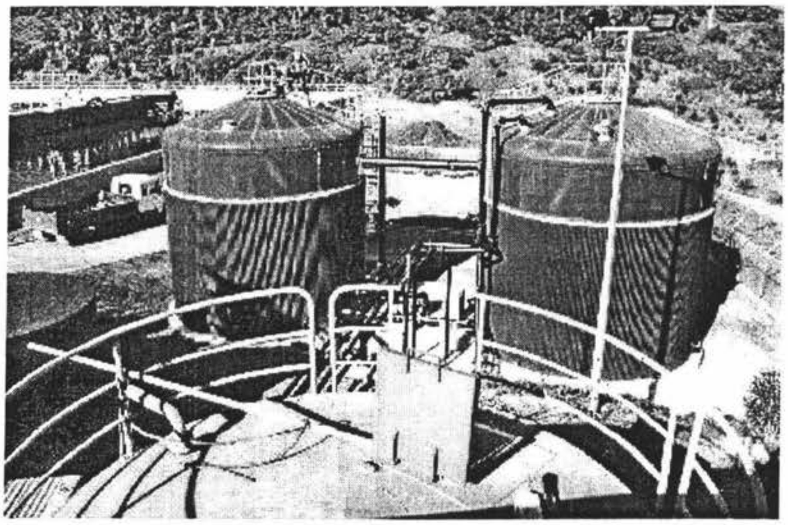
MODEL BASED STUDY OF AUTOTHERMAL THERMOPHILIC AEROBIC DIGESTION (ATAD) PROCESSES



A thesis presented in partial fulfilment of the requirements for the Degree of Master of Technology in Engineering and Automation of Massey University.

BARRY FRYER

2000

Summary

An Autothermal Thermophilic Aerobic Digestion (ATAD) process is a relatively new sewage sludge treatment process. The ATAD process is capable of stabilising and pasteurising sewage sludge so that it can be applied to land as a soil additive or fertiliser with minimal environmental and public health risks. A mathematical model was successfully developed to describe the dynamic behaviour of ATAD processes, which was used extensively to investigate possible improvements to the design, operation and control of ATAD processes.

Every aeration system has an oxygen transfer efficiency that maximises the net heat production of the entire system. The aeration system can be controlled to this optimal oxygen transfer efficiency with a simple PI controller. This control strategy also ensures that sufficient oxygen supplied to the microorganisms. Therefore increasing the rate of stabilisation and disinfection, and hence increasing throughput. Simulations have shown that the control strategy will increase performance and stability of the process, and consequently reduce capital and operational costs.

Simulations showed that the draw and fill strategy has a strong influence on the performance of the system. Unfortunately there are no clear-cut answers to optimising this, as it is very system dependent. The largest sludge throughput is achieved when the disinfection and the stabilisation criteria are achieved at similar times, without saturating the aeration system or dropping the reactor temperature below 50^0C. If the disinfection criterion is the system's constraint for prolonged periods the bacteria population can diminish due to lack of available organic substrates, which can result in process instability.

The mathematical model was used as the basis of a prototype ATAD Design and Simulation software package. This will allow designers to explore different operational and design scenarios before the design even reaches the drawing table.

Acknowledgements

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I would like to thank Nelson City Council and NelMac for allowing me to observe the operation of the ATAD systems at Nelson's Bells Island Sewage Treatment Plant. This provided valuable insight into an actual ATAD system.

Nomenclature

State Variables

SBS(t)	Concentration of slowly biodegradable substrate, (mg/l)
RBS(t)	Concentration of readily biodegradable substrate, (mg/l)
NBS(t)	Concentration of non biodegradable substrate, (mg/l)
VFA(t)	Concentration of Volatile Fatty Acids, (mg/l)
$X_M(t)$	Concentration of mesophilic bacteria, (mg/l)
$X_T(t)$	Concentration of thermophilic bacteria, (mg/l)
DO(t)	Concentration of dissolved oxygen, (mg/l)
Ht(t)	Height of liquid in reactor, (m)
T(t)	Reactor temperature, (^{0}C)

Output Variables

T(t)	Reactor temperature, (^{0}C)
VS(t)	Volatile solids concentration, (mg/l)

Input Variables

$Q_{air}(t)$	Air flow rate, (m^3/s)
$P_{Blow}(t)$	Power consumed by blower, (W)
$P_{pump}(t)$	Power consumed by re-circulation pump, (W)
$T_{air}(t)$	Temperature of ambient air, (^{0}C)
$T_{in}(t)$	Temperature of the feed sludge stream, (^{0}C)
$\dot{M}_{in}(t)$	Mass flow of sludge into reactor, (kg/s)
$\dot{M}_{out}(t)$	Mass flow of sludge out of reactor, (kg/s)

Other Variables

General Variables

H_{gas}	Humidity of exhaust gas stream, (kg of water/kg of air)
H_{amb}	Humidity of the inlet ambient air, (kg of water/kg of air)
V	Process water volume, (m^3)
A	Cross sectional area of reactor, (m^2)

VS	Volatile Solids concentration, (kg of VS/kg of wastewater)
$VS_{Reduction}$	Fraction of Volatile Solids reduced during ATAD process
Q	Daily sludge loading, (m^3/day)
VSL	Volatile Solids Loading, (kg of VS/day)
OTE_{Design}	Design Oxygen Transfer Efficiency, (%)
ρ_{air}	Density of air gas stream, (kg/m^3)
ρ	Density of sludge, (kg/m^3)
M_{react}	Mass of sludge in reactor, (kg)
$\dot{M}_{evap}$	Rate of water evaporated from reactor, (kg/sec)

Heat Variables

U	Overall heat transfer coefficient, ($W/m^2\ {}^0C$)
C_p	Specific Heat Capacity of the sludge, ($J/kg\ {}^0C$)
Cp_{air}	Specific Heat Capacity of air stream, ($J/kg\ {}^0C$)
λ	Thermal conductivity, (W/K m)
h	Film heat transfer coefficient, ($W/m^2\ {}^0C$)
h_{react}	Heat produced per kg of oxygen consumed (J/kg of O_2 consumed)
h_{evap}	Latent heat of vaporisation, (J/kg)
η_{Blow}	Efficiency of blower
η_{pump}	Efficiency of re-circulation pump
ϕ_{wall}	Heat lost through reactor walls, (W)
ϕ_{sludge}	Sensible heat lost by sludge flows, (W)
ϕ_{Air}	Sensible heat lost by air flow through the reactor, (W)
ϕ_{evap}	Heat lost by evaporation of water from reactor, (W)
ϕ_{react}	Heat produced by biochemical reaction, (W)
ϕ_{mech}	Heat produced by mechanical devices, (W)
$\phi_{aeration}$	Net heat produced as a result of the air supply, (W)

Aeration/ Oxygen Variables

OTR(t)	Oxygen transfer rate, (mg/s)
OUR(t)	Oxygen usage rage, (mg/s)
OTE(t)	Oxygen transfer efficiency, (%)
αF	Process water K_La / clean water K_La

K_La_{20}	Apparent volumetric oxygen mass transfer coefficient in water, (hr^{-1})
θ	Temperature adjustment coefficient
τ	Temperature correction factor for dissolved oxygen saturation
Ω	Pressure correction factor for dissolved oxygen saturation
β	Saturation modifier (process water/clean water)
C_s	Dissolved oxygen surface saturation concentration at water temperature, T, standard atmospheric pressure and 100% relative humidity, (mg/l)
C_{s20}	Dissolved oxygen saturation concentration at 20^{0}C and standard atmospheric pressure, (mg/l)
$C_{\infty 20}$	Steady state dissolved oxygen saturation concentration at infinite time and standard conditions, (mg/l)
P_B	Field atmospheric pressure, (kPa)
P_{vT}	Vapour pressure of water at temperature T, (kPa)
P_s	Atmospheric pressure at standard conditions, (kPa)
d_E	Effective saturation depth, (m)
A_{air}	Aeration system performance coefficient
B_{air}	Aeration system performance coefficient
U_{SG}	Superficial gas velocity, (m^3/m^2/day)
$Q_{air\ Opt}$	Optimal airflow rate, (m^3/sec)

Biochemical Reaction Variables

X	General bacteria concentration, (mg/l)
S	General bacterial substrate, (mg/l)
K_s	General substrate limitation, (mg/l)
μ	Specific bacterial growth rate constant, (1/sec)
μ_m	Maximum specific bacterial growth rate constant, (1/sec)
k_m	Specific rate constant for mesophilic bacteria, (1/sec)
k_t	Specific rate constant for thermophilic bacteria, (1/sec)
Y	Yield coefficients, (mg/mg)
Y_{Oxy}	Yield coefficient for dissolved oxygen, (mg/mg)
K_{SBS}	Rate limit for slowly biodegradable substrate, (mg/l)
K_{RBS}	Rate limit for readily biodegradable substrate, (mg/l)

K_{VFA}	Rate limit for Volatile Fatty Acids, (mg/l)
K_{DO}	Rate limit for dissolved oxygen in the oxidation pathway, (mg/l)
K_{DOf}	Rate limit for dissolved oxygen in the fermentation pathway, (mg/l)

Subscripts

Reaction	Accumulation of substrate due to the biochemical reaction
1	Biochemical pathway from SBS to RBS, (hydrolysis)
2	Biochemical pathway from RBS to bacteria, (oxidation)
3	Biochemical pathway from RBS to VFA, (fermentation)
4	Biochemical pathway from VFA to bacteria, (oxidation)
5	Biochemical pathway from bacteria to RBS, (lysis)
6	Biochemical pathway from bacteria to SBS, (lysis)
7	Biochemical pathway from bacteria to NBS, (lysis)

Common Abbreviations

ADP	Adenosine Diphosphate
ATAD	Autothermal Thermophilic Aerobic Digestion
ATP	Adenosine Triphosphate
EPA	Environmental Protection Agency
FAD	Flavin Adenine Dinucleotide
FADH	Flavin Adenine Dinucleotide Hydroxide
FSD	Full Scale Deflection
HRT	Hydraulic Residence Time
NAD	Nicotinamide Adenine Dinucleotide
NADH	Nicotinamide Adenine Dinucleotide Hydroxide
NBS	Non Biodegradable Substrate
OTE	Oxygen Transfer Efficiency
OTR	Oxygen Transfer Rate
OUR	Oxygen Usage Rate
PI	Proportional-Integral Controller
PID	Proportional-Integral-Derivative Controller
RBS	Readily Biodegradable Substrate
SBS	Slowly Biodegradable Substrate

SOUR	Specific Oxygen Usage Rate (determined at standard conditions)
TCA	Tricarboxylic Acid
TS	Total Solids
USEPA	United States Environmental Protection Agency
VFA	Volatile Fatty Acids
VS	Volatile Solids

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1. Introduction

An Autothermal Thermophilic Aerobic Digestion process, or ATAD process, is a relatively new sewage sludge treatment process. The ATAD process has been developed for the disinfection and stabilisation of sewage sludge, which is a by-product of wastewater treatment. The end product can be applied to the land as a soil additive or fertiliser with no restrictions, as the process dramatically reduces public health and environmental risks. The process is comparable to the composting process used for municipal solid waste and garden wastes.

The process requires oxygen, usually in the form of air, to be applied to the sludge by an aeration system. The oxygen stimulates an exothermic biochemical reaction, which in turn heats the sludge up to thermophilic temperatures (between 50 and 65^0C). At these temperatures the pathogenic bacteria, viruses and parasites in the sludge that are harmful to human health are effectively destroyed. The biochemical reaction also degrades a large portion of the organic sludge, which means that unstable, volatile odour generating substances are removed; this reduces the likelihood of smells and the attraction of flies and rodents (vector attraction) to the sludge.

ATAD processes have been widely and successfully implemented in a number of countries around the world, in particular Canada and Europe (Kelly, *et al,* 1993). In New Zealand the ATAD process has only been in operation for about 3½ years and during this time a number of difficulties have been encountered. This thesis was undertaken in an effort to better identify areas of potential difficulties and to reduce the capital and operational costs of an ATAD process.

The main objective of the project was to provide a deeper understanding into the design, operation and control of an ATAD process so that designers and consultants at Waste Solutions Ltd are capable of making informed decisions. A dynamic non-linear mathematical model was developed that includes mass and energy balances along with rudimentary biochemical degradation equations.

The potential uses of this ATAD model are virtually unlimited, but the key areas of interest in this thesis are the effects of air supply rates, draw and fill cycles and Volatile Solids concentrations on the overall performance of an ATAD system. The model has also been used to investigate an ATAD's physical design and the need for temperature and aeration control.

The thesis describes the physical and biochemical ATAD process in detail in Sections 2 and 4 respectively, with a brief biochemical background in Section 3. The mathematical model is developed in Section 5 and validated in Section 6. Section 7 discusses the issues associated with ATAD design; this includes the characteristics of the reactor and the aeration system, the effects of sludge concentrations, and the benefits of multistage ATAD systems. The operational issues investigated are discussed in Section 8, these include possible control strategies, draw and fill strategies, and possible ways of dealing with variations in sludge loads. Section 9 discusses the control an ATAD system with the proposed oxygen transfer efficiency – aeration rate control strategy.

2. Process Description

An Autothermal Thermophilic Aerobic Digestor (ATAD) is a process that treats sewage sludge, a by-product of wastewater treatment. The ATAD process is capable of stabilising and disinfecting both primary and secondary sewage sludge to the United States Environmental Protection Agency (USEPA) Class A biosolid standard (assuming the feed sludge contains sufficiently low levels of heavy metals). The end product of the ATAD process can therefore be beneficially applied to land as a soil additive or fertiliser with no restrictions, as the process dramatically reduces public health and environmental risks.

Primary sewage sludge is the solids that result from the primary screenings of the raw sewage that enters a sewage treatment plant. Secondary sewage sludge, sometimes called waste activated sludge (WAS) is the solids that are recovered from a sewage treatment process such as an aeration basin, sequential batch reactor (SBR), trickling filter, etc. Both of these sludge sources can have considerably different degradation rates and calorific values.

With an adequate supply of oxygen, microorganisms, nutrients and biodegradable organic material an ATAD can degrade complex organic substrates into stable end products, which include carbon dioxide and water. Some of the energy released by microbial degradation is used to form new cellular material but much of it is released as heat. When this heat is retained it pasteurises the sludge.

An ATAD process consists of an enclosed insulated reactor in which concentrated sewage sludge (or biosolids) is both mixed and aerated, as shown in Figure 1. The process requires oxygen, usually in the form of air, to be applied to the sludge by an aeration system. The oxygen stimulates an exothermic (heat releasing) biochemical reaction, which heats the sludge up to thermophilic temperatures (50-65^{0}C). At these temperatures the pathogenic bacteria, viruses and parasites harmful to human health are effectively destroyed. The biochemical reaction also stabilises the sludge, which means that unstable, volatile and odour generating substances are removed; this reduces the likelihood of malodour and vector attraction of the sludge.

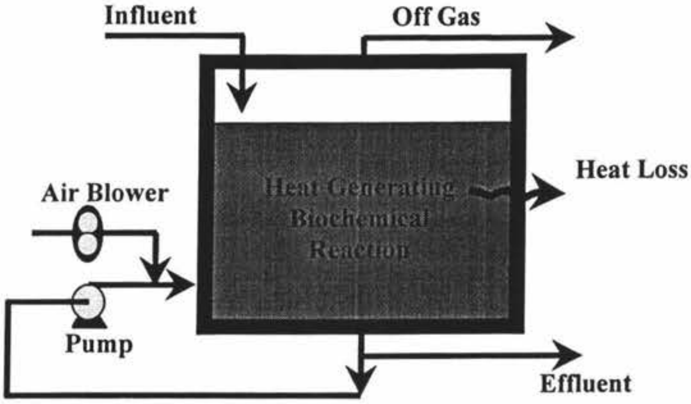

Figure 1 - Basic ATAD System

The thermophilic bacteria that are vital to the process are up to 2-8 times more active than their mesophilic (operate at 25-45^{0}C) counterparts, as a result ATAD reactors are significantly smaller than other mesophilic digestion systems.

Both energy production and energy conservation are important considerations in an ATAD system to ensure that sufficient sludge disinfection can occur. As indicated from Figure 1 the key energy source is the heat releasing biochemical reaction, but the inefficiencies of the blower and the re-circulation pump also add a small amount of heat to the sludge (between 5 and 10%). Energy is lost from an ATAD system by the different temperatures of the incoming and outgoing sludge and air streams (loss of sensible heat), along with heat flow through the walls of the reactor. Energy is also lost due to the latent heat of vaporisation. The exhaust gas has a high enthalpy due to its high relative humidity.

The main advantages of an ATAD system over other sludge treatment processes is that it can produce a product that has no disposal restrictions, with relatively low energy requirements and hydraulic residence time. Since an ATAD is an aerobic process it does not produce any explosive off gases, such as methane, which requires special handling.

2.1 Main ATAD Components

An ATAD system consists of buffer tanks, insulated reactors, a foam control device, aeration equipment, mixing equipment (usually combined with aeration system), a sludge thickening device and an odour control system. Some ATAD systems also use some form of heat exchanger.

2.1.1 Buffer Tanks

Buffer tanks are usually placed before and/or after an ATAD process to equalise load variations in the system. It is quite common for an ATAD process to be before or after a continuous process and since an ATAD is normally a batch or semi-continuous process a buffer tank is required to interface the two systems.

2.1.2 Insulated Reactor

An enclosed insulated tank is used to minimise the heat loss from the processing sludge under all weather conditions. The shape and dimensions of an ATAD reactor are important for mixing and aeration efficiencies. A large number of the original ATADs built in America and Europe did not have an enclosed lid. The enclosed reactor has been found to be beneficial as it reduces heat loss and provides a means of odour control.

2.1.3 Foam Control

Uncontrolled foam production can result in biosolid spillage or over pressurising the reactor. Foam problems can be minimised by one or more of the following methods: use reduced air supply, make the foam denser through mechanical breakers, and/or provide a large head space allowance during design (Kelly and Warren, 1995). Some foaming is a necessary consequence of good oxygen transfer efficiencies (Wolinski, 1985), but excessive foaming causes problems.

2.1.4 Aeration / Mixing Devices

There are various aeration technologies used around the world in ATADs, each have their advantages and disadvantages. The two basic types of aeration technologies used in ATAD process are venturi guns and submerged turbine aspiration systems.

The venturi guns operate by circulating sludge, with a pump, from the bottom of the reactor through a venturi nozzle and back into the reactor which creates mixing. The pressure at which the sludge is pumped through the venturi nozzle causes turbulence, which allows dispersion with the air or oxygen that is injected at this point (Wolinski, 1985). The main benefits of such an aeration system are that the pump and venturi are located outside the reactor for easier repair and maintenance, and allows flexible operation as far as sludge depths are concerned. This is the method of aeration currently adopted by Waste Solutions Ltd., and therefore this investigation mainly focuses on this type of aeration system.

Submerged turbine naturally aspirated aerator/mixers utilise a motor mounted at the top of the reactor, which is driving an impeller that is submerged in sludge. The rotating impeller forms a slight vacuum in the sludge allowing air to be mixed and dispersed within the sludge, the air is delivered to the impellers through the hollow drive shaft. The disadvantages of this type of system is that it is inflexible as far as sludge operational height is concerned, insufficient oxygen transfer can result if foam is not effectively controlled (due to the impeller operating in foam not sludge) and the physical arrangement of the system can make repair and maintenance difficult.

Pure oxygen was initially the predominate source of oxygen for ATAD reactors as it was thought that the air would cause too much cooling to allow thermophilic temperatures to be reached. In the late 1970s and early 1980s it became apparent that it was possible to aerate an ATAD with air and therefore significant savings in operational costs were made.

2.1.5 Sludge Thickeners

For an ATAD process to generate sufficient heat to maintain thermophilic temperatures some form of pre-sludge thickening process is usually required to allow the sludge concentration to get into an acceptable range. The general 'rule of thumb' used is that a sludge concentration should be between 3 and 8% on a dry basis. A full discussion on this 'rule of thumb' is included in Section 7.3.1.

Often Total Solids (TS) and Volatile Solids (VS) are confused. Total Solids concentration is the mass of dry solids in the sludge divided by the total mass of sludge. The Volatile Solids concentration is the mass of dry solids in the sludge that can be oxidised divided by the total mass of sludge. Generally the solids in the sludge consist of between 70 and 90% Volatile Solids and the remainder is ash. It is the quantity of Volatile Solids that is of importance in an ATAD process as this represents the amount of organic material that can be degraded. Generally not all the Volatile Solids are degraded in an ATAD process.

Post ATAD sludge thickeners are also often used to reduce the quantity of sludge to be disposed of. This is largely dependent on how and where the sludge is being disposed of, and therefore some ATAD facilities do not require post ATAD sludge thickeners.

The type of sludge thickeners used for ATAD systems depends largely on the scale of the operation. Gravity thickeners, rotary drum thickeners, centrifuges, belt presses, dissolved air flotation thickeners are just a few that have been successfully used.

2.1.6 Odour Control

An odour control system is often used to minimise the affects of malodour from an ATAD system. It is a common belief that a well aerated ATAD process does not produce malodour, however it is still common for the exhaust gas of an ATAD system to have some type of treatment before it is released into the atmosphere. Edgington and Clay (1992) reported that an ATADs odour was not a problem, but was identified to be unpleasant during start up.

Some effective odour control systems include wet scrubber systems, biofilters or simply diversion of the exhaust gas to other sewage treatment processes.

2.1.7 Heat Exchangers

In principle heat exchangers are not required to operate an effective ATAD process, but they can be used in various configurations for different reasons. The underlining reasons for adding heat exchangers to an ATAD are either economic or process specific. The benefits and requirements of heat exchangers are discussed in more detail in Section 8.6.

2.2 Process Requirements

The sewage sludge that is extracted from primary screenings and/or wastewater treatment processes is becoming more difficult to dispose of with today's increasing environmental regulations. An ATAD process has the capability of transforming the sludge into a stable and pasteurised product that has minimal environmental and health risks. Therefore the biosolids can be used beneficially as a soil additive or fertiliser.

An ATAD process is capable of processing sludge to the United States Environmental Protection Agency's (USEPA) Class A biosolids standard, which allows sludge to be disposed of (or used) with no restrictions. The two key criteria are stabilisation and disinfection, to achieve these criteria an ATAD system must operate in either a batch or semi-continuous mode, as discussed in Section 2.2.3.

2.2.1 Stabilisation

Raw sewage sludge contains unstable, volatile and odour generating substances that causes malodour and attracts pests such as flies, rats and mice. If the sludge is to be applied to land as a soil additive or fertiliser then this vector attraction must be minimised.

The United States Environmental Protection Agency (USEPA) regulates the application of sludge to land. The USEPA through 40CFR Section 503.33 states that biosolids must meet 1 of the 8 vector attraction criteria listed before it can be applied to land with no restrictions. The two criteria that can be best applied to an ATAD process are listed below:

1) At least 38% Volatile Solid reduction must be achieved
2) The specific oxygen uptake rate for sewage sludge treated in an aerobic process shall be equal to or less than 1.5 milligrams of oxygen per hour per gram of Total Solids at a temperature of 20^0C.

(Environmental Protection Agency, 1995)

2.2.2 Dissinfection

If biosolids are to be disposed of on land it is very important that all the pathogenic bacteria, virus and parasites which are harmful to human health are destroyed. The pathogens that are of major concern in sewage sludge are fecal coliforms, salmonella sp., entric viruses and helminth ova. Such pathogens are typically mesophilic and therefore do not survive at temperatures above 47^0C for prolonged periods. An ATAD process operates at temperatures higher than 55^0C and therefore is a feasible method for controlling pathogens (Pagilla, *et al*, 1996).

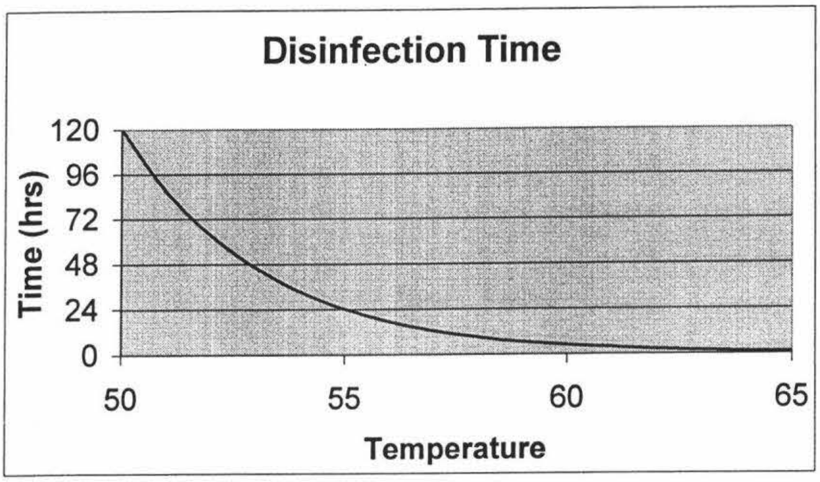

Figure 2 - The relationship between temperature and the time required for sludge disinfection to Class A standards.

$$D = \frac{50{,}070{,}000}{10^{0.1400T}} \qquad \text{(days)} \qquad (1)$$

The USEPA regulates the application of biosolids to land and states in 40CFR Section 503.32 that the sewage sludge must be maintained at a specific temperature for a period of time as shown in Figure 2. For example, if the sludge was at 55^0C, and this temperature (at least) is maintained for 24 hours with no additional sludge added during that period, then the sludge will meet the disinfection criterion for Class A biosolids. The equation for this line is shown in Equation 1, where T represents the sludge temperature and D represents the time it takes to sufficiently pasteurise the sludge at the given temperature. This equation is valid for temperatures higher than 50^0C and sludge concentrations less than seven percent Total Solids. 40CFR Section 503.32 outlines all the disinfection requirements, but Equation 1 represents the most common situation.

2.2.3 Draw-Fill Cycle

In order for the biosolids to meet the required disinfection requirements an ATAD process must operate in either a complete batch or semi-continuous mode. A continuous process would allow some sludge to short circuit the reactor and hence insufficient disinfection would not occur.

A batch or semi-continuous operation causes sudden dramatic energy loads on the system as a result of the cold raw sludge that is added in each cycle. The temperature profile of an ATAD system is therefore a saw tooth type profile similar to that shown in Figure 3. The temperature rarely reaches a steady state condition during a cycle, therefore the operation and control of an ATAD process is very challenging.

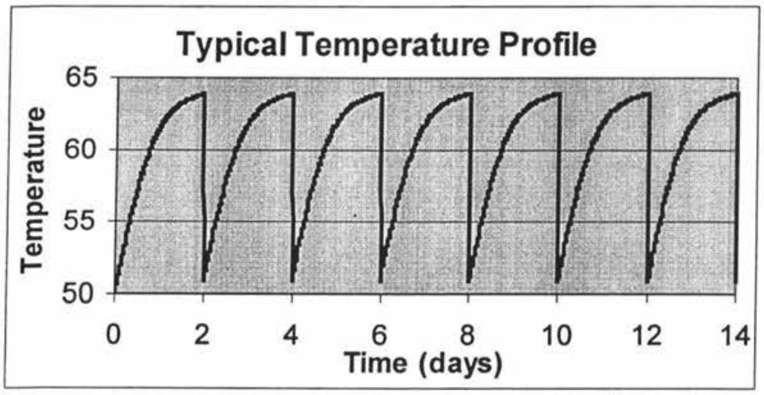

Figure 3 - A typical temperature profile of a semi-continuous ATAD reactor.

A full batch process is where a reactor is completely filled with raw sludge and aerated for several days, until the stabilisation and disinfection criteria is met. The reactor is then emptied and the process repeated. The downfall of this type of operation is each batch has to pass through the mesophilic temperature range into the thermophilic temperatures, where reaction rates are significantly slower.

A semi-continuous system is where a small portion of the sludge is removed from the reactor once it has met the stabilisation and disinfection criteria and then the reactor is topped up with raw sludge. This type of operation prevents the temperature dropping back into the slower mesophilic region, but it still results in large variation in operating conditions.

It is quite common to build an a ATAD process with multiple tanks in series as the first reactor absorbs the majority of the temperature fluctuations, and allows the following reactors to maintain a more consistent temperature, as a result the following reactors are more stable. With multiple tanks in series the process begins to approach the characteristics of a continuous process, which is discussed in more detail in Section 7.4.

2.3 Variations in the ATAD Process

There are two basic types of ATAD processes, the pre-ATAD system and the conventional ATAD system. The conventional ATAD system requires retention times of between 6 and 10 days, while a pre-ATAD has very short retention times of between 2 and 3 days. This thesis predominately investigates the design, operational and control issues associated with the conventional ATAD system.

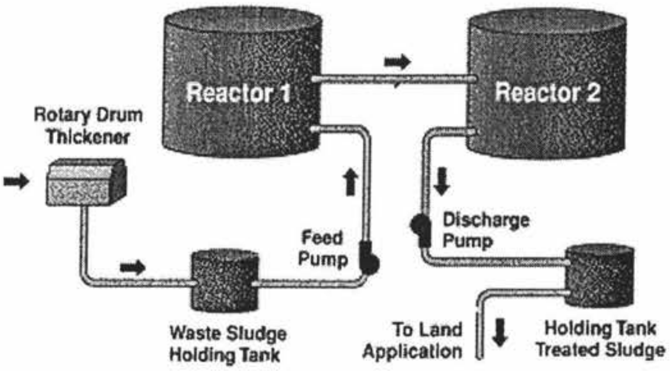

Figure 4 – Typical conventional ATAD configuration

The conventional ATAD operation is where the ATAD system is the last stage of a sludge treatment process; therefore disinfection and stabilisation are key process requirements. Figure 4 shows a typical conventional ATAD system with two ATADs in series. They can be built with a single reactor or many more reactors in series. The design used depends highly on the sludge loading.

As shown in Figure 5 a typical pre-ATAD system is placed before an anaerobic treatment process. The main objective of this type of operation is to disinfect the sludge but only a small amount of the Volatile Solids are stabilised. A pre-ATAD has very short retention times (2-3 days) as the subsequent anaerobic process will stabilise the sludge further and obtain the methane from the process. Additional heat is often required in a pre-ATAD system, as insufficient heat is released by the biochemical reaction to maintain the thermophilic temperatures.

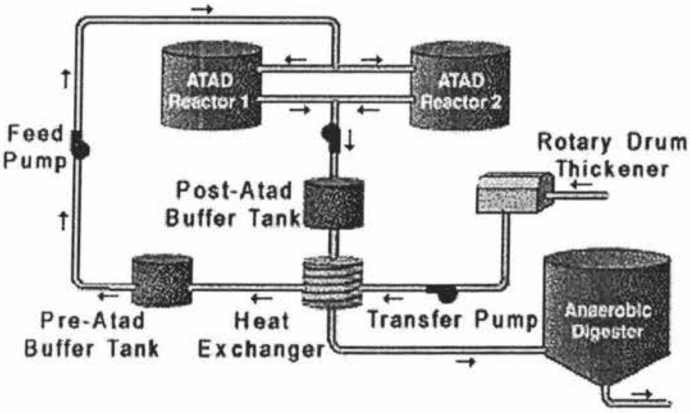

Figure 5 – Typical Pre-ATAD configuration

An additional benefit of a pre-ATAD system is the ability to extend the life of an existing overloaded anaerobic digestor, as well as producing sludge that meets Class A biosolid standards. Pagilla *et al.* (1996) found that a pre-ATAD is capable of reducing *Nocardia* bacteria populations in waste activated sludge and hence prevent foaming in subsequent anaerobic digestors. McIntosh and Oleszkiewicz (1997) found that a pre-ATAD process is capable of producing large quantities of short chain volatile fatty acids (VFA) under oxygen limited conditions, which could be used as a carbon supplement for denitrification.

2.4 Oxygen Transfer in an ATAD process

Oxygen is required to stimulate the oxidation reaction in an ATAD reactor. Oxygen is usually supplied by entraining air into the sludge with the aid of some aeration/mixing device. Pure oxygen has been used in the past but air is now the most popular source of oxygen for an ATAD.

When the concept of ATADs was first approached it was thought that oxygen levels in the sludge of an ATAD reactor are difficult to maintain, due to the reduction in saturation values of oxygen in water at high temperatures. It was therefore thought that pure oxygen would be required to supply sufficient oxygen to the process as air would cool the system too much, but it was soon proved not to be the case.

High temperatures cause a decrease in liquid viscosity, which allows the rate of oxygen transfer to be higher because of an increase in the coefficient of molecular diffusivity of oxygen (Surucu G.A., *et al* 1976). Figure 6 shows how a large increase in the coefficient of oxygen diffusivity offsets the decrease in the saturation values of oxygen at high temperatures, resulting in an overall increase of oxygen transfer ability. Due to the large number of variables associated with aeration of sludge Figure 6 was normalised about the maximum oxygen transfer temperature of 70^0C so no misinterpretation of the result could occur.

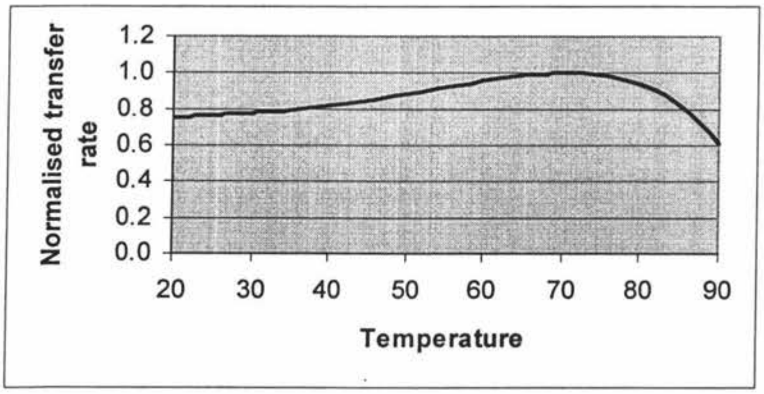

Figure 6 – The effect of temperature on the ability to transfer oxygen into sludge

The reason why it is difficult to maintain a high level of dissolved oxygen in an ATAD process is due to the increased bacteria growth rates at thermophilic temperatures. Therefore the oxygen demand of the microorganisms often exceeds the oxygen supplied. The oxygen levels are generally too low to allow normal aerobic biochemical reactions to proceed, which results in a unique biochemical process often called a micro-aerobic process.

Typical wastewater aerators seldom have oxygen transfer efficiencies over 5% at ambient temperatures (Jewell and Kabrick, 1980), while ATAD systems have been known to be able to get oxygen transfer efficiencies as high as 100% (Wolinski, 1985), but oxygen transfer rates between 15 and 40% are more realistic. The reason for the higher transfer efficiencies in ATAD sludge is a combination of both very low oxygen levels in the sludge and the increased ability of transferring oxygen at elevated temperatures.

3. Biochemistry Background

A majority of wastewater treatment processes use living organisms to allow the destruction and/or transformation of waste organic and inorganic materials into a form that can be extracted and ideally used beneficially. As a result the biochemical behaviour is an integral part of the overall behaviour of the ATAD process.

Bacteria, microorganisms, cells, bugs etc are all words to describe living organisms, which allow chemical reactions to occur at far lower temperatures than would be needed in their absence (Sawyer, *et al*, 1994). The living organisms produce organic catalysts or enzymes as part of their life processes, which lower the activation energy of the reactions. There are various types of microorganisms that can survive in different environments and subsequently cause different chemical reactions. The mircoorgainsms in an ATAD process, which oxidise organic matter for energy, are termed heterotrophic bacteria (Sawyer, *et al*, 1994).

3.1.1 Bacterial Growth Phases

Bacteria can reproduce by binary fission, by sexual mode or by budding. Generally they reproduce by binary fission which is when the original cell divides to become two new organisms (Metcalf and Eddy, 1991). The general mass growth pattern of bacteria during a batch culture (similar to that involved in an ATAD process) is defined into four phases; these consist of the following:

1) *The lag phase.* The bacteria require time to acclimatise to their nutritional environment before they begin to grow and reproduce. The mass growth lag phase is shorter compared to that of the lag phase for bacterial numbers as the bacteria must first gain mass before they divide (reproduce).
2) *The log-growth phase.* There is an excess amount of food surrounding the microorganisms, and the substrate of metabolism and growth is only a function of the ability of the microorganism to process the substrate.
3) *Declining growth phase.* The rate of increase of bacteria mass decreases because of limitations in the food supplies.

4) *Endogenous phase.* The microorganisms are forced to metabolise their own protoplasm without replacement because the concentration of available food is at a minimum. During this phase, a phenomenon known as lysis can occur in which the nutrients remaining in the dead cells diffuse out to furnish the remaining cells with food (known as "cryptic growth")
(Metcalf and Eddy, 1991)

Since an ATAD process is a batch or semi-continuous some or all of these growth phases will be observed within each cycle. This makes controlling and predicting the behaviour of the process more difficult.

3.1.2 General Bacteria Behaviour / Requirements

The bacteria that exist in an ATAD process are called mesophilic and thermophilic bacteria. Mesophilic bacteria exist in the effluent sludge as their optimal temperature range is between 25 and 40^{0}C (Metcalf and Eddy, 1991), and it is some of these bacteria that are infectious to humans. It is these bacteria that an ATAD process endeavours to destroy by operating at temperatures at which they cannot survive for prolonged periods. The bacteria that oxidise the organic matter in an ATAD process are called thermophilic bacteria; their optimal temperature range is between 50 and 65^{0}C (Metcalf and Eddy, 1991).

3.1.2.1 Effects of temperature

It is a common observation that bacteria growth rates approximately double with every 10^{0}C increase in temperature (Metcalf and Eddy, 1991, Sawyer, *et al*, 1994), therefore thermophilic bacteria have significantly higher growth rates than their mesophilic counterparts.

Kuhn, *et al* (1980) discovered that thermophilic bacteria did not require an acclimatisation period if the temperature was changed from one temperature to another as long as the temperature was below the optimal temperature of 65^{0}C. It was found that a small acclimatisation period of about 30 minutes was observed when the temperature was changed from 70 to 55^{0}C.

Kuhn, *et al* (1980) found that death rates become very significant at optimal and supraoptimal temperatures and should not be neglected at these temperatures.

3.1.2.2 Bacteria yield and maintenance requirements

The bacteria yield or mass of bacteria produced per mass of substrate consumed is largely a variable factor. The major influence on bacteria yield is the energy or substrate required for cellular maintenance. The things that can influence the biomass yield are climatic conditions: temperature, pH, oxygen available, etc.

Many authors including Kuhn, *et al* (1980) and Messenger, et al, (1990) discuss an increase in maintenance requirements of thermophilic bacteria compared to their mesophilic counterparts. Possible reasons discussed including a larger energy requirement for osmotic work, increased turnover of cell material and high concentrations of extra-cellular enzymes required for degradation of particle substrates could result in degradation of the organism itself.

Kuhn, *et al* (1980) found that the maintenance energy requirement by thermophilic bacteria was dependent on temperature however they cited many investigators that had found it to be more or less constant over a wide temperature range.

3.1.2.3 Effect of anaerobic and aerobic environments

Typically different microorganisms exist in fermentative (lack of oxygen) environments compared to aerobic (presence of oxygen) environments. Facultative anaerobes can shift from fermentative to aerobic respiratory metabolism, depending upon the presence or absence of molecular oxygen (Metcalf and Eddy, 1991).

Harrison and Pirt (1967) studied the influence of dissolved oxygen on the respiration and metabolism of *klebsiella aerogenes*. They investigated the change in growth with a presence of excess oxygen to the growth with limited oxygen. They discovered the reverse change, from anaerobic to aerobic growth, took significantly longer to reach a steady state, therefore suggesting that complex adaptive changes or selection of variants are involved. This observation could have significant influence in the operation of the aeration system in an ATAD process.

3.1.3 Monod Equations

The rate of bacteria growth in both continuous and batch culture systems can be described by Equation 2. With batch systems, similar to an ATAD, some of the essential nutrients (food and oxygen) for growth may only be available in limited quantities. If these compounds become significantly limited they will slow or even stop the growth of the culture. It has been found experimentally that the effect of a limiting substrate, S, or nutrient (eg. oxygen) can often be described by Equations 3 and 4, which is often referred to as the Monod expression (Metcalf & Eddy, 1991).

$$\dot{X} = \mu X \tag{2}$$

$$\mu = \mu_m \frac{S}{K_S + S} \tag{3}$$

$$\dot{X} = \frac{\mu_m XS}{K_S + S} \tag{4}$$

$$\mu = \mu_m \frac{K_S}{K_S + S} \tag{5}$$

It has also been found that the presence of some nutrients can inhibit a biochemical reaction. For example the presence of oxygen will inhibit an anaerobic biochemical reaction, this effect is described by Equation 5 (Henze, *et al*, 1995).

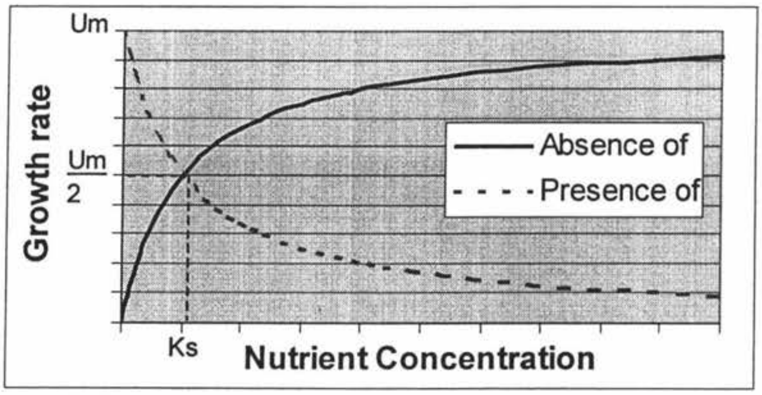

Figure 7 – The effects of the presence and absence of a nutrient on the specific growth rate

Figure 7 illustrates the effect of the absence and the presence of a nutrient on the specific growth rate as described by Equation 3 and 5.

3.1.4 Cell Energy

The oxidation of organic matter such as carbohydrates, proteins and fats, which are present in ATAD sludge, can be thought of as the removal of electrons (or hydrogen atoms) from the organic molecules with the aid of coenzymes. The two coenzymes involved with the oxidation of organic materials are called nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD) and they are reduced to nicotinamide adenine dinucleotide hydroxide (NADH) and flavin adenine dinucleotide hydroxide (FADH) respectively in the process (Sawyer, *et al*, 1994).

These coenzymes need to be converted back to their original state in order for the process to continue, and this is achieved in an electron transport chain or oxidative phosphorylation, as shown in Figure 8. In the electron transport chain the electrons are transferred from the electron carriers (NADH and FADH) through a series of coenzymes to the terminal acceptor, oxygen. The energy that is released during oxidation of this electron transport chain is used by adenosine diphosphate (ADP) to form a bond with phosphate. This forms another molecule called adenosine triphosphate (ATP). The ATP that is formed can travel through the cell wall and give up its energy for cell synthesis (growth) and maintenance by the reverse of the reaction. At each stage where energy is transferred from one molecule to another, during oxidation, heat is also released, as the energy transfers are not 100% efficient (Sawyer, *et al*, 1994).

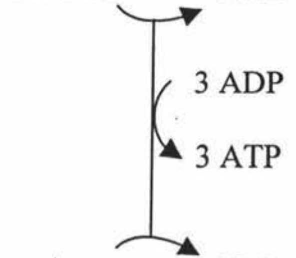

Figure 8 – Electron Transport Chain

ATP can also be formed directly from organic transformation such as the conversion of glucose to pyruvate, however the most significant amount of ATP (energy) is obtained from the electron transport chain.

3.1.5 Tricarboxylic Acid (TCA) Cycle

The tricarboxylic acid cycle or TCA cycle is an oxidation (consumption of oxygen) pathway in which acetyl coenzyme A is oxidised to carbon dioxide and water by going around the TCA cycle twice. For every mole of acetyl coenzyme A that enters the TCA cycle, 4 moles of NAD is converted to 4 moles of NADH. Figure 8 shows that the electron transport chain produces 3 moles of ATP per mole of NADH converted back to NAD. Therefore a total of 12 moles of ATP are produced each time a mole of acetyl coenzyme A is oxidised in the TCA cycle. In comparison only 1.5 moles of ATP are produced by converting a mole of acetyl coenzyme A to acetate in a fermentation reaction (Sawyer, *et al*, 1994).

As discussed in Section 3.1.4 ATP is microorganism energy, while the cell is both producing ATP and consuming ATP a significant amount of heat is generated. Since the TCA cycle generates a significant portion of ATP, this pathway generates most of the heat in an ATAD system.

4. ATAD Biochemical Pathways

Since oxygen demand can often exceed the oxygen supply to an ATAD process, the dissolved oxygen levels in the ATAD sludge can be very low, and therefore uncommon biochemical pathways exist. The biochemical pathways in an ATAD system are a combination of oxidation (aerobic) and fermentation (anaerobic) reactions, hence why an ATAD process is often referred to as a micro-aerobic process.

The basic biochemical equations that occur in an ATAD process can be represented by Equation 6, where bacteria are required to catalyse the reaction. This equation is indicative of a system in which nitrification is inhibited, and as a result 1.4 kg of O_2 is consumed per kg of organic solids degraded and 1 mole of CO_2 is produced per mole of O_2 consumed (Matsch and Drnevich, 1977).

$$C_5H_7NO_2 + 5O_2 \xrightarrow{\text{Bacteria}} 5CO_2 + 2H_2O + NH_3 + \text{energy} \tag{6}$$

$$C_5H_7NO_2 + 7O_2 \xrightarrow{\text{Bacteria}} 5CO_2 + 3H_2O + NO_3^- + H^+ + \text{energy} \tag{7}$$

Equation 7 represents a system in which nitrification is occurring, indicating a theoretical oxygen requirement of 1.98 kg per kg of organic matter reduced. At temperatures above 40^0C nitrification will be totally inhibited and therefore a reaction in an ATAD process would be better described by Equation 6 (Matsch and Drnevich, 1977).

A basic representation of the biochemical pathways that occur in an ATAD process are shown in Figure 9, Varma, *et al* (1993), Chu, *et al* (1994), and Chu, *et al* (1996) have proposed similar pathways. The pathways that are shown in Figure 9 illustrate the basic pathways that occur during the degradation of a complex array of organic substances, similar to that that exists in sewage sludge. Due to the wide variety of the organic substances that exists in sewage sludge it is nearly impossible to describe all the pathways, but Figure 9 illustrates the important pathways that occur in an ATAD process.

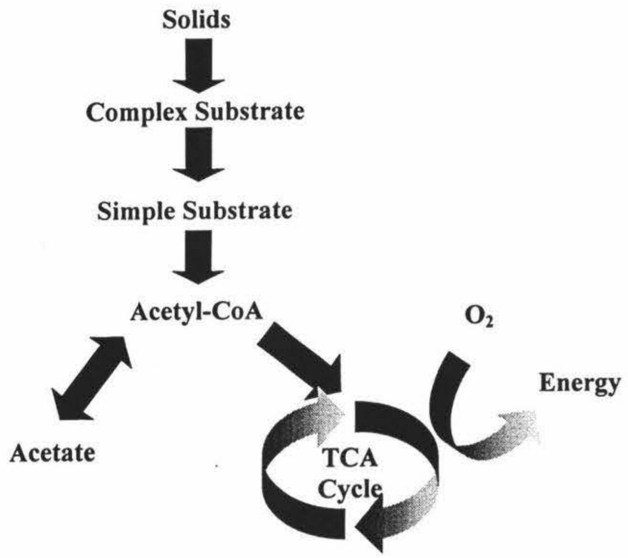

Figure 9 – A basic representation of the biochemical pathways that occur in an ATAD process.

The raw sewage sludge is largely particulate solids, which is first broken down into complex substrates. This process is commonly called hydrolysis. The complex substrates are then transported through the cell wall where they are broken down further to simple organic carbon, such as pyruvate. The simple organic carbon molecules are then converted to acetyl coenzyme A.

Once the carbon source has reached acetyl coenzyme A there is a branch in the pathways. Which one of these two pathways dominates depends on the oxidation potential or the availability of oxygen to the bacteria. Even though one of the pathways is more likely to dominate the carbon flow, it does not mean that the other pathway is inactive. Varma, *et al* (1993) identified five different phases of oxygenation, in which different balances of the fermentation and oxidation pathways occur.

If sufficient oxygen (or oxidation potential) is available the oxidation pathway or tricarboxylic acid (TCA) cycle will dominate the carbon flow. In this pathway CO_2 is released with large amounts of NADH and consequently ATP are produced.

If insufficient oxygen (or oxidation potential) is available then the carbon will proceed down the fermentation pathway to accumulate short chain volatile fatty acids, such as acetate. In doing so it converts a small amount of ADP to ATP to provide a small amount of energy, which is used predominantly for cell maintenance.

If a reduction of available acetyl coenzyme A occurs, either due to an increase in available oxygen or a depletion of up stream carbon, then the volatile fatty acids (acetate) that have been accumulated can be converted back to acetyl coenzyme A. Once the volatile fatty acids have been converted back, they are then available for further oxidation in the TCA cycle. This allows significantly more energy for growth and maintenance.

The TCA cycle is by far the most preferred pathway in a conventional ATAD system as it maximises cell growth, organic stabilisation and consequentially energy production. Since oxygen demand often exceeds the supply, especially at the beginning of each cycle, the fermentation pathway can dominate the system and consequently reduce the potential stabilisation rate and energy production.

4.1 Biochemical Pathways from a Modelling Perspective

The basic pathways that occur in an ATAD are shown in Figure 9, but it is impractical to model all these pathways especially when there are different rate constants for each of the different types of substrates contained in sewage sludge. To simplify the mathematical model the pathways have been rearranged into those shown in Figure 10. The degradation of the complex substrates present in sewage sludge has been simplified by assuming the substrates can be grouped into three basic categories: readily biodegradable substrates (RBS), slowly biodegradable substrates (SBS) and non-biodegradable substrates (NBS).

Readily biodegradable substrate (RBS) is quickly accessible to the bacteria, which could be considered as a simple or complex substrate in relation to Figure 9. Slowly biodegradable substrate (SBS) is less accessible, and therefore will not be used until a large majority of the RBS has been consumed. The non-biodegradable substrate

(NBS) is still theoretically degradable, but the short retention times of an ATAD system mean that this substrate is not consumed.

The pathways described in Figure 9 have neglected bacteria lysis or decay. When the bacteria (both mesophilic and thermophilic) die they then become substrate or food for the remaining bacteria, as explained in Section 3.1.1. Since all of the mesophilic bacteria in the influent will die, and a reasonable number of the thermophilic bacteria will also die these pathways can not be neglected. Figure 10 shows how the bacteria decay to form the three basic substrate categories.

Figure 10 shows that the non-degradable substrate is not degraded in any way, while the slowly degradable substrate must first be transformed into a readily biodegradable substrate before it proceeds further. As before the availability of oxygen determines whether the fermentation reaction (pathway *2*) or the oxidation reaction (pathway *3*) dominates. Comparing Figures 9 and 10 it can also be recognised that pathways *2* and *4* in Figure 10 represent the TCA cycle in which most of the oxygen is consumed and as a result large amounts of ATP are produced, which consequentially generates heat.

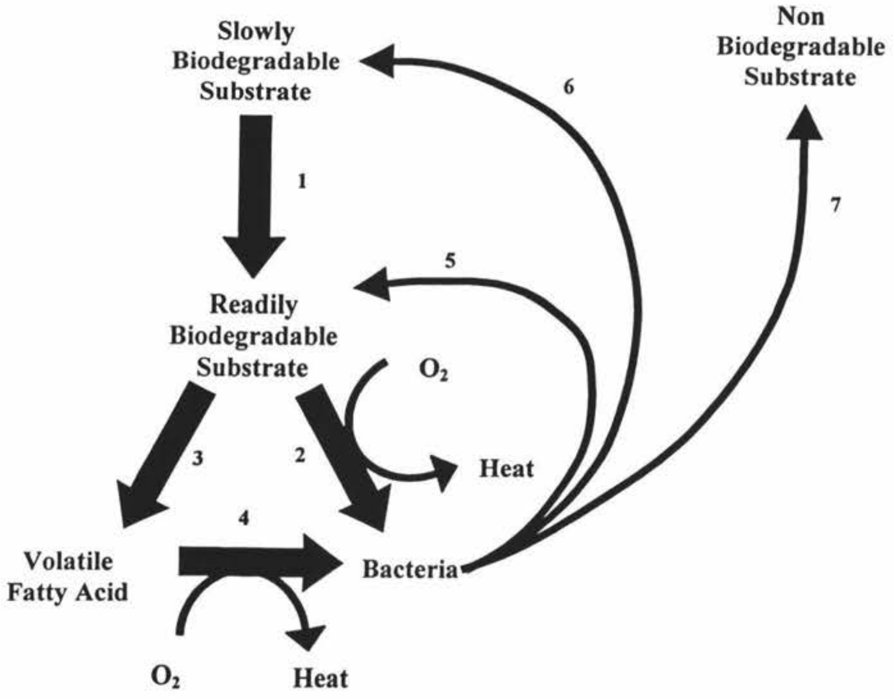

Figure 10 – Modelled Biochemical Pathways that occur in an ATAD process

Figure 10 indicates that the heat produced from the biochemical reaction is coupled with the oxygen consumed in the reaction. This is not completely correct as small amounts of energy are also released in the fermentation and preliminary steps of the process. However it is believed that these pathways produce negligible energy compared to that produced in the TCA cycle, as discussed in Section 3.1.5. Cooney, *et al* (1968) found a correlation between oxygen consumption and heat evolution in a mesophilic aerobic digestor.

5. Mathematical Model

The main objective of developing an ATAD mathematical model was to provide a tool to assist the design, operation and control of an ATAD system. The non-linear dynamic mathematical model presented in this section was coded into Matlab and Simulink.

5.1 Specifications / Requirements of Model

The issues investigated by the mathematical model determine the complexity of the model required. The main issues that required investigation with the model are listed below.

1) Optimal tank sizing, dimensions and insulation
2) Limits of feed sludge concentrations
3) Optimal feed scheduling to ensure Class A biosolids
4) Aeration requirements
5) Single Vs multistage ATAD design
6) Control strategy investigations

A lumped parameter mathematical model is sufficient to investigate the issues listed above. As none of the issues require analysis of mixing efficiencies and/or temperature variations within the reactor itself.

The temperature and organic matter destruction profiles provide the information required to determine when Class A biosolids are produced. Mass and energy balances around the ATAD reactor allow these profiles to be calculated. In order for the above issues to be investigated thoroughly the model must describe the dependence organic matter destruction has on aeration rates, temperature, sludge concentrations and wash out.

An ATAD process is a mixed culture biochemical process and as a result it is very difficult to accurately model all the mechanisms that effect the rates and yields of the biochemical reactions. Taking this into account a mathematical model has been developed that is capable of describing the basic behaviour of an ATAD process.

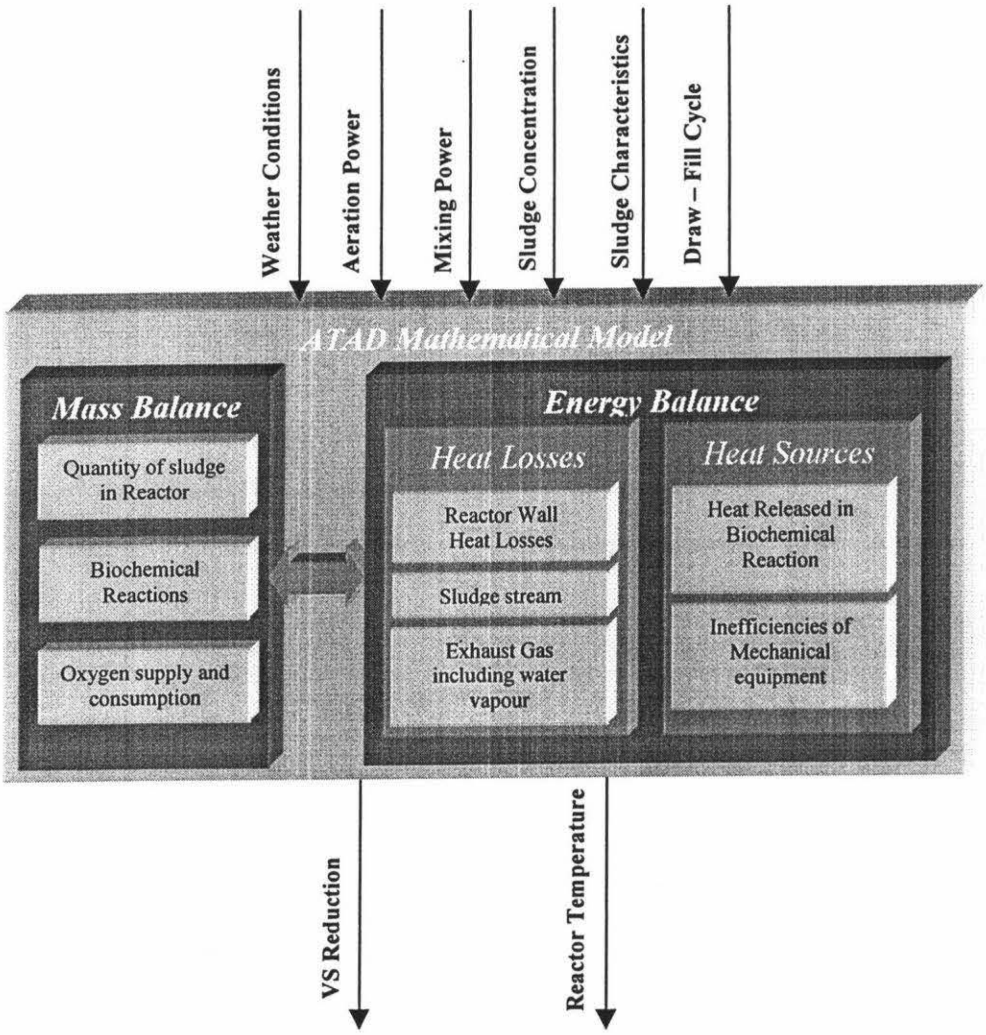

Figure 11 - Schematic of Mathematical Model Subsections

To write a mathematical model of such a large complex system; first the system must be broken into smaller subsystems. An ATAD process has multiple mechanisms that effect its behaviour, but mass and energy balances can describe the basics of an ATAD system. The ATAD process can be broken into the following key subsystems: Mass Balance consisting of the reactor contents, the biochemical reactions and the aeration system and the Energy Balance consisting of the heat releasing biochemical reactions, mechanical equipment, wall heat loss, sludge and air streams and evaporation loss. Figure 11 illustrates how these subsystems are brought together to form a mathematical model of an ATAD system. It can be seen that the temperature and Volatile Solid reduction profile of a ATAD system are dependant on a number of inputs, mainly weather conditions, aeration power, mixing power, sludge concentrations and characteristics and how the system is drawn and fed.

5.2 Major Assumptions

The model assumes that the ATAD reactor is perfectly mixed and therefore the sludge has a homogenous mixture and an even temperature throughout the reactor. In general ATAD systems are well mixed, but this does not mean that the sludge is a homogenous mixture. It is believed that the foam layer on top of the ATAD sludge does not necessarily have the same properties as the sludge itself, but this has been neglected.

The biochemical pathways described in Section 4.1 are assumed to reflect the degradation of organic material in an ATAD system. Even though the sludge has been broken into three basic categories in an effort to simplify the model, it is believed to describe the essential behaviour of organic degradation in an ATAD process.

As briefly discussed in Section 3.1.2.2, it is of some debate whether the biomass yield coefficients are in fact dependant on temperature, since there is some disagreement on this matter it was assumed to be constant.

As briefly discussed in Sections 3.1.1 and 3.1.2, a bacteria growth lag is often observed after a change in environmental conditions such as temperature or oxygen availability. Even though this phenomenon may occur at certain instances in the operation of an ATAD process it has been ignored in the construction of the mathematical model. Kuhn, *et al*, (1980) observed small or no bacteria growth lag after changes in temperature.

It has been assumed that the all densities, heat capacities are constant. Even though these parameters are dependent on temperature and sludge composition it was decided that the increase in accuracy was not worth the increase in model complexity in this case.

Even though numerous authors report (Wolinski, 1985, Edgington and Clay, 1993) that a foam layer on top of the digesting sludge has a strong influence on the oxygen transfer efficiency this has been ignored in the model. A similar effect is also believed to occur for the heat transfer between the sludge and the headspace. However it has been assumed that the foam layer has no effect on heat transfer and therefore it is assumed that the temperature of the headspace and exhaust gas are equivalent to the temperature of the sludge. While observing the operation of the ATAD facility in Nelson, New Zealand the exhaust gas temperature was measured and it was found to be the same or very similar to the temperature of the sludge in the reactor.

It is assumed that the exhaust gas leaving the ATAD system is at the temperature of the sludge in the reactor and is saturated in water. This assumption has been made by numerous authors including Messenger, *et al*, (1990), Kelly and Warren, (1995) and Vismara (1985) and verified by Messenger, *et al*, (1990) and also verified at Nelson, New Zealand, see Section 6.3. This assumption may become less applicable at low temperatures, but since an ATAD generally operates above 50^0C it is believed to be a valid assumption.

Messenger, *et al*, (1990) discussed that approximately 0.68 moles of carbon dioxide replace every mole of oxygen consumed in an ATAD. In a gas stream where there is a significant quantity of inert gas, such as nitrogen in air, this respiration quotient would only cause a small change in the gas flow (Messenger, *et al*, 1990), but a pure oxygen system could result in a significant difference in gas flows. Since this investigation is concerned with an ATAD process, which is aerated by air, it can be assumed that the inlet and exhaust gas flows are the same.

5.3 Mass Balance

The ATAD process must be fed with sludge in a batch or semi-continuous manner to meet the disinfection criterion. The processed sludge is removed and raw sludge added once it is sufficiently stabilised and pasteurised. These draw fill cycles affect the operating temperature of the ATAD, and hence affect the rate of biochemical degradation. The mass balance of an ATAD process needs to describe how the system is drawn and fed, and also how the sludge is stabilised.

There are three main components to the mass balance of an ATAD system. Firstly, the mass balance describes how the contents of the reactor change over time due to draw and fill cycles and water evaporation. Secondly, the model describes how the organic solids are oxidised, which is dependent on the feeding regime, reactor temperature and oxygen availability. The third and final factor that is described by the mass balance is how the oxygen is transferred into the sludge by the aerators and then consumed by the biochemical reaction.

5.3.1 Contents of Reactor

The quantity of sludge in an ATAD reactor changes overtime due to the draw and fill cycles, and also the water that is evaporated. In order for the ATAD model to allow comparisons between different draw and fill strategies this type of behaviour must be described by the model.

The three factors that need to be modelled to determine the mass of sludge in the reactor is the mass of sludge added, $\dot{M}_{in}(t)$, the mass of sludge removed, $\dot{M}_{out}(t)$, and also the mass of water removed by evaporation, $\dot{M}_{evap}$. Equation 8 shows how these three factors affect how the mass of sludge in the reactor changes.

$$\frac{dM_{\mathrm{React}}}{dt} = \dot{M}_{in}(t) - \dot{M}_{out}(t) - \dot{M}_{evap} \qquad \text{(kg/s)} \qquad (8)$$

5.3.1.1 Evaporation loss

The air that passes through an ATAD system is in contact with the sludge for a period of time to increase the oxygen transfer. During this time the air heats up and absorbs water. Hot air can physically hold more water vapour than cold air. Table 1 illustrates water evaporation loss under various conditions and shows how significant water evaporation can be, especially at high temperatures and high aeration rates.

	@ 20^0C	@ 40^0C	@ 55^0C	@65^0C
Mass of water contained in 1 kg of saturated air	0.0108kg	0.044kg	0.109kg	0.195kg
Water loss in one day with aeration rate of 600 kg/hr	155 litres	630 litres	1566 litres	2810 litres
Weekly loss of water as a percentage of mass of reactor	0.54%	2.2%	5.5%	9.8%

Table 1 – Typical Evaporation Loss

Equation 9 shows how the evaporation loss is dependent on the temperature of the reactor sludge, $T(t)$, aeration rate, $Q_{air}(t)$, and the humidity of the air, H_{amb}. The humidity of the exhaust gas is calculated from the temperature of reactor, by assuming that it is saturated in water, as discussed in Section 5.2. To reduce the number of input parameters an equation has been used that relates the ambient air temperature, $T_{air}(t)$, to the quantity of water that it holds, with the assumption that the ambient air has a relative humidity of 50%. Typically the humidity of ambient air depends on weather conditions and location. H_{gas} is significantly larger than H_{amb}, hence it could be assumed that $H_{amb} \approx 0$, and consequently the 50% relative humidity assumption is benign.

$$\dot{M}_{evap} = Q_{air}(t)\rho_{air}(H_{gas} - H_{amb}) \qquad \text{(kg/s)} \qquad (9)$$

Where

$$H_{gas} = (5.06541\exp^{(0.056554796\, T(t))})\text{x}\,10^{-3} \qquad \text{(kg of water/kg of air)}$$

$$H_{amb} = (1.903636\exp^{(0.062893237\, T_{air}(t))})\text{x}\,10^{-3} \qquad \text{(kg of water/kg of air)}$$

In general terms the contents of a tank or reactor is represented by the height of liquid in the reactor. It is difficult to determine the actual height of the sludge in an ATAD reactor as a layer of foam usually forms on top of the sludge during aeration. Pressure transducers are usually used to determine the static head of the sludge in the reactor, which indicates the quantity of sludge in the reactor. The quantity of sludge in an ATAD reactor is therefore normally expressed as a height. Equation 8 shows the differential equation for the mass of sludge in the reactor, while equation 10 shows the differential equation for sludge height, *Ht(t)*, in the reactor with all of the factors substituted.

$$\dot{Ht}(t) = \frac{\dot{M}_{in}(t) - \dot{M}_{out}(t) - Q_{air}(t)\rho_{air}(H_{gas} - H_{amb})}{A\rho} \qquad \text{(m/s)} \qquad (10)$$

5.3.2 Quantity of Organic Matter

The quantity of organic matter in an ATAD can change because of the draw and fill cycle as well as the biochemical reaction. It is the normal convention to describe the quantity of organic matter in the sludge on a concentration basis. Since water is leaving the reactor as a result of evaporation it causes thickening of the solids. As illustrated in Section 5.3.1.1 evaporation loss and hence sludge thickening can be significant at high temperatures and high aeration rates and therefore this must be included in the model.

$$\frac{d\,SV}{d\,t} = S_{in}\dot{V}_{in} - S\dot{V}_{out} + \dot{S}_{\mathrm{Re}\,action}V \qquad (11)$$

$$\text{since}\frac{d\,V}{d\,t} \neq 0,$$

$$\frac{d\,S}{d\,t}V + \frac{d\,V}{d\,t}S = S_{in}\dot{V}_{in} - S\dot{V}_{out} + \dot{S}_{\mathrm{Re}\,action}V \qquad (12)$$

$$\frac{d\,S}{d\,t} = \frac{\dfrac{S_{in}\dot{M}_{in}}{\rho} - \dfrac{S\dot{M}_{out}}{\rho} + \dot{S}_{\mathrm{Re}\,action}\,Ht\,A - \dfrac{d\,Ht}{d\,t}S\,A}{Ht\,A} \qquad (13)$$

The change in mass of substrate in an ATAD is equal to the mass flow of substrate into the reactor minus the mass flow of substrate that leaves the reactor plus the mass of substrate accumulated (or degraded) within the reactor by the biochemical reactions, as shown in Equation 11. To describe the substrate as a concentration the mass of substrate is expressed as a multiplication of the substrate concentration, *S*, and its respective volume, *V*.

Due to evaporation loss the volume of the reactor does not stay constant through out a batch, and therefore a change in volume term appears on the right hand side of Equation 12. Equation 13 expresses Equation 12 in terms of mass flows, and height of sludge in the reactor as expressed in Section 5.3.1.

Section 4.1 described how the sludge is degraded via biochemical pathways and how these pathways are dependent on oxygen availability and also how the growth rates are dependent on temperature. To describe the degradation of primary and secondary sewage sludge it was decided to simplify the substrate into three groups: readily biodegradable substrate, *RBS(t)*, slowly biodegradable substrate, *SBS(t),* and non-biodegradable substrate, *NBS(t)*. In addition to these three substrate groups there is also the bacteria, *X(t)*, and the volatile fatty acids, *VFA(t)*, to be described.

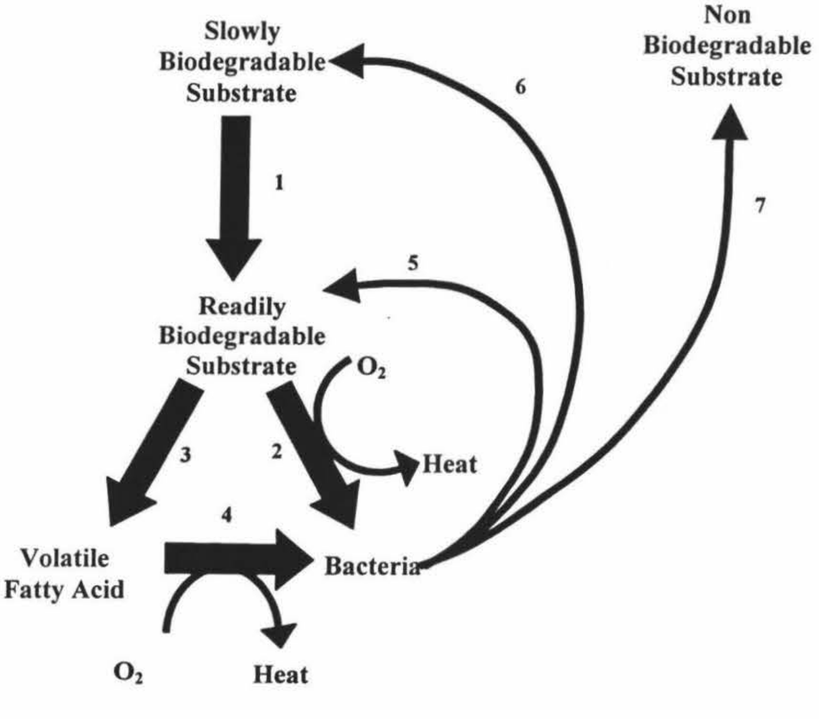

Figure 12 – Modelled biochemical pathways

The five equations used to represent the biochemical reaction accumulation and/or destruction of the five organic compounds can be seen in Equations 14 to 18. These equations describe the biochemical pathways that were outlined in Figure 10 and Section 4.1, for convenience this has been duplicated in Figure 12.

$$\overset{\bullet}{SBS}_{\text{Reaction}}(t) = -\mu_1 \frac{SBS(t)}{K_{SBS}+SBS(t)} X(t) + Y_6 \mu_{5,6} (X(t)\text{-}1) \qquad \text{(mg/l/sec)} \qquad (14)$$

$$\begin{aligned}\overset{\bullet}{RBS}_{\text{Reaction}}(t) = {} & Y_1 \mu_1 \frac{SBS(t)}{K_{SBS}+SBS(t)} X(t) \\ & -\mu_2 \frac{DO(t)}{K_{DO}+DO(t)} \frac{RBS(t)}{K_{RBS}+RBS(t)} X(t) \\ & -\mu_3 \frac{K_{DO_f}}{K_{DO_f}+DO(t)} \frac{RBS(t)}{K_{RBS}+RBS(t)} X(t) \\ & +Y_5 \mu_{5,6} (X(t)-1) \qquad \text{(mg/l/sec)} \qquad (15)\end{aligned}$$

$$\overset{\bullet}{NBS}_{\text{Reaction}}(t) = Y_7 \mu_{5,6} (X(t)\text{-}1) \qquad \text{(mg/l/sec)} \qquad (16)$$

$$\begin{aligned}\overset{\bullet}{VFA}_{\text{Reaction}}(t) = {} & Y_3 \mu_3 \frac{K_{DO_f}}{K_{DO_f}+DO(t)} \frac{RBS(t)}{K_{RBS}+RBS(t)} X(t) \\ & -\mu_4 \frac{DO(t)}{K_{DO}+DO(t)} \frac{VFA(t)}{K_{VFA}+VFA(t)} X(t) \qquad \text{(mg/l/sec)} \qquad (17)\end{aligned}$$

$$\begin{aligned}\overset{\bullet}{X}_{\text{Reaction}}(t) = {} & Y_2 \mu_2 \frac{DO(t)}{K_{DO}+DO(t)} \frac{RBS(t)}{K_{RBS}+RBS(t)} X(t) \\ & +Y_4 \mu_4 \frac{DO(t)}{K_{DO}+DO(t)} \frac{VFA(t)}{K_{VFA}+VFA(t)} X(t) \\ & \text{-}\mu_{5,6} (X(t)\text{-}1) \qquad \text{(mg/l/sec)} \qquad (18)\end{aligned}$$

The above equations have extensively used the Monod expression to describe how the absence (or presence) of substrates and/or oxygen inhibit various biochemical pathways. For further details of how the Monod expression affects the reaction rates refer to Section 3.1.3. Each of the above equations describes how the carbon is converted from one substance to the another. The yield coefficient, *Y*, regulates how much of one substrate is converted to the next substrate. The yield coefficient is rarely 1 as secondary products, such as carbon dioxide and/or water, are produced during the reactions.

The lysis or decay terms in each of the equations above have a rather unusual *(X(t)-1)* term. Under normal conditions it has a negligible affect on the simulation, but if the temperature changes from mesophilic to thermophilic temperatures or vice versa the

(X(t)-1) term allows the previously inactive bacteria culture to establish in the simulation, as it would in reality.

5.3.2.1 Temperature dependence

To investigate both full batch processes and semi-continuous processes, where sludge temperatures fluctuate from as low as 10^0C to as high as 70^0C, the growth rates must reflect these temperature changes. As described in Section 3.1.2.1 a 10^0C increase in temperature can double the biomass growth rate, and two different bacterial cultures can exist depending on the temperature. The temperature can therefore have a significant effect on the performance of the system. Also during the change between the two different bacteria cultures the mesophilic bacteria will die converting themselves back to substrates allowing thermophilic bacteria to grow off them.

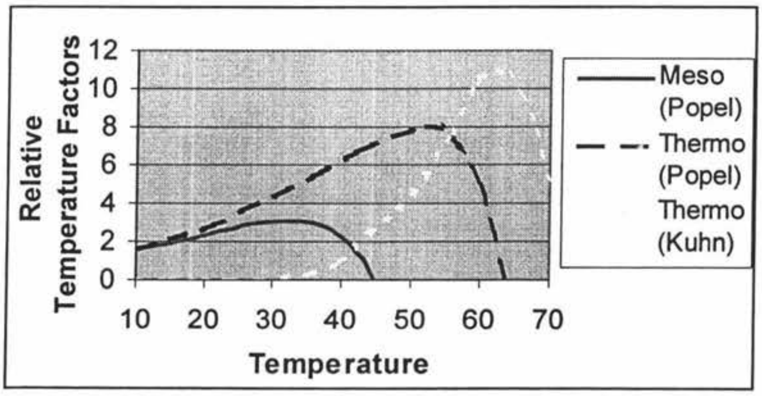

Figure 13 – Relative temperature effects on specific growth rates

Popel and Ohnmacht (1972) proposed the relative temperature effects for both mesophilic and thermophilc bacteria, as shown in Figure 13, and their consequent Equations 19 and 20. The mesophilic profile agrees with other author's observations (Metcalf and Eddy, 1991, Sawyer, *et al*, 1994) as far as the optimal temperature range is concerned but the optimal thermophilic temperature seems significantly lower than other authors observations (Metcalf and Eddy, 1991, Sawyer, *et al*, 1994, Hamer and Zwiefelhofer, 1986, Sonnleitner and Fiechter, 1983, Mason, *et al*, 1987). It is believed that the thermophilic profile proposed by Popel and Ohnmacht (1972) is in fact for thermo-tolerant mesophiles not thermophilic bacteria.

$$k_m = \mu(e^{0.0502T(t)} - 0.034e^{0.126T(t)}) \qquad (19)$$

$$k_t = \mu(e^{0.0502T(t)} - 0.008e^{0.126T(t)}) \qquad (20)$$

$$k_t = \mu e^{\frac{-75700}{8.314(T(t)+273.15)}+28.429} \qquad where\, 45^0 C < T(t) < 60^0 C \qquad (21)$$

$$k_t = \mu e^{\frac{-196000}{8.314(T(t)+273.15)}+73.976} \qquad where\, 37^0 C < T(t) < 45^0 C \qquad (22)$$

Kuhn, *et al* (1980) reinvestigated the kinetic growth of thermophilic bacteria as they believed there were very few kinetic growth investigations and those that had been done were carried out with complex media and under batch conditions which makes kinetic investigations difficult. Kuhn, *et al* (1980) kinetic thermophilic bacteria investigations found a relative temperature profile of that shown in Figure 13. The profile showed three distinct temperature ranges. The suboptimal range (60-45^{0}C) was found to have an Arrhenius equation of that shown in Equation 21 while the range close to the minimal growth temperature (45-37^{0}C) had an Arrhenius equation of that shown in Equation 22. At temperatures above 60^{0}C no Arrhenius relationship could be found.

Since Kuhn, *et al* (1980) investigations resulted in a profile that reflected most other authors (Metcalf and Eddy, 1991, Sawyer, *et al*, 1994, Hamer and Zwiefelhofer, 1986, Sonnleitner and Fiechter, 1983, Mason, *et al*, 1987) observations their thermophilic profile was used in this ATAD model. While the mesophilic bacteria relative temperature profile proposed by Popel and Ohnmacht (1972) was used for the mesophilic bacteria.

As discussed in Section 3.1.2.1 the lysis or decay rates are also dependent on the environmental temperatures, but to simplify the model it was assumed that the temperature profile for lysis or decay had a reciprocal function from its respective growth temperature profile. As the temperature exceeds the bacteria's optimal growth temperature the decay or lysis becomes more significant; this is the characteristic that is observed from the reciprocal growth functions.

$$\dot{SBS}_{\text{Reaction}}(t) = -k_{m_1}\frac{SBS(t)}{K_{SBS}+SBS(t)}X_M(t) + Y_6 k_{m_{5,6}}(X_M(t)\text{-}1)$$
$$-k_{t_1}\frac{SBS(t)}{K_{SBS}+SBS(t)}X_T(t) + Y_6 k_{t_{5,6}}(X_T(t)\text{-}1) \qquad \text{(mg/l/s)} \qquad (23)$$

$$\dot{RBS}_{\text{Reaction}}(t) = Y_1 k_{m_1}\frac{SBS(t)}{K_{SBS}+SBS(t)}X_M(t)$$
$$-k_{m_2}\frac{DO(t)}{K_{DO}+DO(t)}\frac{RBS(t)}{K_{RBS}+RBS(t)}X_M(t)$$
$$-k_{m_3}\frac{K_{DO_f}}{K_{DO_f}+DO(t)}\frac{RBS(t)}{K_{RBS}+RBS(t)}X_M(t)$$
$$+Y_5 k_{m_{5,6}}(X_m(t)-1) + Y_1 k_{t_1}\frac{SBS(t)}{K_{SBS}+SBS(t)}X_T(t)$$
$$-k_{t_2}\frac{DO(t)}{K_{DO}+DO(t)}\frac{RBS(t)}{K_{RBS}+RBS(t)}X_T(t)$$
$$-k_{t_3}\frac{K_{DO_f}}{K_{DO_f}+DO(t)}\frac{RBS(t)}{K_{RBS}+RBS(t)}X_T(t) + Y_5 k_{t_{5,6}}(X_T(t)-1) \qquad \text{(mg/l/s)} \qquad (24)$$

$$\dot{NBS}_{\text{Reaction}}(t) = Y_7 k_{m_{5,6}}(X_M(t)\text{-}1) + Y_7 k_{t_{5,6}}(X_T(t)\text{-}1) \qquad \text{(mg/l/s)} \qquad (25)$$

$$\dot{VFA}_{\text{Reaction}}(t) = Y_3 k_{m_3}\frac{K_{DO_f}}{K_{DO_f}+DO(t)}\frac{RBS(t)}{K_{RBS}+RBS(t)}X_M(t)$$
$$-k_{m_4}\frac{DO(t)}{K_{DO}+DO(t)}\frac{VFA(t)}{K_{VFA}+VFA(t)}X_M(t)$$
$$+Y_3 k_{t_3}\frac{K_{DO_f}}{K_{DO_f}+DO(t)}\frac{RBS(t)}{K_{RBS}+RBS(t)}X_T(t)$$
$$-k_{t_4}\frac{DO(t)}{K_{DO}+DO(t)}\frac{VFA(t)}{K_{VFA}+VFA(t)}X_T(t) \qquad \text{(mg/l/s)} \qquad (26)$$

$$\dot{X}_{M\,\text{Reaction}}(t) = Y_2 k_{m_2}\frac{DO(t)}{K_{DO}+DO(t)}\frac{RBS(t)}{K_{RBS}+RBS(t)}X_M(t)$$
$$+Y_4 k_{m_4}\frac{DO(t)}{K_{DO}+DO(t)}\frac{VFA(t)}{K_{VFA}+VFA(t)}X_M(t)\text{-}k_{m_{5,6}}(X_M(t)\text{-}1) \qquad \text{(mg/l/s)} \qquad (27)$$

$$\dot{X}_{T\,\text{Reaction}}(t) = Y_2 k_{t_2}\frac{DO(t)}{K_{DO}+DO(t)}\frac{RBS(t)}{K_{RBS}+RBS(t)}X_T(t)$$
$$+Y_4 k_{t_4}\frac{DO(t)}{K_{DO}+DO(t)}\frac{VFA(t)}{K_{VFA}+VFA(t)}X_T(t)\text{-}k_{t_{5,6}}(X_T(t)\text{-}1) \qquad \text{(mg/l/s)} \qquad (28)$$

The biochemical reaction equations proposed in Equations 14 through to 18 are extended to include the temperature dependent growth kinetics. The six resulting biochemical reaction equations are shown in Equations 23 to 28, where the bacteria culture, *X(t)*, has been divided into the two bacteria cultures that exist in an ATAD, mesophilic bacteria, *$X_m(t)$*, and thermophilic bacteria, *$X_T(t)$*. The previously temperature independent rate constants, μ, have been replaced with the temperature dependant rate constants, k_m and k_t, as determined by Equations 19, 21 and 22.

The above biochemical reaction equations can be substituted into Equations 29 through to 34. These equations describe how the concentration of the six organic compounds change due to the draw and fill cycle, water evaporation, and the biochemical degradation.

$$\dot{SBS}(t) = \frac{\dot{M}_{in}(t)\, SBS_{in} - \dot{M}_{out}(t)\, SBS(t) + A\, Ht(t)\, \rho\, \dot{SBS}_{react}(t) - SBS(t)\, A\, \rho\, \dot{Ht}(t)}{A Ht(t) \rho} \quad \text{(mg/l/s)} \qquad (29)$$

$$\dot{RBS}(t) = \frac{\dot{M}_{in}(t) RBS_{in} - \dot{M}_{out}(t)\, RBS(t) + A\, Ht(t)\, \rho\, \dot{RBS}_{react}(t) - RBS(t)\, A\, \rho\, \dot{Ht}(t)}{A Ht(t)\, \rho} \quad \text{(mg/l/s)} \qquad (30)$$

$$\dot{NBS}(t) = \frac{\dot{M}_{in}(t) NBS_{in} - \dot{M}_{out}(t)\, NBS(t) + A\, Ht(t)\, \rho\, \dot{NBS}_{react}(t) - NBS(t)\, A\, \rho\, \dot{Ht}(t)}{A Ht(t)\, \rho} \quad \text{(mg/l/s)} \qquad (31)$$

$$\dot{VFA}(t) = \frac{\dot{M}_{in}(t) VFA_{in} - \dot{M}_{out}(t)\, VFA(t) + A\, Ht(t)\, \rho\, \dot{VFA}_{react}(t) - VFA(t) A\, \rho\, \dot{Ht}(t)}{A Ht(t)\, \rho} \quad \text{(mg/l/s)} \qquad (32)$$

$$\dot{X}_M(t) = \frac{\dot{M}_{in}(t) X_{M_{in}} - \dot{M}_{out}(t)\, X_M(t) + A\, Ht(t)\, \rho\, \dot{X}_{Mreact}(t) - X_M(t)\, A\, \rho\, \dot{Ht}(t)}{A Ht(t)\, \rho} \quad \text{(mg/l/s)} \qquad (33)$$

$$\dot{X}_T(t) = \frac{\dot{M}_{in}(t)\, X_{T_{in}} - \dot{M}_{out}(t)\, X_T(t) + A\, Ht(t) \rho\, \dot{X}_{Treact}(t) - X_T(t)\, A\, \rho\, \dot{Ht}(t)}{A Ht(t)\, \rho} \quad \text{(mg/l/s)} \qquad (34)$$

5.3.3 Oxygen Supply and Consumption

As previously discussed in Section 4 the biochemical reactions that occur in an ATAD system are largely dependent on the amount of dissolved oxygen available to the microorganisms. The oxygen is supplied to the sludge by an aeration device. Once the oxygen has been transferred into the sludge it is then available for the microorganisms to oxidise the organic matter in the sludge.

5.3.3.1 Aeration

Oxygen is usually transferred into the sludge by forcing air and sludge in contact with one another. As a result of the contact between the air and the sludge a mass transportation of oxygen into the sludge occurs due to the difference in dissolved oxygen concentrations in the sludge and the air.

The factors that influence the rate of mass transfer are, contact surface area, sludge dissolved oxygen concentration, temperature, pressure, time of contact etc. These factors along with operational costs need to be carefully considered during the design of aeration equipment.

Equation 35 shows a typical aeration equation for wastewater treatment aeration equipment. This equation has been used extensively for designing and calculating the performance of aeration systems in wastewater treatment plants. The use of this equation requires some knowledge of the specific conditions, such as the 'alpha' and 'beta' values, that are relevant for ATAD systems.

$$OTR(t) = \frac{1000}{3600}\alpha F\, K_L a_{20}\, \Theta^{T(t)-20}\left[\tau\,\Omega\beta\, C_{\infty 20} - DO(t)\right]V \qquad \text{(mg/sec)} \qquad (35)$$

where

$$K_L a_{20} = A_{air} U_{SG}{}^{B_{air}}$$

$$U_{SG} = \frac{3600 \times 24 \times Q_{air}(t)}{A}$$

$$\tau = \frac{C_S^{\bullet}}{C_{S20}^{\bullet}}$$

$$\Omega = \frac{P_B - P_{VT} + d_E\left[\dfrac{101.325kPa}{10.34m}\right]}{P_S - P_{VT} + d_E\left[\dfrac{101.325kPa}{10.34m}\right]}$$

$$C_S^{\bullet} \approx -0.00002671T(t)^3 + 0.00467T(t)^2 - 0.34532T(t) + 14.48$$

$$P_{VT} \approx 0.0001475T(t)^3 + 0.0077832T(t)^2 + 0.2866T(t) - 1.1885$$

The $\tau\ \Omega\ \beta\ C_{\infty 20}$ terms in Equation 35 calculates the saturated dissolved oxygen concentration of the sludge at the current temperature, pressure and sludge characteristics. The term in the brackets therefore determines how easy it is to transfer oxygen into the sludge. If the dissolved oxygen concentration in the sludge is low then the oxygen can be easily transferred into the sludge. As the dissolved oxygen concentration approaches the saturated dissolved oxygen concentration it becomes more difficult to transfer oxygen into the sludge.

The volumetric oxygen mass transfer coefficient, K_La_{20}, is a measure of the performance of the aeration system. K_La_{20} is dependent on the aeration rate, $Q_{air}(t)$, and is determined in clean water at 20^0C. Since an ATAD aeration system does not operate in clean water or at 20^0C this coefficient requires adjustment. The αF coefficient adjusts the volumetric oxygen transfer coefficient from clean water to the required process water (sludge). $\theta^{T(t)-20}$ adjusts the volumetric oxygen transfer coefficient to the temperature of the sludge being aerated. The 1000/3600 factor in Equation 35 converts the oxygen transfer rate from g/hr to mg/sec.

5.3.3.2 Oxidation Reaction

As discussed in Sections 3.1.5, the TCA cycle consumes the majority of the oxygen in an ATAD process and therefore the oxygen consumption can be correlated with the biochemical pathways *2* and *4* as shown in Figure 12. Since both mesophilic and thermophilic bacteria are capable of consuming oxygen the oxygen usage rate or OUR can be described by Equation 36.

$$\begin{aligned}
OUR(t) = {} & Y_{Oxy_2} k_{m_2} \frac{DO(t)}{K_{DO} + DO(t)} \frac{RBS(t)}{K_{RBS} + RBS(t)} X_M(t) \\
& + Y_{Oxy_4} k_{m_4} \frac{DO(t)}{K_{DO} + DO(t)} \frac{VFA(t)}{K_{VFA} + VFA(t)} X_M(t) \\
& + Y_{Oxy_2} k_{t_2} \frac{DO(t)}{K_{DO} + DO(t)} \frac{RBS(t)}{K_{RBS} + RBS(t)} X_T(t) \\
& + Y_{Oxy_4} k_{t_4} \frac{DO(t)}{K_{DO} + DO(t)} \frac{VFA(t)}{K_{VFA} + VFA(t)} X_T(t) \qquad \text{(mg/s)} \qquad (36)
\end{aligned}$$

Similar to the organic compounds present in the sludge it is possible to lose and/or gain dissolved oxygen through the sludge streams during the draw and fill cycles and the evaporation loss causes a slight increase in dissolved oxygen concentration. The resulting equation that describes the behaviour of the dissolved oxygen present in the ATAD sludge is shown in Equation 37. The 1000 factor present in some of the terms is used to correct for the different units used (m^3 and litres).

$$\dot{DO}(t)=\frac{1}{1000AHt(t)}\begin{bmatrix}1000\left(\frac{\dot{M}_{in}(t)}{\rho}DO_{in}-\frac{\dot{M}_{out}(t)}{\rho}DO(t)\right)\\+OTR(t)-OUR(t)-1000A\,\dot{Ht}(t)\,DO(t)\end{bmatrix}\qquad \text{(mg/l/s)}\qquad (37)$$

5.4 Energy Balance

An energy balance is used to calculate how the temperature of the ATAD reactor changes over time. From this it is possible to calculate when the disinfection criterion has been reached. The energy balance of an ATAD reactor involves identifying and quantifying the heat lost and produced within the system.

The three major sources of heat loss in an ATAD reactor are the heat lost through the walls of the reactor, the energy lost in the sludge during the draw and fill cycles along with the energy lost in the exhaust gas. The two major sources of heat production in an ATAD system are the heat released during the biochemical oxidation reactions and a small amount of heat is also released by the inefficiencies of the mechanical devices such as the re-circulation pump and aeration blower.

5.4.1 Heat loss

5.4.1.1 Reactor Wall Heat Loss

The heat lost through the walls of the reactor is due to a combination of convection and conduction effects. The heat is transported to and from the surface of the reactor walls by convection while conduction allows the heat to be transported through the walls. The standard heat loss equation for conduction and convection is shown by Equation 38. The heat transfer coefficient, U, for an ATAD reactor is dependant on a large number of factors, including: reactor volume, reactor shape, reactor dimensions, type of construction material, type of insulation, thickness of construction material, thickness of insulation, head space above liquid, foundation thickness, and weather conditions. For further details of how the heat transfer coefficients were calculated refer to Appendix I.

$$\phi_{wall}=UA(T_{air}(t)-T(t))\qquad \text{(W)}\qquad (38)$$

5.4.1.2 Sludge Sensible Heat Flow

The sludge that leaves the ATAD reactor during a draw cycle is replaced with raw sludge in the feed cycle. The sludge that leaves the system during the draw cycle is at the temperature of reactor, *T(t)*, normally around 60^{0}C, while the raw sludge is pumped in at significantly lower temperatures, $T_{in}(t)$, typically around ambient temperatures. These different temperatures result in a net loss of sensible heat from the system; Equation 39 shows how this energy loss is calculated.

$$\phi_{Sludge} = \dot{M}_{in}(t)C_pT_{in}(t) - \dot{M}_{out}(t)C_pT(t) \qquad \text{(W)} \qquad (39)$$

5.4.1.3 Aeration Gas Stream

With an inefficient aeration system the energy lost by the aeration gas stream can contribute as much as 60% of the total energy loss. Typically about 40% of the energy lost by the aeration system. A small amount of the energy lost in the exhaust gas is due to the different temperatures of the air leaving compared to that entering the ATAD system (sensible heat). But the majority of the energy lost in the exhaust gas is due to the latent heat of vaporisation. The exhaust gas carries large quantities of water vapour and the energy required to convert that water from liquid to gas is lost when it leaves the system.

	@ 20^{0}C	@ 40^{0}C	@ 55^{0}C	@65^{0}C
Mass of water contained in 1 kg of saturated air	0.0108kg	0.044kg	0.109kg	0.195kg
Water lost in one day with aeration rate of 600 kg/hr	155 litres	630 litres	1566 litres	2810 litres
Sensible Heat lost per day	72.6MJ	362.9MJ	580.6MJ	725.8MJ
Latent heat of vaporisation lost per day	370.4MJ	1500MJ	3726MJ	6688MJ
Total Aeration loss	5.1kW	21.6kW	49.9kW	85.8kW

Table 2 – Typical aeration gas stream energy loss

In an effort to increase oxygen transfer the air is in contact with the sludge for a long period before it leaves the ATAD system, during this time the air is absorbing water. 1kg of air is capable of holding 0.11kg of water at 55^{0}C, and for that water to change phase from liquid to vapour a total of 260.7 kJ of energy is required, it is this energy that is lost when the water vapour leaves the system. This energy loss can very quickly become significant, as illustrated by Table 2.

Equations 40 and 41 show how the temperature and evaporation loss of the aeration gas stream effects the heat lost from the system. Equation 42 shows how the quantity of water held in the exhaust gas is a function of the reactor temperature, as justified in Section 5.2 the exhaust gas is assumed to be saturated in water vapour. To reduce the number of input parameters required, the quantity of water in the ambient air entering the ATAD system is calculated from the ambient temperature by Equation 43, assuming that the ambient air has a relative humidity of 50%. Equations 42 and 43 were also used during the mass balance, see Section 5.3.1.

$$\phi_{Air} = Q_{air}(t)\,\rho_{air}C_{airp}(T_{air}(t) - T(t)) \qquad \text{(W)} \qquad (40)$$

$$\phi_{evap} = Q_{air}(t)\rho_{air}h_{evap}(H_{amb} - H_{gas}) \qquad \text{(W)} \qquad (41)$$

Where

$$H_{gas} = (5.06541\exp^{(0.056554796\,T(t))})\text{x}\,10^{-3} \qquad \text{(kg of water/kg of air)} \qquad (42)$$

$$H_{amb} = (1.903636\exp^{(0.062893237\,T_{air}(t))})\text{x}\,10^{-3} \qquad \text{(kg of water/kg of air)} \qquad (43)$$

5.4.2 Heat Production

5.4.2.1 Exothermic Biochemical Reaction

As outlined in Section 3.1.5 the TCA cycle produces by far the most significant amount of ATP out of all the biochemical pathways involved in an ATAD system. Consequentially it is this pathway that generates a majority of the heat. Oxygen is used as the electron acceptor in the electron transport chain where the ATP is produced and therefore a majority of the oxygen is also consumed by the TCA cycle. For simplicity reasons it has been assumed that the oxygen that is consumed in the TCA cycle results in a direct release of heat. Cooney *et al* (1968) found that the consumption of oxygen in a mesophilic aerobic digester could be correlated with the heat evolved from the biochemical reaction. If such a correlation exists for mesophilic bacteria it is likely to be also true for the ATAD process.

Investigators (Messenger, *et al*, 1990, Kelly and Warren, 1995) have identified that typical ATAD sludge produces between 12.5 and 14MJ of heat per kg of oxygen consumed. Kelly and Warren (1995) have found that typical ATAD sludge produces 21-23MJ of heat per kg of Volatile Solids destroyed, and since approximately 1.3 to 1.8kg of oxygen is required to oxidise 1 kg of Volatile Solids (Trim and McGlashan, 1985, Smith, *et al*, 1975) it shows that both produce similar results. However the exact calorific value of the sludge is highly dependent on the source of the sludge.

Since oxygen consumption and heat production from the biochemical reaction can be coupled by a factor, h_{react}, of approximately 13J per mg of oxygen consumed this allows the heat produced by the reaction to be calculated by Equation 44. The oxygen usage rate, *OUR(t)*, is given by Equation 36.

$$\phi_{react} = h_{react} OUR(t) \qquad \text{(W)} \qquad (44)$$

5.4.2.2 Mechanical Equipment

The mechanical equipment in an ATAD system such as the re-circulation pump and the aeration blower are not 100% efficient. The inefficiencies of mechanical equipment are generally due to friction and the slippage between the process fluid and the impellers. The inefficiencies of pumps, blowers etc. result in the generation of heat, which can be assumed to be absorbed by the sludge. The inefficiencies of the mechanical devices can generate about 5% of the total heat produced in an ATAD system. The basic equation used to model the mechanical heat supplied to the ATAD sludge is shown by Equation 45.

$$\phi_{mech} = P_{Blow}(t)(1-\eta_{Blow}) + P_{pump}(t)(1-\eta_{pump}) \qquad \text{(W)} \qquad (45)$$

5.4.2.3 Reactor Temperature

Equation 46 describes the dynamic energy balance, rearranging and substituting the mass of sludge in the reactor, M_{react}, with $HtA\rho$ gives an expression for the change in reactor temperature, *T(t)*, Equation 47. Both Equations 46 and 47 are constructed from equations proposed previously in this section, see Equations 38, 39, 40, 41, 44 and 45.

$$M_{react}(t)C_p\dot{T}(t)+\dot{M}_{react}(t)C_pT(t)=\phi_{wall}+\phi_{Sludge}+\phi_{Air} \\ +\phi_{evap}+\phi_{react}+\phi_{mech} \qquad \text{(W)} \quad (46)$$

$$\dot{T}(t)=\frac{1}{AHt(t)C_p\rho}\begin{bmatrix}\phi_{wall}+\phi_{Sludge}+\phi_{Air}+\phi_{evap} \\ +\phi_{react}+\phi_{mech}-A\dot{Ht}(t)C_p\rho T(t)\end{bmatrix} \qquad ({}^0\text{C/s}) \quad (47)$$

5.5 Model Outputs

The issues to be investigated with the model, as discussed in Section 5.1, require the model to determine how the organic solids degrade over time and how the reactor temperature responds. The reactor temperature profile can be obtained directly from Equation 47, but the quantity of organic solids in the reactor at any given time can be determined by the addition of all the organic components in the mass balance, as shown by Equation 48.

$$VS(t)=RBS(t)+SBS(t)+NBS(t)+VFA(t)+X_M(t)+X_T(t) \qquad \text{(mg/l)} \quad (48)$$

6. Model Validation

Model validation is required to ensure that the mathematical model is a true representation of an actual ATAD system, so that ATAD design, operation and control investigations could be carried out with the aid of the mathematical model. Due to the complexity of the mathematical model it is very difficult to identify all constants and parameters in the model with great confidence. Model validation was capable of illustrating that the model did represent the behaviour of an actual ATAD system.

6.1 Pilot Plant Validation

During 1997 Waste Solutions Ltd. conducted a feasibility study on an ATAD pilot plant at Paraparaumu Sewage Treatment plant. The data recorded during these trails was used to give an indication of the validity of the ATAD model.

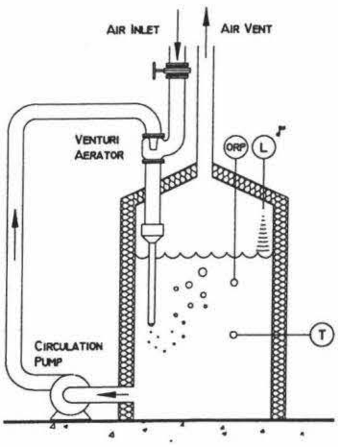

Figure 14 - Pilot scale ATAD reactor at Paraparaumu Sewage Treatment Plant.

A schematic representation of the ATAD reactor erected at Paraparaumu STP is shown in Figure 14. The ATAD pilot plant consisted of a thermally insulated tank, which had an active volume of approximately 4.5m^3. The pilot plant used a venturi aerator consisting of a circulation pump and a venturi aerator gun inserted from the top of the tank. The venturi aerator was operated by natural aspiration of air through an air inlet. The process monitoring equipment, consisted of sensors for temperature, Oxidation Reduction Potential (ORP) and an ultrasonic level sensor, as well as a few Volatile Solid concentration measurements.

6.1.1 Model Comparison

The aeration rate and quantity of sludge in the reactor has a very strong influence on the heat balance. Since these factors were not recorded during the investigation it made a comprehensive validation of the model impossible. The mathematical model and the data recorded during the pilot plant trail were used to illustrate the potential of the mathematical model.

The pilot plant did not have a means of controlling foam production, and as a result it was hampered with foaming problems, including reduced oxygen transfer efficiencies due to cavition in the re-circulation pump, as well as loss of sludge from the reactor.

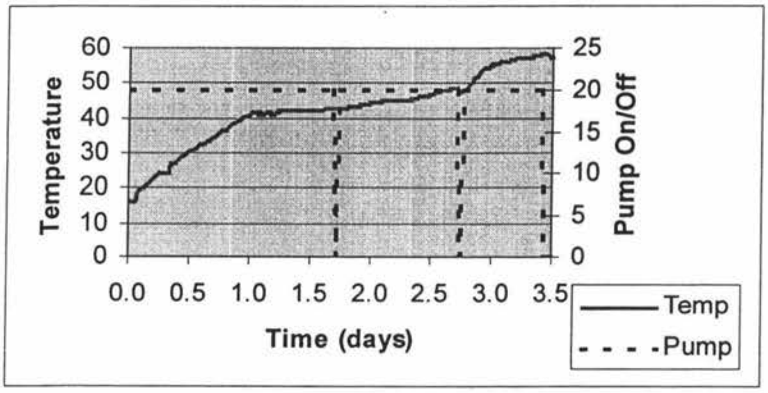

Figure 15 – Temperature and Pump on/off profile for ATAD pilot plant

Significant foaming production occurred once the temperature of the reactor reached about 40^{0}C. Foam production became so intense it was believed that the re-circulation pump was pumping predominately foam. This was believed to cause a significant reduction in airflow rate, which consequentially causes a reduction in oxygen transfer. This is believed to be the cause of the flat region in the temperature profile, as shown in Figure 15. The foam also caused the pump to vibrate heavily. Therefore the pump was turned off several times during the trail for maintenance, as shown by Figure 15.

The physical parameters of the pilot plant at Paraparaumu were entered into the ATAD model, along with the recorded inlet sludge characteristics. An aeration rate profile was estimated and a simulation performed. Figure 16 compares a simulation and the actual data collected during the pilot plant study. Even though this simulation has been obtained with an estimated aeration profile it does illustrate the potential of the model.

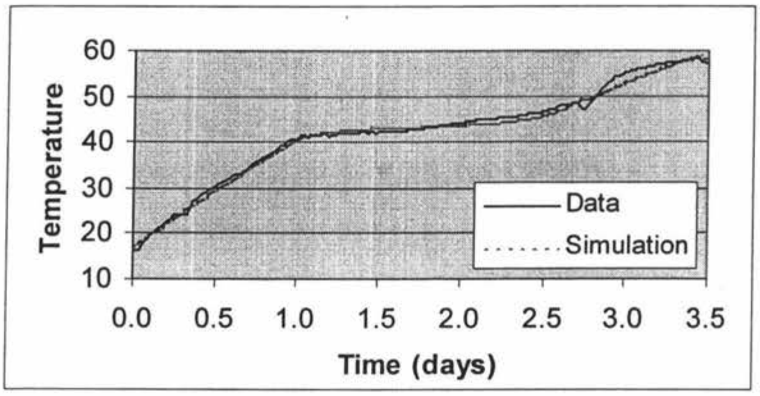

Figure 16 – Pilot plant data comparison with simulation.

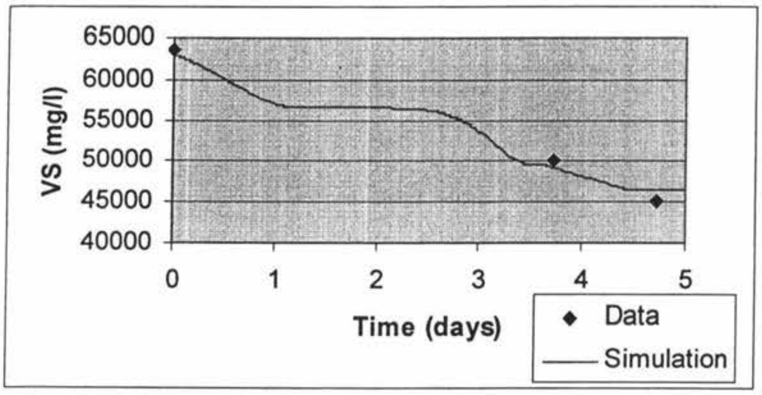

Figure 17 – Comparison between actual and simulated Volatile Solid degradation

Further confirmation that the mathematical model is of a reasonable quality is the comparison between the Volatile Solid degradation profile obtained from the model and a few data points collected during the pilot plant trial. This comparison can be seen in Figure 17.

The data obtained from the Paraparaumu ATAD pilot plant could not be used for a rigorous validation, as airflow and sludge quantities were not recorded. However, it has shown that the mathematical model is capable of describing the basic temperature and Volatile Solid destruction profiles that are necessary for design, operation and control investigations.

6.2 Experimental Validation

A small laboratory experiment was undertaken in an effort to provide an insight into the operation of an ATAD process. The main objective of the experiment was to obtain an insight into the effect of temperature on the bacteria growth rates as this was seen to be one of the major factors in the mathematical model.

6.2.1 Experimental set up

Three 2L flask jars were prepared with aeration and sampling tubes. Sludge from a wastewater treatment plant at a venison processing plant was used as a bacterium culture and feed substrate. The sludge was thickened to between 5 and 6% Total Solids. Approximately one litre of hot raw sludge was placed into the each of the three 2L flask jars.

The control reactor had 20ml of household bleach added to it, in an effort to prevent any microorganism activity. All three of the reactor bottles were placed into a water bath that was controlled to 60^0C. The sludge was then aerated continuously with air. Total Solid and Volatile Solid measurements were taken at least three times a day. The reactors were fed with additional sludge every day. Additional experiments were conducted at 55 and 65^0C. Sludge from a municipal wastewater treatment plant was also used briefly in one of the reactor bottles.

6.2.2 Experimental Findings

The scale of the experiment made accurate data collection difficult. Therefore no strong conclusions could be made from the data collected, but it did provide an insight in to some key issues associated with ATAD systems.

Total Solid and Volatile Solid sampling was removing large quantities of sludge each day, which contributed to the experimental error. Total Solid and Volatile Solid concentrations were used to determine the rates of the biochemical reactions. While these measurements are very imprecise (Messenger, *et al*, 1990) it did provide an insight into an ATAD system.

6.2.2.1 Bacteria population

The control reactor was fed daily like the other two reactor bottles, but bleach was also added in an attempt to stop any bacterial activity. However this reactor still had some organic degradation occurring, but less than the other two. This indicates that the bacteria population that was established during this experiment was a robust culture. It maybe implied that an ATAD system would be unlikely to fail due to undetected chemical additions.

Within the first day a large quantity of Volatile Solid degradation occurred. This indicated that a thermophilic bacteria population could establish very quickly in a controlled environment. This indicates that small hydraulic residence time can be used for pre-ATAD systems or individual reactors in a multistage conventional ATAD system without bacteria washout. However, hydraulic residence times less than 24 hours should be treated with care.

The organic degradation was found to be significantly faster at 65^0C than at 55 and 60^0C. Insufficient experiments were conducted to confirm this finding but it does suggest that the reduction in growth rates above the optimal temperature of 62^0C is either minimal or as a result of some other phenomena such as the ability of the aeration equipment to supply sufficient oxygen.

6.2.2.2 Foaming

Foam production was not as large as expected. The reduction in foam production may be due to the type of aeration used or maybe the stable operating temperature significantly reduced foam production.

While heating the raw sludge before feeding no foaming was observed. If a cold sludge sample was aerated no foaming or bubbles would form, but if the hot sludge sample was aerated bubbles did form on the top of the sludge. The control reactor appeared to foam more than the other two reactors. These observations would tend to agree with Kelly and Warren (1995), who hypothesises that ATAD foaming is caused by the intracellular material released during bacteria decay.

6.3 Full Scale Validation

At Nelson's Bells Island Sewage Treatment Plant there are two different aeration systems operating. There are two two-tank ATAD trains with naturally aspirated aerators operating and one two-tank ATAD train with venturi aeration system. During observation of the process only one of the naturally aspirated systems was operating and it was still not operating to its full potential as it had recently be decommissioned for maintenance, and only one of the two venturi reactors were operating due to a recent pump failure. However invaluable data was obtained from both systems.

Data collected during observation of the operation included Total and Volatile Solid concentrations, volatile fatty acid concentrations, temperature profiles, aeration rates, and exhaust gas analysis. It was not possible to accurately measure the volume of sludge fed to each system, since no level sensor equipment was installed in the reactors.

6.3.1 Data Comparison

Due to the complexity of the model and the limited data it is impossible to identify any of the many parameters or constants in the mathematical model to a high degree of confidence. The data was used to ensure that the parameters that were estimated from literature on other biochemical and mechanical systems where appropriate for an ATAD system.

Figure 18 compares the temperature profiles of a simulated ATAD system and the data obtained from Nelson's ATAD venturi system. While the profile is by no means exact it does demonstrate that the model displays a similar response to changing aeration rates. It is this behaviour that will prove vital during operation and control investigations.

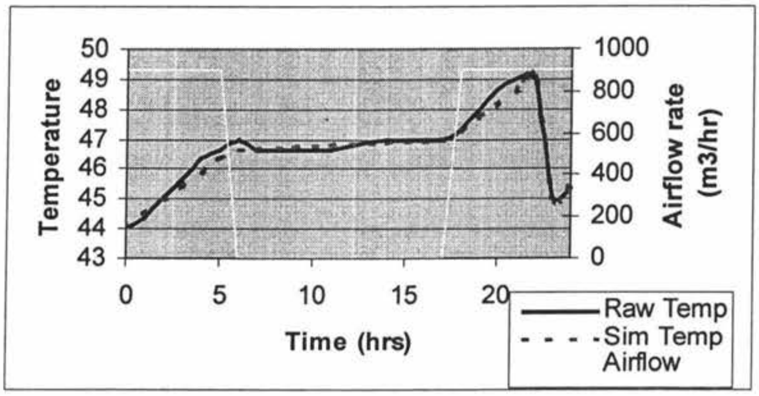

Figure 18 – Comparison between the temperature profile at Nelson ATAD plant and the corresponding simulation.

Since the ATAD systems were not operating under a stable condition it is likely that other process mechanisms could be occurring that are not explicitly included in the mathematical model. This may account for the difficulty in obtaining a better correlation between the model and the data.

During the visit to Nelson's ATAD facility the exhaust gas was temporally vented to atmosphere. The malodour from the exhaust vents was not offensive in anyway. The vent gas looked very similar to the steam rising from the spout of a boiling kettle. The temperature of the gas was similar to the temperature of the sludge in the reactor. These observations would agree with the assumption that the exhaust gas leaving an ATAD system is approximately the temperature of the sludge and saturated in water vapour.

6.4 Validation Results

Due to the complexity of the model it was not possible to identify a large number of the constants in the mathematical model. However estimations of each of the parameters where obtained from literature, simulation results and validation data. The data that was obtained from the various sources indicates that the mathematical model has the potential to represent a true ATAD system.

Appendix II shows the two major m-files used to input the major parameters and constants into the Simulink model. The constants and parameters displayed in these m-files are a true representation of the typical parameters used during operation and control investigations.

Even though the model has not been validated to the extent required for accurate design calculations it does have numerous uses in its current state. Since the mathematical model appears to illustrate the majority of trends seen in an actual ATAD system it can be used extensively for investigating possible improvements to the operational and control of an ATAD system.

It could be argued that the mathematical model is too complex, in particular the biochemical portion of the model. This portion of the model requires extensive experimentation to ensure that all parameters are identified accurately. But it was this complexity that allowed the operational and control strategy investigations to be carried out. A mathematical model that did not have a biochemical model that includes relationships of oxygen supply, substrate availability and temperature would not have resulted in the conclusions obtained in Sections 7, 8 and 9.

7. ATAD Design

There are a large number of factors to consider during the design of an ATAD system. ATAD systems are capable of processing a wide range of sludges, which have different rates of degradation and calorific values, but the same sludge source also can vary from season to season. This variation in sludge characteristics effects the performance of an ATAD system, and therefore adds to the complexity of ATAD design.

7.1 ATAD Reactor

The required working volume of an ATAD system is largely determined by the raw sludge characteristics and the average and peak loadings. The physical construction, shape and dimensions also have an effect on the system.

7.1.1 Reactor Loading

The amount of sludge that an ATAD can process is dependent on a number of factors. These predominantly are the sludge characteristics and the capability and performance of the aeration system.

Typically a conventional ATAD system can process between a $1/10^{th}$ and $1/6^{th}$ of the working volume per day. Also referred to as a hydraulic residence time (HRT) of between 6 and 10 days. If the solids are easily biodegradable (ie primary solids), then residence times can be reduced, similarly a larger and higher performing aeration system will allow higher organic solid concentrations to be processed.

Kelly and Warren, 1995, proposed Equation 49 and 50 for determining the organic solids degradation for a reactor with a working volume, V, and daily feed rate, Q. Rearranging this equation allows designers to determine the required working volume, V, for an ATAD with the daily sludge load, Q, and the required organic degradation, $VS_{reduction}$, Equation 51. All of these equations require knowledge of the rate of organic degradation. The rate of organic degradation is dependent on temperature, oxygen availability and sludge characteristics and is therefore difficult to obtain accurately.

$$\frac{X_{out}}{X_{in}} = \frac{1}{1 + K_T * \frac{V}{Q}} \qquad (49)$$

$$VS_{reduction} = 1 - \frac{1}{1 + K_T * \frac{V}{Q}} \qquad (50)$$

$$V = \frac{Q\,VS_{reduction}}{K_T\left(1 - VS_{reduction}\right)} \qquad (51)$$

$$K_T = 0.025 * 1.03^{(T-20)} \qquad (52)$$

The properties of the sludge being processed can change from one sewage treatment plant to another, and even from season to season. The two key areas of interest in ATAD sludge are the ease of biological degradation and the heat that is liberated. Due to the difficulty of determining such parameters without a large a number of tests it is usual to design an ATAD with typical rate constants and ensure a reasonable safety factor is applied. As shown in Equations 49 through to 51, Kelly and Warren (1995) have used a typical rate constant of that shown in Equation 52. As discussed in Section 6.5, a software design and simulation package could prove to be very useful tool while improving or designing an ATAD system.

7.1.2 Physical Properties

The physical shape and dimensions of the reactor have an affect on construction costs, mixing efficiencies, oxygen transfer efficiencies and wall heat loss. It is the designer's responsibility to ensure all these factors are considered during the design process.

During the design of an ATAD system it is important to ensure that all materials meet temperature and erosion-corrosion requirements. Corrosion rates, like biological rates, double every 10^0C increase. A mild steel pipe in use at 15^0C may last 20 years, but at 60^0C will last only 2 to 3 years (Kelly and Warren, 1995).

7.1.2.1 Construction Costs

The shape, materials and dimensions of an ATAD system can have an influence on the construction cost of the reactor. Usually an ATAD reactor is constructed in the form of a mild steel cylindrical tank, however a large number of concrete and/or square reactors have also be used. It is often common to retrofit aeration, mixing and foam control systems into an already existing reactor/tank on site.

The dimensions of an ATAD reactor influence to some degree the cost of construction. If a high tank were used then extra cost would be required to sustain the increased hydraulic pressures. Similarly a short reactor would require substantially more land and foundation work.

7.1.2.2 Mixing Efficiency

Mixing energy is required to maximise the contact between the thermophilic bacteria and the organic solids. Tank geometry, mixing power and mixing equipment are all interrelated. Poorly shaped reactors may require greater mixing power. A circular reactor with liquid depth equal to ½ to ¾ of its diameter requires a shear gradient of $450s^{-1}$. For temperatures between 50 and 60^0C this is about $100W/m^3$. Less efficient shapes may require mixing power densities between 150 and $200W/m^3$ (Kelly and Warren, 1995).

7.1.2.3 Aeration Efficiency

The longer the air has in contact with the sludge the better the oxygen transfer will be, as a result a very tall thin reactor is best as a far as oxygen transfer is concerned.

A layer of foam above the sludge has been found to increase the oxygen transfer efficiency (Wolinski, 1985). Therefore a freeboard of between 1½ to 3m is advised to allow the foam to develop on top of the sludge (Kelly and Warren, 1995). This freeboard is also a large help as far as foam control is concerned.

7.1.2.4 Reactor wall heat loss

Heat lost through the walls of a reactor gets smaller, on a volume basis, as the volume of the reactor increases. This is due to the change in surface area to volume ratio.

Due to the different heat transfer coefficients around the reactor (e.g. heat transferred from sludge to earth, sludge to ambient air, headspace to ambient air) there exists an optimal dimension for the reactor to minimise the heat lost through the walls. Unfortunately this is also dependent on a large number of factors such as construction material and thickness and the amount of insulation used.

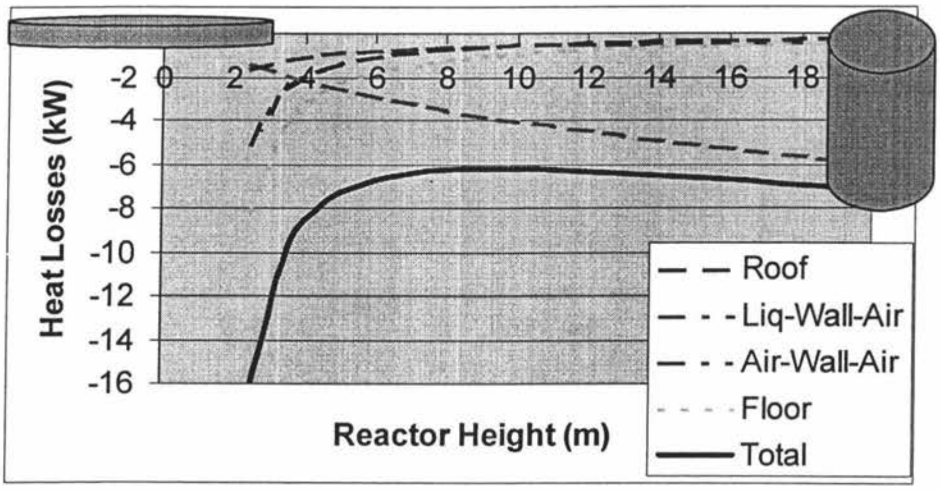

Figure 19 – Relationship between reactor wall heat loss and reactor dimensions for a fixed working volume and foam headspace

Figure 19 shows how the heat lost through the walls of a reactor is dependent on the dimensions of reactor. The heat lost from a reactor, with a fixed working volume and a fixed headspace height, changes significantly as the dimensions of the reactor change. The headspace is the height of freeboard available above the sludge in which foam can accumulate.

7.1.2.5 Insulation Requirements

It is normal to apply some insulation onto the exterior of an ATAD reactor, even if climatic conditions are normally good. A concrete reactor has a larger thermal resistance than a steel reactor, but a small amount of insulation may still be required.

Even a small amount of insulation will significantly reduce the affects of changing climatic conditions. Changing climatic conditions from a calm sunny day to a wet and windy day can increase wall heat loss by up 200%. It would be very difficult to maintain a stable operating temperature if weather conditions had such a dramatic affect on the heat loss. 50mm of glass wool cladding on the exterior of an ATAD reactor can reduce the heat lost by about 95% and reduces the affects of weather to a change in heat loss of approximately 60%.

7.2 Aeration System

The performance and capability of the aeration system dictates the performance and efficiency of the entire ATAD system.

7.2.1 Aeration Performance

The efficiency of the aeration system influences the performance of the ATAD system. The aeration system has two effects on the energy balance of an ATAD system. The volume of air going through the ATAD causes heat loss. This heat loss is due the change in sensible heat, but the more significant heat loss is caused by the evaporation of water. The oxygen that is transferred into the sludge stimulates the heat generating biochemical reaction. The efficiency of the aeration system at transferring oxygen into the sludge determines the balance of heat loss and heat generation.

Figure 20 shows a plot of the oxygen transfer efficiency at which the heat lost by the gas stream is equal to the heat generated by the biochemical reaction as a result of the oxygen being transferred into the sludge. It is important that the oxygen transfer efficiency is maintained above this line to ensure a net heat production exists.

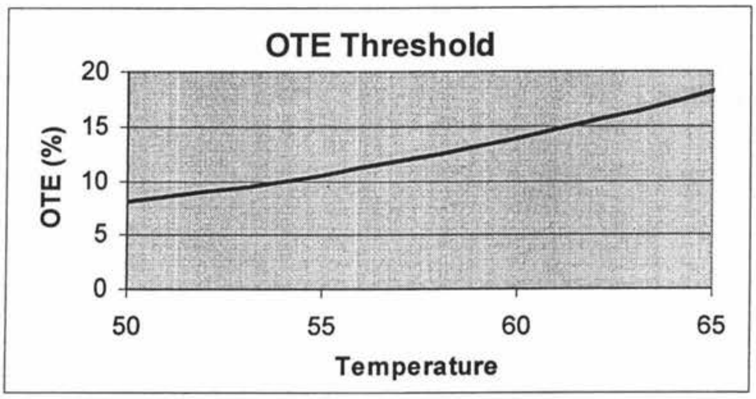

Figure 20 – Relationship between minimum oxygen transfer efficiency and sludge temperature

Increasing the Volatile Solids concentration or decreasing the aeration rate will cause a reduction in dissolved oxygen concentration. A decrease in dissolved oxygen will increase the driving force, which increases oxygen transfer efficiency. It is important not to increase the oxygen transfer efficiency by doing this, as it is likely that insufficient oxygen will be supplied to the microorganisms. An ATAD system that is not receiving sufficient oxygen will begin to produce large quantities of odorous gases, and the stabilisation process will be significantly reduced.

7.2.2 Aeration Capability

The performance of the aeration system dictates the volume of air required to transfer a specific volume of oxygen into the sludge. The microoganisms in the sludge require oxygen so that they can proceed to oxidise the organic portion of the sludge. The aeration system must supply sufficient oxygen to prevent the sludge becoming malodorous.

Oxygen demand in an ATAD system can be very high. The thermophilic bacteria degrade organic solids significantly faster than their mesophilic counterparts. The ATAD sludge concentrations are also high, which causes an increase in oxygen demand.

If insufficient oxygen is supplied to the sludge then the anaerobic (absence of oxygen) pathways will begin to dominate. If this is allowed to occur odorous gases are produced and the stabilisation will slow. Conversely, due to the high oxygen demand of the sludge it is unrealistic to design an aeration that can maintain an aerobic (excess oxygen) process under all operating conditions.

A trade off needs to be determined between the cost of increased aeration capability and increased hydraulic residence times and therefore larger reactors.

7.2.3 Aeration Operating Costs

Even though the transfer efficiency and aeration capacity is important for the systems performance it is also important to consider the energy consumed by the aeration system. One of the largest operating costs of an ATAD system is the aeration system, therefore it is important to consider the operating costs of the system.

Since it is often difficult to increase transfer efficiency without increasing energy consumption a trade off has to be made during the design of the aeration system. Similarly a large aeration system may cause a reduction in capital cost (smaller reactor), but will result in increased operating expenses.

$$Q_{air\ Design} = \frac{1.4VS_{reduction}\ VSL}{24 \times 0.209 \dfrac{OTE_{Design}}{100\%} \rho_{air}} \qquad (\mathrm{m^3/hr}) \qquad (53)$$

Where

$$VSL = Q\rho\ VS \qquad (\text{kg of solids/day})$$

Matsch and Drnevich (1977) have shown that an ATAD process requires approximately 1.4 kg of oxygen to oxidise 1kg of Volatile Solids. With an estimated Volatile Solids loading, *VSL*, and oxygen transfer efficiency, OTE_{Design}, it is possible to size the aeration system, as shown by Equation 53. Kelly and Warren (1995) suggested a design oxygen transfer efficiency of 70%, but New Zealand experience has shown that ATAD oxygen transfer efficiencies are usually between 20 and 40% efficient.

7.3 Sludge Characteristics

The characteristics of ATAD sludge can vary greatly from ATAD system to ATAD system, as well as over the year at the same facility. ATAD systems often degrade primary sludge, secondary sludge or a mixture of the two.

Primary sludge is the solids obtained from the initial screening that occurs as the wastewater enters a sewage treatment plant. Secondary sludge or waste activated sludge (WAS) is the solids removed from other biological treatment process. Primary sludge is usually easier to degrade, as secondary sludge is predominantly bacterial biomass, which has grown in the previous biological treatment process. This bacterial biomass must first be destroyed and the cell wall penetrated before the thermophilic bacteria can degrade it.

Organic sludge can come from a number of different sources, and each organic compound liberates a different amount of energy during oxidation. Therefore any variation in the sludge characteristics can also cause an affect on both degradation rate and/or energy liberated.

7.3.1 Sludge Concentrations

The general rule of thumb for the sludge concentrations required for an ATAD process to work effectively when aerated with air is generally referred to be between 3 and 8 percent Volatile Solids.

A high solids concentration of solids makes effective mixing difficult and expensive. The high concentration of organic solids can also make suppling sufficient oxygen more difficult and costly. The general consensus on the maximum limit is about 100g/l Total Solids. Since most sludge contains about 80% Volatile Solids this equates to approximately 8% or 80g/l Volatile Solids.

The minimum solids concentration is brought about due to the pasteurisation requirement in an ATAD system. To prevent the addition of supplementary heat a minimum amount of organic solids must be present to allow sufficient heat to be released during its oxidation to maintain the thermophilic temperatures.

With the assumption of no heat loss it can be shown that a Volatile Solids concentration of 2% or 20g/l can raise the temperature by 40^0C. However a real ATAD system does lose heat through the walls of the reactor along with heat removed by the exhaust gas stream. Therefore an additional quantity of organic solids is required to counteract this heat loss. Since most sludge sources have sludge concentrations less than 2% Volatile Solids it is required to have some type of pre-sludge thickening process.

To determine the practical minimum sludge concentration a heat balance around the complete ATAD system has to be preformed. With the following basic assumptions it is possible to estimate the minimal sludge concentration.

1) Ambient temperature of 15^0C,
2) The average reactor temperature 55^0C,
3) The reactor is a cylindrical steel tank insulated with 80mm of glass wool,
4) Aeration system has a oxygen transfer efficiency of 25%,
5) Mechanical heat of 160W/m^3 at 75% efficient,
6) Reduce Volatile Solids by 38%.

The calculation of the minimum solid concentration is an iterative process, since the aeration rate influences the heat lost, and the oxygen demand is determined by the solid concentration. With the above assumptions it was found that this ATAD system could effectively operate with a minimum Volatile Solids concentration of 3.1% or 31g/l. This minimum sludge concentration correlates with that determined by Kelly and Warren, 1995.

7.4 Multistage ATAD Systems

A multistage ATAD system is one in which multiple reactors are connected together in series. Generally only the larger ATAD systems are constructed in this way, as the increased performance, does not warrant the larger capital cost. A multistage ATAD system is easier to operate and control, as the operating conditions of each reactor do not change as dramatically as a single stage ATAD system. The larger (many reactors in series) multistage ATAD systems can operate as a continuous process as the possibility of sludge by-passing the system without sufficient disinfection is significantly reduced.

The first reactor, in a multistage ATAD system, absorbs most of the dramatic heat load caused by the cold raw sludge that is added during the draw and fill cycles. This allows the subsequent reactors to maintain a more stable temperature. A stable operating environment is beneficial, as bacterium have a small acclimatisation period when their environment changes.

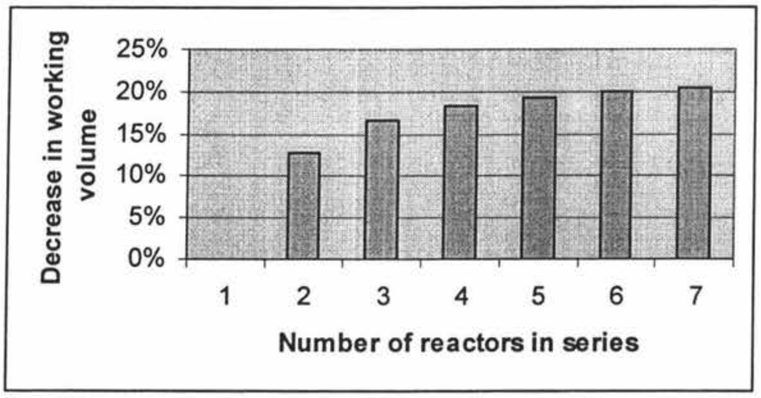

Figure 21 – Comparison between the working volume of a single ATAD system and a multistage ATAD system

The overall reaction rate in a multistage ATAD system is higher. Therefore it can process more sludge with the same total working volume. Figure 21 illustrates how the total working volume can be reduced when multiple reactors are put in series.

Thermophilic bacteria have relatively fast growth rates and therefore washout should not occur. But a hydraulic residence time of much less than 1 day in each reactor could cause problems, especially in the initial reactors. Therefore an ATAD system with any more than 7 reactors in series should be avoided.

If a multistage ATAD system is under loaded it is quite possible that the bacteria culture in the last few reactors can die off due to lack of available substrate. It is for this reason that the organic solid loading and aeration rate be carefully controlled in a similar manor to a single stage ATAD system.

The first few reactors in a multistage ATAD system have a high oxygen demand, as a result of the high organic loadings. The oxygen demand progressively reduces as you move through the train of reactors. The aeration control strategy proposed in Section 7.2, needs to be used with care in the first few reactors. The low temperatures in these reactors make it difficult for the aeration system to provide sufficient aeration to reach the optimal oxygen transfer efficiency. Therefore the aeration supply to the initial reactors should be restricted to some extent to reduce operational costs.

7.5 Design and Simulation Software

The mathematical model was used to investigate a number of the design issues. This highlighted that a large number of interrelated factors need to be considered during the design of an ATAD system. A basic prototype design and simulation software package was developed. When this package is fully developed it will allow designers to design an ATAD system and then simulate several operational scenarios to ensure the design will meet all requirements.

At this stage the package is very basic and as discussed in Section 5.4 more model validation is still required. Even though the model is believed to be a true likeness to an ATAD system further validation is required to ensure that the design and simulation package represents the system under a wide range of operational scenarios. Future developments of the software could allow the simulation part of the package to allow existing ATAD systems to be optimised, or possibly assess future upgrade options.

8. ATAD Operation

An ATAD operates in a batch or semi-continuous operation, to ensure sufficient disinfection occurs. Therefore a steady state condition rarely exists; this makes operation and control more challenging.

In the past the aeration rate has been manipulated by manual or automatic control. An ATAD is a relatively slow system. Therefore it is not difficult to maintain a stable process with manual control. With the information that is typically available to operators, it is sometimes difficult to make effective operational adjustments to the process.

On-line aeration control has also been used by measuring Oxidation-Reduction Potential (ORP) of the sludge. These sensors are known to have a short lifetime in ATAD sludge. A direct relationship between the output of an ORP sensor and the behaviour of the biochemical process is not evident. The new control strategy would preferably attempt to optimise both the stabilisation and disinfection processes as well as being cheaper and easier to operate and maintain.

All operational and control investigations were carried out on a single stage conventional ATAD system. It is believed that the conclusions reached from such an investigation can be adapted to multistage and pre-ATAD systems. Further research into these process variations is still required.

There are a number of other operational issues that could potentially increase throughput, stability, performance, and/or reduce operational costs. Some of these include the draw and fill strategy and Volatile Solids concentrations.

8.1 Optimising the ATAD process

An ATAD control system would ideally control the process to ensure that a Class A biosolids are produced consistently even when the raw sludge properties alter significantly. Further control system benefits accrue from increasing the throughput of the system and/or reducing operational costs. Increasing the rate of stabilisation and/or the rate of disinfection can increase the solid throughput.

8.1.1 Increasing Stabilisation Rate

The stabilisation rate in an ATAD process can be maximised by providing excess oxygen to the sludge. This ensures that the oxidation biochemical pathway or the TCA cycle dominates. In this biochemical pathway the carbon source is completely oxidised to carbon dioxide and water and releases significant quantities of heat.

Maintaining the sludge at the optimal thermophilic temperature can also increase the stabilisation rate. It is assumed, with partial experimental confirmation, that the thermophilic bacteria that catalyses the organic stabilisation process preforms best at a temperature of 62^0C; assuming excess oxygen is available to them.

8.1.2 Increasing Disinfection Rate

Heating the sludge up as quickly as possible and maintaining this high temperature can increase the rate of disinfection. Disinfection time is a non-linear function with respect to temperature, so a small increase in operating temperature can have a large decrease in the disinfection time.

The oxidation biochemical reaction generates the majority of the heat; therefore it is important to ensure that this pathway dominates. This is achieved by suppling sufficient oxygen to the sludge.

8.2 Effective Aeration Control

The ideal control strategy for an ATAD system would be to optimise the production of Class A biosolids. Since it is currently difficult to measure the rate of stabilisation on-line this control strategy would be difficult to implement. It has been found that maximising the net heat production while suppling adequate oxygen to the process can increase the performance of the system. This control strategy manipulates the aeration rate to regulate the oxygen transfer efficiency.

The biochemical process requires sufficient oxygen to ensure that organic stabilisation is not restricted. When excessive aeration is applied, excessive cooling occurs. This is due to the heat lost by the sensible heat flow of the air, but more significantly is the heat lost due to the evaporation of water. This excessive cooling can cause an increase in disinfection time. It is therefore important to ensure that sufficient air is applied to the system, but no more.

Effective aeration control will ensure that organic stabilisation is occurring without being restricted by the lack of oxygen. Even though this control strategy does not ensure that the optimal thermophilic operating temperature of 62^0C is maintained it will ensure a high net heat production from the system. A high net heat production will allow the sludge temperature to increase rapidly towards the optimal temperature, therefore increasing the rates of disinfection and stabilisation.

The mathematical model was used to simulate the effective aeration control strategy. Simulations were carried out with dissolved oxygen concentration as the process variable, and aeration rate as the manipulated variable. With a simple proportional-integral (PI) controller it was possible to maintain a dissolved oxygen set point. The simulations illustrated that this control strategy provided a very stable system. The simulations showed that the controlled aeration rate would decrease if the biochemical reaction slowed for whatever reason and prevented excessive cooling of the system.

The simulations illustrated that aeration rate could be effectively controlled to a dissolved oxygen concentration set point, but this would not be the possible in practise. The dissolved oxygen concentrations in ATAD sludge are typically very low, below 1mg/l. The dissolved oxygen sensors presently on the market can only measure dissolved oxygen concentrations reliably above about 2mg/l. Therefore dissolved oxygen can not be used as a process variable.

Through the mathematical model it was found that the oxygen transfer rate (OTR) closely represented the oxygen usage rate (OUR) of the biochemical reaction. The OTR could be determined by measuring the quantity of oxygen that remained in the exhaust gas. This provided an indirect way of determining what the reaction was doing. The difficulty with these measurements is determining if the microorganisms wanted more or less oxygen than they were receiving.

The mathematical model illustrated that the oxygen transfer efficiency (OTE) of the aeration system displayed similar behaviour to the dissolved oxygen concentration. Oxygen transfer efficiency is a parameter that assesses the performance of the aeration system; it can be calculated from Equation 54. OTE can be calculated by measuring the amount of oxygen still present in the exhaust gas of an ATAD reactor. From this and the aeration rate, $Q_{air}(t)$, it is possible to determine how much oxygen has been transferred into the sludge, $OTR(t)$, and consequently the $OTE(t)$.

$$OTE(t) = \frac{OTR(t)}{0.209 Q_{air}(t)} \times 100\% \qquad (54)$$

Simulations carried out with a constant aeration rate showed that at the beginning of each cycle the OTE was high and at a particular point in time it began to reduce. Oxygen is the rate-limiting factor in the initial stage of the cycle. Therefore the dissolved oxygen concentration in the sludge is very low, which provides a large driving force and allows easy oxygen transfer. At some point in time the concentration of readily biodegradable organic substrates becomes limited and the reaction rate slows. Oxygen is no longer the rate-limiting factor, this causes the dissolved oxygen concentration to increase. The reduction in driving force makes oxygen transfer more difficult, reducing the oxygen transfer efficiency. Therefore excessive (oxygen) air is being supplied to the system when the OTE efficiency reduces.

Exhaust gas analysis was preformed on a few gas samples taken from Nelson's Bells Island ATAD systems. Analysis showed that the oxygen transfer efficiency of the system showed similar properties to that identified by the mathematical model.

8.2.1 Matching Microorganism Oxygen Demand

Aeration control by maintaining an oxygen transfer efficiency set point ensures that the microorganisms are supplied with all the oxygen that they require, but no more (see Section 8.2.4 for exceptions). The stabilisation rate is therefore high and operational costs and heat loss is kept to a minimum.

If the microorganisms require large quantities of oxygen to oxidise the sludge then the dissolved oxygen concentration will be driven down. The lower dissolved oxygen concentration increases the driving force, therefore increasing oxygen transfer. An increase in oxygen transfer rate at a constant aeration rate will cause an increase in OTE. If the aerator is controlled to an oxygen transfer efficiency set point then the aeration rate must be increased to maintain that set point. An increase in aeration rate will reduce the oxygen transfer efficiency, and increase the oxygen transfer rate further. The increase in oxygen transfer rate will slow the decrease in dissolved oxygen concentration and eventually a steady state condition will be achieved. When the steady state condition is reached the oxygen supplied to the sludge will equal the oxygen demanded by the biochemical reaction. A similar effect occurs when the biochemical reduces its consumption of oxygen.

Any sewage treatment plant is subject to environmental and seasonal changes as far as the organic loading is concerned. An ATAD facility is no exception to this. The quantity and characteristics of the raw sludge will change from season to season. The proposed effective aeration control strategy will ensure that the microorgansims oxygen demand is matched all year around, providing a more stable operation.

8.2.2 Optimal Oxygen Transfer Efficiency Set Point

Aerating an ATAD system with air has two major energy affects on the ATAD system. The flow of air through the ATAD promotes evaporation of water; this along with the sensible heat loss results in a significant heat loss. Secondly the oxygen that is transferred from the air into the sludge is used for organic matter degradation, which releases large quantities of heat.

If the aeration rate is high the heat lost by the sensible gas flow and evaporation loss can be significantly greater than the heat produced by the biochemical reaction. At a very low aeration rate nearly all the oxygen in the air will be transferred into the sludge, therefore the net heat production per unit of air is high. But only small volumes of oxygen are supplied, causing the stabilisation process to be very slow and hence the overall net heat production is minimal. In the middle there exists an aeration rate that promotes significant organic matter degradation and therefore a large net heat production exists, Figure 22 illustrates this effect. Ideally the oxygen transfer efficiency set point should promote this operating condition. Figure 22 shows that every temperature and dissolved oxygen concentration their exists an aeration rate that maximises the net heat production.

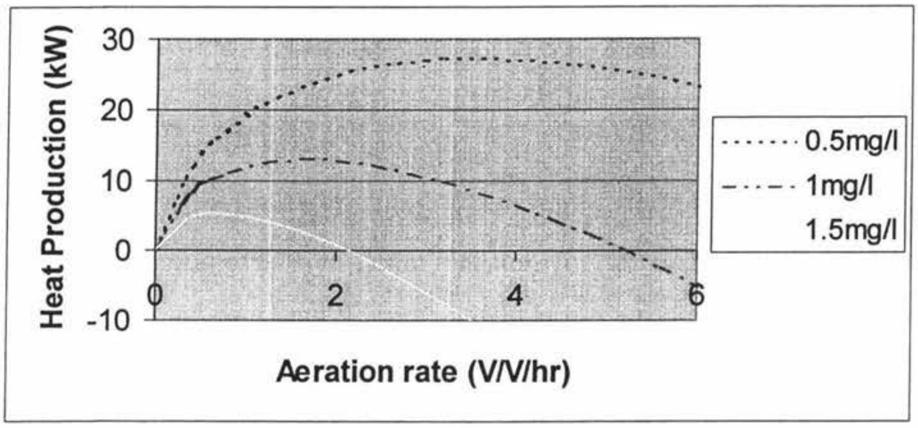

Figure 22 – Relationship between aeration rate associated heat production and aeration rate at 60^0C and various dissolved oxygen concentrations.

Equation 55 shows how the aeration rate in an ATAD system can influence the net heat production in an ATAD system. When the dissolved oxygen concentration in the ATAD sludge is at a steady state condition it can be assumed that the oxygen used by the biochemical reaction is equal to the oxygen transferred into the sludge by the aeration system. Therefore the oxygen usage rate, *OUR(t)*, is substituted by the oxygen transfer rate, *OTR(t)*, in Equation 56, which is then expanded to Equation 57.

Figure 22 illustrates how the slope of each line is equal to zero at every optimal net heat production. The slope of the net heat production versus aeration rate graph can be calculated from Equation 58, while Equation 59 determines the aeration rate required to optimise the net heat production at any given temperature and dissolved oxygen concentration.

$$\begin{aligned}\phi_{aeration} &= Q_{air}(t)\rho_{air}C_{airp}\left(T_{air}(t)-T(t)\right)\\ &\quad +h_{react}OUR(t)-Q_{air}(t)\rho_{air}h_{evap}\left(H_{gas}-H_{amb}\right) \qquad \text{(W)} \qquad (55)\end{aligned}$$

assume $\qquad OTR(t) \approx OUR(t)$

$$\begin{aligned}\phi_{aeration} &= Q_{air}(t)\rho_{air}C_{airp}\left(T_{air}(t)-T(t)\right)\\ &\quad +h_{react}OTR(t)-Q_{air}(t)\rho_{air}h_{evap}\left(H_{gas}-H_{amb}\right) \qquad \text{(W)} \qquad (56)\end{aligned}$$

$$\begin{aligned}\phi_{aeration} &= Q_{air}(t)\rho_{air}C_{airp}\left(T_{air}(t)-T(t)\right)\\ &\quad +h_{react}\alpha_{air}Q_{air}(t)^{B_{air}}\left(\gamma-DO(t)\right)\\ &\quad -Q_{air}(t)\rho_{air}h_{evap}\left(H_{gas}-H_{amb}\right) \qquad \text{(W)} \qquad (57)\end{aligned}$$

where

$$\alpha_{air} = \frac{1000}{3600}\alpha FVA_{air}\left(\frac{3600\times 24}{A}\right)^{B_{air}}\Theta^{T(t)-20}$$

$$\gamma = \tau\Omega\beta C_{\infty 20}$$

slope of heat production vs aeration rate graph :

$$\begin{aligned}\frac{d\phi_{aeration}}{dQ_{air}} &= \rho_{air}C_{airp}\left(T_{air}(t)-T(t)\right)\\ &\quad +h_{react}\alpha_{air}B_{air}Q_{air}(t)^{B_{air}-1}\left(\gamma-DO(t)\right)\\ &\quad -\rho_{air}h_{evap}\left(H_{gas}-H_{amb}\right) \qquad \text{(W/m}^3\text{/sec)} \qquad (58)\end{aligned}$$

optimal heat production occurs when :

$$\frac{d\phi_{aeration}}{dQ_{air}} = 0$$

the aeration rate that corresponds to the optimal heat production :

$$Q_{air\,Opt} = \left[\frac{\rho_{air}C_{airp}\left(T(t)-T_{air}(t)\right)+\rho_{air}h_{evap}\left(H_{gas}-H_{amb}\right)}{h_{react}\alpha_{air}B_{air}\left(\gamma-DO(t)\right)}\right]^{\frac{1}{B_{air}-1}} \qquad \text{(m}^3\text{/sec)} \qquad (59)$$

Equation 60 shows how the oxygen transfer efficiency, *OTE(t)*, is calculated. The oxygen transfer rate, *OTR(t)*, is substituted and simplified to Equation 61. The aeration rate that produces the optimal net heat production (Equation 59) for any given temperature and dissolved oxygen concentration is substituted into this equation. The simplified optimal oxygen transfer efficiency set point, $OTE_{Opt\ SP}$, is shown in Equation 62. It shows that the optimal oxygen transfer efficiency set point is dependant on the sludge temperature, *T(t)*, air temperature, $T_{air}(t)$, aeration performance, B_{air}, and the calorific value of the sludge, h_{react}.

More importantly note that the optimal oxygen transfer efficiency set point does not depend on the dissolved oxygen concentration, or the rate of biochemical degradation. The optimal oxygen transfer efficiency set point can therefore be calculated on-line, once the aeration performance and the sludge calorific value have been estimated for the given system.

$$OTE(t) = \frac{OTR(t)}{0.201 Q_{air}(t)} \times 100\% \qquad (60)$$

$$OTE(t) = \frac{\alpha_{air} Q_{air}(t)^{B_{air}} \left(\gamma - DO(t)\right)}{0.201 Q_{air}(t)} \times 100\%$$

$$OTE(t) = \frac{\alpha_{air} Q_{air}(t)^{B_{air}-1} \left(\gamma - DO(t)\right)}{0.201} \times 100\% \qquad (61)$$

Substiting the optimal aeration rate

$$OTE_{Opt\,SP} = \frac{\alpha_{air} \left[\frac{\rho_{air} C_{airp} \left(T(t) - T_{air}(t)\right) + \rho_{air} h_{evap} \left(H_{gas} - H_{amb}\right)}{h_{react} \alpha_{air} B_{air} \left(\gamma - DO(t)\right)} \right]^{\frac{B_{air}-1}{B_{air}-1}} \left(\gamma - DO(t)\right)}{0.201} \times 100\%$$

$$OTE_{Opt\,SP} = \frac{\rho_{air} C_{airp} \left(T(t) - T_{air}(t)\right) + \rho_{air} h_{evap} \left(H_{gas} - H_{amb}\right)}{0.201 h_{react} B_{air}} \times 100\% \qquad (62)$$

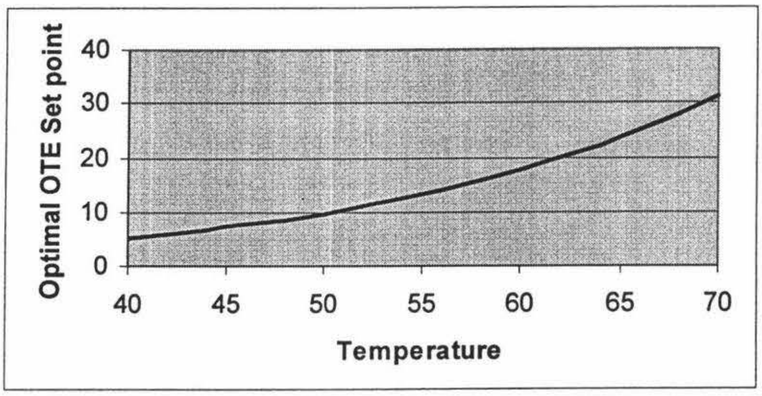

Figure 23 – Relationship between the optimal Oxygen Transfer Efficiency (OTE) set point and reactor temperature.

Figure 23 shows the relationship between the optimal oxygen transfer efficiency set point and the temperature of the reactor. Since sludge temperature probes are usually installed in ATAD systems it will be possible to track the optimal oxygen transfer efficiency set point.

8.2.3 Excessive Heat Production

The proposed effective aeration control strategy may allow the temperature to exceed the optimal thermophilic temperature of 62^0C. If the sludge temperature exceeds the optimal operating temperature, the decay rate exceeds the growth rate, causing a reduction in the bacteria population. This will slow the stabilisation rate. A reduction in bacteria population becomes a problem if the culture takes a significant period of time to re-establish.

As discussed in Section 6.2.3.1, the laboratory scale experiments undertaken indicated that a thermophilic bacteria population could establish very quickly. Also the experiments indicated that excessive temperatures do not have a strong influence on stabilisation rates. If this is the case in full-scale ATAD systems then excessive temperatures will not dramatically affect the rate of stabilisation.

It is believed that an ATAD system controlled with the proposed control strategy will become a self-regulated system. However, if it is found that excessive temperatures do dramatically reduce the stabilisation rate, it may be possible to adjust the OTE set point so that more aeration cooling occurs as the temperature approaches and exceeds the optimal thermophilic temperature. This problem may also be minimised by using a different draw and fill strategy or implementing external heat exchangers to remove the excess heat, see Sections 8.4 and 8.6 respectively for further details.

8.2.4 Aeration requirements

Figure 24 illustrates that an ATAD system requires significantly more aeration at low temperatures and dissolved oxygen concentrations than at high temperatures and dissolved oxygen concentrations. As discussed in Section 8.2.1, the higher the oxygen demand from the microorganisms the lower the dissolved oxygen concentration will be driven. As a result more aeration is required to maintain the optimal set point. Similarly the optimal oxygen transfer efficiency increases with increasing temperature, so the aeration rate must be decreased to allow the optimal set point to be reached.

Figure 24 illustrates that this particular aeration system requires an aeration rate of 17.3V/V/hr to maintain the optimal oxygen transfer efficiency set point at 55^{0}C and 0mg/l dissolved oxygen. This quantity of aeration is unpractical. An aeration system of this size would be costly to construct and operate. If a less powerful aerator was constructed and the optimal oxygen transfer efficiency set point was still used in the controller the aeration system would saturate.

A saturated aerator would force the oxygen transfer efficiency higher than the set point, but the net heat production would still be the highest possible for that system, hence this strategy is still applicable. Unfortunately the biochemical reaction will not be supplied with all the oxygen that it requires, so the stabilisation process will be restricted. The controlled aeration system would come into affect when the oxygen transfer efficiency set point came within the range of the aeration system, for example at high temperatures and high dissolved oxygen concentrations.

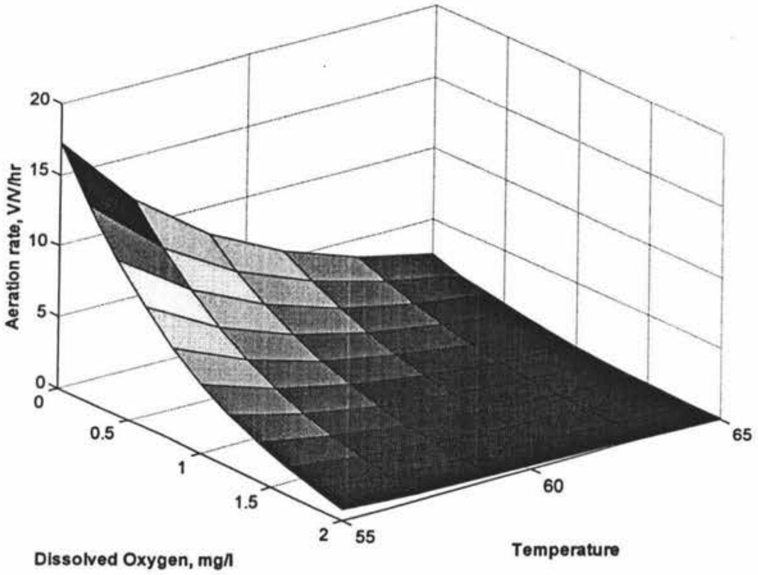

Figure 24 – Example of required aeration rate to maintain optimal oxygen transfer efficiency set point.

Even with a high aeration capability it is still be likely that the aeration system would saturate under certain operating regimes. It is therefore advised that any controller implemented with the proposed control strategy have an anti-integral windup algorithm implemented.

An anti-integral windup algorithm prevents the integrator of the controller producing large values while the aerator is saturated. If this is allowed to occur the controller will take a long time to respond to a required drop in aeration rate.

8.2.5 Practicality of Effective Aeration Control

There are no gas oxygen sensors presently on the market that are designed for the temperatures and condensing vapours that are typically found in the exhaust gas stream of an ATAD. With a cooling and drying attachment it is believed that the sensors currently on the market will be able to preform the required measurements.

Edington and Clay (1992) installed an electrochemical oxygen instrument on the exhaust gas of a pilot plant ATAD plant at Castle Donington sewage treatment works, but the device failed almost immediately. They found it difficult to obtain a dried, on-line sample of the head-gas and as a result the sensor failed.

Wolinski (1985) installed a paramagnetic oxygen sensor on an ATAD plant at Palmersford with no major problems mentioned. The on-line analysis of the vent gases provided an excellent indication of the digestion process. If too much air is being injected, this is immediately reflected in high oxygen concentrations in the vent gas. Conversely too little air results in 100% removal of oxygen, (Wolinski, 1985).

It is unclear whether Wolinski actually used a control system to manipulate the aeration rate or if the information was simply used as an effective decision making tool for the operators. Whichever method was adopted it does illustrate that oxygen transfer efficiency can provide the required information for effective aeration control, but as Edington and Clay (1992) discussed it is of importance to install an effective means of cooling and drying the exhaust gas sample.

The electrochemical sensors that are available on the market are around NZ$200, with a life span of about 12 months. The main problem with these sensors is they have a maximum expected 2% full-scale deflection (FSD) drift per month, which would cause a 2.4% drift in OTE per month.

8.2.5.1 Sensor Drift

If the oxygen sensor used for calculating the OTE has a maximum 2% full-scale deflection drift per month, this equates to maximum drift of 2.4% in the oxygen transfer efficiency set point per month.

If the aeration system were controlled to an OTE set point 2.4% away from the optimal set point, a reduction in heat production, or worse a heat loss would occur. The drift in the oxygen sensor could also cause a reduction in stabilisation rate. The significance of these two factors is largely dependent on the performance of the aeration system, and the operating conditions of the particular ATAD system.

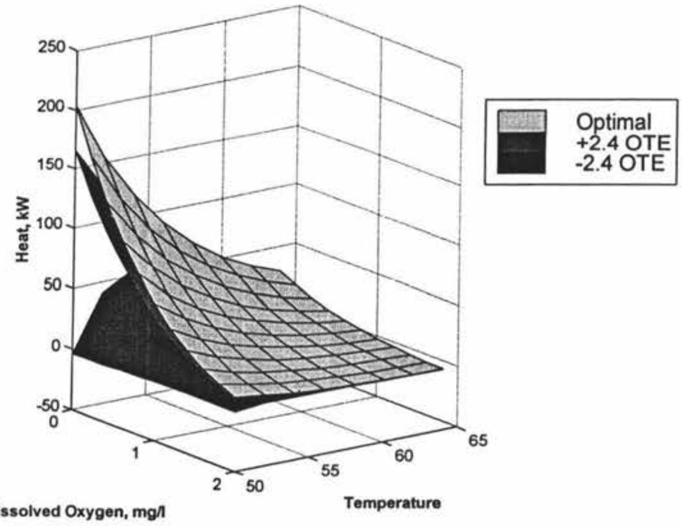

Figure 25 – Effect on heat production as a result in a 2% FSD drift in the oxygen sensor

Figure 25 illustrates that a positive drift in the OTE set point will cause a slight decrease in heat production and a slight reduction in oxygen transfer rate at any given operating point. Conversely, a negative drift in OTE set point causes an even larger reduction in heat production, and a large increase in aeration rate at any given operating point. The difference magnitude between a positive and negative drift of OTE set point is due to the non-linear relationship between aeration rate and oxygen transfer efficiency as shown in Figure 31.

Even though Figure 25 illustrates a huge drop in heat production due to a negative drift in the OTE set point this will not be as dramatic in reality. No aeration system could maintain the required negative drift in oxygen transfer efficiency. Figure 26 illustrates that a huge increase in aeration is required to meet a decrease in OTE set point, since the aeration system is likely to saturate before this is achieved the large decrease in heat production would also not occur.

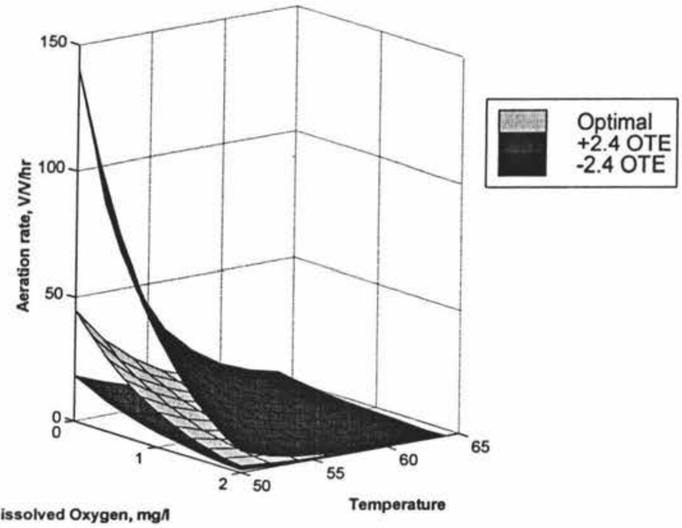

Figure 26 – Aeration required too maintain a drift in oxygen transfer efficiency

A 2.4 drift per month in OTE can move the operation of an ATAD system into an undesirable operational state. The significance of this drift will depend on the sensors installed and the performance of the aeration system. Further investigations need to be carried out to determine if these sensors are adequate. If the sensor drift is found to be a significant issue there are a number of possible solutions to this problem. Some possible solutions include the following:

1) recalibrate sensors each week
2) on-line weekly calibration or set point adjustment

3) use multiple sensors and compare answers, (similar to parallel redundancies employed in modern fly-by-wire aircraft)
4) use a time based set point drift to counteract sensor drift
5) different sensors

The practicality of each of the above ideas will depend on the predicability of the sensor drift and the cost of implementing such a solution.

8.2.6 Further Investigations

The simulations have indicated that controlling the oxygen transfer efficiency to a set point by manipulating the aeration rate is an effective means of controlling an ATAD process. Further practical investigations need to be carried out to ensure that this control strategy is in fact a practical solution.

The other main issues that need to be investigated further before the proposed control strategy is implemented widely include:

1) Sensor drift
2) Effect of excessive temperatures on stabilisation rates
3) Influence on foam production

8.2.7 Other Control Strategies Investigated – Temperature Control

As discussed in Section 8.1 temperature can play an important part in increasing both the rate of disinfection and the rate of stabilisation. Therefore it was initially thought that temperature would be an ideal process variable. Investigations showed that temperature based control strategies were ineffective in increasing the performance of an ATAD system.

There are two possible ways of controlling the temperature in an ATAD process, either attempt to maintain the temperature at the maximum growth rate temperature of 62^0C or ensure that the temperature follows an ideal temperature trajectory. The temperature in an ATAD can be manipulated either by external heat exchangers and may be manipulated to some extent by the aeration rate.

8.2.7.1 By Manipulation of Aeration Rate

If the ATAD temperature could be manipulated effectively by the aeration rate, there would be no extra expense in installing and operating external heat exchangers.

Aerating an ATAD system with air has two major energy effects on the ATAD system. Firstly the flow of air through the ATAD promotes evaporation; this along with the sensible heat loss results in a significant heat loss. Secondly the oxygen that is transferred from the air into the sludge is used for organic matter degradation, which results in heat generation.

If an ATAD is aerated heavily the heat lost by the air sensible heat flow and water evaporation can be greater than the heat produced by the biochemical reaction. Generally high aeration rates can promote foam production, and therefore this situation should be avoided (Kelly, *et al*, 1995). At a very low aeration rate nearly all the oxygen in the air will be transferred into the sludge, therefore the net heat production per unit of air is very high. But only small volumes of oxygen are supplied, causing the stabilisation process to be slow and hence the heat production is also minimal. In the middle there exists an aeration rate that promotes significant organic matter degradation and therefore a large net heat production exists. Therefore the manipulation of the aeration rate can significantly effect the net heat production of an ATAD system. Hence the aeration rate could be potentially used to control the temperature of the reactor.

Further analysis illustrates why manipulating the aeration rate is not an intelligent means of controlling the temperature of an ATAD system. When the temperature of the reactor begins to approach or exceed its set point the aeration rate should decrease (since heavy aeration can cause foam production problems), which decreases the net heat production as desired. This reduction in aeration rate may actually slow the stabilisation process by making the supply of oxygen to the microorganisms limited. Since the stabilisation process is often the process constraint in a conventional ATAD system, this decrease in stabilisation rate would actually reduce the throughput of the system. Therefore temperature control by manipulating the aeration rate in a conventional ATAD system is ineffective.

8.2.7.2 By Manipulation of External Heat Exchangers

Since temperature control by manipulating the aeration rate could result in a reduction in sludge throughput, temperature control by external heat exchangers was investigated.

Investigations showed that external heat exchanges where capable of heating the sludge up to 62^0C faster than without them. But once the temperature had reached the optimal growth temperature of 62^0C the exothermic biochemical process continued to heat the sludge. If the temperature continued to rise, the stabilisation rate may slow as the temperature exceeds the optimal operating temperature for thermophilic bacteria. Therefore a cooling mechanism should also be installed to ensure that the temperature does not exceed the thermophilic operating temperatures.

Even with the expensive of installing, maintaining and operating a heating and cooling mechanism a significant increase in performance would not necessarily occur. This control strategy does not ensure that sufficient oxygen is available to the microorganisms to promote fast stabilisation.

To ensure an adequate supply of oxygen the aeration system could be left on full power and the heat exchangers could regulate the temperature. This control strategy would ensure a greater sludge throughput, but the operating costs would increase significantly. Unnecessary aeration is expensive on its own without considering the cost of suppling heat to counteract the extra heat loss from the excessive aeration rate.

8.2.8 Other Control Strategies Investigated – Derivative of Temperature

For this control strategy, the aeration rate would be set to maximum following a feed cycle, as it can be assumed that the system is limited by the oxygen supply. When the biochemical system changes from being limited by oxygen to limited by readily biodegradable substrate, the slope or first derivative of the temperature profile reduces. When this change in temperature gradient is detected the aeration rate should be reduced by a pre-set amount.

The slope of the temperature profile represents the net heat production (or loss) of the entire system. All parameters in the heat balance except the heat evolved from the biochemical reaction can be theoretically calculated or measured on-line. It is therefore possible to estimate the heat evolved by the biochemical reaction with the use of the heat balance.

The heat evolved by the biochemical reaction could be used to indicate the required aeration rate. If the heat evolved by the biochemical reaction reduced it would indicate a necessary reduction in aeration rate. The large mass of sludge would also cause a lengthy delay before a change in biological heat production could be positively identified.

Conceptually this control strategy would prevent over aeration, but it does not provide the information that the oxygen transfer efficiency control strategy does. Therefore it is believed that oxygen transfer efficiency is the ideal control strategy.

This control strategy may appeal to some clients, as it is a cheaper alternative to the oxygen transfer efficiency control strategy as no additional sensors are required. But this control strategy does not monitor oxygen demand in any way, therefore the performance will inevitably be worse than the oxygen transfer efficiency control strategy.

No controllability investigations where carried out with this proposed control strategy once the oxygen transfer efficiency control strategy was found to be the preferred option. If this control strategy is found to be a viable option in the future it is advised to carry out a controllability study before implementing such a strategy.

8.3 On-line Class A Biosolids Detection System

Before the sludge from a conventional ATAD system can be disposed of on land with no restrictions it must meet both the stabilisation and disinfection criteria outlined by USEPA Class A biosolids standard, as discussed in Section 2.2. A on-line Class A biosolid measurement system could increase sludge throughput, as the operators would not need to over process the sludge to ensure its quality. An on-line detection system would ensure the Class A biosolids are consistently produced no matter what type of raw solids is processed. Such a system would provide significantly more flexibility, but unfortunately such a system is not currently available.

Every time raw sludge is added to an ATAD reactor the disinfection clock must be restarted. To determine when the sludge has been sufficiently pasteurised a calculation from the temperature profile of the sludge can be made. Since the temperature in the ATAD is often increasing throughout the batch it is not as simple as calculating the disinfection time from the initial temperature. Due to the non-linear characteristics of the temperature–disinfection calculation a temperature later through the batch usually results in a shorter disinfection time. Appendix IV shows the code used to calculate the disinfection time during simulations. This or similar code could be used to calculate the required disinfection time on-line. This would give operators a definite time when sufficient pasteurised is made, and automate the calculation.

The USEPA standard states that the sludge is stable when the ATAD has reduced the Volatile Solids by at least 38%. To accurately determine the Volatile Solids concentration of the sludge an 8 hour test must be preformed. This type of test can not realistically be used in the day to day running of an ATAD facility.

One other test also outlined in the USEPA Class A biosolid standard. The specific oxygen uptake rate (SOUR) of the sludge is to be less than 1.5mg of oxygen per hour per gram of Total Solids at a temperature of 20^0C. Even though this test can be preformed relatively easily it is still a time consuming exercise and not an ideal means of determining the stabilisation criterion.

The USEPA SOUR test could be used on the day to day operation of an ATAD but it would become very time consuming if multiple draw and fill cycles were preformed each day. An on-line measurement system to determine how the stabilisation is progressing would be ideal.

The on-line solid concentration sensors that are currently on the market are only able to measure low solid concentrations reliably. Therefore these types of sensors cannot be realistically used for stabilisation testing.

With the use of extensive Total Solids, Volatile Solids, temperature and oxygen transfer rate (OTR) profiles from an ATAD facility it is believed that a relationship between OTR and the stabilisation criterion can be determined, resulting in an on-line stabilisation test.

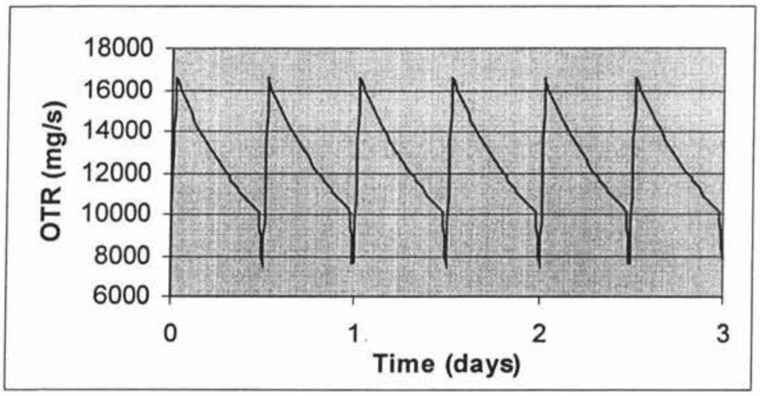

Figure 27 – Typical oxygen transfer rate profile under proposed control strategy.

Figure 27 shows the oxygen transfer rate profile from a simulation undertaken with effective aeration control. It is hoped that with some dependence on temperature a cut-off oxygen usage rate (OUR) (assume OTR equal to OUR) can be determined. For example once the oxygen transfer rate drops below 10,000mg/l the sludge can be assumed stable. Note the drop in OTR at the end of each batch in Figure 27 is due to the draw and fill cycle. This type of test is would be similar to the EPA SOUR requirement, except it is preformed in the reactor instead of in the lab under standard conditions. Another possible idea; the integral of OTR may indicate the quantity of sludge stabilised.

The problem with these ideas and probably any on-line Class A detection system is determining the raw sludge concentration. The raw sludge concentration may vary considerably. The on-line detection system would therefore need to be a conservative system, and require laboratory results entered into it on a regular basis.

If such a measurement can be obtained then an on-line Class A biosolids detection system could be implemented into the control system. Such a system would guarantee consistent Class A biosolid production. This system has the potential of increasing throughput as the safety factors involved with the hydraulic residence times and batch cycles can be reduced or removed. With the use of on-line disinfection and stabilisation measurements the process will be able to adapt the throughput of the system to each sludge load.

8.4 Draw and Fill Strategy

The draw and fill cycle should occur once the sludge in the reactor is stable and pathogen free according to the USEPA Class A biosolid standard. As discussed in Section 8.3 there is no easy means of determining the stabilisation criteria during the day to day running of an ATAD system.

Once it has been determined that the sludge in the ATAD meets the Class A biosolid criteria a draw and fill is required to take place. The operator or control system needs to know how much sludge to remove and consequentially how much raw sludge to add. This is not a trivial problem as there are a large number of factors that influence the optimal draw and fill. The major factors that influence the optimal draw fill strategy are listed below:

1) Reactor temperature
2) Feed temperature
3) Capability and performance of aeration system
4) Properties and concentration of the raw sludge

The reactor and feed temperature effect how low the temperature will drop when the raw sludge is added. The drop in temperature will result in a decrease in bacteria growth and therefore slow the stabilisation process. The required disinfection time is not a linear relationship with temperature, so every degree increase in the minimum temperature also results in a significant reduction in disinfection time. The capability and performance of the aeration system along with the properties and concentration of the raw sludge affects the rate of stabilisation and therefore the rate of temperature rise. A small draw and fill would require several draw and fill cycles in one day, while a large draw and fill could take several days to process.

The two ends of the spectrum;

1) If the ATAD reactor was 60^0C for example and a very small portion of the reactor was removed and refilled with raw sludge. The sludge temperature would drop a small amount and there would be a negligible affect on the biochemical reaction. The raw sludge that was added would quickly be stabilised to the required standard. The disinfection time at 60^0C is 4.78hrs. This is a very long time to process a very small amount of sludge.

2) A draw and fill of one half of the reactor's volume would cause a significant drop in temperature and consequentially bacterial activity. The bacteria culture would have to change from the slower mesophilic bacteria population to the thermophilic bacteria. The large organic load would cause a large oxygen demand, and the aeration system may struggle to supply sufficient oxygen. If this occurs the stabilisation process will be inhibited. Therefore the disinfection criterion is likely to be met significantly before the sludge is sufficiently stable.

Ideally the stabilisation process should not be inhibited by lack of oxygen or the slower mesophilic bacteria. The batch sizes should not be so small that the stabilisation criterion is met well before the disinfection criterion. A balance between these needs to be achieved. Simulations have shown that a more stable process is achieved when the stabilisation criterion is the systems constraint. If an ATAD system operates for prolonged periods as a pasteurised constrained system the bacteria culture diminishes, as a result of lack of food.

It is recommended to start optimising the draw and fill strategy by determining the maximum batch size that can be achieved without saturating the aeration system under OTE control. This will depend on the capability and performance of the aeration system, the raw sludge concentration and also the temperature of the sludge. Once this has been determined slowly (over many weeks) reduce the quantity of each draw and fill cycle allowing the stabilisation and disinfection criteria to approach each other. Always ensure that the stabilisation criterion is the system's constraint.

In some ATAD systems the aeration system may saturate even at high temperatures and small batch sizes. This suggests that the aeration system is undersized for the quantity of solids being processed. Even if the aeration system is undersized it does not mean that the ATAD system cannot be operated effectively.

8.5 Sludge Concentration

The sludge concentration can have a large affect on the operating temperature, and therefore stabilisation and disinfection rate. Section 7.3.1 showed that a sludge concentration of at least 3.1% Volatile Solids is required to reach an operating temperature of 55^0C.

The sludge concentration and the hydraulic residence time (HRT) of an ATAD process are interrelated. A high sludge concentration requires a longer HRT to ensure the solids are adequately stabilised. However a higher sludge concentration has less water to be heated unnecessarily, therefore allowing the sludge to heat up quickly and to a higher temperature. This could potentially increase the throughput, by increasing the stabilisation and disinfection rates; hence the HRT can be reduced slightly.

Theoretically the higher the sludge concentration the more solids that can be processed in a given ATAD. As discussed in Section 7.3 a high sludge concentration takes significantly more effort to mix and aerate. Therefore a trade off between operational and capital cost needs to be made to determine the ideal sludge concentration for the given ATAD system.

8.5.1 Organic Solid Load Fluctuations

It is advised to find a sludge concentration and hydraulic residence time that best suits the processes aeration system and solid loadings. When a good solid concentration has been identified it is advised to ensure that these are a maintained as close as practical possible. Variations in organic solid loadings can dramatically affect the performance of the system.

Figure 28 shows the effect of a decrease in organic solid loadings. The solid concentration is reduced from 5% to 3% for 7 days, while maintaining the same hydraulic residence time of 7 days. The aeration rate was controlled with the oxygen transfer efficiency control strategy proposed in Section 8.2. The simulation showed that the same temperature profile was a maintained for four days after the decrease in solids loading. Four days after the reduction in organic solid loading the temperature began to decrease as insufficient heat is liberated by the biochemical reaction to maintain the temperature. When the organic solid loading is increased back to its original value the temperature immediately begins to climb. It takes nearly 10 days before the temperature settles back to its original value. This is significantly faster than the 20 days that Kambhu and Andrews, 1969 discovered when they simulated a similar scenario.

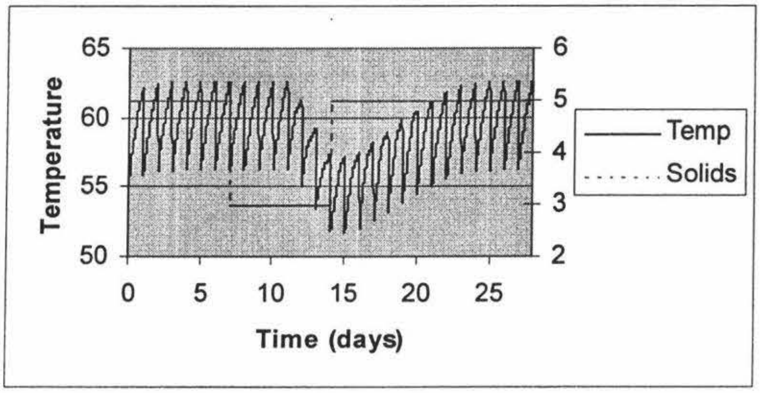

Figure 28 – Effect of reactor temperature when the fed solids concentration is decreased and the hydraulic residence time remains constant - aerator controlled with proposed oxygen transfer efficiency control strategy

A similar simulation was carried out with a constant aeration rate. Figure 29 shows that the temperature drops significantly the day after the change in organic solid loading. The temperature does not recover once the solid concentration is increased again. This illustrates that the proposed effective aeration control strategy is capable of minimising the effects of any variations in organic solid loadings.

The simulation illustrates that large changes in solids loadings for prolong periods will eventually cause a reduction in operating temperatures. If a reduction in organic solid loading is allowed to occur, it will take several days to regain the original operating temperatures. For this reason it is believed beneficial to maintain a constant sludge concentration and hydraulic residence time. Any seasonal changers to the organic solid loadings are best dealt with by changing the working volume to ensure a similar hydraulic residence time is maintained. This operational philosophy will ensure that the heat production and heat loss is proportional all year around. Therefore a similar operating temperature can be maintained.

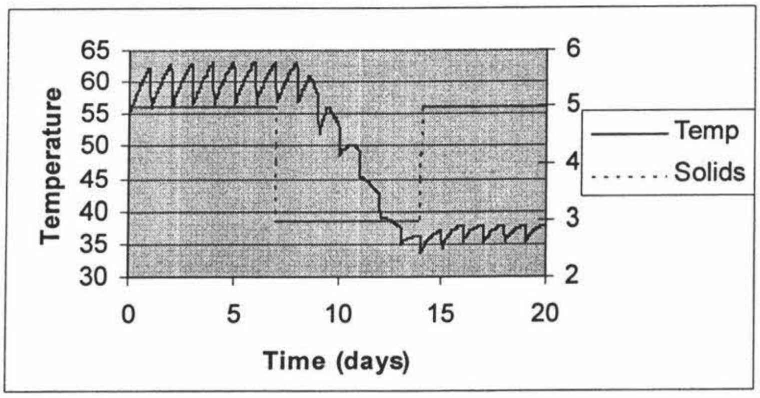

Figure 29 – Effect of reactor temperature when the fed solids concentration is decreased and the hydraulic residence time remains constant – constant aeration rate

8.6 Heat Exchangers

As discussed in Section 8.2.7.2 controlling the temperature with the use of heat exchangers is pointless without first implementing an aeration control system, similar to that proposed in Section 8.2. But in some cases it may prove beneficial to install heat exchangers to recover waste heat or provide supplementary heat.

In countries such as Canada the heat loss during winter months could potentially decrease the operating temperature below the required thermophilic temperatures. Also in some situations sludge with low organic content needs to be digested and pasteurised, therefore insufficient heat will be released by the biochemical reaction to maintain thermophilic operating temperatures. In cases such it may be viable to install heat exchangers to recover some of the waste heat or provide supplementary heat.

A typical break down of the heat lost in an ATAD system is shown in Table 3. It shows large quantities of heat could be recovered from the sludge and exhaust gas streams with the use of heat exchangers.

Type of Heat Loss	Typical Heat Loss
Wall Heat Loss	5%
Sensible sludge Flow	57%
Sensible air flow	5%
Exhaust evaporation loss	33%

Table 3 – Typical heat loss in an ATAD system

In the cases where high performing aeration systems are installed it will be possible to process sludge with high organic content. In such cases too much heat generation could push temperatures above thermophilic operating temperatures. Excess heat may need to be dumped or used to provide heat to surrounding building etc. to ensure that high temperatures do not inhibit bacterial activity.

A number of heat transfer configurations are possible. The quantity of heat transfer required too maintain an appropriate operating temperature will determine which configuration will best suit the situation.

Due to the consistency of sewage sludge it is recommended that a spiral heat exchangers be used. The centrifugal force of the flowing sludge helps to prevent fouling of the heat exchanger surface. These heat exchangers are generally more expensive but they will minimise maintenance requirements.

If post ATAD sludge thickening is required it is sometimes necessary to install some type of heat recovery system, as this generally can not be preformed with hot sludge.

One idea to minimise the cost of heat exchangers is to build the finished ATAD buffer tank enclosed inside the raw sludge buffer tank. With minimal mixing in each tank sufficient heat transfer may be provided to allow cooling of the final product and heating of the raw sludge. The viability of this idea will depend on the residence time of the buffer tanks.

8.7 Foaming

Foam production in an ATAD system can be a major problem if sufficient foam control is not undertaken. Uncontrolled foam production can substantially increase the pressure inside a reactor, which can consequentially cause permanent tank deformation, or spill large quantities of sludge around the sewage treatment facility.

The reasons for foam production in an ATAD are not fully understood. Kelly and Warren, (1995) believe that the foam is due to a population shift of competitive bacteria. The less temperature tolerant strains die, and release intracellular materials, which contribute to the foaming by lowering the liquid surface tension.

Wolinski (1985) observed that foam production did not occur when the ATAD was operated with pure oxygen, but did occur when aerated with air. Wolinski (1985) could not explain this phenomenon but discovered that the high mass flow rates of the air were not the cause. The observations of Wolinski appear to contradict the theory of Kelly and Warren, (1995).

This topic is really outside the scope of this project but it is believed that a process can be designed and operated to minimise the effects of foam production. It is believed that the bacteria populations change at temperatures between 40 and 50^0C, as well as temperatures greater than 65^0C. Designing an ATAD that avoids these temperatures, and ensure that the microorganisms have sufficient organic matter could reduce foam production problems.

8.8 Summary

The rate of stabilisation in an ATAD system can be maximised by ensuring that sufficient oxygen is supplied to the sludge. The temperature of the sludge and hence the net heat production also has a strong influence on the rate of stabilisation and disinfection. A control strategy has been proposed that will ensure sufficient oxygen is supplied to the sludge and the maximum net heat production is achieved. Therefore potentially increasing the rate of stabilisation and disinfection, and hence increasing the sludge throughput. This is achieved by manipulating the aeration rate to an optimal oxygen transfer efficiency set point. The optimal oxygen transfer efficiency set point is calculated on-line, as it is dependent on the sludge temperature, as shown by Equation 62. Simulations with the mathematical model have shown that the control strategy can increase performance and stability of the process, which could reduce capital and operational costs.

A control strategy that is slightly cheaper (less sensors required) to implement but less effective than the aeration rate – oxygen transfer efficiency control strategy was also briefly investigated. This control strategy uses the slope or first derivative of the temperature profile to determine the progress of the biochemical reaction, and from this the aeration rate can be regulated to prevent excessive aeration. This control strategy does not ensure that the biochemical reaction is achieving sufficient oxygen, and does not attempt to maximise the net heat production, therefore the oxygen transfer efficiency control strategy is the preferred option.

Simulation showed that the draw and fill strategy has a strong influence on the performance of the system. Unfortunately there are no clear-cut answers to optimising this as it is very system dependent. The mathematical model did indicate that the largest sludge throughput is achieved when the disinfection and the stabilisation criteria are achieved at similar times, without saturating the aeration system or dropping the reactor temperature below 50^0C. Also, if the disinfection criterion is the system's constraint for prolonged periods the bacteria population can diminish due to lack of available organic substrates, which can result in process instability.

Investigations showed a change in the organic solid loadings has dramatic effects on the operating temperature, and hence the system's performance. To avoid these fluctuations in operating temperature the Volatile Solid concentration and hydraulic residence times should remain constant as much as possible. Any variations in organic loadings should be dealt with by changing the working volume of the system.

Heat exchangers are not theoretically necessary for the successful operation of an ATAD system. But, they can be used beneficial to recover waste heat or supply supplementary heat in cold environmental conditions and/or where low organic loadings are necessary.

9. ATAD Control

To allow the effective aeration control strategy proposed in Section 8.2 to be implemented with a simple proportional-integral (PI) or proportional-integral-derivative (PID) controller the process gain and process dynamics between aeration rate and oxygen transfer efficiency should not change significantly over the entire operating regime.

The process gain and process dynamics describe the behaviour of a system; this information is used to effectively tune a controller. With an understanding of the variation of the process gain and process dynamics, it is possible to ensure that the process remains stable under all operating conditions. If the process behaviour changes dramatically from one operating regime to another it may be difficult to effectively reject process disturbances in some operating regimes, and therefore simple control techniques are not advised.

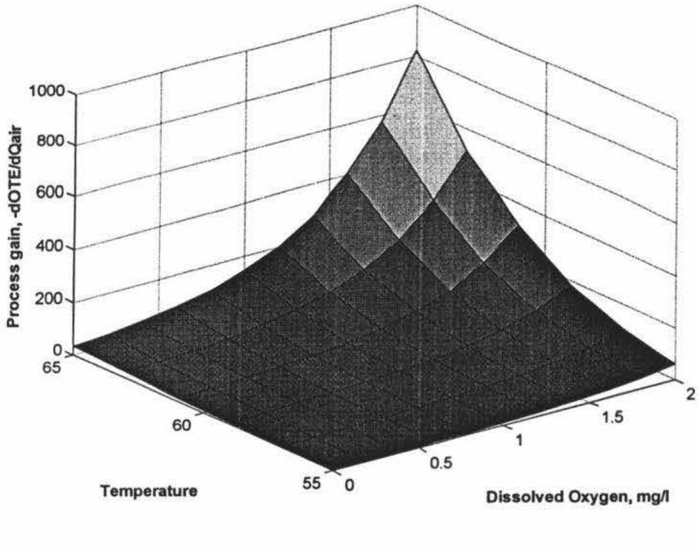

Figure 30 – Variation of gain over a typical operating region

Figure 30 shows how the open loop transfer function gain from the aeration rate, $Q_{air}(t)$, to oxygen transfer efficiency, $OTE(t)$, changes from -3 to -827 over a typical operating region. This large change in gain is due to the changing oxygen transfer efficiency curves as illustrated by Figure 31. The horizontal line on this graph represents the optimal oxygen transfer efficiency at 60^0C. The slope at the intersection of the optimal line and the dissolved oxygen graphs changes significantly. It is this change in slope that causes the large variations in process gain. The controller gain should be tuned when the process has high temperatures and high dissolved oxygen concentration (ie. at the end of a batch) to prevent the system becoming unstable at this operation regime.

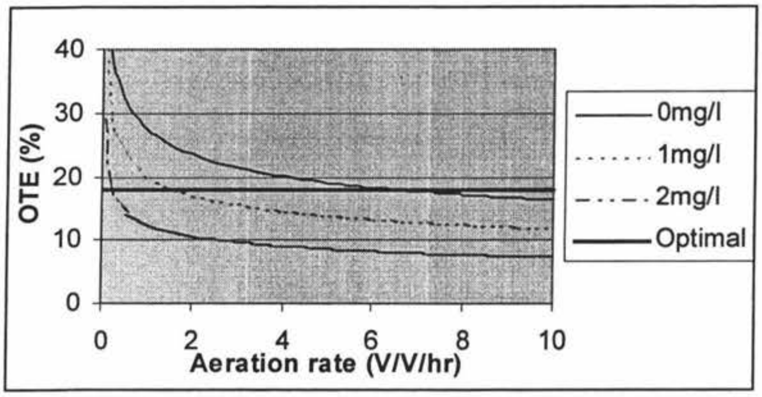

Figure 31 – Relationship between Oxygen Transfer Efficiency and aeration rate at ***60^0C and various dissolved oxygen concentrations***

Under all operating regimes the oxygen usage rate (OUR) and the oxygen transfer rate (OTR) are approximately equal, and therefore the inertia of the dissolved oxygen concentration is small. Therefore, the process dynamics between the aeration rate and the oxygen transfer efficiency are dominated by transport lags, such as the aeration system and the gas hold up in the reactor. This indicates that the process dynamics between the aeration rate and the oxygen transfer efficiency do not change greatly over the entire operating regime as the dominating transport lags are independent of the operating conditions. Therefore the variations in process dynamics should not effect the controllability of an ATAD process.

Further practical investigations need to be carried out to determine if the large variation in process gain will effect the controllability of the ATAD process. If the variation in the process gain prevents the controller from adequately rejecting disturbances at low temperatures and low dissolved oxygen concentrations (ie at the beginning of a batch) it is advised to implement a gain scheduled controller. Gain scheduling is a technique in which different controller settings are used in different operating regions. As the process moves from one operating regime to another the controller gain and/or integral time changes accordingly. The justification of gain scheduling will depend greatly on the size of the draw and fill cycles employed at the particular ATAD facility. If small batches are used there should be no reason for gain scheduling.

A simulation was carried out to compare an uncontrolled aeration system with a fixed aeration rate and an aeration system controlled with a simple PI controller with the OTE process variable. The settings used for the PI controller were a gain of –0.1 and an integral time of 0.001 rad/sec. Figure 32 illustrates that the controlled aeration system provides a stable system and is capable of adapting the aeration rate to the biochemical process. The uncontrolled system with a constant aeration rate causes the temperature to drop quickly when the biochemical process slows due to a lack of readily biodegradable substrate and/or thermophilic bacteria. While the controlled system is capable of rejecting the variation in the reaction rate and maintain a similar operating temperature, and hence a stable process.

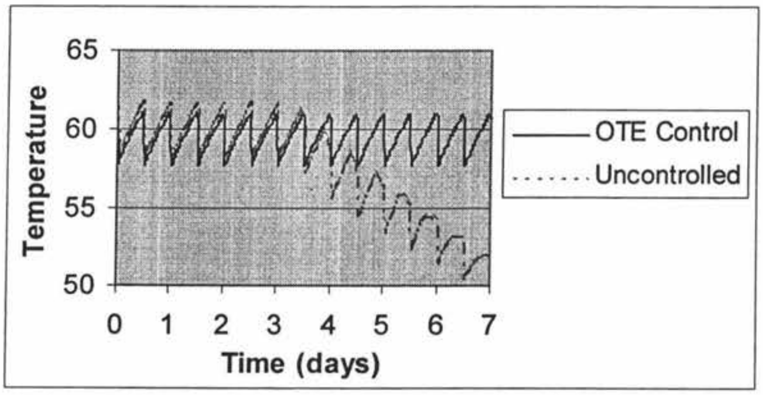

Figure 32 – Comparison between a controlled aeration system (OTE) and uncontrolled system (constant).

10. Recommendations and Conclusions

A non-linear mathematical model was successfully developed to describe the dynamic behaviour of ATAD processes. The dynamic model was used extensively to investigate possible improvements to the design, operation and control of ATAD processes. The investigations highlighted a number of areas where significant improvements could be made to the process.

The rate of stabilisation in an ATAD system can be maximised by ensuring that sufficient oxygen is supplied to the sludge. The temperature of the sludge and hence the net heat production also has a strong influence on the rate of stabilisation and disinfection. The mathematical model allowed the development of a new control strategy that will ensure sufficient oxygen is supplied to the sludge and the maximum net heat production is achieved. Therefore potentially increasing the rate of stabilisation and disinfection, and hence increasing the sludge throughput. This is achieved by manipulating the aeration rate to an optimal oxygen transfer efficiency set point, with a simple PI controller. The optimal oxygen transfer efficiency set point is calculated on-line, as it is dependent on the sludge temperature, as shown by Equation 63. Simulations with the mathematical model have shown that the control strategy can increase performance and stability of the process, which could reduce capital and operational costs.

$$OTE_{Opt\,SP} = \frac{\rho_{air} C_{airp} \left(T(t) - T_{air}(t)\right) + \rho_{air} h_{evap} \left(H_{gas} - H_{amb}\right)}{0.201 h_{react} B_{air}} \times 100\% \qquad (63)$$

The proposed oxygen transfer efficiency-aeration control strategy needs to be implemented into an actual full scale ATAD system to determine the practical advantages and disadvantages of such a control strategy. The major problem most likely to be encountered during the implementation of the control strategy, will be sensor reliability and performance.

A control strategy that is slightly cheaper (less sensors required) to implement but less effective than the aeration rate – oxygen transfer efficiency control strategy was also briefly investigated. This control strategy uses the slope or first derivative of the temperature profile to determine the progress of the biochemical reaction, and from this the aeration rate can be regulated to prevent excessive aeration. This control strategy does not ensure that the biochemical reaction is achieving sufficient oxygen, and does not attempt to maximise the net heat production, therefore the oxygen transfer efficiency control strategy is the preferred option.

Investigations showed that the draw and fill strategy of an ATAD system has a strong influence on its performance. Unfortunately there are no clear-cut answers to optimising the draw and fill strategy, as it is very system dependent. The mathematical model did indicate that the largest sludge throughput is achieved when the disinfection and the stabilisation criteria are achieved at similar times, without saturating the aeration system or dropping the reactor temperature below 50^0C. Also, if the disinfection criterion is the system's constraint for prolonged periods the bacteria population can diminish due to lack of available organic substrates, which can result in process instability.

The mathematical model was able to demonstrate that the minimal Volatile Solids concentration for an ATAD system to generate sufficient energy to remain within the thermophilic temperature is approximately 3.1% or 31g/l.

Investigations showed a change in the organic solid loadings has dramatic effects on the operating temperature. To avoid these fluctuations in operating temperature the Volatile Solid concentration and hydraulic residence times should remain constant as much as possible. Any variations in organic loadings should be dealt with by changing the working volume of the system.

The model illustrated the effects of reactor geometry, and dimensions on mixing and aeration efficiencies, along with heat loss. The model was also able to illustrate the importance of insulation. The design investigations highlighted the number of interrelated factors that have to be considered during the design of an ATAD system.

It was this that initiated the development of a prototype design and simulation software package. After further refinement and model validation this will allow designers to explore different operational and design scenarios before the design even reaches the drawing table.

10.1 Further Research

Even though the research that has been undertaken with this thesis has potentially enhanced the performance, reliability, stability and economics of ATAD systems there has been a few areas of further research highlighted during this investigation.

The mathematical model requires more validation, to ensure that the model is capable of describing an ATAD system under a wide range of operational scenarios. Once the model has been successfully validated it could be used extensively in a wide range of applications, including design, simulation and optimisation software, or perhaps even incorporating the model into an advanced control system which optimises Class A biosolid production. Further research is required to find a satisfactory on-line method of determining when biosolids meet the Class A biosolid standard.

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Appendix I - Heat Transfer Coefficients

The overall heat transfer coefficient for an ATAD reactor is dependent on the size, geometry, weather conditions, construction type, insulation type, construction thickness, insulation thickness and headspace. To help designers determine the best properties as far as heat transfer is concerned the affects of each of these factors were included into the heat transfer calculation.

There are two different heat transfer coefficient equations needed for the two different possible reactor shapes. An ATAD reactor can be either a cylindrical reactor or a square reactor. It is more common to use a cylindrical reactor as better mixing can be achieved, but square tanks are sometimes also used for various reasons including retrofitting an existing tank.

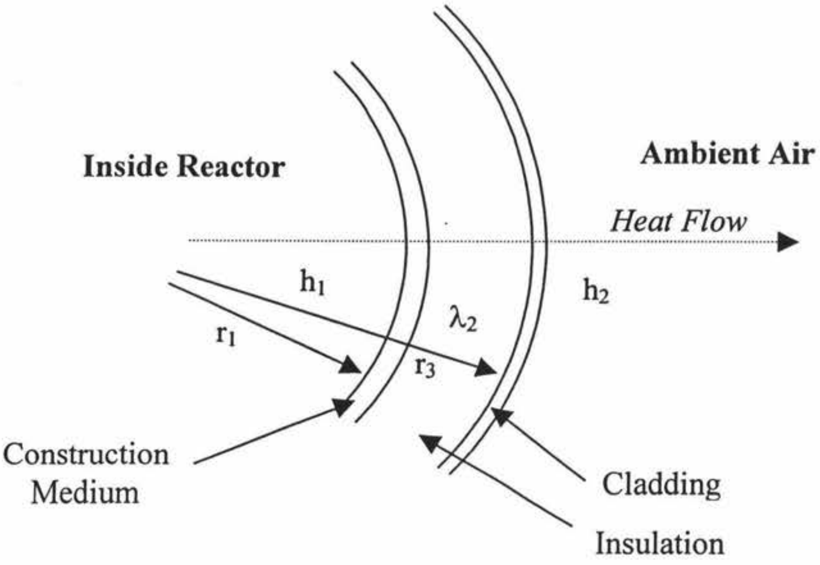


Figure 33 – Heat flow through a cylindrical wall

The heat transfer through a typical cylindrical reactor can be seen in Figure 33. Equation 64 shows how the heat transfer coefficient is calculated. The heat transfer through a typical square walled reactor can be seen in Figure 34 and Equation 65 shows how the heat transfer coefficient is calculated in this case. Table 4 shows some typical values thermal conductivity, λ, of various construction and insulation materials.

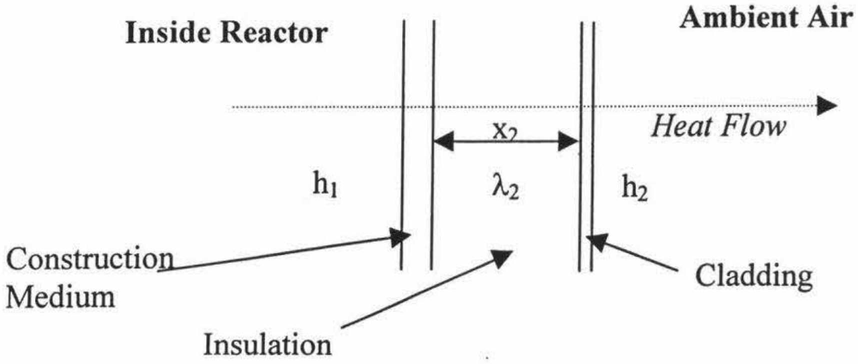


Figure 34 – Heat flow through a square wall

$$\frac{1}{U}=\frac{1}{h_1}+\frac{x_1}{\lambda_1}+\frac{x_2}{\lambda_2}+\frac{x_3}{\lambda_3}+\frac{1}{h_2} \tag{64}$$

$$\frac{1}{UA}=\frac{1}{2\Pi L}\left(\frac{1}{h_1 r_1}+\frac{\ln(r_2/r_1)}{\lambda_1}+\frac{\ln(r_3/r_2)}{\lambda_2}+\frac{\ln(r_4/r_3)}{\lambda_3}+\frac{1}{h_2 r_4}\right) \tag{65}$$

Material	**Thermal Conductivity, W/m ^{0}C**
Concrete	1.53
Steel	50
Polystyrene	0.035
Glass wool	0.055

Table 4 – Typical thermal conductivity

Appendix II – M-file Code

The constants and parameters required by the mathematical model are first calculated and then placed into the Matlab workspace by two m-files. These are called ATAD.m and ATADrates.m. Once the constants and parameters are in the Matlab workspace the Simulink model can call them during simulations.

ATAD.m provides all the physical parameters, such as the size of the reactor, the hydraulic residence times, heat transfer coefficients and fluid properties. ATADrates.m provides all the biochemical parameters, such as the rate constants, yield coefficients, initial starting parameters and the composition of the raw sludge.

The m-files are listed below with typical parameters used during all investigations.

ATAD.m

```
%----------------------------------------
%m-file for entering physical data for ATAD model
%see ATADrates.m for biochemical parameters
%----------------------------------------

global Patho

NRG=13.5;
ThermoGain=3.5;

%-----------------------------------------
%reactor parameters
%-----------------------------------------

if exist('tes','var') == 0,
   Vt=220;              %Working reactor volume, m3
   Ht=2.86;             %Working Reactor Height, m
   space=5.517-Ht;      %safety space above liquid, m
   shape=2;             %geometry selector, square=1, cylindical=2
   ConType=2;           %construction selection, concrete=1, steel=2
   ConT=0.012;          %construction thickness, m
   InsT=0.13;           %insulation thickness, m
   SteelT=0.003;        %steel cladding thickness, m
   InsType=2;           %insulation selection 1=polystrene, 2=glass
                        %wool, 3=none
   Weath=1;             %type of weather conditions 1=Hot&calm,
                        %2=Hot&windy,3=mild&calm, 4=mild&windy,
                        %5=cold&calm, 6=cold%&windy.
end
```

```
 Den=992;                              %Sludge density, kg/m3
 ConTB=0.15;                           %thickness of concrete at base, (m)
 load=Vt/7;                            %m3/cycle load
 flowout=(Den*load)/(0.25*3600);       %sludge flow rate during emptying
 flowin=(Den*load)/(0.25*3600);        %sludge flow rate during loading
 fulllev=Ht;                           %Height of sludge when full
 emplev=Ht-(load/(Vt/Ht));             %Empty reactor down to this height
 Patho=[0,0];                          %initiate disinfection parameters
 Pathof=[];                            %initiate disinfection parameters
 Pathos=[];                            %initiate disinfection parameters

 %-----------------------------------------
 %Mechanical efficiencies and operation
 %-----------------------------------------

 Peff=0.72;             %Pumps electrical to fluid efficiency
 Beff=0.6;              %Blower electrical to fluid efficiency
 Meff=0.95;             %Motor electrical to mechanical efficiency
 BPress=500;            %differential blower pressure mbar
 Patm=101.325;          %atmospheric Pressure kPa

 %-----------------------------------------
 %Fluid constants
 %-----------------------------------------

 Cp=4179;               %heat capacity, J/kg K
 Cpair=1008;            %heat capacity of air, J/kg K
 DenAir=1.1;            %density of air, kg/m3

 %-----------------------------------------
 %Air dissolvibility Data
 %-----------------------------------------

 Cs20=9.07;             %saturation concentration of air in water at 20
                        %degrees mg/l
 alphaF=0.9;            %Process water Kla/clean water Kla
 Beta=0.7;              %saturation modifier
 Aair=0.284;            %Kla calculation, Aair*Vs^Bair.
 Bair=0.771;            %Kla calculation, Aair*Vs^Bair.
 Fed=0.335;             %fractional effective saturation depth

 %-----------------------------------------
 %biochemical reaction properties
 %-----------------------------------------

 %see atadrates.m

 %-----------------------------------------
 %weather conditions
 %-----------------------------------------

 if Weath==1|Weath==3|Weath==5,        %calm condition
    Wind=1.5;                          %wind speed, m/s
 else                                  %windy condition
    Wind=5;
 end

 if Weath == 1|Weath == 2,             %Hot Weather
    OutTemp=25;                            %Air Temperature
    GroTemp=25;                            %Ground Temperature
```

```
elseif Weath == 3|Weath == 4,       %Mild Weather
   OutTemp=15;
   GroTemp=15;
else                                %cold Weather
   OutTemp=5;
   GroTemp=5;
end

%----------------------------------------
%thermal properties
%----------------------------------------

Carea=Vt/Ht;                  %Tank Cross section
Rad=(Carea/pi)^0.5;           %radius of reactor, m

ResSteel=50;                  %heat conductivity of steel, W/mk
Resconcrete=1.53;             %heat conductivity of concrete, W/mk
ResAirIn=2.5;                 %air heat transfer coeff, W/km2 2.5
ResAirOut=(0.025*0.239*((58823.529*(2*Rad)*Wind)^0.805))/(2*Rad);
                              %air heat transfer coeff, W/km2
ResLiq=160;                   %liquid heat transfer coeff, W/mk
ResGro=0.8;                   %ground heat conductivity, W/km2

%Select Construction Material
if ConType == 1,
   ResCon=Resconcrete;        %heat conductivity of concrete, W/mk
elseif ConType == 2,
   ResCon=ResSteel;           %heat conductivity of steel, W/mk
else
   error('Incorrect Construction selection');
end

%Select heat conductivity of insulation
if InsType == 1,
   ResIns=0.035;              %heat conductivity of polystrene, W/mk
elseif InsType == 2,
   ResIns=0.055;              %heat conductivity of Glass wool, W/mk
elseif InsType == 3,
   ResIns=0;                  %heat conductivity No Insulation, W/mk
else
   %Insulation type test
   disp('   WARNING: Incorrect Insulation Selection');
   disp('      Please enter a number between 1 and 3,');
   error('     1=Polystrene, 2=Glass wool, 3=None.');
end

%----------------------------------------
%Calculations
%----------------------------------------

%Check correct Construction Thickness
if ConT == 0,
   error('Incorrect thickness for Construction material or
Insultion');
end

%Check range of pump efficiency
if Peff > 1 | Peff < 0,
   error('  Warning: Pump efficiency out of acceptable range');
end
```

```
%Check range of blower efficiency
if Beff > 1 | Beff < 0,
   error('  Warning: Blower efficiency out of acceptable range');
end

%---------------------------------------
%Calculate heat resistance
%---------------------------------------

%heat resistance through ground
Ugro=1/(1/ResLiq+ConTB/Resconcrete+1/ResGro);
UAgro=Carea*Ugro;

if shape == 1,                           %square tank
   Peri=4*Carea^0.5;                     %perimeter
   SArea=2*Carea+Peri*(Ht+space);        %surface area of tank
   if SteelT == 0,                       %if no steel cladding
      Utop=1/(1/ResAirIn+ConT/ResCon+InsT/ResIns+1/ResAirOut);
               %roof of reactor
      Ul_a=1/(1/ResLiq+ConT/ResCon+InsT/ResIns+1/ResAirOut);
               %sludge to air
   elseif InsType ==3,                   %if no insulation
      Utop=1/(1/ResAirIn+ConT/ResCon+1/ResAirOut);
      Ul_a=1/(1/ResLiq+ConT/ResCon+1/ResAirOut);
   else        %if insulated with steel cladding
      Utop=1/(1/ResAirIn+ConT/ResCon+InsT/ResIns...
         +SteelT/ResSteel+1/ResAirOut);
      Ul_a=1/(1/ResLiq+ConT/ResCon+InsT/ResIns...
         +SteelT/ResSteel+1/ResAirOut);
   end
   UAtop=Carea*Utop;                     %roof of reactor
   Ua_a=Utop;                            %head space to air
   UAl_a=Peri*Ul_a;                      %sludge to air
   UAa_a=Peri*Ua_a;                      %head space to air
elseif shape == 2,                       %cylindrical tank
   SArea=2*Carea+2*Rad*pi*(Ht+space);
   %difference between steel and non-steel cladding
   if SteelT == 0,                       %if no steel cladding
      UAl_a=1/((1/(2*pi))*(1/(ResLiq*Rad)...
         +log((Rad+ConT)/Rad)/ResCon...
         +log((Rad+ConT+InsT)/(Rad+ConT))/ResIns...
         +1/(ResAirOut*(Rad+ConT+InsT))));          %sludge to air
      UAa_a=1/((1/(2*pi))*(1/(ResAirIn*Rad)...
         +log((Rad+ConT)/Rad)/ResCon...
         +log((Rad+ConT+InsT)/(Rad+ConT))/ResIns...
         +1/(ResAirOut*(Rad+ConT+InsT))));        %head space to air
      Utop=1/(1/ResAirIn+ConT/ResCon+InsT/ResIns+1/ResAirOut);
                                                 %reactor roof
  elseif InsType == 3,                 %if no insulation
      UAl_a=1/((1/(2*pi))*(1/(ResLiq*Rad)...
         +log((Rad+ConT)/Rad)/ResCon...
         +1/(ResAirOut*(Rad+ConT))));
      UAa_a=1/((1/(2*pi))*(1/(ResAirIn*Rad)...
         +log((Rad+ConT)/Rad)/ResCon...
         +1/(ResAirOut*(Rad+ConT))));
      Utop=1/(1/ResAirIn+ConT/ResCon+1/ResAirOut);
  else                                  %if insulated and cladded
     UAl_a=1/((1/(2*pi))*(1/(ResLiq*Rad)+...
        log((Rad+ConT)/Rad)/ResCon...
        +log((Rad+ConT+InsT)/(Rad+ConT))/ResIns...
```

```
        +log((Rad+ConT+InsT+SteelT)/(Rad+ConT+InsT))/ResSteel...
        +1/(ResAirOut*(Rad+ConT+InsT+SteelT))));

UAa_a=1/(1/((2*pi))*(1/(ResAirIn*Rad)+log((Rad+ConT)/Rad)/ResCon...
        +log((Rad+ConT+InsT)/(Rad+ConT))/ResIns+...
        +log((Rad+ConT+InsT+SteelT)/(Rad+ConT+InsT))/ResSteel...
        +1/(ResAirOut*(Rad+ConT+InsT+SteelT))));
     Utop=1/(1/ResAirIn+ConT/ResCon+InsT/ResIns+SteelT/ResSteel...
        +1/ResAirOut);
  end
  UAtop=Carea*Utop;             %roof of reactor
else
  %shape test
  error('  WARNING: Wrong Shape input Characteristic');
end

%--------------------------------------
%cleaning up workspace
%--------------------------------------
clear ResSteel ResAirIn ResAirOut ResLiq ResGro ResIns,
clear Utop Ul_a Ua_a Ugro,
clear ResCon Resconcrete load
```

ATADrates.m

While coding reading the code and the mathematical model it is necessary to realise the following alterations of terminology between the code and the thesis.

Total Suspended Solids (TSS) = Slowly Biodegradable Substrate (SBS)

Suspended Solids (SS) = Slowly Biodegradable Substrate (SBS)

Substrate (S) = Readily Biodegradable Substrate (RBS)

Non-Biodegradable Substrate (NB) = Non-Biodegradable Substrate (NBS)

Reduced Substrate (RS) = Volatile Fatty Acids (VFA)

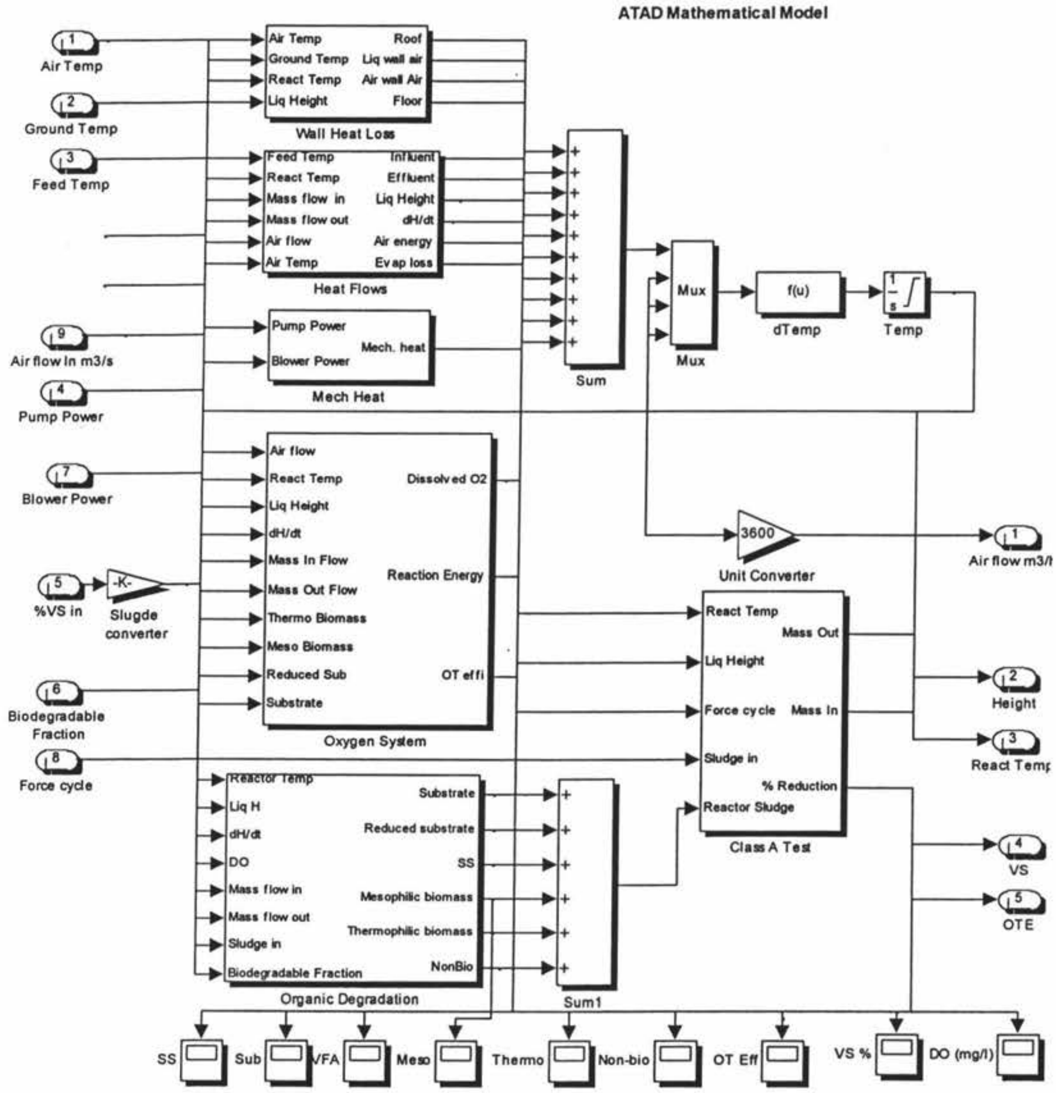
Hydrolysis = pathway from SBS to RBS

```
%-----------------------------------------
%Enters Biochemical parameters for ATAD model
%-----------------------------------------

%calls physical parameters
atad;

day=3600*24;          %seconds in a day

%Rate Constants
Us_b=0.0245168;        %rate constant for substrate to bacteria
Urs_b=0.01288988;      %rate constant for reduced substrate to bacteria
Us_rs=1.37243e-5;      %rate constant for substrate to reduced
substrate
Udie=6.34075e-5;       %rate constant for bacteria decay
```

```
Uhyd=0.0000237163;    %rate constant for hydrolysis

%substrate limits
Kdo=0.0858565;        %DO limitation on oxidation reaction
Kdof=0.0167095;       %DO limitation on fermentation reaction
Ks=512.802;           %substrate limitation
Krs=3372.15;          %reduced substrate limitation
Ktss=1500;            %TSS limitation

%feed stream
sludge=5*0.85;        %sludge concentration
BioFract=0.7;         %fraction of sludge that is biodegradable.
Xtin=10;              %thermophilic bacteria
Xmin=800;             %mesophilic bacteria
Sin=1000.57;          %substrate
RSin=0;               %reduced substrate 50

%initial conditions
Xto=800;              %thermophilic bacteria
Xmo=10;               %mesophilic bacteria
So=800*5;             %substrate
RSo=10;               %reduced substrate
TSSo=1500*4;          %total suspended solids
NBo=20800;            %non-biodegradable solids
Tempo=55;             %reactor Temperature 44
DOo=2;                %dissolved oxygen

%Yeild Coefficients

%substrate
SubDie=0.4;           %amount of substrate produced per bacteria death
Subhyd=0.95;          %amount of substrate produce per TSS consumed

%Resubstrate
ReSubS_RS=0.45;       %amount of reduced substrate produced per
                      %substrate consumed

%Oxygen
OxRS_B=1.4;           %amount of oxygen consumed per reduced substrate
                      %converted to bacteria
OxS_B=1.4;            %amount of oxygen consumed per substrate
                      %converted to bacteria
OxDie=0;              %amount of oxygen consumed per bacteria death

%bacteria
BactS_B=0.4;          %amount of bacteria produced per substrate
                      %consumed
BactRS_B=0.9;         %amount of bacteria produced per reduced
                      %substrate consumed

%hydrolysis
TSSdie=0.45;          %amount of TSS produced per bacteria death

%Non-Biodegradable
NBdie=1-TSSdie-SubDie;  %amount of bacteria that is converted to
                        %non-biodegradable sludge per 1 death.

BacMin=10;            %the minimum amount the bacteria
```

Appendix III – Simulink Model

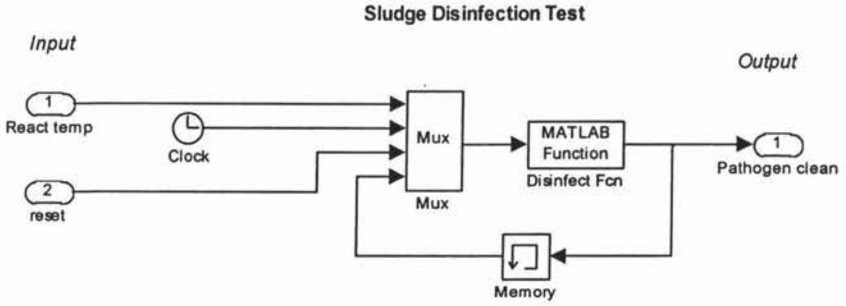
The simulink model was constructed in a number of subsystems, similar to the way it was discussed in Section 5. The complete model is shown below, this gives the reader a feel for the complexity of the model and how the subsystems interact with each other. The six subsystems are the wall heat loss, heat flows, mechanical heat, oxygen system, organic degradation and Class A test. The subsystems have not been expanded, as it is difficult to display them suitably on paper.



Appendix IV – Disinfection Test

To help with operation and control investigations a disinfection test was developed in a Matlab m-file. This m-file is able to flag when the sludge in the reactor has had sufficient pasteurisation to meet the USEPA Class A pathogen standard.

The Simulink subsystem, which calls the Disinfect.m m-file and the actual m-file, are shown below. This or similar code could be implemented into a SCADA (supervisory control and data acquisition) system to assist operators in determining when the sludge meets the required pasteurisation standards.



```
function clean=disinfect(u),

%-------------------------------------------------------
%clean = 1 when sufficient disinfection has occurred
%else clean = 0
%-------------------------------------------------------

global Patho
%Patho is used to store disinfection and temperature data

%------------------------------
%loading input parameters
%------------------------------
temp=u(1);          %current Temperature
time=u(2);          %current Time
flowin=u(3);        %Is new raw sludge being added
lastclean=u(4);     %the last disinfection flag

%----------------------------
%Main Disinfection test
%----------------------------

if flowin~=0,
```

```
    %if the reactor is being filled with raw sludge
    %reset the disinfection test

    Patho=[0,0];
    clean=0;
elseif lastclean==1,
    %if disinfected previously it is still disinfected
    clean=1;
elseif temp<50,
    %if the temperature is below 50 degrees no disinfection occurs.
    clean=0;
    Patho=[inf -inf];
elseif abs(temp-Patho(1,2))>0.25,
    %if the temperature has changed by more
    %than 0.25 degrees recalculate disinfection time
    %this is done to minimise data storage

    Distime=50070000/(10^(0.14*temp))*24*3600;
    %calculate the disinfection time at the current temperature
    %equation from USEPA 40CFR

    if Patho(1,2)==0,
       %if the disinfectin test has just been reset previously
       %make the Patho parameter empty
       Patho=[];
    end

    if Distime<1800,
       %if the disifection time is
       %less than 30 minutes use a different formula
       Distime=131700000/(10^(0.14*temp))*24*3600;
       %equation from USEPA 40CFR
       if Distime<15,
          %minimum disfection time of 15 seconds
          Distime=15;
       end
    end

    totaltime=Distime+time;
    %calculate time of expected disinfection
    Patho=[Patho; totaltime temp];
    %store time of disinfection and temperature

    if max(Patho(:,2)>temp)==1,
       %if the temperature has dropped go into loop
       cold=find(Patho(:,2)>temp);
       %find all disinfection times that were calculated
       %with a temperature that is higher than the current temperature
       Patho(cold,:)=[];
       %remove all disinfection times that were calculated
       %with a temperature higher than the current temperature
    end

    if min(Patho(:,1))<time,
       %if sludge has had minimal disinfection time
       %flag that sludge is disinfected
       clean=1;
    else
       clean=0;
    end
```

```
elseif min(Patho(:,1))<time,
   %if sludge has had minimal disinfection time
   %flag that sludge is disinfected
   clean=1;
else
   %if not disinfected flag not disinfected
   clean=0;
end
```