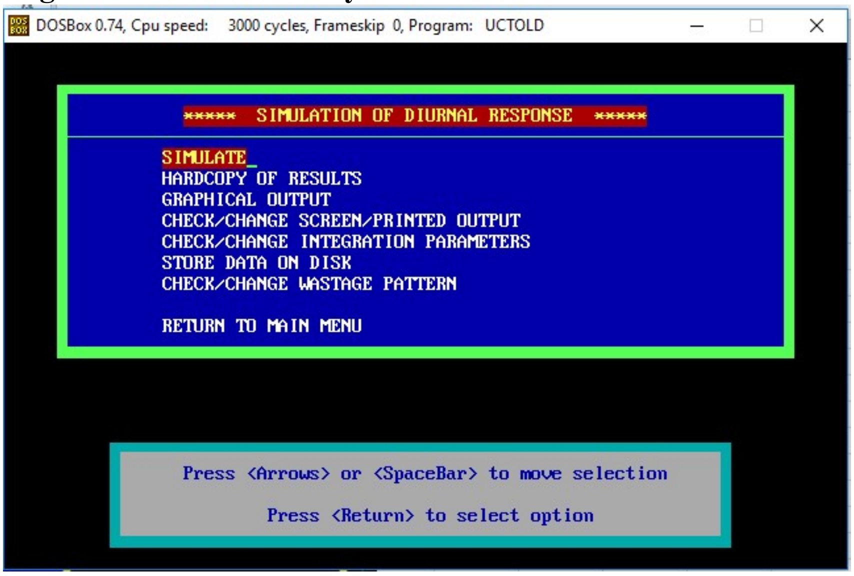


Figure B-21 UCT-sized system wastage pattern

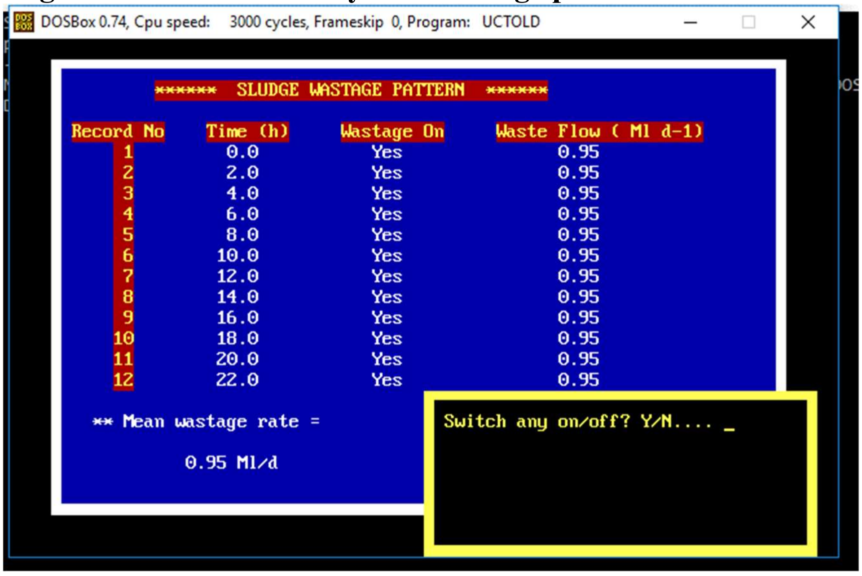


Figure B-22 M&E-sized system wastage pattern

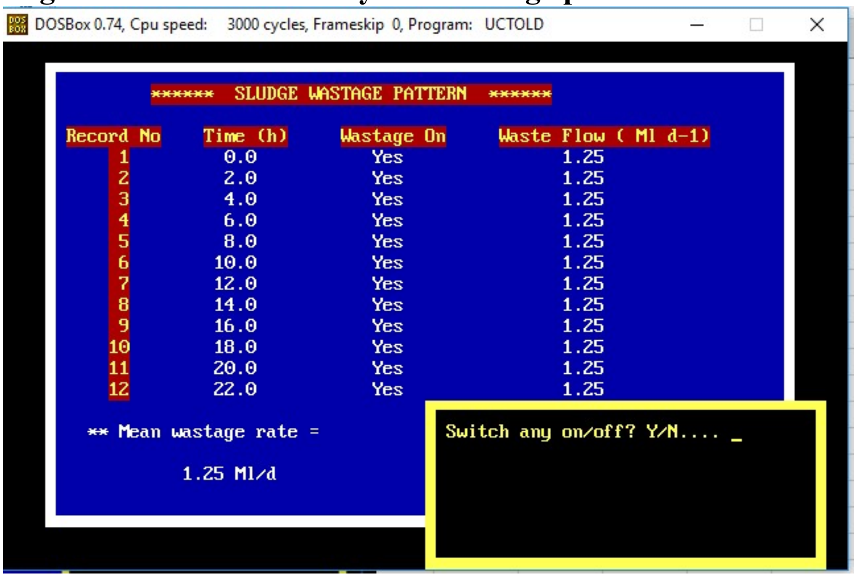


Figure B-23 Parameters for UCTOLD

Concentrations of the following parameters are stored by the program **UCTOLD**

1.	Z_{BH}	- active heterotrophic biomass	(g COD m^{-3})
2.	Z_{BA}	- active autotrophic biomass	(g COD m^{-3})
3.	Z_E	- endogenous mass	(g COD m^{-3})
4.	Z_I	- inert mass	(g COD m^{-3})
5.	S_{ads}	- adsorbed slowly biodegradable substrate	(g COD m^{-3})
6.	S_{enm}	- enmeshed slowly biodegradable substrate	(g COD m^{-3})
7.	N_{obp}	- nitrogen organic biodegradable particulate	(g N m^{-3})
8.	S_{bs}	- soluble readily biodegradable substrate	(g COD m^{-3})
9.	N_a	- ammonia nitrogen	(g N m^{-3})
10.	N_{obs}	- nitrogen organic biodegradable soluble	(g N m^{-3})
11.	N_{O3}	- nitrate nitrogen	(g N m^{-3})
12.	Alk	- H_2CO_3* alkalinity	(moles m^{-3})
13.	S_{us}	- soluble unbiodegradable substrate	(g COD m^{-3})
14.	O_c	- carbonaceous oxygen utilization rate	(g O_2 m^{-3} h^{-1})
15.	O_n	- nitrification oxygen utilization rate	(g O_2 m^{-3} h^{-1})
16.	O_t	- total oxygen utilization rate	(g O_2 m^{-3} h^{-1})
17.	X_v	- volatile settleable solids (VSS)	(g VSS m^{-3})
18.	N_t	- total Kjeldahl nitrogen (TKN)	(g N m^{-3})

Figure B-24 UCT-sized system dynamic simulation results

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
Reactor 1:																		
00:00:00	1841.68	60.40	869.72	1779.52	272.36	12.86	13.84	1.85	9.57	0.02	0.71	7.40	55.04	0.00	0.00	0.00	3267.94	11.34
00:15:00	1842.61	60.41	869.71	1779.14	270.43	11.84	13.78	1.55	9.01	0.02	0.79	7.37	54.97	0.00	0.00	0.00	3266.31	10.49
00:30:00	1843.52	60.42	869.70	1778.92	268.06	11.74	13.72	1.52	8.56	0.02	0.86	7.35	54.92	0.00	0.00	0.00	3265.11	10.04
00:45:00	1844.53	60.43	869.70	1778.80	265.95	11.71	13.68	1.51	8.17	0.02	0.92	7.33	54.89	0.00	0.00	0.00	3264.26	9.65
01:00:00	1845.57	60.43	869.70	1778.73	264.04	11.71	13.64	1.50	7.83	0.02	0.97	7.32	54.87	0.00	0.00	0.00	3263.64	9.31
01:15:00	1846.63	60.44	869.70	1778.70	262.24	11.74	13.60	1.49	7.52	0.02	1.00	7.31	54.85	0.00	0.00	0.00	3263.15	9.00
01:30:00	1847.68	60.45	869.71	1778.69	260.61	11.71	13.56	1.48	7.24	0.02	1.03	7.30	54.84	0.00	0.00	0.00	3262.74	8.72
01:45:00	1848.73	60.45	869.72	1778.70	259.08	11.67	13.52	1.48	6.98	0.02	1.05	7.29	54.84	0.00	0.00	0.00	3262.40	8.46
02:00:00	1849.75	60.46	869.72	1778.72	257.61	11.65	13.49	1.48	6.74	0.02	1.07	7.28	54.83	0.00	0.00	0.00	3262.10	8.22
02:15:00	1849.48	60.46	869.67	1777.10	253.13	9.06	13.43	0.86	6.17	0.02	1.27	7.23	54.70	0.00	0.00	0.00	3256.01	7.54
02:30:00	1849.22	60.45	869.64	1775.87	247.50	8.84	13.37	0.84	5.71	0.02	1.47	7.19	54.60	0.00	0.00	0.00	3251.03	7.09
02:45:00	1849.20	60.45	869.63	1774.88	242.50	8.79	13.30	0.84	5.32	0.02	1.62	7.16	54.52	0.00	0.00	0.00	3246.92	6.69
03:00:00	1849.31	60.45	869.62	1774.05	238.04	8.78	13.24	0.83	4.97	0.02	1.74	7.13	54.45	0.00	0.00	0.00	3243.41	6.34
03:15:00	1849.47	60.45	869.62	1773.31	233.95	8.78	13.17	0.83	4.67	0.02	1.83	7.11	54.39	0.00	0.00	0.00	3240.25	6.04
03:30:00	1849.63	60.44	869.62	1772.63	230.11	8.80	13.09	0.83	4.40	0.02	1.90	7.09	54.33	0.00	0.00	0.00	3237.32	5.78
03:45:00	1849.77	60.43	869.63	1772.00	226.54	8.77	13.02	0.83	4.17	0.02	1.94	7.08	54.28	0.00	0.00	0.00	3234.55	5.55
04:00:00	1849.88	60.42	869.63	1771.38	223.16	8.73	12.94	0.83	3.98	0.02	1.96	7.07	54.24	0.00	0.00	0.00	3231.90	5.35
04:15:00	1848.57	60.40	869.59	1769.09	216.54	6.12	12.84	0.33	3.47	0.02	2.17	7.03	53.94	0.00	0.00	0.00	3223.18	4.52
04:30:00	1847.27	60.38	869.56	1767.19	208.94	5.91	12.74	0.33	3.08	0.02	2.37	7.00	53.70	0.00	0.00	0.00	3215.70	4.13
04:45:00	1846.16	60.35	869.55	1765.55	202.14	5.87	12.64	0.33	2.78	0.02	2.50	6.98	53.50	0.00	0.00	0.00	3209.20	3.83
05:00:00	1845.15	60.33	869.54	1764.09	196.02	5.86	12.52	0.33	2.55	0.02	2.58	6.97	53.32	0.00	0.00	0.00	3203.37	3.60
05:15:00	1844.15	60.30	869.54	1762.72	190.38	5.86	12.41	0.33	2.37	0.02	2.63	6.96	53.16	0.00	0.00	0.00	3197.94	3.42
05:30:00	1843.12	60.27	869.54	1761.43	185.09	5.90	12.29	0.33	2.23	0.02	2.65	6.96	53.01	0.00	0.00	0.00	3192.80	3.29
05:45:00	1842.02	60.23	869.54	1760.18	180.19	5.86	12.16	0.33	2.14	0.02	2.65	6.96	52.87	0.00	0.00	0.00	3187.85	3.19
06:00:00	1840.85	60.20	869.54	1758.96	175.56	5.82	12.03	0.33	2.07	0.02	2.64	6.96	52.74	0.00	0.00	0.00	3183.06	3.12

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
06:15:00	1839.06	60.16	869.53	1757.09	169.75	4.81	11.89	0.16	1.87	0.02	2.71	6.95	52.47	0.00	0.00	0.00	3175.94	2.61
06:30:00	1837.20	60.12	869.52	1755.39	163.77	4.72	11.74	0.16	1.73	0.02	2.77	6.95	52.24	0.00	0.00	0.00	3169.40	2.48
06:45:00	1835.32	60.09	869.52	1753.80	158.27	4.70	11.59	0.16	1.62	0.02	2.81	6.95	52.04	0.00	0.00	0.00	3163.30	2.37
07:00:00	1833.40	60.05	869.51	1752.28	153.18	4.71	11.44	0.16	1.55	0.02	2.84	6.95	51.84	0.00	0.00	0.00	3157.52	2.30
07:15:00	1831.40	60.01	869.51	1750.80	148.40	4.76	11.29	0.16	1.50	0.02	2.86	6.96	51.65	0.00	0.00	0.00	3151.95	2.25
07:30:00	1829.30	59.97	869.51	1749.35	144.00	4.72	11.13	0.16	1.47	0.02	2.88	6.96	51.48	0.00	0.00	0.00	3146.53	2.22
07:45:00	1827.10	59.93	869.51	1747.93	139.88	4.67	10.97	0.16	1.45	0.02	2.90	6.97	51.30	0.00	0.00	0.00	3141.23	2.20
08:00:00	1824.79	59.90	869.51	1746.51	135.97	4.65	10.81	0.16	1.44	0.02	2.93	6.97	51.13	0.00	0.00	0.00	3136.04	2.19
08:15:00	1822.71	59.86	869.54	1745.43	132.76	4.98	10.69	0.22	1.67	0.02	2.91	7.00	50.79	0.00	0.00	0.00	3131.94	2.70
08:30:00	1820.46	59.83	869.55	1744.27	129.90	5.01	10.55	0.22	1.85	0.02	2.89	7.02	50.48	0.00	0.00	0.00	3127.72	2.88
08:45:00	1818.04	59.80	869.56	1743.06	127.16	5.01	10.42	0.23	1.99	0.02	2.90	7.04	50.21	0.00	0.00	0.00	3123.40	3.02
09:00:00	1815.47	59.77	869.57	1741.83	124.54	4.99	10.28	0.23	2.11	0.02	2.92	7.06	49.95	0.00	0.00	0.00	3119.03	3.14
09:15:00	1812.77	59.73	869.56	1740.58	122.08	4.95	10.15	0.23	2.20	0.02	2.95	7.07	49.71	0.00	0.00	0.00	3114.65	3.23
09:30:00	1809.96	59.71	869.56	1739.32	119.79	4.87	10.01	0.23	2.28	0.02	3.00	7.08	49.48	0.00	0.00	0.00	3110.27	3.31
09:45:00	1807.06	59.68	869.55	1738.05	117.47	4.95	9.88	0.23	2.35	0.02	3.06	7.09	49.25	0.00	0.00	0.00	3105.92	3.38
10:00:00	1804.06	59.65	869.54	1736.78	115.32	4.98	9.75	0.23	2.41	0.02	3.14	7.10	49.03	0.00	0.00	0.00	3101.58	3.43
10:15:00	1804.58	59.65	869.74	1739.80	121.61	10.99	9.82	1.53	4.09	0.02	2.62	7.24	48.73	0.00	0.00	0.00	3112.41	5.74
10:30:00	1804.70	59.64	869.86	1741.69	130.09	11.41	9.87	1.57	5.28	0.02	2.15	7.36	48.46	0.00	0.00	0.00	3119.85	6.94
10:45:00	1804.09	59.63	869.92	1742.91	136.83	11.49	9.91	1.59	6.19	0.02	1.81	7.44	48.20	0.00	0.00	0.00	3124.91	7.84
11:00:00	1803.06	59.62	869.95	1743.71	142.31	11.54	9.94	1.60	6.89	0.02	1.56	7.51	47.96	0.00	0.00	0.00	3128.51	8.55
11:15:00	1801.83	59.61	869.96	1744.27	146.96	11.56	9.97	1.62	7.46	0.02	1.38	7.56	47.73	0.00	0.00	0.00	3131.21	9.12
11:30:00	1800.53	59.61	869.97	1744.69	151.09	11.55	10.01	1.63	7.93	0.02	1.25	7.60	47.50	0.00	0.00	0.00	3133.40	9.59
11:45:00	1799.24	59.61	869.96	1745.03	154.80	11.57	10.05	1.65	8.33	0.02	1.16	7.64	47.28	0.00	0.00	0.00	3135.27	9.98
12:00:00	1797.99	59.61	869.95	1745.31	158.17	11.60	10.09	1.66	8.67	0.02	1.09	7.67	47.07	0.00	0.00	0.00	3136.91	10.33
12:15:00	1798.39	59.61	869.98	1748.31	167.32	15.99	10.22	3.10	9.72	0.02	0.77	7.73	47.74	0.00	0.00	0.00	3148.38	11.72
12:30:00	1798.84	59.62	869.99	1750.59	177.82	16.36	10.34	3.46	10.50	0.02	0.48	7.78	48.19	0.00	0.00	0.00	3157.58	12.51
12:45:00	1798.81	59.63	869.99	1752.44	187.03	16.48	10.48	3.89	11.15	0.02	0.30	7.82	48.49	0.00	0.00	0.00	3165.12	13.15

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
13:00:00	1798.48	59.64	869.98	1754.04	195.32	16.56	10.62	4.43	11.69	0.02	0.22	7.84	48.71	0.00	0.00	0.00	3171.62	13.69
13:15:00	1798.13	59.64	869.97	1755.48	202.93	16.62	10.77	4.93	12.17	0.02	0.18	7.87	48.88	0.00	0.00	0.00	3177.54	14.17
13:30:00	1797.91	59.65	869.95	1756.83	210.04	16.65	10.92	5.34	12.59	0.02	0.16	7.89	49.01	0.00	0.00	0.00	3183.13	14.59
13:45:00	1797.85	59.66	869.94	1758.13	216.68	16.71	11.08	5.67	12.96	0.02	0.15	7.90	49.12	0.00	0.00	0.00	3188.49	14.96
14:00:00	1797.96	59.67	869.92	1759.40	222.93	16.79	11.23	5.94	13.30	0.02	0.14	7.91	49.22	0.00	0.00	0.00	3193.70	15.29
14:15:00	1798.05	59.68	869.86	1760.35	228.78	16.38	11.39	5.78	13.54	0.02	0.14	7.90	49.66	0.00	0.00	0.00	3198.03	15.76
14:30:00	1798.37	59.68	869.81	1761.34	233.90	16.39	11.54	5.69	13.77	0.02	0.14	7.90	50.00	0.00	0.00	0.00	3202.37	15.99
14:45:00	1798.90	59.69	869.78	1762.37	238.75	16.42	11.69	5.65	13.98	0.02	0.14	7.89	50.28	0.00	0.00	0.00	3206.69	16.20
15:00:00	1799.58	59.70	869.75	1763.41	243.36	16.47	11.84	5.62	14.18	0.02	0.14	7.89	50.52	0.00	0.00	0.00	3211.00	16.40
15:15:00	1800.39	59.72	869.73	1764.46	247.79	16.52	11.99	5.61	14.37	0.02	0.14	7.88	50.74	0.00	0.00	0.00	3215.28	16.59
15:30:00	1801.31	59.73	869.71	1765.52	252.02	16.61	12.15	5.60	14.54	0.02	0.14	7.88	50.94	0.00	0.00	0.00	3219.53	16.77
15:45:00	1802.33	59.74	869.70	1766.59	256.17	16.63	12.30	5.59	14.71	0.02	0.14	7.88	51.12	0.00	0.00	0.00	3223.75	16.93
16:00:00	1803.44	59.75	869.68	1767.65	260.20	16.63	12.45	5.58	14.86	0.02	0.14	7.87	51.30	0.00	0.00	0.00	3227.95	17.09
16:15:00	1804.26	59.76	869.62	1767.52	262.06	14.64	12.57	4.28	14.73	0.02	0.17	7.84	51.46	0.00	0.00	0.00	3228.28	17.08
16:30:00	1805.21	59.77	869.57	1767.67	262.59	14.48	12.69	3.62	14.66	0.02	0.20	7.82	51.61	0.00	0.00	0.00	3229.24	17.01
16:45:00	1806.27	59.78	869.54	1768.00	263.27	14.46	12.81	3.29	14.63	0.02	0.23	7.80	51.76	0.00	0.00	0.00	3230.62	16.98
17:00:00	1807.43	59.79	869.52	1768.43	264.14	14.46	12.92	3.11	14.62	0.02	0.26	7.78	51.91	0.00	0.00	0.00	3232.28	16.98
17:15:00	1808.66	59.80	869.50	1768.92	265.10	14.48	13.03	3.01	14.63	0.02	0.27	7.77	52.06	0.00	0.00	0.00	3234.10	16.98
17:30:00	1809.94	59.81	869.48	1769.46	266.12	14.52	13.13	2.94	14.64	0.02	0.29	7.76	52.20	0.00	0.00	0.00	3236.03	17.00
17:45:00	1811.26	59.83	869.47	1770.01	267.12	14.59	13.24	2.89	14.66	0.02	0.30	7.74	52.34	0.00	0.00	0.00	3238.03	17.02
18:00:00	1812.60	59.84	869.46	1770.58	268.28	14.52	13.34	2.85	14.68	0.02	0.31	7.73	52.48	0.00	0.00	0.00	3240.05	17.04
18:15:00	1813.77	59.85	869.42	1770.95	269.31	14.13	13.32	2.65	14.20	0.02	0.34	7.70	52.82	0.00	0.00	0.00	3241.51	16.32
18:30:00	1815.01	59.86	869.40	1771.37	269.97	14.08	13.32	2.57	13.83	0.02	0.36	7.68	53.11	0.00	0.00	0.00	3243.03	15.95
18:45:00	1816.32	59.87	869.38	1771.82	270.58	14.07	13.34	2.52	13.55	0.02	0.39	7.65	53.37	0.00	0.00	0.00	3244.63	15.67
19:00:00	1817.68	59.89	869.36	1772.30	271.16	14.08	13.37	2.49	13.31	0.02	0.41	7.63	53.60	0.00	0.00	0.00	3246.26	15.43
19:15:00	1819.07	59.90	869.35	1772.78	271.71	14.09	13.40	2.45	13.11	0.02	0.42	7.62	53.82	0.00	0.00	0.00	3247.91	15.23
19:30:00	1820.49	59.91	869.34	1773.28	272.23	14.13	13.43	2.43	12.93	0.02	0.44	7.60	54.02	0.00	0.00	0.00	3249.58	15.05

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
19:45:00	1821.92	59.92	869.34	1773.77	272.78	14.12	13.47	2.41	12.76	0.02	0.45	7.58	54.22	0.00	0.00	0.00	3251.25	14.88
20:00:00	1823.36	59.94	869.33	1774.28	273.32	14.09	13.50	2.39	12.61	0.02	0.46	7.56	54.42	0.00	0.00	0.00	3252.92	14.73
20:15:00	1825.06	59.95	869.36	1775.08	274.24	14.51	13.54	2.56	12.49	0.02	0.45	7.56	54.45	0.00	0.00	0.00	3255.54	14.45
20:30:00	1826.73	59.97	869.37	1775.82	275.42	14.56	13.57	2.60	12.37	0.02	0.43	7.56	54.52	0.00	0.00	0.00	3258.02	14.33
20:45:00	1828.34	59.98	869.38	1776.52	276.56	14.57	13.61	2.62	12.25	0.02	0.41	7.55	54.61	0.00	0.00	0.00	3260.36	14.21
21:00:00	1829.91	60.00	869.38	1777.18	277.66	14.56	13.65	2.64	12.14	0.02	0.41	7.55	54.72	0.00	0.00	0.00	3262.63	14.10
21:15:00	1831.46	60.01	869.39	1777.83	278.73	14.54	13.70	2.65	12.03	0.02	0.40	7.54	54.83	0.00	0.00	0.00	3264.83	13.99
21:30:00	1833.01	60.02	869.39	1778.47	279.78	14.49	13.74	2.66	11.92	0.02	0.39	7.53	54.94	0.00	0.00	0.00	3267.00	13.88
21:45:00	1834.56	60.03	869.39	1779.11	280.75	14.49	13.78	2.66	11.81	0.02	0.39	7.53	55.05	0.00	0.00	0.00	3269.14	13.77
22:00:00	1836.11	60.05	869.39	1779.74	281.68	14.51	13.82	2.67	11.71	0.02	0.38	7.52	55.16	0.00	0.00	0.00	3271.27	13.67
22:15:00	1837.19	60.05	869.38	1779.42	280.56	13.07	13.82	2.09	11.29	0.02	0.45	7.50	55.05	0.00	0.00	0.00	3270.04	13.06
22:30:00	1838.27	60.07	869.37	1779.33	278.76	12.93	13.82	1.98	10.97	0.02	0.52	7.48	54.99	0.00	0.00	0.00	3269.41	12.74
22:45:00	1839.48	60.08	869.36	1779.37	277.29	12.89	13.83	1.93	10.69	0.02	0.57	7.46	54.97	0.00	0.00	0.00	3269.24	12.46
23:00:00	1840.76	60.09	869.36	1779.50	276.08	12.89	13.84	1.91	10.44	0.02	0.61	7.45	54.97	0.00	0.00	0.00	3269.38	12.22
23:15:00	1842.09	60.10	869.36	1779.68	275.03	12.91	13.84	1.89	10.22	0.02	0.63	7.43	54.98	0.00	0.00	0.00	3269.71	12.00
23:30:00	1843.43	60.11	869.37	1779.90	274.07	12.96	13.85	1.88	10.02	0.02	0.66	7.42	54.99	0.00	0.00	0.00	3270.15	11.79
23:45:00	1844.78	60.12	869.37	1780.13	273.30	12.89	13.86	1.87	9.83	0.02	0.67	7.41	55.02	0.00	0.00	0.00	3270.66	11.60
00:00:00	1846.12	60.13	869.38	1780.37	272.58	12.84	13.86	1.86	9.65	0.02	0.69	7.40	55.04	0.00	0.00	0.00	3271.22	11.42
Reactor 2:																		
00:00:00	1867.38	61.04	875.07	1777.69	195.87	4.26	11.90	0.04	4.25	0.06	6.25	6.60	54.79	30.87	15.04	45.90	3230.62	6.07
00:15:00	1868.72	61.05	875.08	1777.91	195.01	4.22	11.89	0.04	4.05	0.06	6.27	6.58	54.82	30.78	14.96	45.74	3231.08	5.57
00:30:00	1869.96	61.06	875.10	1778.06	193.90	4.20	11.87	0.04	3.81	0.06	6.29	6.57	54.83	30.73	14.86	45.59	3231.27	5.33
00:45:00	1871.12	61.07	875.10	1778.17	192.65	4.20	11.85	0.04	3.55	0.06	6.32	6.56	54.84	30.68	14.74	45.42	3231.29	5.07
01:00:00	1872.24	61.08	875.11	1778.25	191.34	4.19	11.82	0.04	3.30	0.06	6.34	6.55	54.85	30.62	14.60	45.22	3231.22	4.82
01:15:00	1873.32	61.08	875.12	1778.31	190.02	4.17	11.79	0.04	3.04	0.06	6.36	6.54	54.85	30.57	14.44	45.01	3231.09	4.56
01:30:00	1874.36	61.09	875.13	1778.37	188.68	4.16	11.76	0.04	2.80	0.06	6.36	6.53	54.85	30.51	14.27	44.78	3230.93	4.32
01:45:00	1875.37	61.09	875.14	1778.41	187.34	4.16	11.72	0.04	2.56	0.06	6.37	6.52	54.85	30.45	14.07	44.52	3230.75	4.08

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
02:00:00	1876.36	61.09	875.14	1778.45	186.02	4.16	11.69	0.04	2.34	0.06	6.36	6.52	54.85	30.39	13.86	44.25	3230.56	3.86
02:15:00	1877.34	61.10	875.18	1778.37	183.99	4.04	11.64	0.02	2.08	0.06	6.38	6.51	54.83	30.17	13.57	43.74	3229.75	3.50
02:30:00	1878.07	61.10	875.20	1778.11	181.40	4.00	11.58	0.02	1.83	0.06	6.41	6.50	54.81	30.03	13.21	43.24	3228.30	3.24
02:45:00	1878.61	61.09	875.22	1777.74	178.52	3.99	11.52	0.02	1.58	0.06	6.44	6.49	54.78	29.88	12.77	42.65	3226.47	2.99
03:00:00	1879.00	61.09	875.24	1777.30	175.48	3.98	11.45	0.02	1.34	0.06	6.46	6.48	54.74	29.71	12.26	41.97	3224.38	2.76
03:15:00	1879.28	61.08	875.25	1776.81	172.42	3.97	11.38	0.02	1.14	0.06	6.46	6.47	54.69	29.54	11.69	41.22	3222.16	2.56
03:30:00	1879.46	61.06	875.27	1776.29	169.38	3.94	11.30	0.02	0.97	0.06	6.44	6.47	54.65	29.36	11.09	40.44	3219.87	2.38
03:45:00	1879.56	61.04	875.28	1775.76	166.37	3.93	11.22	0.02	0.83	0.06	6.39	6.47	54.60	29.18	10.49	39.67	3217.52	2.25
04:00:00	1879.57	61.02	875.29	1775.21	163.42	3.93	11.14	0.02	0.72	0.06	6.32	6.47	54.56	28.99	9.94	38.94	3215.16	2.14
04:15:00	1879.54	61.00	875.32	1774.56	159.93	3.83	11.04	0.01	0.62	0.06	6.27	6.48	54.50	28.68	9.29	37.97	3212.28	1.71
04:30:00	1879.20	60.97	875.34	1773.73	155.92	3.79	10.94	0.01	0.52	0.06	6.21	6.48	54.41	28.41	8.58	36.99	3208.75	1.62
04:45:00	1878.62	60.94	875.36	1772.77	151.66	3.77	10.83	0.01	0.45	0.06	6.14	6.49	54.30	28.12	7.94	36.06	3204.81	1.54
05:00:00	1877.83	60.90	875.38	1771.74	147.31	3.76	10.71	0.01	0.40	0.06	6.06	6.50	54.19	27.80	7.42	35.22	3200.62	1.49
05:15:00	1876.88	60.86	875.39	1770.66	143.00	3.75	10.59	0.01	0.37	0.06	5.97	6.52	54.06	27.48	7.07	34.56	3196.31	1.46
05:30:00	1875.77	60.82	875.40	1769.54	138.78	3.72	10.46	0.01	0.35	0.06	5.89	6.53	53.94	27.16	6.88	34.04	3191.92	1.45
05:45:00	1874.53	60.78	875.41	1768.41	134.67	3.71	10.33	0.01	0.35	0.06	5.81	6.54	53.81	26.82	6.84	33.66	3187.51	1.44
06:00:00	1873.15	60.74	875.41	1767.27	130.69	3.71	10.19	0.01	0.35	0.06	5.74	6.56	53.68	26.49	6.85	33.34	3183.09	1.44
06:15:00	1871.65	60.71	875.43	1766.09	126.66	3.68	10.05	0.00	0.34	0.06	5.68	6.57	53.54	26.11	6.81	32.92	3178.52	1.14
06:30:00	1869.94	60.67	875.44	1764.83	122.56	3.66	9.90	0.00	0.34	0.06	5.64	6.58	53.39	25.74	6.74	32.48	3173.71	1.13
06:45:00	1868.05	60.63	875.45	1763.52	118.49	3.65	9.75	0.00	0.33	0.06	5.61	6.59	53.23	25.36	6.70	32.06	3168.77	1.13
07:00:00	1865.98	60.59	875.45	1762.18	114.53	3.63	9.59	0.00	0.33	0.06	5.58	6.60	53.07	24.98	6.68	31.66	3163.76	1.13
07:15:00	1863.76	60.55	875.45	1760.81	110.73	3.61	9.43	0.00	0.34	0.06	5.57	6.61	52.90	24.59	6.73	31.33	3158.73	1.13
07:30:00	1861.39	60.52	875.46	1759.44	107.07	3.60	9.27	0.00	0.35	0.06	5.56	6.62	52.73	24.21	6.84	31.05	3153.70	1.14
07:45:00	1858.89	60.48	875.46	1758.06	103.58	3.60	9.11	0.00	0.36	0.06	5.56	6.63	52.56	23.83	6.96	30.79	3148.70	1.15
08:00:00	1856.26	60.44	875.46	1756.68	100.28	3.60	8.95	0.00	0.37	0.06	5.58	6.64	52.38	23.46	7.08	30.53	3143.72	1.17
08:15:00	1853.44	60.41	875.44	1755.28	97.29	3.62	8.80	0.01	0.40	0.06	5.59	6.65	52.20	23.12	7.36	30.48	3138.84	1.47
08:30:00	1850.57	60.37	875.43	1753.92	94.56	3.62	8.65	0.01	0.43	0.06	5.62	6.66	51.99	22.79	7.73	30.52	3134.10	1.51

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
08:45:00	1847.63	60.34	875.41	1752.59	92.04	3.62	8.51	0.01	0.47	0.06	5.67	6.67	51.78	22.47	8.08	30.55	3129.48	1.54
09:00:00	1844.62	60.32	875.40	1751.27	89.69	3.62	8.37	0.01	0.51	0.06	5.73	6.68	51.56	22.17	8.38	30.56	3124.94	1.58
09:15:00	1841.54	60.29	875.40	1749.96	87.50	3.62	8.23	0.01	0.54	0.06	5.80	6.68	51.33	21.89	8.65	30.53	3120.48	1.61
09:30:00	1838.39	60.27	875.38	1748.65	85.44	3.65	8.10	0.01	0.57	0.06	5.89	6.69	51.10	21.61	8.87	30.48	3116.06	1.64
09:45:00	1835.16	60.24	875.37	1747.35	83.57	3.62	7.97	0.01	0.60	0.06	5.98	6.69	50.88	21.35	9.07	30.41	3111.70	1.67
10:00:00	1831.87	60.22	875.36	1746.06	81.81	3.61	7.85	0.01	0.63	0.06	6.07	6.70	50.65	21.10	9.23	30.33	3107.38	1.70
10:15:00	1828.35	60.19	875.25	1744.93	81.65	3.89	7.78	0.04	0.79	0.06	6.10	6.72	50.39	21.33	10.14	31.46	3104.22	2.48
10:30:00	1825.53	60.17	875.18	1744.32	83.16	3.97	7.75	0.04	1.05	0.06	6.09	6.74	50.12	21.53	11.23	32.76	3102.92	2.74
10:45:00	1823.21	60.17	875.13	1744.04	85.47	3.99	7.73	0.04	1.36	0.06	6.09	6.77	49.85	21.82	12.11	33.92	3102.70	3.05
11:00:00	1821.27	60.16	875.09	1743.94	88.13	4.00	7.74	0.04	1.67	0.06	6.08	6.79	49.59	22.14	12.76	34.90	3103.11	3.36
11:15:00	1819.61	60.16	875.06	1743.96	90.92	4.01	7.77	0.04	1.99	0.06	6.07	6.82	49.33	22.47	13.23	35.70	3103.87	3.68
11:30:00	1818.17	60.17	875.04	1744.05	93.69	4.03	7.80	0.04	2.29	0.06	6.06	6.84	49.07	22.79	13.59	36.38	3104.83	3.98
11:45:00	1816.89	60.17	875.02	1744.17	96.40	4.05	7.84	0.04	2.57	0.06	6.05	6.87	48.82	23.09	13.87	36.96	3105.88	4.26
12:00:00	1815.75	60.18	875.00	1744.32	99.03	4.06	7.89	0.04	2.84	0.06	6.05	6.89	48.58	23.37	14.08	37.46	3106.98	4.52
12:15:00	1814.86	60.18	874.96	1744.72	102.49	4.27	7.97	0.08	3.16	0.06	6.01	6.91	48.40	24.03	14.30	38.34	3109.10	5.20
12:30:00	1814.46	60.19	874.93	1745.46	107.07	4.34	8.06	0.09	3.53	0.06	5.93	6.94	48.34	24.58	14.51	39.10	3112.47	5.57
12:45:00	1814.42	60.20	874.91	1746.40	112.19	4.37	8.16	0.10	3.91	0.06	5.84	6.96	48.34	25.17	14.69	39.86	3116.54	5.95
13:00:00	1814.64	60.21	874.88	1747.45	117.53	4.39	8.29	0.12	4.30	0.05	5.76	6.99	48.38	25.77	14.85	40.62	3121.01	6.33
13:15:00	1815.03	60.22	874.86	1748.58	122.95	4.41	8.42	0.13	4.66	0.05	5.68	7.01	48.45	26.36	14.97	41.33	3125.71	6.70
13:30:00	1815.57	60.23	874.85	1749.74	128.33	4.44	8.56	0.14	5.01	0.05	5.62	7.02	48.52	26.90	15.08	41.98	3130.51	7.05
13:45:00	1816.25	60.24	874.83	1750.93	133.63	4.47	8.72	0.15	5.34	0.05	5.57	7.04	48.61	27.40	15.16	42.56	3135.36	7.37
14:00:00	1817.04	60.25	874.81	1752.13	138.84	4.48	8.87	0.16	5.65	0.05	5.54	7.05	48.69	27.86	15.24	43.09	3140.24	7.68
14:15:00	1817.99	60.27	874.82	1753.27	143.46	4.42	9.02	0.15	5.89	0.05	5.53	7.06	48.81	28.13	15.29	43.42	3144.74	8.15
14:30:00	1818.96	60.28	874.81	1754.39	147.89	4.42	9.17	0.15	6.12	0.05	5.54	7.06	48.96	28.43	15.34	43.77	3149.16	8.38
14:45:00	1819.97	60.29	874.81	1755.49	152.20	4.43	9.32	0.15	6.34	0.05	5.54	7.06	49.13	28.72	15.38	44.10	3153.51	8.60
15:00:00	1821.06	60.31	874.80	1756.59	156.37	4.44	9.48	0.15	6.54	0.05	5.55	7.06	49.32	28.99	15.42	44.41	3157.81	8.80
15:15:00	1822.21	60.32	874.78	1757.67	160.43	4.45	9.63	0.15	6.74	0.05	5.55	7.05	49.51	29.25	15.46	44.71	3162.07	9.00

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
15:30:00	1823.43	60.33	874.77	1758.76	164.37	4.44	9.79	0.15	6.92	0.05	5.56	7.05	49.71	29.50	15.49	44.99	3166.28	9.18
15:45:00	1824.72	60.35	874.76	1759.84	168.18	4.45	9.94	0.15	7.09	0.05	5.57	7.05	49.91	29.74	15.52	45.25	3170.46	9.35
16:00:00	1826.07	60.36	874.75	1760.91	171.87	4.47	10.09	0.15	7.25	0.05	5.58	7.04	50.10	29.96	15.54	45.50	3174.61	9.51
16:15:00	1827.52	60.38	874.76	1761.86	174.70	4.38	10.23	0.11	7.34	0.05	5.62	7.03	50.28	29.86	15.56	45.42	3178.10	9.74
16:30:00	1828.85	60.39	874.76	1762.67	177.00	4.36	10.36	0.09	7.41	0.05	5.66	7.02	50.46	29.85	15.57	45.43	3181.10	9.81
16:45:00	1830.14	60.41	874.76	1763.41	178.94	4.36	10.49	0.08	7.47	0.05	5.70	7.00	50.63	29.90	15.58	45.48	3183.79	9.86
17:00:00	1831.42	60.42	874.75	1764.09	180.63	4.36	10.61	0.08	7.52	0.05	5.74	6.99	50.81	29.96	15.59	45.55	3186.26	9.91
17:15:00	1832.72	60.44	874.75	1764.74	182.16	4.36	10.72	0.08	7.56	0.05	5.77	6.97	50.97	30.03	15.60	45.64	3188.62	9.96
17:30:00	1834.03	60.45	874.74	1765.37	183.57	4.35	10.83	0.07	7.60	0.05	5.81	6.96	51.14	30.11	15.61	45.72	3190.89	10.00
17:45:00	1835.37	60.46	874.73	1765.99	184.91	4.32	10.94	0.07	7.64	0.05	5.84	6.94	51.30	30.18	15.62	45.80	3193.10	10.04
18:00:00	1836.74	60.48	874.72	1766.61	186.11	4.34	11.04	0.07	7.68	0.05	5.87	6.93	51.46	30.25	15.63	45.88	3195.27	10.08
18:15:00	1838.17	60.49	874.73	1767.19	186.97	4.34	11.12	0.07	7.66	0.05	5.91	6.91	51.63	30.26	15.63	45.89	3197.22	9.82
18:30:00	1839.58	60.51	874.73	1767.74	187.77	4.34	11.18	0.06	7.59	0.06	5.95	6.89	51.82	30.30	15.62	45.92	3199.09	9.75
18:45:00	1840.98	60.52	874.73	1768.28	188.50	4.34	11.24	0.06	7.48	0.06	5.99	6.87	52.02	30.34	15.61	45.95	3200.91	9.64
19:00:00	1842.38	60.53	874.72	1768.81	189.19	4.34	11.29	0.06	7.35	0.06	6.03	6.85	52.22	30.38	15.60	45.98	3202.68	9.51
19:15:00	1843.80	60.55	874.72	1769.33	189.84	4.33	11.34	0.06	7.22	0.06	6.06	6.84	52.43	30.43	15.59	46.01	3204.43	9.38
19:30:00	1845.22	60.56	874.72	1769.85	190.47	4.30	11.38	0.06	7.07	0.06	6.09	6.82	52.64	30.47	15.57	46.03	3206.16	9.23
19:45:00	1846.65	60.57	874.71	1770.36	191.04	4.31	11.42	0.06	6.93	0.06	6.12	6.80	52.85	30.51	15.55	46.06	3207.87	9.09
20:00:00	1848.10	60.59	874.71	1770.87	191.58	4.31	11.46	0.06	6.78	0.06	6.14	6.78	53.05	30.55	15.53	46.08	3209.57	8.94
20:15:00	1849.52	60.60	874.69	1771.42	192.35	4.37	11.50	0.06	6.65	0.06	6.14	6.77	53.25	30.64	15.51	46.15	3211.45	8.65
20:30:00	1851.01	60.61	874.68	1772.00	193.19	4.38	11.54	0.06	6.52	0.06	6.14	6.75	53.43	30.71	15.49	46.20	3213.43	8.52
20:45:00	1852.55	60.62	874.68	1772.59	194.06	4.39	11.58	0.06	6.39	0.06	6.14	6.74	53.59	30.77	15.48	46.25	3215.46	8.39
21:00:00	1854.11	60.63	874.67	1773.20	194.93	4.39	11.62	0.06	6.27	0.06	6.13	6.73	53.74	30.84	15.46	46.29	3217.53	8.27
21:15:00	1855.69	60.65	874.67	1773.82	195.79	4.40	11.66	0.07	6.14	0.06	6.12	6.72	53.89	30.90	15.44	46.33	3219.60	8.14
21:30:00	1857.29	60.66	874.67	1774.43	196.63	4.42	11.70	0.07	6.02	0.06	6.11	6.71	54.03	30.96	15.42	46.37	3221.69	8.02
21:45:00	1858.90	60.67	874.67	1775.06	197.46	4.43	11.74	0.07	5.90	0.06	6.11	6.70	54.17	31.02	15.40	46.41	3223.77	7.90
22:00:00	1860.52	60.68	874.67	1775.68	198.29	4.42	11.78	0.07	5.79	0.06	6.10	6.69	54.30	31.08	15.37	46.45	3225.85	7.78

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
22:15:00	1862.14	60.69	874.68	1776.22	198.76	4.32	11.81	0.05	5.64	0.06	6.10	6.68	54.41	31.00	15.34	46.35	3227.57	7.45
22:30:00	1863.65	60.71	874.69	1776.66	198.77	4.29	11.84	0.05	5.46	0.06	6.11	6.67	54.50	30.99	15.31	46.30	3228.89	7.28
22:45:00	1865.09	60.72	874.70	1777.04	198.52	4.29	11.86	0.05	5.28	0.06	6.13	6.66	54.57	30.99	15.27	46.25	3229.97	7.09
23:00:00	1866.50	60.73	874.70	1777.37	198.12	4.28	11.88	0.05	5.09	0.06	6.15	6.65	54.62	30.98	15.22	46.20	3230.88	6.90
23:15:00	1867.88	60.74	874.71	1777.68	197.64	4.27	11.89	0.05	4.90	0.06	6.17	6.64	54.67	30.97	15.17	46.14	3231.70	6.71
23:30:00	1869.25	60.75	874.71	1777.98	197.13	4.24	11.90	0.05	4.71	0.06	6.19	6.62	54.72	30.96	15.12	46.07	3232.47	6.52
23:45:00	1870.60	60.76	874.72	1778.26	196.55	4.25	11.91	0.04	4.53	0.06	6.20	6.61	54.76	30.94	15.06	46.00	3233.20	6.34
00:00:00	1871.93	60.77	874.73	1778.54	195.95	4.26	11.91	0.04	4.35	0.06	6.21	6.60	54.79	30.92	15.00	45.93	3233.90	6.16
Reactor 2																		
min	1814.42	60.16	874.67	1743.94	81.65	3.60	7.73	0.00	0.33	0.05	5.53	6.47	48.34	21.10	6.68	30.33	3102.70	1.13
max	1879.57	61.10	875.46	1778.54	198.77	4.48	11.91	0.16	7.68	0.06	6.46	7.06	54.85	31.08	15.63	46.45	3233.90	10.08
ave	1849.46	60.58	875.02	1764.49	154.05	4.11	10.25	0.05	**3.73**	0.06	**5.97**	6.74	52.28	27.89	12.85	40.74	3180.89	**5.41**

Figure B-25 M&E-sized system dynamic simulation results

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
<u>Reactor 1:</u>																		
00:00:00	1867.37	31.27	539.33	1317.36	197.46	28.46	9.45	8.68	6.30	0.03	15.24	6.12	55.53	0.00	0.00	0.00	2690.03	8.08
00:15:00	1868.48	31.25	539.29	1316.02	193.52	25.51	9.23	7.19	5.22	0.02	15.32	6.09	55.30	0.00	0.00	0.00	2685.18	6.71
00:30:00	1869.64	31.24	539.28	1315.69	190.42	25.33	9.13	7.01	4.87	0.02	15.29	6.09	55.23	0.00	0.00	0.00	2683.52	6.35
00:45:00	1870.91	31.21	539.29	1315.63	188.20	25.29	9.06	6.98	4.73	0.02	15.16	6.11	55.21	0.00	0.00	0.00	2682.79	6.22
01:00:00	1872.17	31.18	539.31	1315.65	186.20	25.37	8.99	6.98	4.68	0.02	14.99	6.13	55.19	0.00	0.00	0.00	2682.34	6.17
01:15:00	1873.37	31.15	539.32	1315.66	184.41	25.35	8.93	6.97	4.66	0.02	14.80	6.15	55.18	0.00	0.00	0.00	2681.93	6.15
01:30:00	1874.51	31.12	539.34	1315.69	182.77	25.31	8.87	6.97	4.66	0.02	14.61	6.17	55.17	0.00	0.00	0.00	2681.58	6.14
01:45:00	1875.60	31.09	539.35	1315.72	181.24	25.27	8.81	6.96	4.66	0.02	14.42	6.20	55.16	0.00	0.00	0.00	2681.27	6.14
02:00:00	1876.63	31.06	539.37	1315.76	179.79	25.23	8.75	6.96	4.66	0.02	14.23	6.22	55.15	0.00	0.00	0.00	2680.97	6.15
02:15:00	1875.50	31.02	539.21	1311.43	170.62	17.82	8.61	3.70	3.62	0.02	14.76	6.11	54.82	0.00	0.00	0.00	2665.95	4.99
02:30:00	1874.82	30.98	539.18	1309.74	163.48	17.52	8.51	3.53	3.30	0.02	14.93	6.09	54.68	0.00	0.00	0.00	2659.26	4.68
02:45:00	1874.65	30.94	539.18	1308.78	158.73	17.46	8.42	3.52	3.19	0.02	14.89	6.09	54.60	0.00	0.00	0.00	2655.22	4.57
03:00:00	1874.55	30.89	539.19	1308.03	154.84	17.49	8.33	3.52	3.16	0.02	14.79	6.10	54.54	0.00	0.00	0.00	2652.02	4.53
03:15:00	1874.34	30.85	539.21	1307.32	151.26	17.55	8.24	3.52	3.15	0.02	14.66	6.12	54.48	0.00	0.00	0.00	2649.01	4.53
03:30:00	1874.02	30.80	539.22	1306.63	148.06	17.51	8.15	3.52	3.15	0.02	14.53	6.14	54.43	0.00	0.00	0.00	2646.11	4.53
03:45:00	1873.58	30.76	539.24	1305.96	145.10	17.47	8.06	3.53	3.16	0.02	14.42	6.16	54.37	0.00	0.00	0.00	2643.32	4.54
04:00:00	1873.02	30.72	539.25	1305.29	142.35	17.44	7.96	3.53	3.17	0.02	14.31	6.17	54.32	0.00	0.00	0.00	2640.58	4.55
04:15:00	1869.44	30.67	539.11	1300.00	130.92	9.85	7.80	1.21	2.18	0.02	15.00	6.07	53.59	0.00	0.00	0.00	2621.62	3.24
04:30:00	1866.82	30.62	539.08	1297.48	122.16	9.57	7.66	1.19	1.88	0.02	15.29	6.04	53.27	0.00	0.00	0.00	2611.98	2.93
04:45:00	1864.76	30.57	539.08	1295.76	116.25	9.53	7.54	1.19	1.77	0.02	15.36	6.04	53.07	0.00	0.00	0.00	2605.38	2.83

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
05:00:00	1862.75	30.52	539.09	1294.29	111.46	9.57	7.41	1.19	1.74	0.02	15.37	6.04	52.90	0.00	0.00	0.00	2599.78	2.80
05:15:00	1860.55	30.47	539.10	1292.87	107.14	9.64	7.29	1.20	1.74	0.02	15.36	6.05	52.74	0.00	0.00	0.00	2594.45	2.79
05:30:00	1858.18	30.42	539.11	1291.48	103.34	9.61	7.16	1.20	1.75	0.02	15.36	6.06	52.59	0.00	0.00	0.00	2589.28	2.80
05:45:00	1855.61	30.37	539.12	1290.10	99.91	9.59	7.03	1.20	1.76	0.02	15.37	6.07	52.44	0.00	0.00	0.00	2584.25	2.81
06:00:00	1852.86	30.33	539.13	1288.72	96.79	9.56	6.90	1.20	1.77	0.02	15.40	6.08	52.30	0.00	0.00	0.00	2579.32	2.82
06:15:00	1848.65	30.28	539.08	1285.53	90.32	6.59	6.74	0.54	1.36	0.02	15.76	6.04	51.79	0.00	0.00	0.00	2567.87	2.11
06:30:00	1844.83	30.23	539.07	1283.43	85.22	6.49	6.59	0.54	1.23	0.02	15.95	6.03	51.50	0.00	0.00	0.00	2560.32	1.98
06:45:00	1841.11	30.19	539.07	1281.65	81.46	6.48	6.46	0.54	1.19	0.02	16.07	6.03	51.28	0.00	0.00	0.00	2554.02	1.94
07:00:00	1837.29	30.14	539.07	1279.96	78.29	6.53	6.32	0.54	1.18	0.02	16.16	6.04	51.07	0.00	0.00	0.00	2548.17	1.93
07:15:00	1833.32	30.10	539.07	1278.30	75.55	6.54	6.20	0.54	1.18	0.02	16.25	6.04	50.88	0.00	0.00	0.00	2542.49	1.93
07:30:00	1829.19	30.05	539.07	1276.66	73.14	6.55	6.07	0.54	1.18	0.02	16.34	6.04	50.68	0.00	0.00	0.00	2536.94	1.93
07:45:00	1824.91	30.01	539.07	1275.03	71.02	6.53	5.95	0.55	1.19	0.02	16.44	6.05	50.49	0.00	0.00	0.00	2531.47	1.94
08:00:00	1820.50	29.97	539.07	1273.40	69.15	6.52	5.84	0.55	1.19	0.02	16.54	6.05	50.30	0.00	0.00	0.00	2526.08	1.94
08:15:00	1816.78	29.93	539.16	1272.67	68.97	7.52	5.85	0.80	1.82	0.02	16.31	6.12	49.65	0.00	0.00	0.00	2523.66	2.85
08:30:00	1812.51	29.90	539.17	1271.37	68.44	7.54	5.80	0.81	2.04	0.02	16.30	6.15	49.27	0.00	0.00	0.00	2519.55	3.07
08:45:00	1808.00	29.87	539.17	1269.94	67.67	7.55	5.73	0.81	2.13	0.02	16.37	6.16	48.98	0.00	0.00	0.00	2515.00	3.16
09:00:00	1803.38	29.84	539.16	1268.45	66.94	7.50	5.66	0.81	2.16	0.02	16.48	6.16	48.72	0.00	0.00	0.00	2510.32	3.19
09:15:00	1798.69	29.81	539.15	1266.96	66.26	7.47	5.60	0.81	2.18	0.02	16.60	6.16	48.47	0.00	0.00	0.00	2505.63	3.21
09:30:00	1793.97	29.78	539.13	1265.46	65.61	7.46	5.53	0.81	2.18	0.02	16.73	6.16	48.22	0.00	0.00	0.00	2500.96	3.21
09:45:00	1789.21	29.75	539.11	1263.96	65.01	7.48	5.48	0.82	2.18	0.02	16.87	6.16	47.97	0.00	0.00	0.00	2496.30	3.21
10:00:00	1784.43	29.72	539.09	1262.46	64.45	7.51	5.42	0.82	2.18	0.02	17.00	6.16	47.72	0.00	0.00	0.00	2491.67	3.21
10:15:00	1786.54	29.74	539.68	1272.30	84.31	25.37	6.02	7.30	6.51	0.04	14.61	6.60	47.41	0.00	0.00	0.00	2525.62	8.19

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
10:30:00	1785.51	29.74	539.80	1274.80	96.91	26.02	6.22	7.89	7.83	0.04	13.77	6.74	47.15	0.00	0.00	0.00	2535.66	9.51
10:45:00	1783.41	29.76	539.81	1275.60	103.97	26.15	6.35	7.97	8.35	0.04	13.51	6.79	46.91	0.00	0.00	0.00	2539.65	10.03
11:00:00	1781.29	29.78	539.79	1275.99	109.22	26.21	6.46	7.99	8.62	0.04	13.44	6.82	46.67	0.00	0.00	0.00	2542.08	10.29
11:15:00	1779.41	29.81	539.77	1276.28	113.82	26.09	6.56	8.00	8.78	0.04	13.44	6.83	46.44	0.00	0.00	0.00	2544.03	10.45
11:30:00	1777.81	29.84	539.74	1276.56	117.72	26.22	6.67	8.01	8.88	0.04	13.48	6.84	46.22	0.00	0.00	0.00	2545.88	10.56
11:45:00	1776.45	29.88	539.72	1276.81	121.20	26.31	6.78	8.02	8.95	0.04	13.52	6.84	46.01	0.00	0.00	0.00	2547.54	10.63
12:00:00	1775.30	29.92	539.69	1277.06	124.36	26.37	6.89	8.02	9.00	0.04	13.58	6.84	45.80	0.00	0.00	0.00	2549.11	10.68
12:15:00	1776.01	29.96	539.77	1284.32	140.85	39.16	7.21	15.19	11.10	0.05	13.11	6.92	47.85	0.00	0.00	0.00	2574.38	13.13
12:30:00	1776.78	30.01	539.77	1287.10	152.35	39.75	7.40	16.50	11.76	0.05	12.91	6.95	48.42	0.00	0.00	0.00	2584.97	13.79
12:45:00	1777.63	30.05	539.75	1288.87	160.12	39.90	7.57	16.77	12.06	0.05	12.85	6.96	48.64	0.00	0.00	0.00	2592.11	14.09
13:00:00	1778.71	30.10	539.72	1290.42	166.63	39.99	7.73	16.81	12.25	0.05	12.83	6.96	48.77	0.00	0.00	0.00	2598.36	14.28
13:15:00	1780.06	30.15	539.69	1291.90	172.66	39.91	7.90	16.82	12.39	0.05	12.84	6.95	48.88	0.00	0.00	0.00	2604.30	14.42
13:30:00	1781.65	30.20	539.67	1293.38	178.11	40.00	8.07	16.81	12.50	0.05	12.85	6.95	48.99	0.00	0.00	0.00	2610.14	14.52
13:45:00	1783.45	30.25	539.64	1294.84	183.17	40.09	8.23	16.79	12.58	0.05	12.87	6.94	49.09	0.00	0.00	0.00	2615.84	14.61
14:00:00	1785.45	30.30	539.62	1296.30	187.92	40.16	8.40	16.78	12.65	0.05	12.90	6.93	49.18	0.00	0.00	0.00	2621.45	14.67
14:15:00	1787.15	30.35	539.46	1297.03	192.19	39.08	8.53	16.04	12.52	0.05	13.30	6.84	50.16	0.00	0.00	0.00	2625.17	14.77
14:30:00	1789.23	30.40	539.40	1298.18	195.68	39.08	8.67	15.87	12.47	0.05	13.49	6.79	50.57	0.00	0.00	0.00	2629.71	14.73
14:45:00	1791.49	30.45	539.37	1299.43	199.07	39.10	8.81	15.82	12.45	0.05	13.62	6.76	50.82	0.00	0.00	0.00	2634.39	14.71
15:00:00	1793.89	30.51	539.35	1300.69	202.24	39.18	8.96	15.79	12.43	0.05	13.73	6.74	51.04	0.00	0.00	0.00	2639.09	14.68
15:15:00	1796.39	30.56	539.32	1301.97	205.27	39.24	9.10	15.77	12.41	0.05	13.83	6.71	51.24	0.00	0.00	0.00	2643.75	14.66
15:30:00	1798.98	30.61	539.31	1303.24	208.21	39.24	9.23	15.75	12.38	0.05	13.93	6.69	51.44	0.00	0.00	0.00	2648.37	14.64
15:45:00	1801.66	30.67	539.29	1304.51	211.01	39.23	9.37	15.72	12.36	0.05	14.03	6.66	51.63	0.00	0.00	0.00	2652.95	14.61

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
16:00:00	1804.42	30.72	539.27	1305.78	213.68	39.22	9.49	15.70	12.33	0.05	14.12	6.64	51.81	0.00	0.00	0.00	2657.50	14.58
16:15:00	1806.39	30.76	539.10	1304.00	211.56	33.55	9.53	12.40	11.49	0.04	14.70	6.51	51.96	0.00	0.00	0.00	2652.27	13.87
16:30:00	1808.52	30.81	539.05	1304.09	210.07	33.29	9.61	11.77	11.17	0.04	15.03	6.45	52.12	0.00	0.00	0.00	2652.59	13.55
16:45:00	1810.83	30.86	539.03	1304.64	209.84	33.24	9.70	11.64	10.99	0.04	15.25	6.40	52.29	0.00	0.00	0.00	2654.34	13.37
17:00:00	1813.21	30.91	539.02	1305.32	209.91	33.30	9.79	11.64	10.86	0.04	15.44	6.37	52.45	0.00	0.00	0.00	2656.52	13.24
17:15:00	1815.60	30.96	539.00	1306.00	210.03	33.31	9.87	11.58	10.74	0.04	15.60	6.33	52.61	0.00	0.00	0.00	2658.71	13.13
17:30:00	1817.99	31.00	538.99	1306.70	210.24	33.26	9.94	11.56	10.65	0.04	15.75	6.30	52.77	0.00	0.00	0.00	2660.94	13.03
17:45:00	1820.40	31.05	538.98	1307.41	210.46	33.22	10.01	11.55	10.57	0.04	15.89	6.27	52.93	0.00	0.00	0.00	2663.19	12.95
18:00:00	1822.80	31.09	538.98	1308.12	210.68	33.17	10.08	11.53	10.50	0.04	16.01	6.24	53.08	0.00	0.00	0.00	2665.43	12.88
18:15:00	1824.86	31.13	538.89	1308.29	210.66	32.18	9.81	11.01	9.03	0.03	16.40	6.15	53.77	0.00	0.00	0.00	2666.21	11.16
18:30:00	1827.07	31.17	538.86	1308.78	210.28	32.12	9.74	10.91	8.45	0.03	16.62	6.10	54.11	0.00	0.00	0.00	2667.75	10.58
18:45:00	1829.33	31.20	538.85	1309.35	210.03	32.08	9.72	10.88	8.13	0.03	16.77	6.06	54.37	0.00	0.00	0.00	2669.48	10.27
19:00:00	1831.60	31.23	538.84	1309.94	209.76	32.11	9.71	10.86	7.92	0.03	16.87	6.04	54.59	0.00	0.00	0.00	2671.27	10.06
19:15:00	1833.87	31.25	538.84	1310.54	209.52	32.12	9.71	10.85	7.77	0.03	16.92	6.02	54.81	0.00	0.00	0.00	2673.07	9.91
19:30:00	1836.13	31.27	538.84	1311.14	209.35	32.07	9.70	10.83	7.66	0.03	16.94	6.00	55.02	0.00	0.00	0.00	2674.86	9.80
19:45:00	1838.37	31.28	538.84	1311.74	209.19	32.02	9.70	10.82	7.58	0.03	16.92	5.99	55.22	0.00	0.00	0.00	2676.65	9.72
20:00:00	1840.60	31.29	538.84	1312.34	209.03	31.98	9.70	10.80	7.53	0.03	16.89	5.99	55.42	0.00	0.00	0.00	2678.43	9.67
20:15:00	1843.21	31.31	538.92	1313.71	209.85	33.14	9.71	11.54	7.65	0.03	16.57	6.04	55.21	0.00	0.00	0.00	2682.53	9.63
20:30:00	1845.66	31.31	538.94	1314.61	210.59	33.15	9.71	11.65	7.69	0.03	16.39	6.06	55.26	0.00	0.00	0.00	2685.32	9.66
20:45:00	1848.05	31.32	538.95	1315.40	211.07	33.14	9.71	11.66	7.69	0.03	16.27	6.07	55.37	0.00	0.00	0.00	2687.78	9.67
21:00:00	1850.41	31.32	538.96	1316.15	211.49	33.07	9.72	11.65	7.70	0.03	16.16	6.08	55.49	0.00	0.00	0.00	2690.13	9.67
21:15:00	1852.76	31.33	538.97	1316.89	211.88	32.99	9.72	11.64	7.70	0.03	16.05	6.09	55.62	0.00	0.00	0.00	2692.45	9.67

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
21:30:00	1855.12	31.33	538.97	1317.63	212.19	32.98	9.73	11.62	7.69	0.03	15.95	6.10	55.74	0.00	0.00	0.00	2694.74	9.67
21:45:00	1857.48	31.34	538.98	1318.36	212.47	32.96	9.73	11.61	7.69	0.03	15.85	6.10	55.86	0.00	0.00	0.00	2697.02	9.67
22:00:00	1859.84	31.34	538.99	1319.09	212.74	32.95	9.74	11.59	7.69	0.03	15.75	6.11	55.98	0.00	0.00	0.00	2699.29	9.67
22:15:00	1861.53	31.34	538.94	1317.38	208.20	28.73	9.63	9.13	6.79	0.03	15.90	6.07	55.52	0.00	0.00	0.00	2693.32	8.58
22:30:00	1863.23	31.34	538.94	1317.16	205.16	28.51	9.59	8.75	6.50	0.03	15.92	6.06	55.42	0.00	0.00	0.00	2692.12	8.28
22:45:00	1865.06	31.34	538.95	1317.34	203.38	28.46	9.57	8.69	6.38	0.03	15.86	6.06	55.41	0.00	0.00	0.00	2692.25	8.17
23:00:00	1866.93	31.33	538.96	1317.62	201.93	28.52	9.55	8.68	6.33	0.03	15.76	6.07	55.43	0.00	0.00	0.00	2692.76	8.11
23:15:00	1868.76	31.32	538.97	1317.91	200.63	28.51	9.52	8.67	6.31	0.03	15.63	6.08	55.46	0.00	0.00	0.00	2693.31	8.09
23:30:00	1870.56	31.31	538.98	1318.21	199.46	28.48	9.50	8.66	6.30	0.03	15.50	6.09	55.49	0.00	0.00	0.00	2693.91	8.08
23:45:00	1872.32	31.30	539.00	1318.52	198.38	28.44	9.48	8.65	6.30	0.03	15.37	6.11	55.52	0.00	0.00	0.00	2694.55	8.08
00:00:00	1874.04	31.29	539.01	1318.83	197.36	28.39	9.45	8.64	6.30	0.03	15.24	6.12	55.54	0.00	0.00	0.00	2695.21	8.08
<u>Reactor 2:</u>																		
00:00:00	1886.50	31.69	545.39	1315.00	144.94	4.85	8.44	0.19	0.45	0.05	20.74	5.28	55.29	29.18	10.86	40.04	2654.30	2.25
00:15:00	1888.12	31.68	545.40	1315.19	143.51	4.73	8.39	0.15	0.38	0.05	20.60	5.29	55.30	28.83	10.02	38.85	2654.48	1.90
00:30:00	1889.56	31.65	545.42	1315.26	141.69	4.70	8.34	0.15	0.32	0.05	20.42	5.31	55.30	28.66	9.01	37.67	2654.24	1.83
00:45:00	1890.89	31.63	545.43	1315.31	139.84	4.69	8.28	0.15	0.29	0.05	20.21	5.34	55.29	28.53	8.44	36.96	2653.90	1.80
01:00:00	1892.14	31.59	545.45	1315.35	138.07	4.67	8.22	0.15	0.28	0.05	19.98	5.36	55.27	28.40	8.20	36.60	2653.56	1.79
01:15:00	1893.33	31.56	545.46	1315.38	136.38	4.66	8.15	0.15	0.28	0.05	19.75	5.39	55.26	28.28	8.16	36.43	2653.23	1.79
01:30:00	1894.46	31.53	545.48	1315.42	134.78	4.65	8.09	0.15	0.28	0.05	19.53	5.42	55.25	28.16	8.17	36.33	2652.91	1.79
01:45:00	1895.52	31.50	545.49	1315.45	133.26	4.64	8.03	0.15	0.28	0.05	19.31	5.45	55.24	28.04	8.21	36.25	2652.61	1.79
02:00:00	1896.52	31.47	545.51	1315.49	131.82	4.64	7.97	0.15	0.28	0.05	19.09	5.47	55.23	27.93	8.25	36.18	2652.33	1.79
02:15:00	1897.28	31.44	545.55	1315.21	129.35	4.33	7.90	0.08	0.23	0.05	18.93	5.49	55.20	27.17	7.21	34.38	2650.78	1.64

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
02:30:00	1897.58	31.39	545.57	1314.64	125.83	4.26	7.83	0.07	0.20	0.05	18.76	5.51	55.14	26.82	6.43	33.25	2648.16	1.60
02:45:00	1897.64	31.35	545.59	1313.99	122.23	4.24	7.74	0.07	0.19	0.05	18.60	5.53	55.08	26.49	6.20	32.69	2645.29	1.60
03:00:00	1897.53	31.30	545.60	1313.32	118.76	4.22	7.65	0.07	0.19	0.05	18.43	5.55	55.02	26.18	6.19	32.37	2642.39	1.60
03:15:00	1897.27	31.26	545.62	1312.65	115.51	4.20	7.56	0.07	0.19	0.05	18.28	5.58	54.96	25.87	6.33	32.20	2639.53	1.60
03:30:00	1896.87	31.21	545.64	1311.97	112.45	4.19	7.46	0.07	0.20	0.05	18.14	5.60	54.90	25.57	6.52	32.08	2636.71	1.61
03:45:00	1896.33	31.17	545.65	1311.29	109.59	4.19	7.37	0.07	0.21	0.05	18.02	5.61	54.84	25.28	6.68	31.96	2633.94	1.62
04:00:00	1895.67	31.13	545.67	1310.62	106.93	4.18	7.27	0.07	0.22	0.05	17.91	5.63	54.78	25.00	6.82	31.82	2631.21	1.62
04:15:00	1894.69	31.09	545.70	1309.65	103.42	3.89	7.17	0.02	0.18	0.05	17.84	5.64	54.68	24.23	5.98	30.22	2627.32	1.27
04:30:00	1893.17	31.04	545.72	1308.37	98.94	3.83	7.05	0.02	0.16	0.05	17.79	5.66	54.53	23.72	5.42	29.14	2622.35	1.24
04:45:00	1891.33	30.98	545.74	1307.01	94.47	3.81	6.93	0.02	0.16	0.05	17.74	5.67	54.38	23.19	5.33	28.52	2617.13	1.24
05:00:00	1889.23	30.93	545.75	1305.63	90.28	3.80	6.80	0.02	0.16	0.05	17.71	5.68	54.22	22.66	5.42	28.08	2611.90	1.25
05:15:00	1886.90	30.88	545.76	1304.24	86.42	3.78	6.67	0.02	0.17	0.05	17.69	5.69	54.05	22.16	5.65	27.81	2606.74	1.25
05:30:00	1884.36	30.83	545.78	1302.85	82.87	3.77	6.54	0.02	0.18	0.05	17.69	5.70	53.90	21.68	5.90	27.58	2601.66	1.27
05:45:00	1881.63	30.79	545.79	1301.46	79.63	3.76	6.41	0.02	0.19	0.05	17.71	5.71	53.74	21.22	6.11	27.33	2596.66	1.27
06:00:00	1878.70	30.74	545.79	1300.08	76.68	3.76	6.28	0.02	0.20	0.05	17.74	5.72	53.58	20.79	6.29	27.08	2591.73	1.28
06:15:00	1875.53	30.70	545.81	1298.58	73.63	3.66	6.15	0.01	0.19	0.05	17.79	5.73	53.40	20.22	6.08	26.29	2586.42	0.97
06:30:00	1872.02	30.65	545.81	1296.97	70.41	3.63	6.02	0.01	0.18	0.05	17.86	5.73	53.20	19.71	5.90	25.60	2580.74	0.96
06:45:00	1868.27	30.61	545.82	1295.33	67.39	3.62	5.89	0.01	0.18	0.05	17.93	5.74	52.99	19.21	5.91	25.13	2575.02	0.96
07:00:00	1864.30	30.56	545.82	1293.67	64.66	3.61	5.76	0.01	0.19	0.05	18.01	5.74	52.79	18.75	6.00	24.75	2569.34	0.97
07:15:00	1860.16	30.52	545.82	1292.02	62.20	3.60	5.63	0.01	0.19	0.05	18.09	5.75	52.58	18.31	6.13	24.44	2563.73	0.97
07:30:00	1855.86	30.47	545.82	1290.37	60.01	3.59	5.51	0.01	0.20	0.05	18.19	5.75	52.38	17.92	6.23	24.14	2558.19	0.98
07:45:00	1851.41	30.43	545.82	1288.72	58.05	3.59	5.40	0.01	0.20	0.05	18.29	5.76	52.17	17.55	6.31	23.86	2552.71	0.98

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
08:00:00	1846.83	30.39	545.81	1287.07	56.32	3.59	5.29	0.01	0.20	0.05	18.40	5.76	51.97	17.21	6.37	23.58	2547.30	0.98
08:15:00	1842.13	30.35	545.80	1285.45	54.93	3.65	5.19	0.02	0.23	0.05	18.50	5.77	51.73	16.98	7.02	24.00	2542.10	1.29
08:30:00	1837.44	30.31	545.78	1283.89	53.89	3.66	5.11	0.02	0.26	0.05	18.61	5.77	51.47	16.77	7.61	24.38	2537.15	1.32
08:45:00	1832.71	30.28	545.77	1282.36	53.02	3.66	5.04	0.02	0.28	0.05	18.74	5.77	51.20	16.59	7.92	24.50	2532.30	1.34
09:00:00	1827.95	30.26	545.76	1280.83	52.25	3.67	4.97	0.02	0.29	0.05	18.88	5.77	50.92	16.42	8.06	24.48	2527.50	1.34
09:15:00	1823.14	30.23	545.74	1279.31	51.56	3.67	4.90	0.02	0.29	0.05	19.02	5.77	50.65	16.27	8.10	24.37	2522.74	1.35
09:30:00	1818.31	30.20	545.73	1277.79	50.96	3.67	4.85	0.02	0.29	0.05	19.16	5.77	50.38	16.14	8.10	24.23	2518.01	1.35
09:45:00	1813.45	30.17	545.71	1276.27	50.42	3.67	4.79	0.02	0.29	0.05	19.30	5.77	50.12	16.02	8.07	24.09	2513.30	1.35
10:00:00	1808.58	30.14	545.69	1274.75	49.95	3.67	4.74	0.02	0.29	0.05	19.44	5.77	49.85	15.90	8.04	23.95	2508.63	1.34
10:15:00	1804.15	30.12	545.60	1273.94	52.03	4.46	4.76	0.16	0.55	0.05	19.43	5.80	49.55	17.45	11.49	28.94	2506.95	2.23
10:30:00	1801.00	30.13	545.55	1273.93	56.84	4.63	4.83	0.19	0.87	0.05	19.39	5.83	49.25	18.51	13.93	32.45	2508.17	2.55
10:45:00	1798.50	30.15	545.53	1274.12	61.74	4.67	4.93	0.19	1.13	0.05	19.39	5.85	48.95	19.38	15.19	34.57	2509.94	2.80
11:00:00	1796.43	30.18	545.50	1274.35	66.24	4.69	5.03	0.19	1.32	0.04	19.42	5.86	48.66	20.11	15.91	36.02	2511.75	2.99
11:15:00	1794.69	30.22	545.47	1274.60	70.29	4.72	5.14	0.19	1.46	0.04	19.47	5.87	48.38	20.73	16.36	37.09	2513.51	3.13
11:30:00	1793.22	30.25	545.44	1274.84	73.97	4.74	5.25	0.19	1.55	0.04	19.54	5.87	48.11	21.26	16.63	37.90	2515.17	3.22
11:45:00	1791.98	30.29	545.41	1275.09	77.30	4.75	5.37	0.19	1.61	0.04	19.61	5.87	47.85	21.73	16.82	38.55	2516.77	3.29
12:00:00	1790.95	30.33	545.38	1275.33	80.34	4.76	5.48	0.19	1.66	0.05	19.69	5.87	47.59	22.13	16.95	39.08	2518.31	3.33
12:15:00	1790.51	30.37	545.34	1276.17	84.93	5.36	5.61	0.37	1.85	0.04	19.72	5.87	47.52	23.99	17.39	41.38	2522.09	3.87
12:30:00	1790.94	30.42	545.31	1277.51	91.32	5.51	5.76	0.42	2.10	0.04	19.73	5.88	47.61	25.12	17.87	42.99	2527.70	4.12
12:45:00	1791.85	30.46	545.28	1278.95	97.68	5.55	5.92	0.43	2.32	0.04	19.74	5.88	47.74	25.92	18.23	44.14	2533.63	4.34
13:00:00	1793.09	30.51	545.25	1280.42	103.69	5.58	6.09	0.44	2.50	0.04	19.76	5.87	47.87	26.57	18.50	45.07	2539.56	4.53
13:15:00	1794.60	30.56	545.22	1281.89	109.29	5.62	6.26	0.44	2.65	0.04	19.79	5.87	48.00	27.14	18.70	45.84	2545.40	4.67

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
13:30:00	1796.35	30.62	545.20	1283.36	114.55	5.64	6.42	0.43	2.77	0.04	19.82	5.86	48.13	27.64	18.86	46.50	2551.16	4.79
13:45:00	1798.30	30.67	545.17	1284.83	119.50	5.66	6.59	0.43	2.86	0.04	19.86	5.85	48.25	28.09	18.99	47.08	2556.85	4.88
14:00:00	1800.43	30.72	545.15	1286.30	124.16	5.67	6.76	0.43	2.93	0.04	19.91	5.83	48.37	28.50	19.09	47.59	2562.46	4.95
14:15:00	1802.69	30.78	545.14	1287.66	128.13	5.54	6.91	0.40	2.93	0.04	20.02	5.81	48.56	28.61	19.12	47.74	2567.53	5.18
14:30:00	1804.99	30.83	545.12	1288.97	131.70	5.54	7.06	0.39	2.92	0.04	20.15	5.78	48.80	28.87	19.14	48.02	2572.40	5.17
14:45:00	1807.39	30.89	545.10	1290.27	135.06	5.54	7.21	0.39	2.89	0.04	20.29	5.75	49.05	29.14	19.16	48.30	2577.19	5.15
15:00:00	1809.88	30.94	545.08	1291.56	138.25	5.54	7.35	0.39	2.87	0.04	20.42	5.72	49.30	29.39	19.17	48.56	2581.93	5.12
15:15:00	1812.47	31.00	545.06	1292.86	141.27	5.54	7.49	0.39	2.84	0.05	20.55	5.68	49.54	29.63	19.17	48.80	2586.62	5.09
15:30:00	1815.15	31.05	545.04	1294.14	144.13	5.55	7.62	0.39	2.81	0.05	20.68	5.65	49.78	29.85	19.17	49.03	2591.26	5.06
15:45:00	1817.92	31.11	545.02	1295.43	146.85	5.56	7.76	0.38	2.78	0.05	20.80	5.62	50.01	30.06	19.17	49.24	2595.86	5.03
16:00:00	1820.75	31.16	545.00	1296.72	149.43	5.56	7.88	0.38	2.74	0.05	20.92	5.60	50.24	30.26	19.17	49.43	2600.42	5.00
16:15:00	1823.50	31.21	545.01	1297.72	150.92	5.28	7.99	0.29	2.61	0.05	21.10	5.56	50.45	29.75	19.06	48.81	2603.81	5.00
16:30:00	1826.02	31.27	545.00	1298.51	151.46	5.22	8.09	0.27	2.46	0.05	21.31	5.51	50.65	29.65	18.90	48.55	2606.39	4.84
16:45:00	1828.47	31.32	544.98	1299.25	151.76	5.20	8.18	0.27	2.31	0.05	21.52	5.47	50.85	29.67	18.72	48.39	2608.77	4.70
17:00:00	1830.91	31.37	544.97	1299.98	152.00	5.19	8.27	0.27	2.18	0.05	21.71	5.43	51.04	29.70	18.55	48.25	2611.09	4.56
17:15:00	1833.34	31.41	544.96	1300.70	152.22	5.18	8.34	0.26	2.06	0.05	21.90	5.39	51.23	29.73	18.38	48.12	2613.39	4.45
17:30:00	1835.78	31.46	544.95	1301.42	152.42	5.18	8.41	0.26	1.96	0.05	22.07	5.35	51.42	29.76	18.23	47.99	2615.68	4.35
17:45:00	1838.21	31.50	544.94	1302.14	152.60	5.18	8.48	0.26	1.87	0.05	22.23	5.32	51.60	29.80	18.08	47.88	2617.95	4.26
18:00:00	1840.64	31.55	544.94	1302.86	152.76	5.17	8.54	0.26	1.80	0.05	22.37	5.29	51.78	29.83	17.96	47.78	2620.21	4.19
18:15:00	1843.05	31.59	544.94	1303.52	152.66	5.11	8.57	0.25	1.62	0.05	22.54	5.25	51.99	29.72	17.55	47.27	2622.21	3.77
18:30:00	1845.40	31.63	544.94	1304.14	152.45	5.10	8.58	0.24	1.37	0.05	22.70	5.21	52.24	29.70	16.87	46.57	2624.09	3.53
18:45:00	1847.72	31.66	544.93	1304.75	152.23	5.09	8.58	0.24	1.15	0.05	22.81	5.18	52.49	29.70	16.07	45.77	2625.93	3.31

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
19:00:00	1850.02	31.68	544.93	1305.36	152.01	5.08	8.57	0.24	0.98	0.05	22.88	5.16	52.74	29.71	15.24	44.95	2627.76	3.13
19:15:00	1852.31	31.70	544.93	1305.97	151.80	5.07	8.57	0.24	0.84	0.05	22.91	5.14	52.98	29.71	14.47	44.19	2629.58	3.00
19:30:00	1854.58	31.72	544.93	1306.58	151.59	5.07	8.57	0.24	0.75	0.05	22.90	5.13	53.22	29.72	13.84	43.56	2631.39	2.90
19:45:00	1856.84	31.73	544.93	1307.19	151.38	5.06	8.57	0.24	0.69	0.05	22.86	5.12	53.46	29.72	13.37	43.09	2633.19	2.84
20:00:00	1859.09	31.73	544.93	1307.79	151.18	5.06	8.56	0.24	0.65	0.05	22.80	5.12	53.69	29.73	13.04	42.77	2634.99	2.80
20:15:00	1861.36	31.74	544.92	1308.47	151.27	5.15	8.56	0.26	0.65	0.05	22.70	5.12	53.89	29.91	13.01	42.92	2637.10	2.64
20:30:00	1863.71	31.74	544.92	1309.20	151.55	5.16	8.56	0.26	0.65	0.05	22.58	5.13	54.06	29.98	13.03	43.01	2639.38	2.64
20:45:00	1866.07	31.75	544.92	1309.94	151.86	5.17	8.57	0.26	0.65	0.05	22.46	5.13	54.22	30.03	13.04	43.07	2641.70	2.64
21:00:00	1868.45	31.75	544.93	1310.69	152.16	5.17	8.57	0.26	0.65	0.05	22.34	5.14	54.38	30.07	13.04	43.11	2644.01	2.64
21:15:00	1870.83	31.76	544.94	1311.43	152.44	5.17	8.58	0.26	0.65	0.05	22.22	5.15	54.53	30.11	13.04	43.15	2646.32	2.64
21:30:00	1873.21	31.76	544.94	1312.17	152.71	5.17	8.58	0.26	0.65	0.05	22.10	5.16	54.67	30.15	13.02	43.17	2648.62	2.64
21:45:00	1875.59	31.77	544.95	1312.91	152.97	5.17	8.59	0.26	0.64	0.05	21.99	5.17	54.82	30.19	13.01	43.19	2650.92	2.64
22:00:00	1877.98	31.77	544.96	1313.65	153.21	5.16	8.59	0.26	0.64	0.05	21.87	5.17	54.96	30.22	13.00	43.22	2653.20	2.63
22:15:00	1880.24	31.77	544.97	1314.20	152.82	4.95	8.59	0.20	0.58	0.05	21.77	5.18	55.05	29.79	12.42	42.21	2654.69	2.39
22:30:00	1882.28	31.77	544.99	1314.57	151.69	4.90	8.57	0.19	0.51	0.05	21.66	5.19	55.10	29.64	11.71	41.34	2655.54	2.32
22:45:00	1884.23	31.76	545.00	1314.90	150.44	4.89	8.56	0.19	0.47	0.05	21.52	5.20	55.14	29.56	11.20	40.76	2656.23	2.28
23:00:00	1886.12	31.75	545.01	1315.22	149.20	4.87	8.54	0.19	0.45	0.05	21.37	5.21	55.17	29.48	10.93	40.42	2656.88	2.26
23:15:00	1887.96	31.74	545.03	1315.54	148.02	4.86	8.51	0.19	0.44	0.05	21.21	5.23	55.21	29.41	10.83	40.25	2657.53	2.25
23:30:00	1889.76	31.73	545.04	1315.86	146.88	4.85	8.49	0.19	0.44	0.05	21.05	5.24	55.24	29.35	10.81	40.16	2658.19	2.25
23:45:00	1891.52	31.72	545.05	1316.17	145.80	4.84	8.46	0.19	0.44	0.05	20.90	5.26	55.27	29.28	10.83	40.12	2658.85	2.25
00:00:00	1893.24	31.71	545.07	1316.49	144.76	4.84	8.44	0.19	0.45	0.05	20.75	5.27	55.31	29.22	10.87	40.10	2659.52	2.25

Time	Z_{bh}	Z_{ba}	Z_e	Z_i	S_{ads}	S_{enm}	N_{obp}	S_{bs}	N_a	N_{obs}	NO_3	Alk	S_{us}	O_c	O_n	O_t	X_v	N_t
Reactor 2																		
min	1790.51	30.12	544.92	1273.93	49.95	3.59	4.74	0.01	0.16	0.04	17.69	5.12	47.52	15.90	5.33	23.58	2506.95	0.96
max	1897.64	31.77	545.82	1316.49	153.21	5.67	8.59	0.44	2.93	0.05	22.91	5.88	55.31	30.26	19.17	49.43	2659.52	5.18
ave	1850.91	31.08	545.34	1299.04	115.10	4.68	7.16	0.19	**1.00**	0.05	**20.08**	5.54	52.31	25.63	12.12	37.75	2598.74	**2.68**